ACME ELEMENTARY SCHOOL

MOUNT BAKER SCHOOL DISTRICT, WHATCOM COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

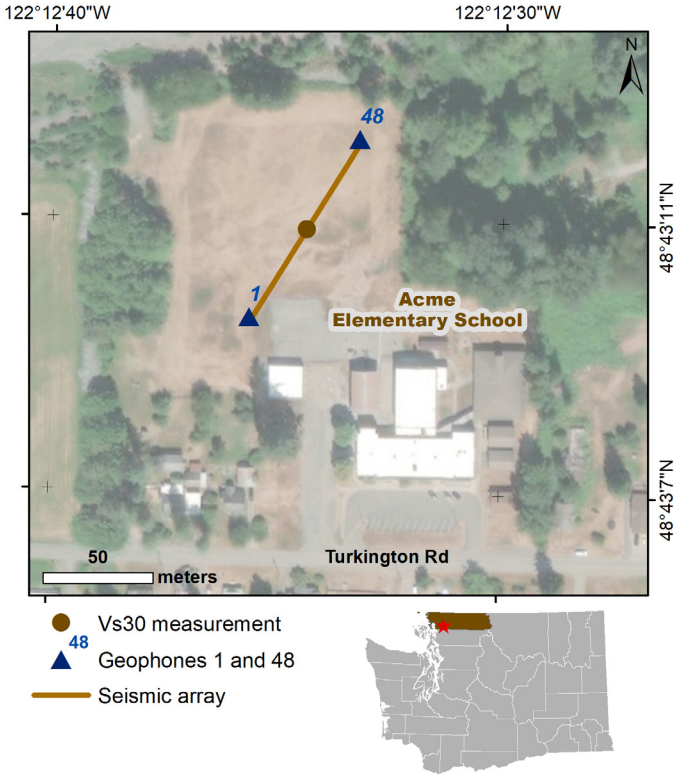
On October 29, 2020, a team from the Washington Geological Survey conducted a seismic survey at Acme Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvial fan deposits consisting of silt, sand, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

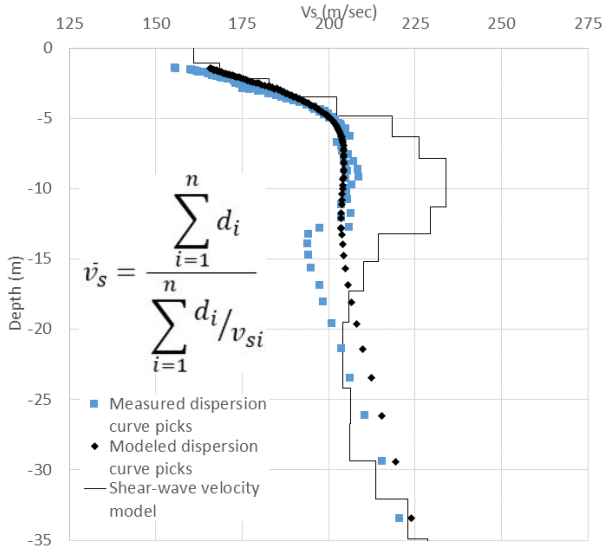
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 4.5 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 2.6 percent. The final model is unconstrained in the top 1.5 m (5 ft), and below this shows rapidly increasing velocity to 10 m (33 ft), then a velocity reversal down to 23 m (75 ft), and then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 208 m/sec, which places the site solidly in the D site class. This is the same as the predicted site class of D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

ADAMS ELEMENTARY SCHOOL

YAKIMA SCHOOL DISTRICT, YAKIMA COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

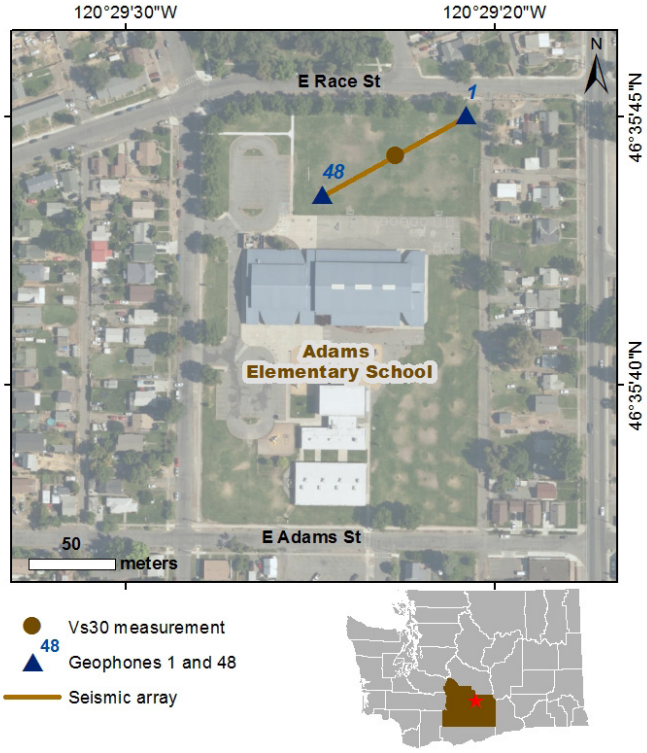
On October 5, 2020, a team from the Washington Geological Survey conducted a seismic survey at Adams Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on stream terrace deposits.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low to low

Ground Shaking
Very strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

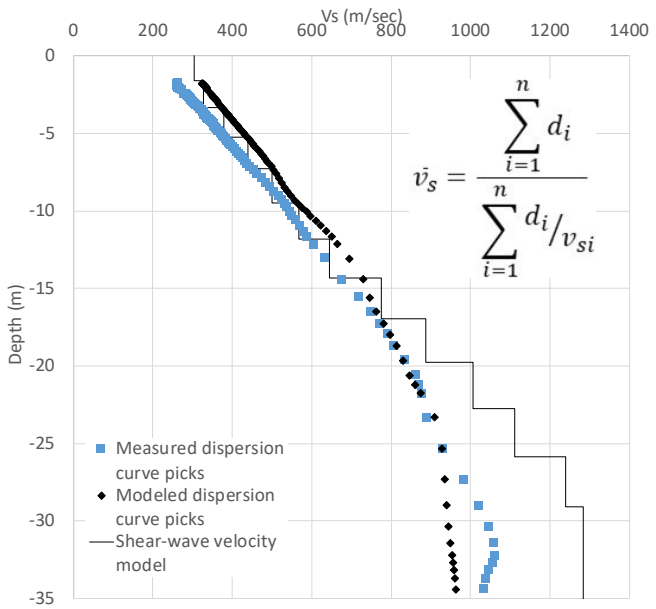
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is excellent quality. MAM and the forward MASW dispersion curves correlate well, depicting similar trends. Therefore the two dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 13.0 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 7.7 percent. The final model shows rapidly increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 627 m/sec, which places the site solidly in the C site class. All initial models are of the C class, so the site can be confidently classified. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the top right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in

A.J. WEST ELEMENTARY SCHOOL

ABERDEEN SCHOOL DISTRICT, GRAYS HARBOR COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

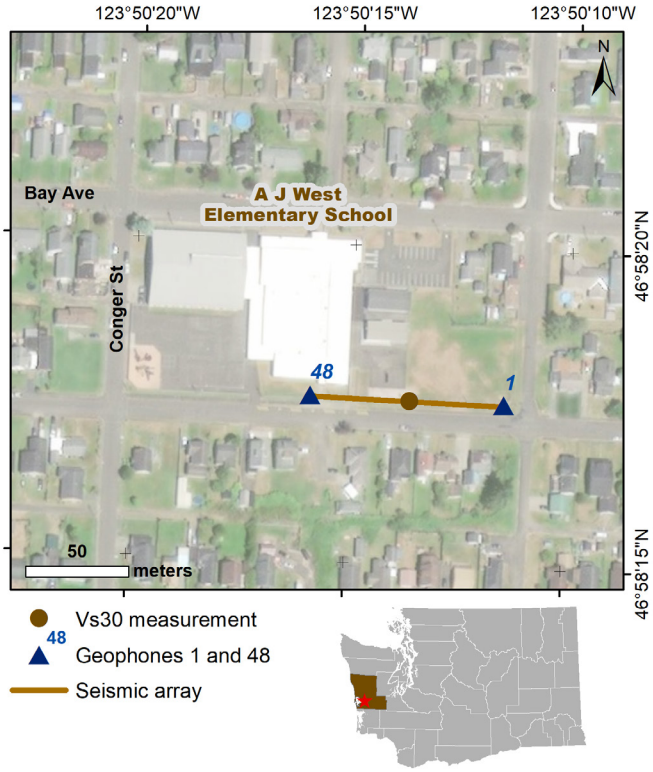
On October 21, 2020, a team from the Washington Geological Survey conducted a seismic survey at A.J. West Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium; river sediments consisting mostly of boulder, cobble, and pebble gravel and sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Extreme

Tsunami
In a mapped tsunami hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

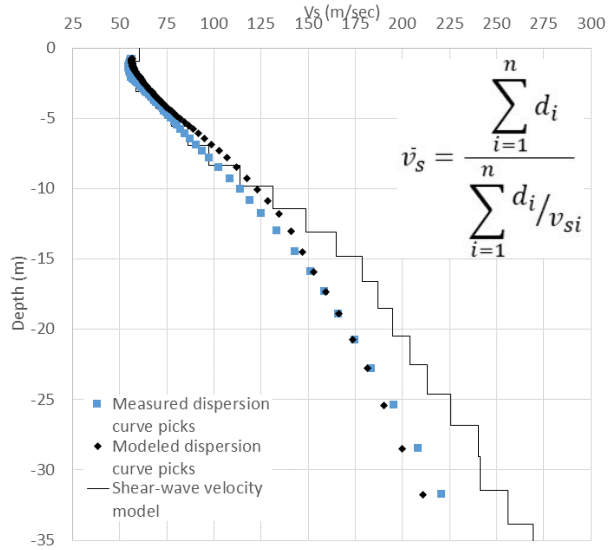
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also excellent quality, and MAM and the forward and reverse MASW dispersion curves correlate well. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 10.4 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.6 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 128 m/sec, which places the site solidly in the E site class. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

ALBERT EINSTEIN ELEMENTARY SCHOOL

LAKE WASHINGTON SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

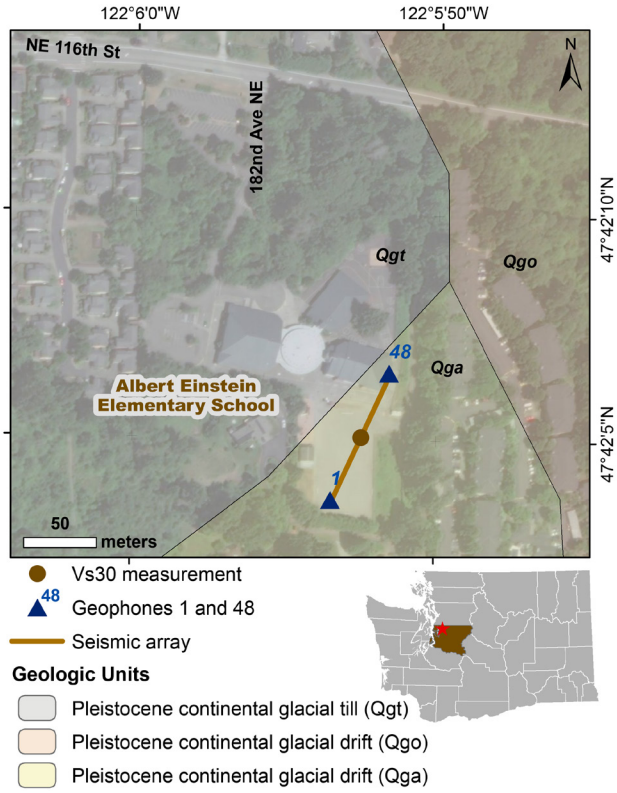
On July 28, 2020, a team from the Washington Geological Survey conducted a seismic survey at Albert Einstein Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

Most of the school buildings are on continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel (unit Qgt). The eastern and southeastern edge of the campus is on Pleistocene continental glacial drift (units Qgo and Qga).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

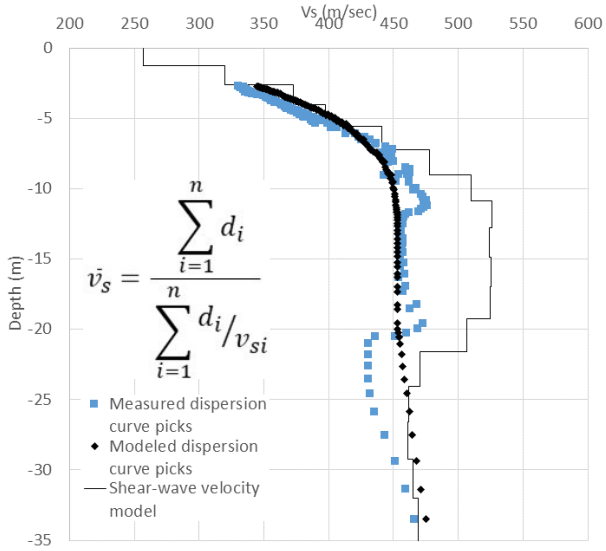
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is excellent quality but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 6.7 percent. The inversion was carried out for three iterations and resulted in a final model with an RMSE of 5.0 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows generally increasing velocity to 11 m (36 ft), then nearly constant velocity to 19 m (62 ft), a velocity reversal to 24 m (79 ft), then nearly constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 450 m/sec, which places the site solidly in the C site class. This is the same as the predicted site class of C.

GEOLOGY

The 1:100,000-scale geologic map shows a contact between geologic units under the school building. Most of the building is on Pleistocene continental glacial till (Qgt) with a predicted site class of C, but the eastern edge is on Pleistocene continental glacial drift (unit Qga), with a predicted site class of C–D. the northeastern edge of the campus is on another unit of glacial drift (Qgo), also with a predicted site class of C–D. Nearby boreholes show mostly unconsolidated sediments with the occasional more cemented layer in the top 30 m. The seismic array is on unit Qga, which has the possibility for a lower site class. As our Vs30 is solidly in the C site class, we can confidently assign a site class C to the campus.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

BAINBRIDGE HIGH SCHOOL, COMMODORE OPTIONS SCHOOL, AND ORDWAY ELEMENTARY SCHOOL

BAINBRIDGE ISLAND SCHOOL DISTRICT, KITSAP COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

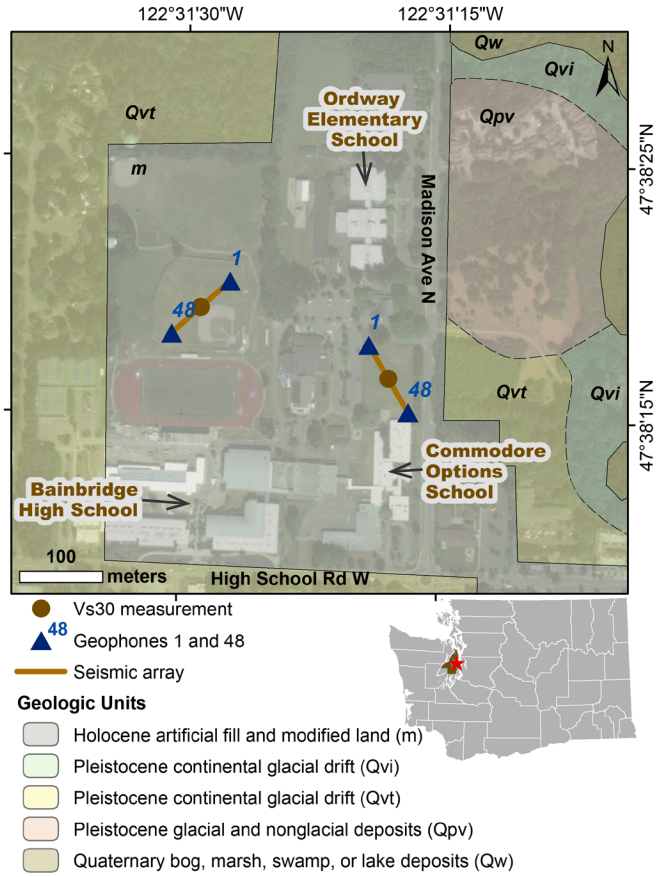
On October 7, 2020 and April 16, 2021, a team from the Washington Geological Survey conducted seismic surveys at Bainbridge High School, Commodore Options School, and Ordway Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in 94 m (308 ft) arrays. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the schools.

WHAT DID WE LEARN?

- The schools are built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic arrays at the school campus.

WHAT SOILS ARE UNDER THE SCHOOLS?

The schools are sitting on artifcial, manmade fill of unknown depth (unit m). The schools are flanked on the east and west with glacial and nonglacial deposits.

GEOLOGIC HAZARDS AT THE SCHOOLS

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

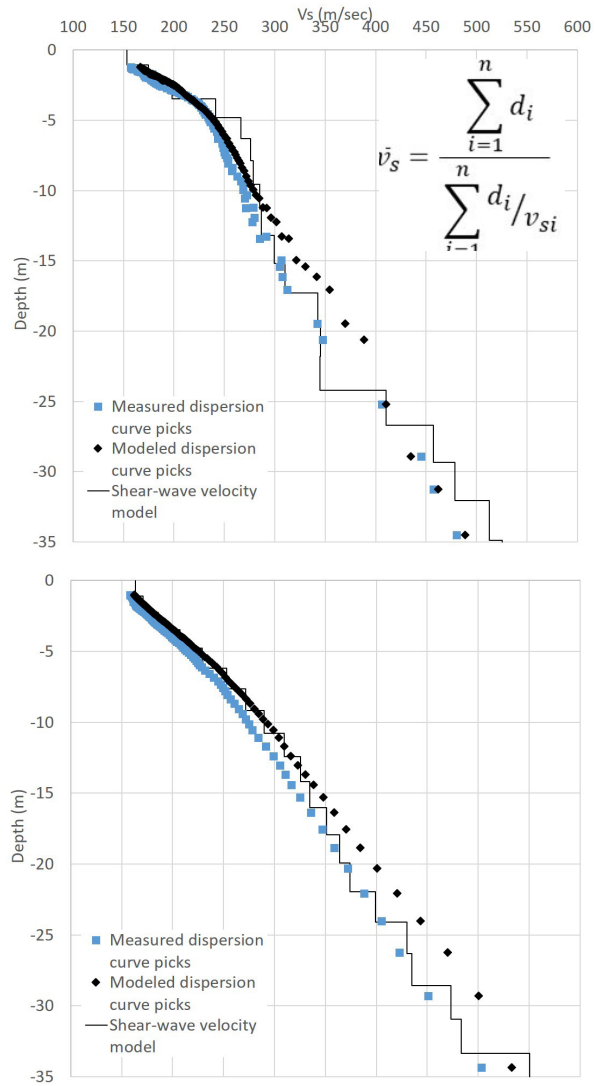
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality for both lines, so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is excellent quality for both lines. The MAM dispersion curves correlate well with their respective MASW curves. For both lines, three dispersion curves (MAM and forward and reverse MASW) are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves for both arrays. The initial model for the line on the east side of the campus had an RMSE of 9.35 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.9 percent. Our best Vs30 measurement for this line is 295 m/sec. The initial model for the line in the center of campus (near the baseball field) had an RMSE of 9.8 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.3 percent. Our best Vs30 measurement for this line is 300 m/sec. The Vs30s from both lines are similar, and solidly in the D site class. All initial and inverted models from both lines place this site in the D class, so the site can be confidently classified. This is different from the predicted site class of C.

GEOLOGY

The 1:24,000-scale geologic map shows both seismic arrays and most of the school buildings are located on artificial fill (unit m) surrounded by continental glacial drift (units Qvt, Qvi), and other deposits (unit Qpv). The 1:100,000-scale geologic map places the entire campus on glacial till (unit Qgt) with a predicted site class of C. Closely to the east (~300 m) are mapped glacial drift and Quaternary alluvium with predicted site class of D and D-E, respectively. Nearby boreholes show mostly unconsolidated sediments in the top 30 m, with frequent layers of hardpan of a wide range of thicknesses. This is a good indication of heterogeneity within the 1:100,000-scale geologic unit. The 1D velocity models for both arrays indicate weaker, less consolidated material in the upper 5 m (16 ft) underlain by materials that become significantly denser with depth. The change in site class could be due to a thick layer of fill, lateral heterogeneity within the unit, or low-resolution mapping.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner of the top figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer. Top: east line; Bottom: center line.

BANCROFT (THE COMMUNITY SCHOOL)

SPOKANE SCHOOL DISTRICT, SPOKANE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

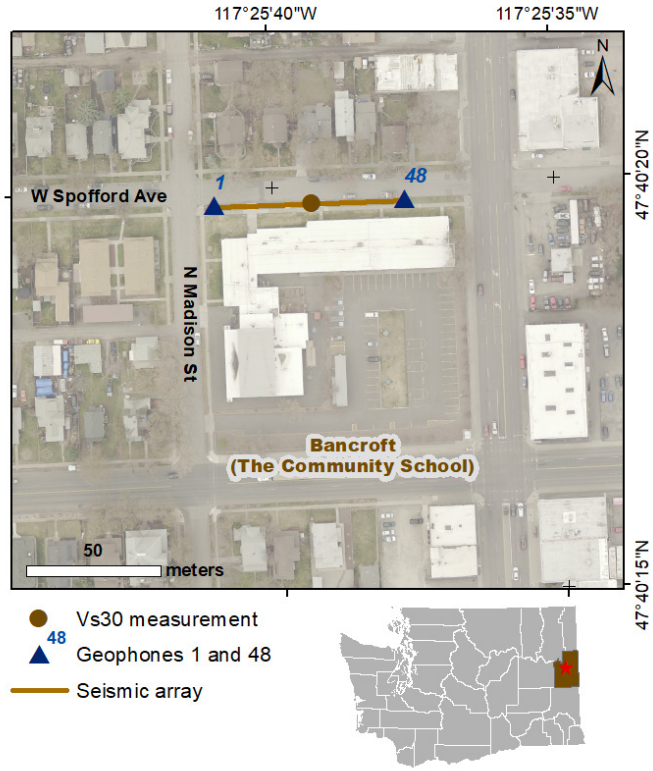
On September 29, 2020, a team from the Washington Geological Survey conducted a seismic survey at Bancroft (The Community School). We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (231 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of B.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene glacial flood-channel deposits, comprised mostly of thick-bedded to massive mixtures of boulders, cobbles, pebbles, granules, and sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Unknown, not negligible

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

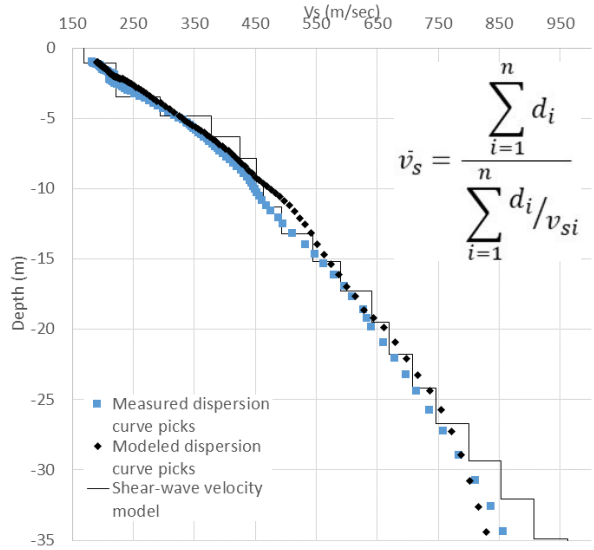
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the top 5 m (16 ft). MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 11.4 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.4 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 461 m/sec, which places the site solidly in the C site class. All initial and inverted models place this site in the C class, so the site can be confidently classified. This is different from the predicted site class of B.

GEOLOGY

The 1:100,000-scale geologic map places the school building and seismic array on basalt (unit $Mv_{(gN2)}$) with a predicted site class of B, and ~200 m (650 ft) north of the school are outburst flood deposits (unit Qfg) with a predicted site class of C. However, the 1:24,000-scale higher-resolution map depicts the school building, array, and surrounding area as on outburst flood deposits. Nearby boreholes show cobbles, gravels, and sand down to 30 m (100 ft), which correlates with the 1:24,000-scale map. The 1D velocity model does not reach rock velocity until ~24 m (79 ft), which indicates basalt is not at the surface. Thus, the change in site class is likely due to low resolution mapping.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

BEAVER VALLEY SCHOOL

CASCADE SCHOOL DISTRICT, CHELAN COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

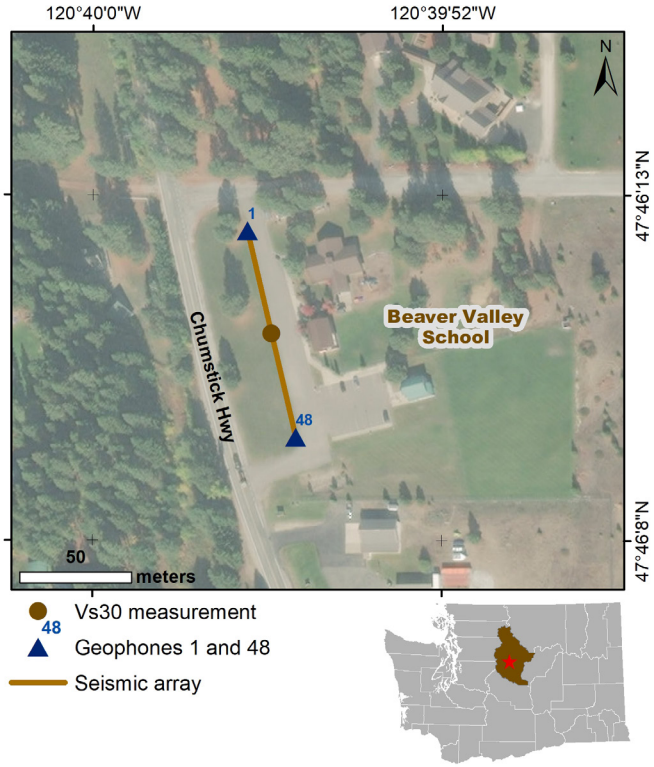
On April 5, 2017, a team from the Washington Geological Survey conducted a seismic survey at Beaver Valley School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary terrace deposits consisting mostly of sand and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low to low

Ground Shaking
Severe

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

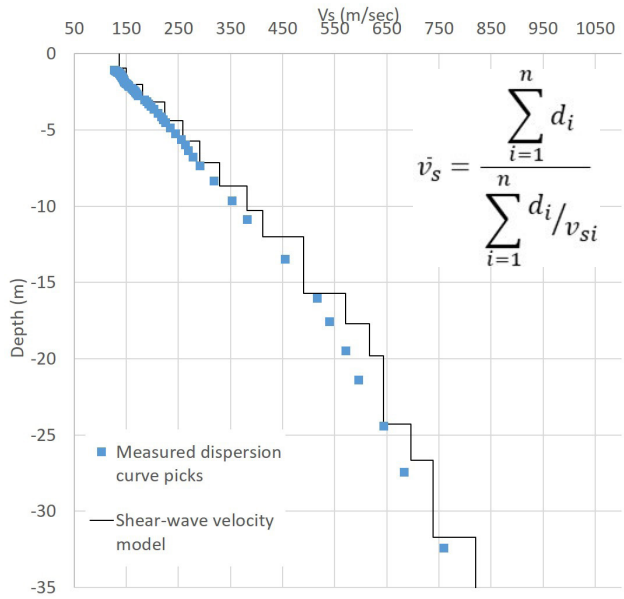
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with reasonable confidence. The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the deeper layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. However, because the MAM dosn't sample past 30 m (100 ft), it is not used and the MASW dispersion curves from the forward and reverse direction are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. Although inverted models converge to a reasonable RMSE after 15 iterations, they model unrealistic velocity structure. Therefore, the initial model is used as the final model, which is unconstrained in the top 1 m (3 ft), but shows generally increasing velocity to 30 m (100 ft). Our best Vs30 measurement is 386 m/sec, which is the same as the predicted site class of C. All initial models are firmly in the C class and we do not observe heterogeneity across the array, so the site can confidently be assigned to C site class.



Final velocity model with measured dispersion curve based on the intial model. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

BELFAIR ELEMENTARY SCHOOL

NORTH MASON SCHOOL DISTRICT, MASON COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

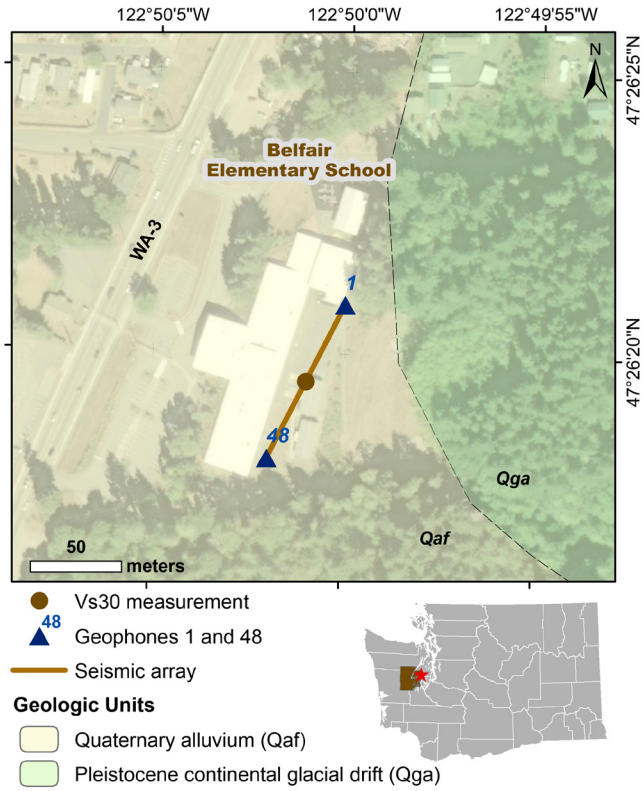
On August 23, 2019, a team from the Washington Geological Survey conducted a seismic survey at Belfair Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvial fan deposits consisting of silt, sand, and gravel (unit Qaf), with Pleistocene continental glacial drift (unit Qga) mapped closely to the east.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low to low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

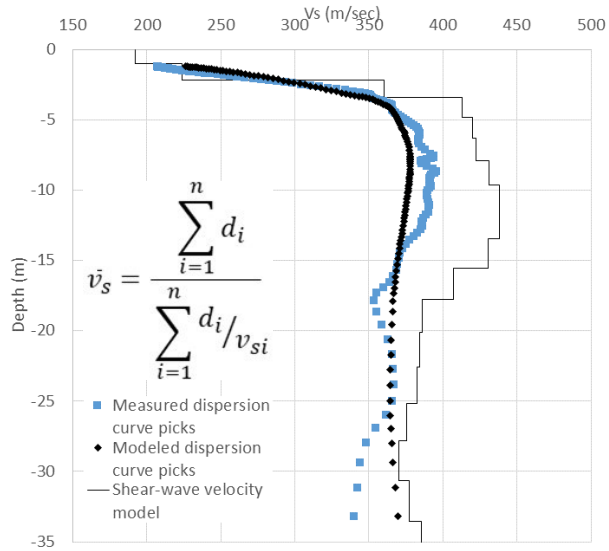
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image from the forward and reverse directions are poor quality so that the fundamental mode can be picked with some confidence. The microtremor analysis method (MAM) dispersion image is decent quality, and the resulting dispersion curve depicts trends similar to the MASW dispersion curves. The MAM and forward direction MASW dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 8.6 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.0 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows rapidly increasing velocity to about 10 m (30 ft), a slight reversal to 15 m (45 ft), and then generally constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 376 m/sec, which places the site near the C/D boundary, in the C site class. All initial and inverted models are of the C class. This is within the predicted site class of C–D.

GEOLOGY

The 1:24,000-scale geologic map on the previous page shows a contact crossing the school campus, but not through any buildings. The seismic site class map, however, places the school buildings and surrounding areas (at least 300 m (1000 ft) around the school) on a predicted site class C-D. Nearby boreholes confirm compact sediments past 30 m (100 ft) and we do not see any evidence for significant heterogeneity across the array, so this site can be classified a site class C with reasonable confidence.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

BEVERLY PARK ELEMENTARY SCHOOL

HIGHLINE SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

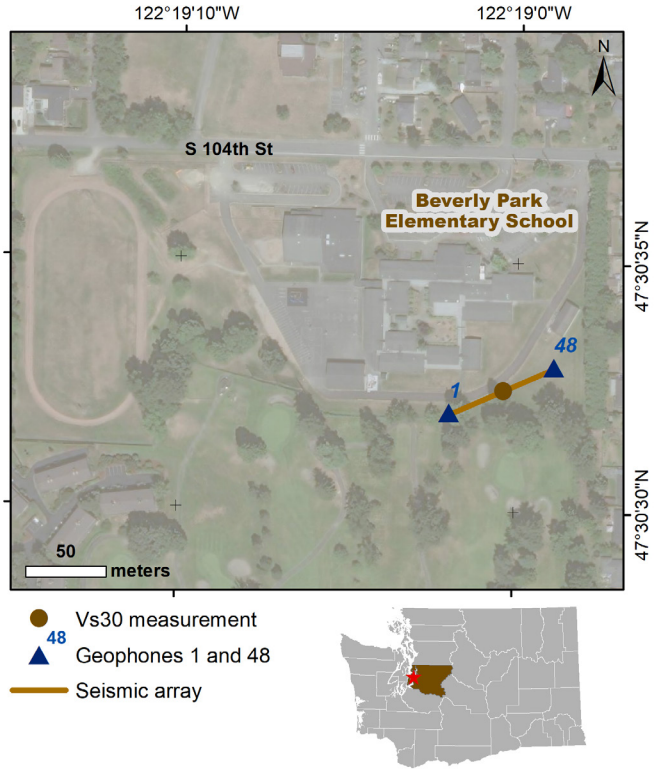
On August 19, 2020, a team from the Washington Geological Survey conducted a seismic survey at Beverly Park Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (231 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

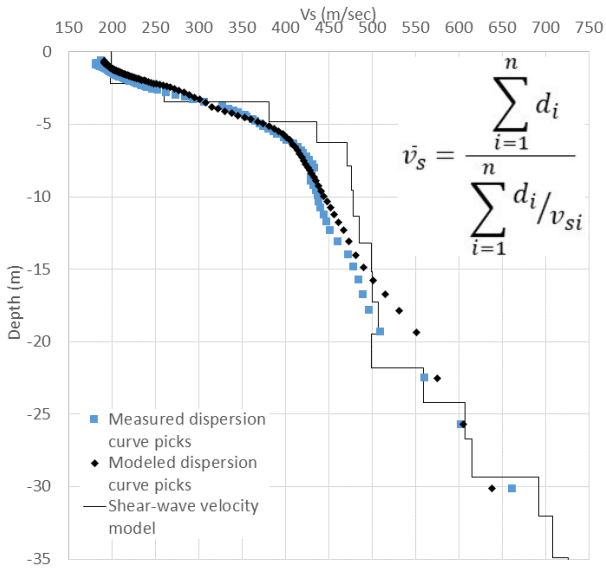
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is also decent quality, and depicts trends similar to the forward and reverse MASW dispersion curves. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 10.0 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 4.7 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows rapidly increasing velocity to 6 m (20 ft), then nearly constant velocity down to 22 m (72 ft), and then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 443 m/sec, which places the site solidly in the C site class. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

BLUE HERON MIDDLE SCHOOL

PORT TOWNSEND SCHOOL DISTRICT, JEFFERSON COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

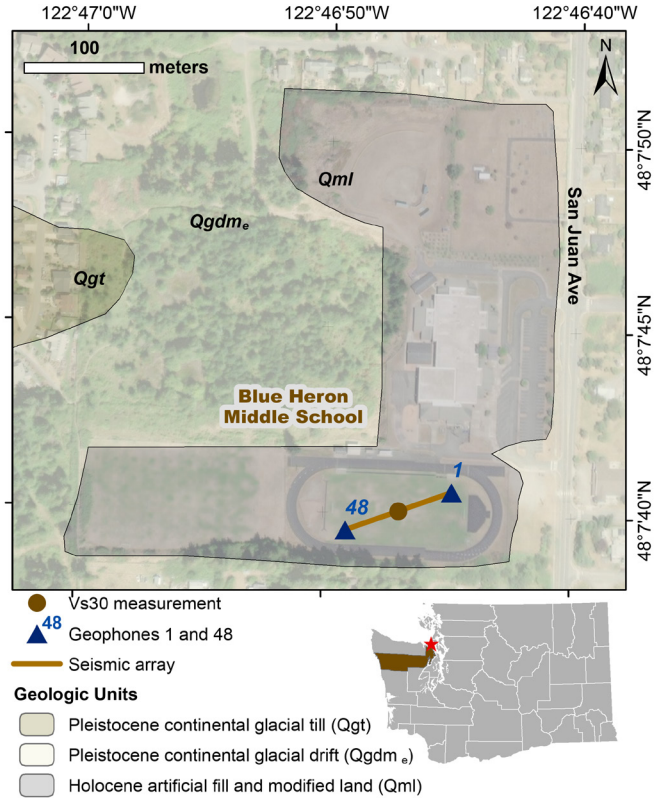
On December 14, 2019, a team from the Washington Geological Survey conducted a seismic survey at Blue Heron Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Holocene artificial fill and modified land (unit Qml). Mapped around the school is Pleistocene continental glacial drift (unit Qgdm$_e$), consisting mostly of gravelly silt with dropstones and layers of gravel, sand, silt, and clay.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

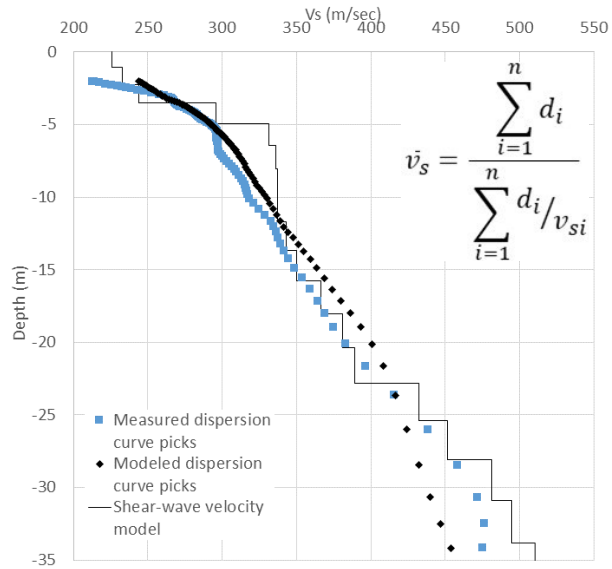
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image from the forward direction is poor quality, but the reverse direction is decent quality so that the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is decent quality, but does not sample the shallower layers. MAM and forward and reverse MASW dispersion curves correlate well. Therefore the three curves are combined into a single final model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 5.9 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.3 percent. The final model shows generally increasing velocity to 5 m (16 ft), then nearly constant velocity to 12 m (39 ft), then generally increasing velocity to 23 m (75 ft), and more quickly increasing velocity to 30 m (100 ft). Our best Vs30 measurement is 350 m/sec, which places the site in the D class, near the C/D site class boundary. This is different from the predicted site class of C.

GEOLOGY

The 1:100,000-scale geologic map, which is used to predict site classes, places the school buildings on continental glacial till, with a predicted site class of C, and maps glacial drift to the north, with a predicted site class of C–D. The 1:24,000-scale geologic map, however, places the school buildings and seismic array on artificial fill (unit Qml), surrounded by glacial drift (unit $Qgdm_e$). As artifical fill is generally shallow, it is likely that the fill is underlain by glacial drift. Since glacial drift has a predicted site class of C–D, this better matches the measured site class of D, and the site class change could be due to low-resolution mapping. Alternatively, the velocity model shows a sharp change at ~4 m (13 ft), so it is also possible a layer of artificial fill overlays till and reduces Vs30 to just below the C/D boundary.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

BOSTON HARBOR ELEMENTARY SCHOOL

OLYMPIA SCHOOL DISTRICT, THURSTON COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

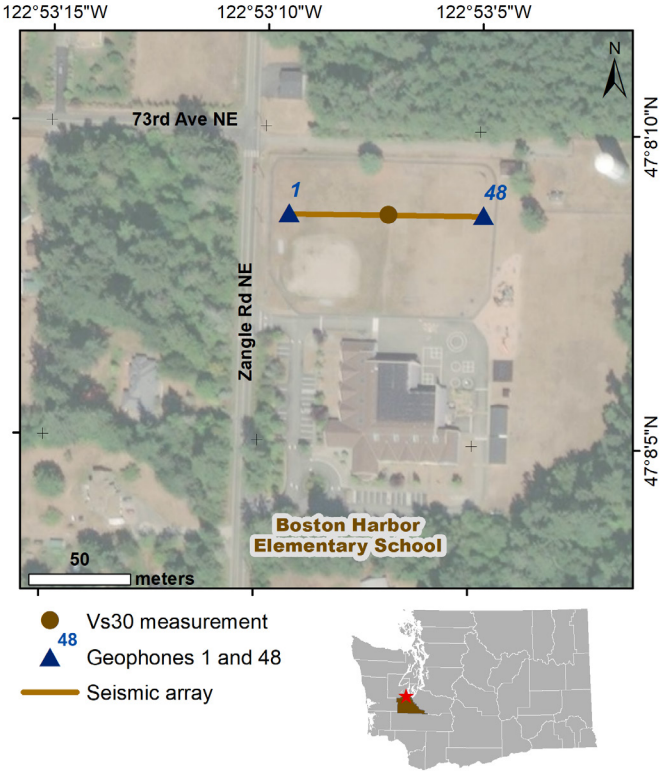
On August 5, 2020, a team from the Washington Geological Survey conducted a seismic survey at Boston Harbor Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

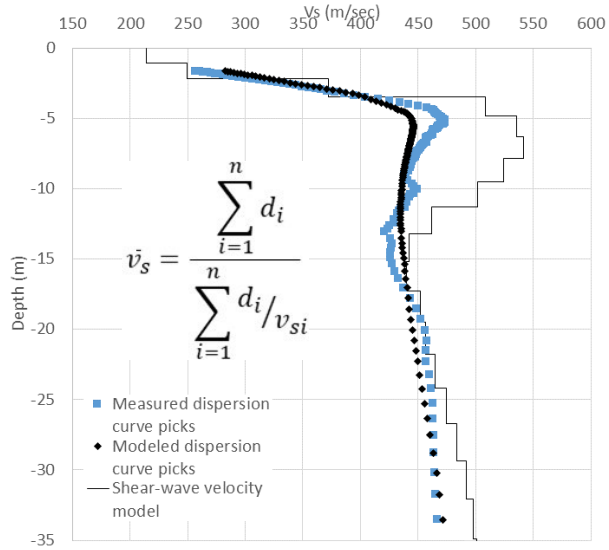
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the top 5 m (16 ft). MAM and the forward and reverse MASW dispersion curves depict similar trends, therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 8.7 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.5 percent. The final model is unconstrained in the upper 1 m (3 ft), and below this shows rapidly increasing velocity to 5 m (16 ft), then a significant velocity reversal down to 15 m (49 ft), and then steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 439 m/sec, which places the site solidly in the C site class. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = Shear wave velocity in m/sec of the layer.

BRIGADOON ELEMENTARY SCHOOL

FEDERAL WAY SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

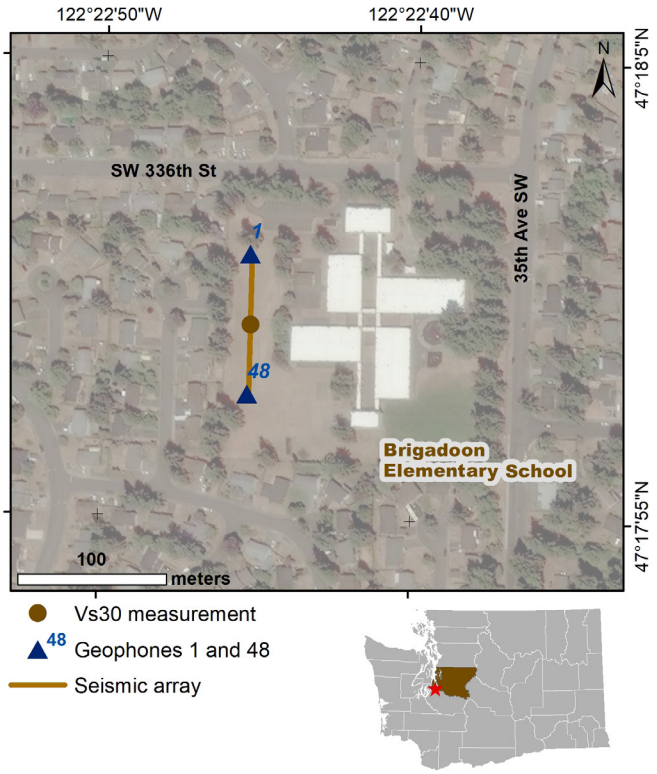
On February 26, 2020, a team from the Washington Geological Survey conducted a seismic survey at Brigadoon Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on glacial till deposits consisting of mostly silt and sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

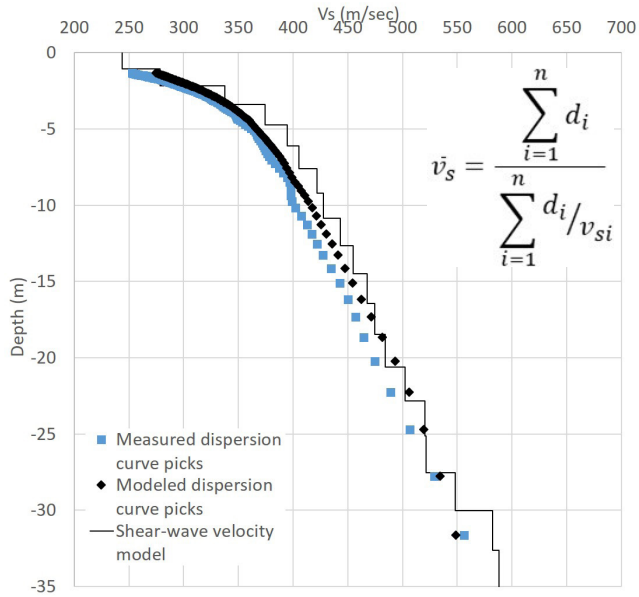
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also excellent quality. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. The three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 7.0 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.6 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows rapidly increasing velocity to 5 m (16 ft), and then steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 435 m/sec, which places the site in the middle of the C site class. All the initial and inverted models are in site class C, so the site can be confidently classified. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

BRINNON ELEMENTARY SCHOOL

BRINNON SCHOOL DISTRICT, JEFFERSON COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

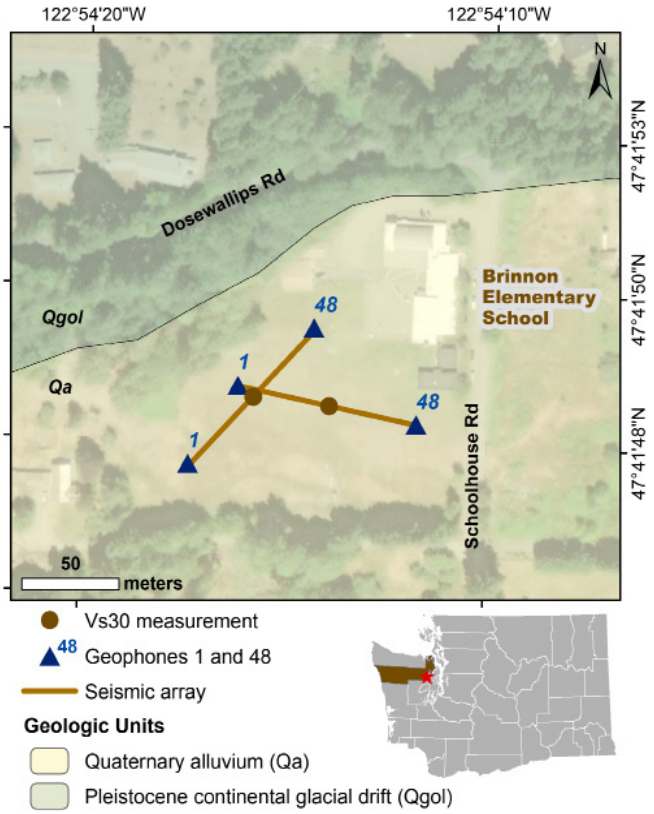
On November 14, 2019, a team from the Washington Geological Survey conducted a seismic survey at Brinnon Elementary School. We measured Vs30 by laying out 2 lines of 48 geophones (ground motion sensors) in a 94 m (308 ft) array each. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school. The survey at this campus had 2 seismic lines, due to suspected heterogeneity in the geology.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS C



WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium (unit Qa), consisting mostly of boulder, cobble, and pebble gravel and sand. Mapped to the north is Pleistocene continental glacial drift (unit Qgol).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

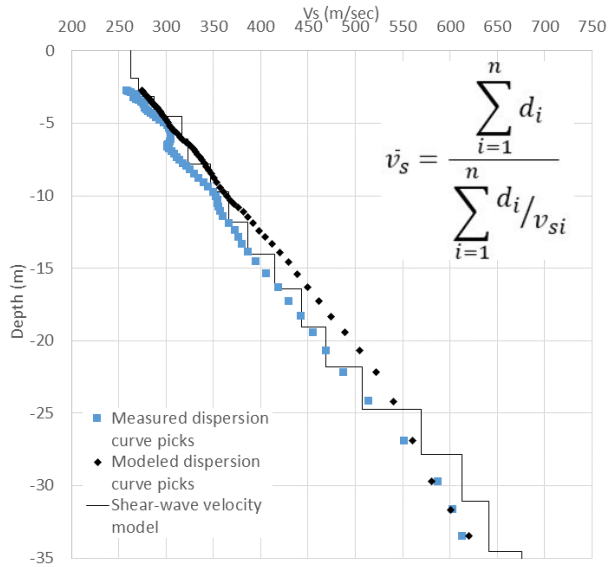
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality for both the SW–NE and W–E lines, so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is excellent quality for the SW–NE line and decent quality for the W–E line. The resulting dispersion curves correlate well with their respective MASW curves. For both lines, three dispersion curves (MAM and forward and reverse MASW) are combined into a single model.

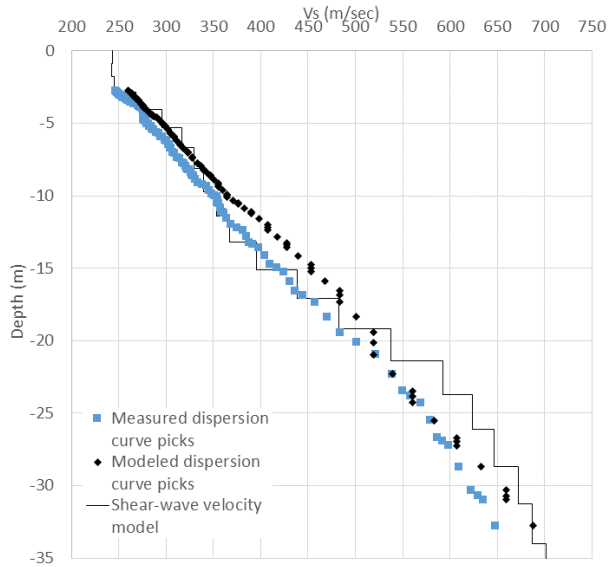
VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves for both arrays. The initial model for the SW–NE line had an RMSE of 10.9 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.7 percent. The final model shows generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement for this line is 396 m/sec, which places the site solidly in the C site class. The initial model for the W–E line had an RMSE of 12.2 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 5.5 percent. The final model shows slowly increasing velocity down to 15 m (49 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement for this line is 403 m/sec, which again places the site solidly in the C site class. All initial and inverted models from both lines place this site in the C class, so the site can be confidently classified. This is different from the predicted site class of D–E.

GEOLOGY

The 1:24,000-scale geologic map places both seismic arrays and the school buildings on alluvium (unit Qa), with a predicted site class of D–E, and mapped to the north is glacial drift (unit Qgol) with a predicted site class of C-D. Nearby boreholes indicate clay, sand, and gravel down to ~20 m, then hardpan or a lightly cemented layer below that. The velocity models for both arrays are very similar, and while neither confirms a contact with bedrock or between units Qa and Qgol within the upper 30 m (100 ft), higher velocities associated with more consolidated materials do show up at ~20–25 m (66–82 ft). Thus, the change in site class could be due to a subsurface geologic contact, a lateral change within unit Qa such as more cemented deposits, or mismapping of the Qa/Qgol geologic unit contact.





Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner of the top figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer. Top: SW–NE line; bottom: W–E line.

BRYANT CENTER

SPOKANE SCHOOL DISTRICT, SPOKANE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

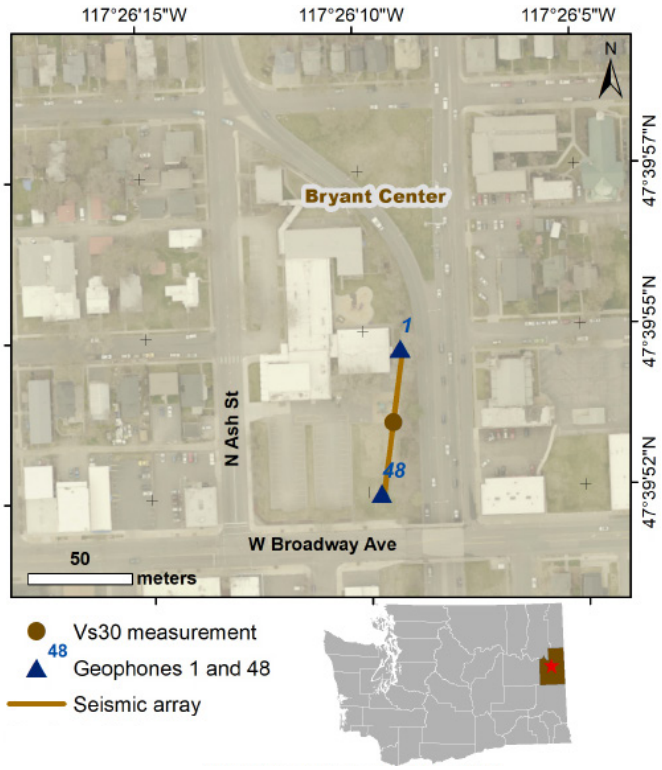
On September 29, 2020, a team from the Washington Geological Survey conducted a seismic survey at Bryant Center. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (230 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of B.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on glacial flood-channel deposits, predominantly gravel (unit Qfcg).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Unknown, not negligible

Ground Shaking
Very Strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

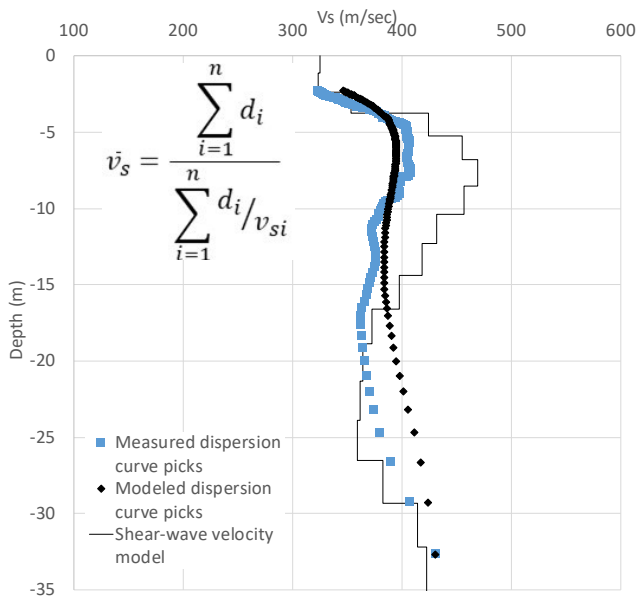
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so the fundamental mode can be picked with high confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also excellent quality, but does not sample the shallow layers. MAM and the reverse and forward MASW dispersion curves correlate well, depicting similar trends. Therefore the dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 5.3 percent. The inversion was carried out for three iterations and resulted in a final model with an RMSE of 4.0 percent. The final model shows rapidly increasing velocity until a large velocity reversal at about 7 m (21 ft) depth to 17 m (56 ft), then steadily increasing velocity down to 30 m (100 ft). The upper 3 m (9 ft) are unconstrained, however manually adjusting the upper layers does not result in a significant velocity change. Our best Vs30 measurement is 389 m/sec, which places the site within the C site class near the D/C boundary. All initial and inverted models are within the C class, so the site can be confidently classified. This is different from the predicted site class of B.

GEOLOGY

The 1:24,000-scale geologic map shows the seismic array and the school buildings are located on glacial flood deposits (unit Qfcg), which does not match the 1:100,000-scale geologic map that shows the site sitting on the contact between glacial flood deposits (unit Qfg) and Grande Ronde Basalt (unit Mv_{gN2}). The higher resolution 1:24,000-scale geologic map shows this contact mapped further to the northeast. Nearby boreholes also indicate sands and gravels in the upper 3 m (10 ft) coarsening to larger gravel by 5 ft (15 m), similar to the velocity structure of the 1D model. The initial predicted site class of B was based on the 1:100,000-scale geology map, however the 1:24,000-scale geologic map is more accurate and correlates with the measured site class of C. Thus, the change in site class is likely due to poor mapping resolution.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper left corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

BURLINGTON-EDISON HIGH SCHOOL AND WEST VIEW ELEMENTARY SCHOOL

BURLINGTON-EDISON SCHOOL DISTRICT, SKAGIT COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

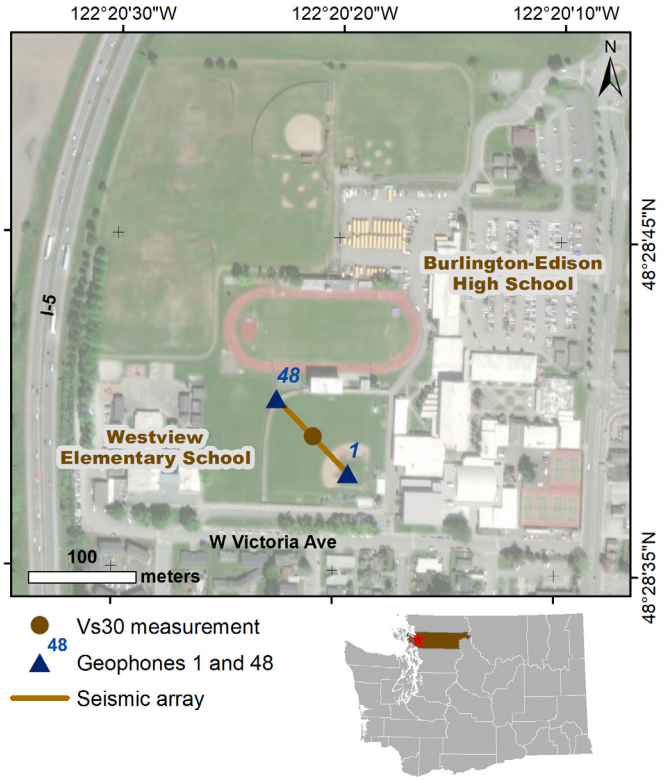
On December 2, 2020, a team from the Washington Geological Survey conducted a seismic survey at Burlington-Edison High School and West View Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The schools are built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The schools are sitting on fluvial sand, silt, and gravel with minor lacustrine deposits.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Violent

Lahar
In a mapped lahar hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

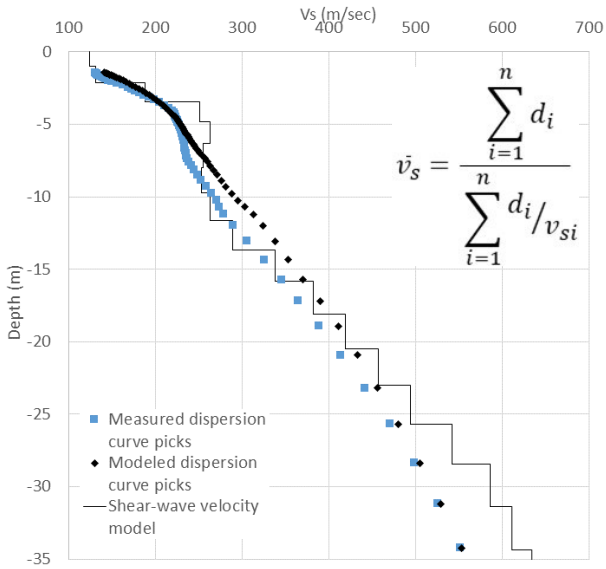
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are of decent quality so the fundamental mode can be picked with confidence, but these do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of excellent quality and the fundamental mode can be picked with high confidence, but does not sample the shallow layers. Thus, the forward MASW and MAM dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 12.6 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.9 percent. The final model shows generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 189 m/sec, which places this site in the D class but near the D/E site class boundary. Initial and inverted models all place this site in the D class, so the site can be confidently classified. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

CAMAS PRAIRIE ELEMENTARY SCHOOL

BETHEL SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

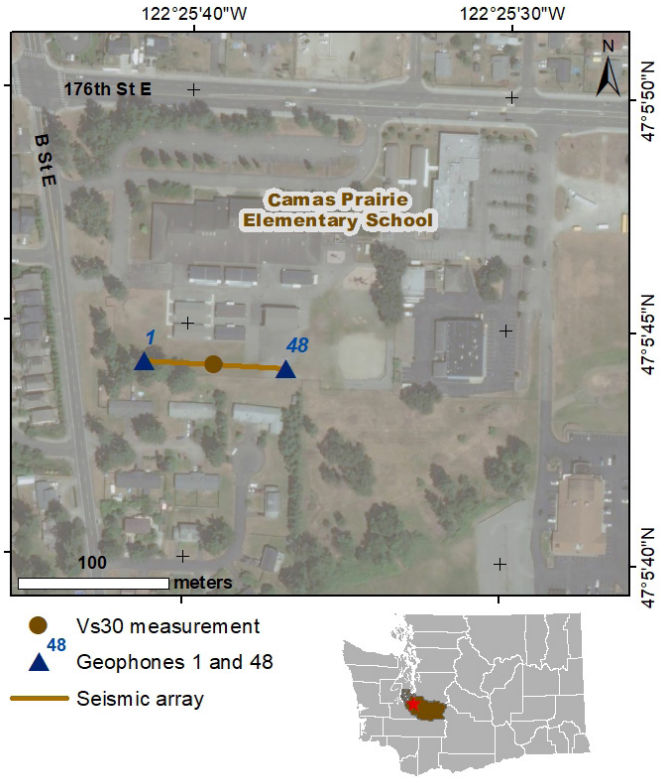
On March 11, 2020, a team from the Washington Geological Survey conducted a seismic survey at Camas Prairie Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low to low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

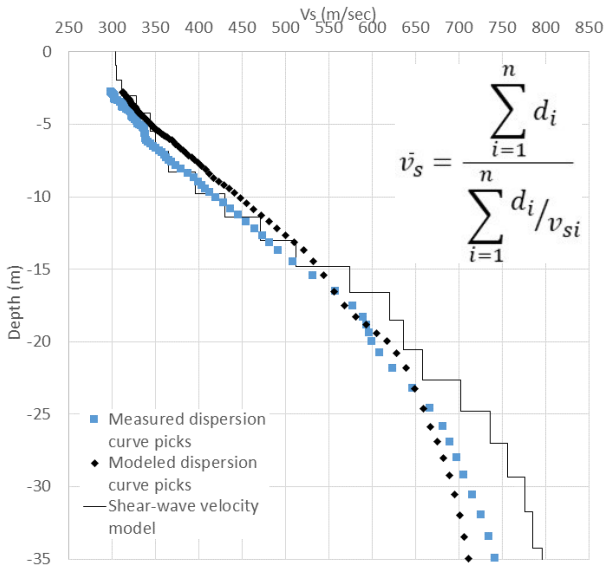
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is also decent quality, and the resulting dispersion curve correlates well with the MASW dispersion curves. The three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 11.8 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 5.3 percent. The top 3 m (10 ft) of the final model are unconstrained, but below that the model shows steadily increasing velocity to 8 m (26 ft), then gradually increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 484 m/sec, which places the site solidly in the C site class. All initial and inverted models place this site in the C class, so the site can be confidently classified. This is within the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_S) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

CAMELOT ELEMENTARY SCHOOL

FEDERAL WAY SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

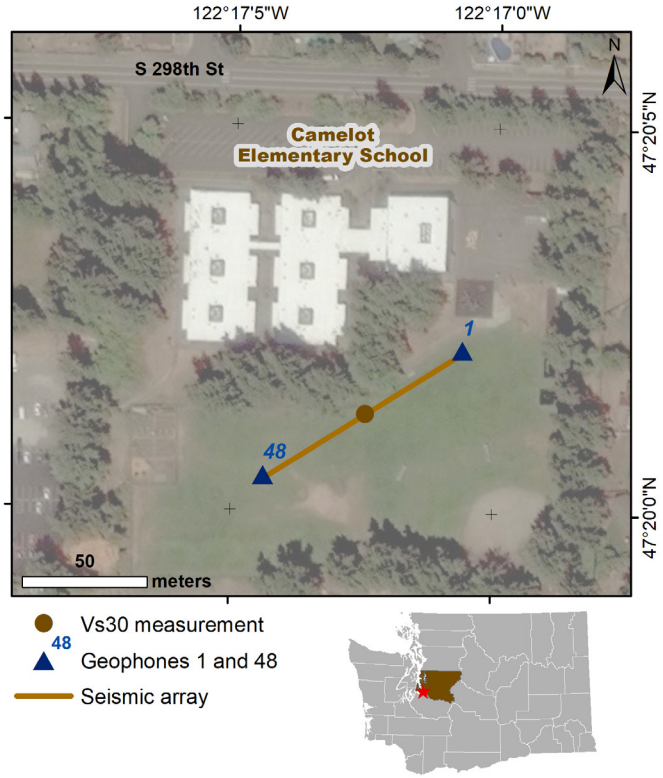
On September 28, 2020, a team from the Washington Geological Survey conducted a seismic survey at Camelot Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

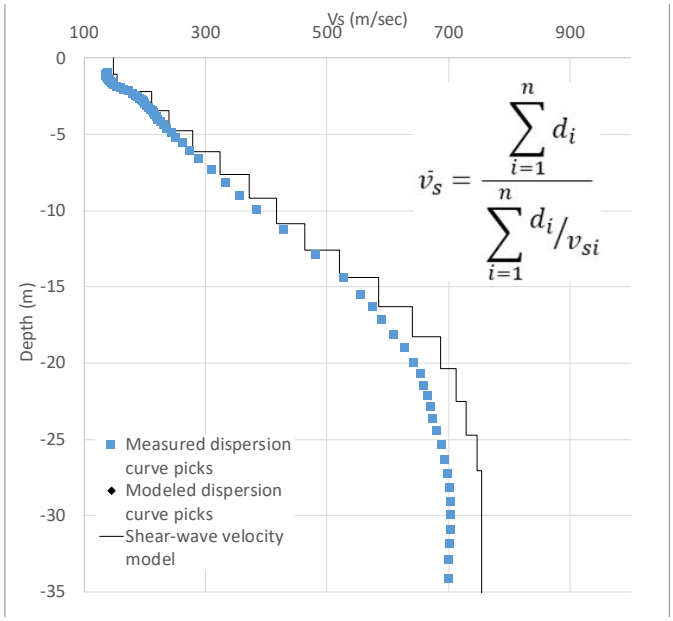
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality so that the fundamental mode can be picked with some confidence. The microtremor analysis method (MAM) dispersion image is also poor quality, but is combined with the the reverse direction MASW into a single model that adequately samples below 30 m (100 ft).

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model is used as the inverted model converges well above 5 percent and forces unrealistic velocity structure. The final model is unconstrained in the top 1 m (3 ft), and below this shows generally increasing velocity down to 25 m (82 ft), then nearly constant velocity to 30 m (100 ft). Our best Vs30 measurement is 412 m/sec, which places the site solidly in the C site class. All initial and inverted models are in the C class, so the site can be confidently classified. This is the same as the predicted site class of C.



Final initial velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

CANYON CREEK ELEMENTARY SCHOOL

NORTHSHORE SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

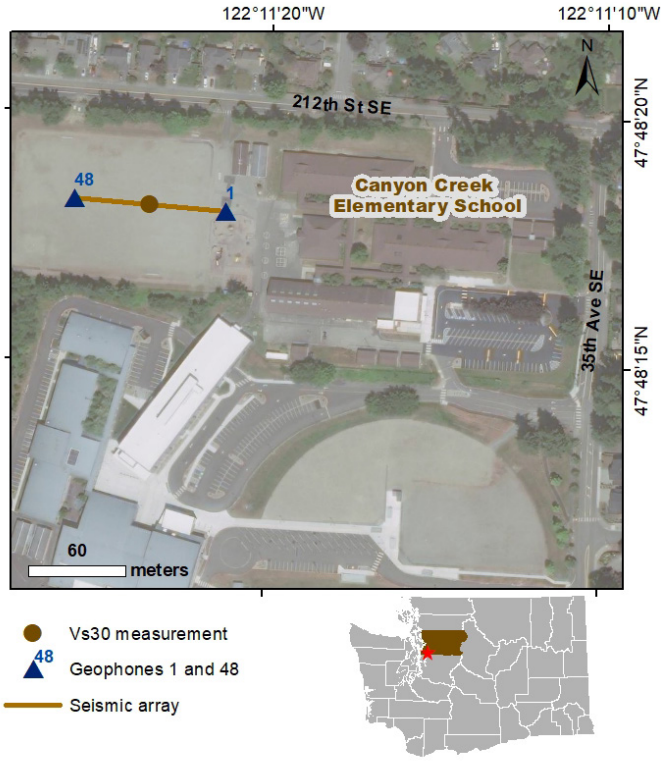
On March 17, 2021, a team from the Washington Geological Survey conducted a seismic survey at Canyon Creek Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

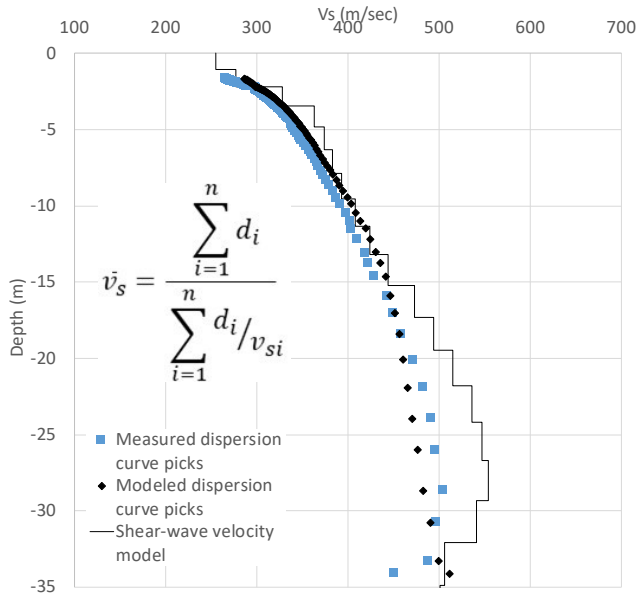
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is excellent quality. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 6.6 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.7 percent. The final model shows generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 431 m/sec, which places the site in the C site class. All initial and final models are of the C class, so the site can be confidently classified. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

CARSON ELEMENTARY SCHOOL AND WIND RIVER EDUCATION

STEVENSON-CARSON SCHOOL DISTRICT, SKAMANIA COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

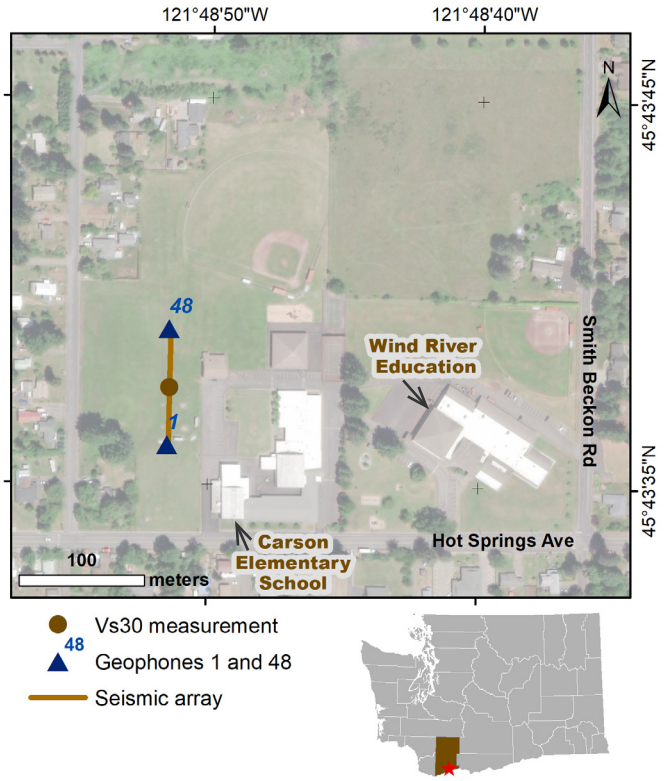
On August 30, 2020, a team from the Washington Geological Survey conducted a seismic survey at Carson Elementary School and Wind River Education. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The schools are built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of B.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The schools are mapped as sitting on basalt flows.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Unknown, not negligible

Ground Shaking
Severe

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

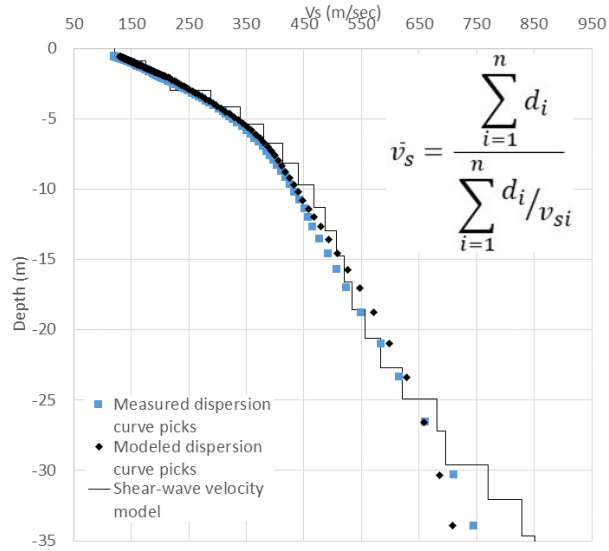
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. The microtremor analysis method (MAM) dispersion image is of decent quality but is not needed to adequately sample below 30 m (100 ft). The reverse and forward MASW dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 12.8 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.8 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows generally increasing velocity to 8 m (26 ft), then more slowly increasing velocity to 30 m (100 ft). Our best Vs30 measurement is 419 m/sec, which places the site in the C site class. All of the initial and final models are in the C class, so the site can be confidently classified. This is different from the predicted site class of B.

GEOLOGY

The 1:24,000-scale geologic map places the seismic arrays and the school buildings on geologic unit Qvb_{tch}, which matches the 1:100,000-scale geology map that predicts a seismic site class of B. Nearby boreholes indicate clay, silt, sand, boulders and gravel with occasional basalt present above 30 m (100 ft). The 1D velocity model is consistent with these boreholes, and indicates generally consolidated sediments. While basalt is likely present at adjacent higher elevations to the school and at depth, it does not seem to be within the upper 30 m at the school campus. Therefore, the change in site class is likely due to mismapping.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

CASCADE ELEMENTARY SCHOOL

MARYSVILLE SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

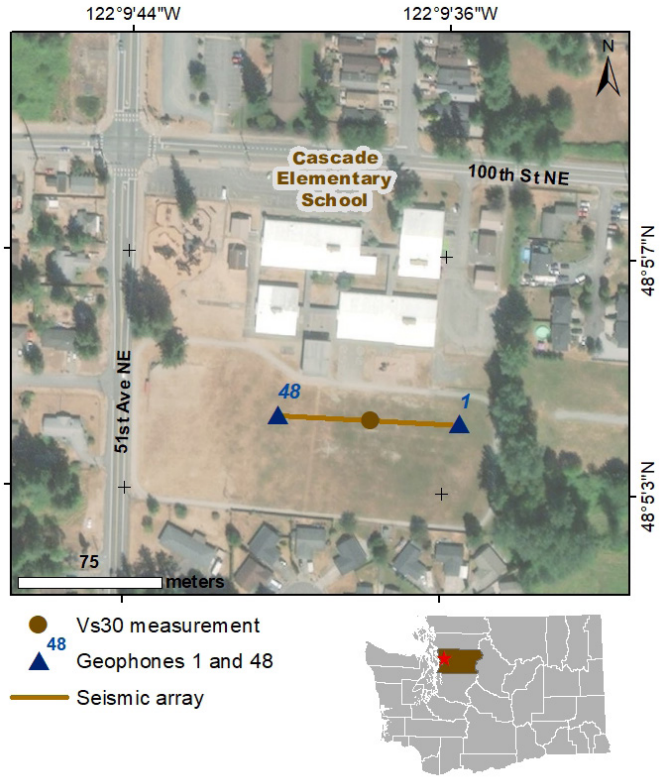
On July 13, 2020, a team from the Washington Geological Survey conducted a seismic survey at Cascade Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till, which consists of a compact and unsorted mixture of sand, silt, clay, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

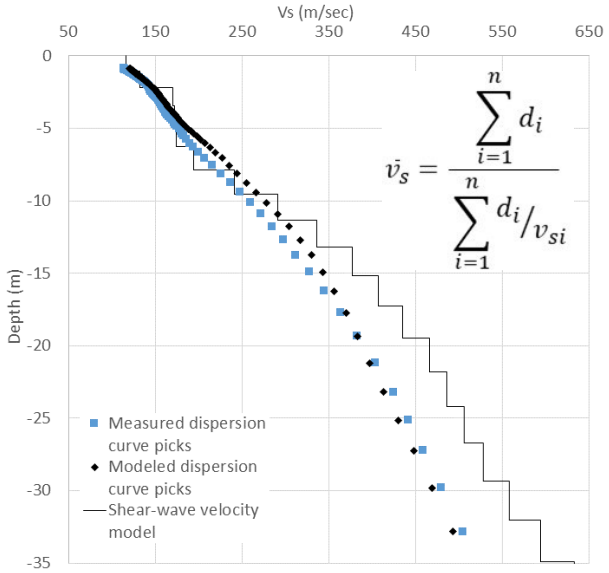
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are of excellent quality and the fundamental mode can be picked. The MASW dispersion curves are similar across the array. The microtremor analysis method (MAM) dispersion image is also of excellent quality, and the resulting dispersion curve agrees well with the MASW dispersion curves. Reverse MASW and MAM are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model had an RMSE of 10.8 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.9. The final model shows generally constant velocity from 2 m (7 ft) to 6 m (20 ft), then steadily increasing velocity to 30 m (100 ft). Our best Vs30 measurement is 289 m/sec, which places the site in the middle of the D class. The MASW dispersion curves from the reverse and forward directions and MAM dispersion curve each place this location in the middle of site class D, so the site can be confidently classified. This is within the predicted D–E class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_S) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

CATHCART ELEMENTARY SCHOOL

SNOHOMISH SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

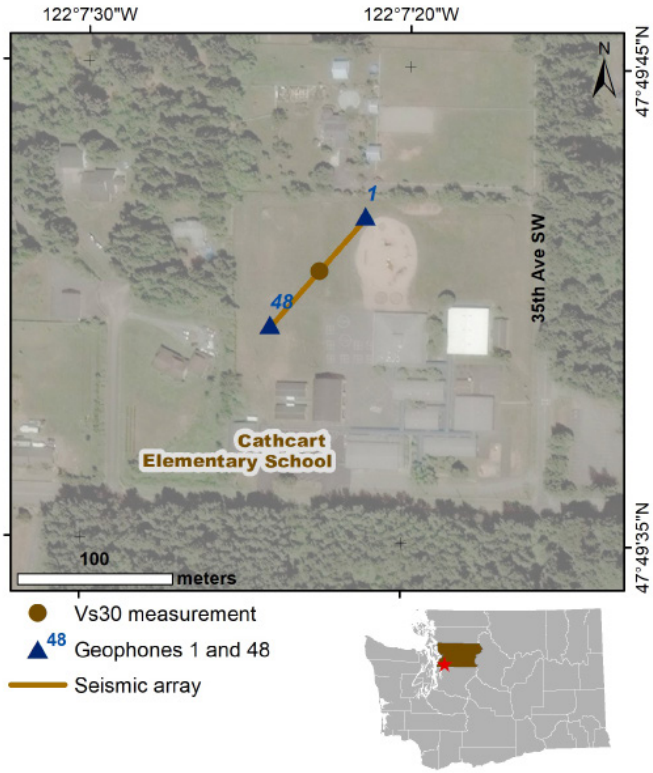
On October 27, 2020, a team from the Washington Geological Survey conducted a seismic survey at Cathcart Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

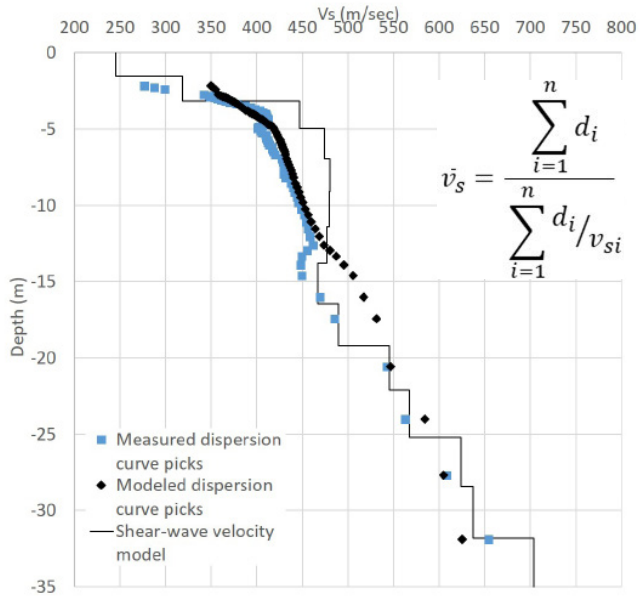
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with some confidence despite noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is of poor quality and the fundamental mode cannot be identified with confidence. The forward and reverse MASW dispersion curves correlate well, depicting similar trends. Both the forward and reverse MASW sample past 30 m depth and the two dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 5.6 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.8 percent. The final model shows rapidly increasing velocity from 1 m (3 ft) to 5 m (16 ft), then mostly constant velocity down to 18 m (59 ft) with a small reversal at 15 m (49 ft), and then steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 474 m/sec, which places the site in the middle of the C site class. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_S) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

CENTRAL ELEMENTARY SCHOOL

FERNDALE SCHOOL DISTRICT, WHATCOM COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

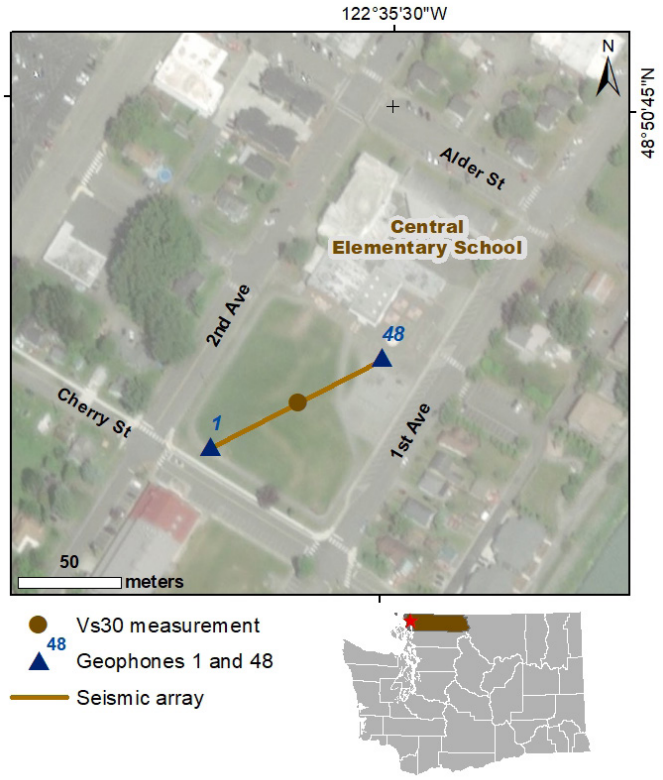
On September 20, 2019, a team from the Washington Geological Survey conducted a seismic survey at Central Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on river sediments consisting mostly of boulder, cobble, and pebble gravel and sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Violent

Lahar
In a mapped lahar hazard zone

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

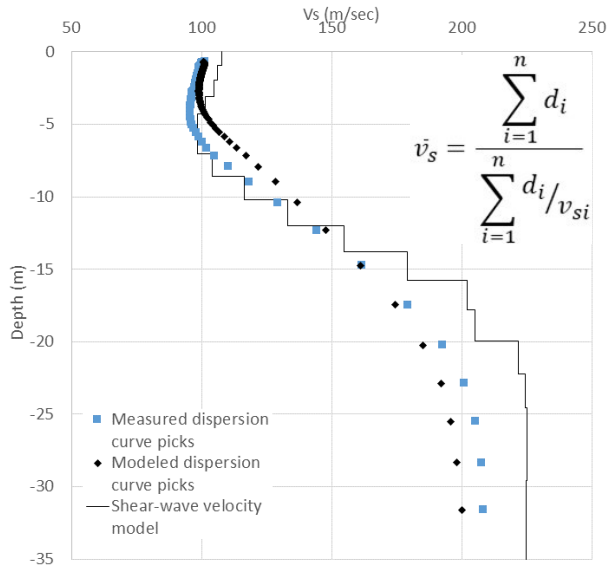
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is excellent quality, and the fundamental mode can be picked with high confidence, but does not sample the top 3 m (10 ft). Forward and reverse direction MASW dispersion curves are combined with the MAM dispersion curve to create a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 5.1 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 2.6 percent. The final model shows a slight velocity reversal down to 7 m (23 ft), then generally increasing velocity to 20 m (66 ft), and nearly constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 151 m/sec, which places the site solidly in the E site class. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

CENTRAL ELEMENTARY SCHOOL

HOQUIAM SCHOOL DISTRICT, GRAYS HARBOR COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

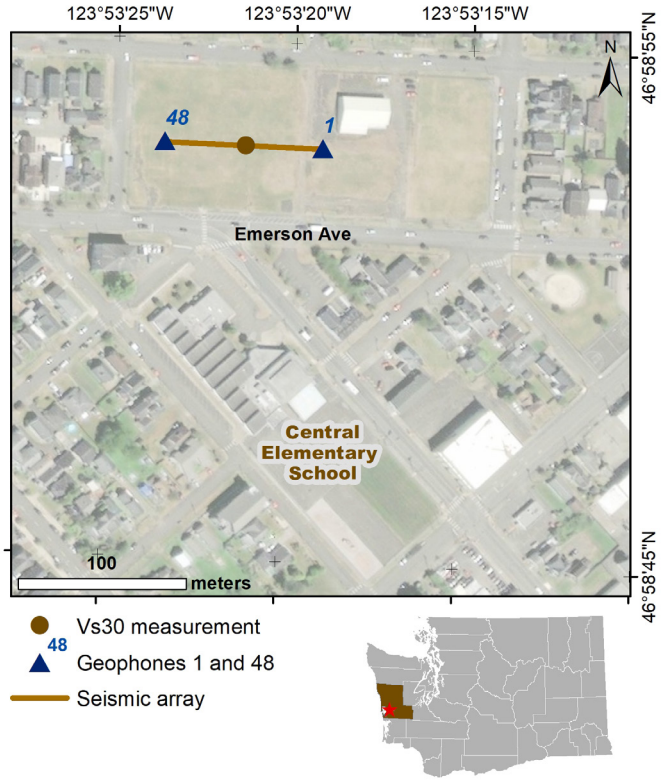
On November 6, 2019, a team from the Washington Geological Survey conducted a seismic survey at Central Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Extreme

Tsunami
In a mapped tsunami hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

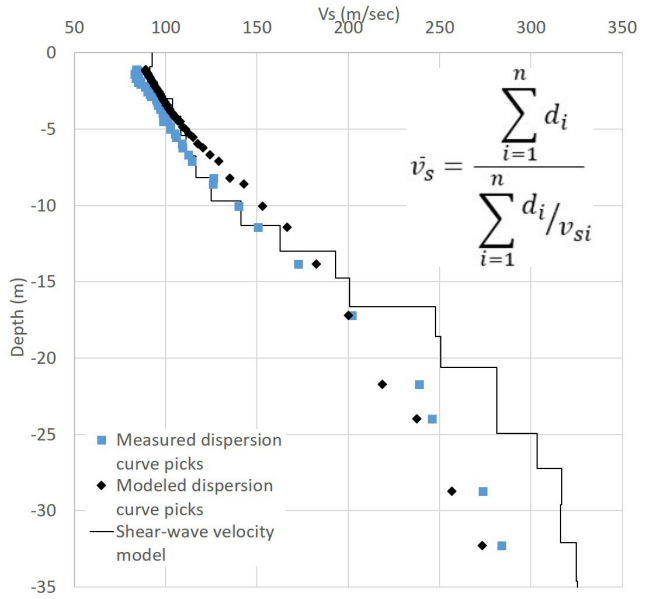
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the reverse direction are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves are more coherent in the reverse direction compared to the forward. The microtremor analysis method (MAM) dispersion image is also of decent coherency, and is combined with the reverse direction MASW into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 14.2 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 7.7 percent. The final model shows generally increasing velocity from 1 m (3 ft) to 30 m (100 ft), but is unconstrained in the upper 1 m (3 ft). Our best Vs30 measurement is 168 m/sec, which places the site in the E class. All initial and inverted models are in the E site class, so the site can be confidently classified. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

CENTRAL ELEMENTARY SCHOOL

SNOHOMISH SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

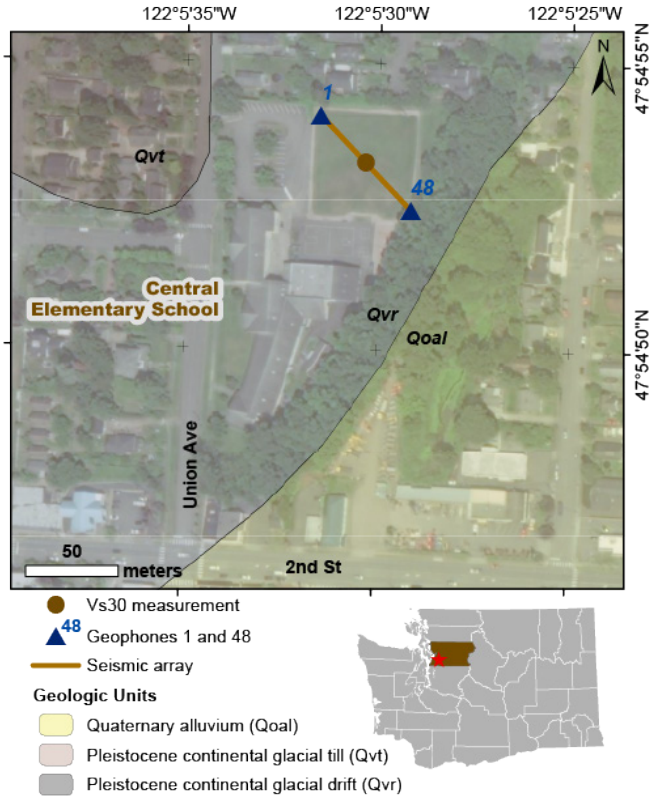
On October 28, 2020, a team from the Washington Geological Survey conducted a seismic survey at Central Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (231 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift consisting mostly of sand and gravel (unit Qvr). To the southeast is mapped Quaternary alluvium, consisting mostly of silt, sand, and gravel (unit Qoal). To the northwest is Pleistocene glacial till (unit Qvt).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low

Ground Shaking
Violent

Landslide
Hazard present, based on terrain data

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

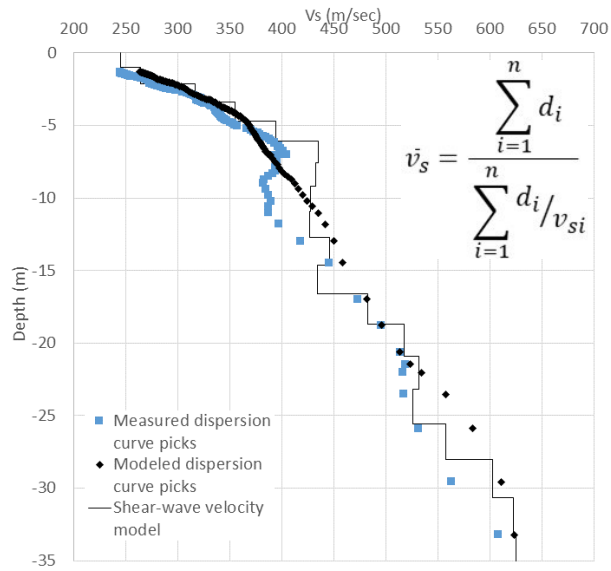
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is poor quality, but the resulting dispersion curve fills in some gaps in the MASW dispersion curves. The forward and reverse MASW dispersion curves show some variance, but follow a similar trend to the MAM dispersion curve, so all three are combined into a single model.

VELOCITY MODEL

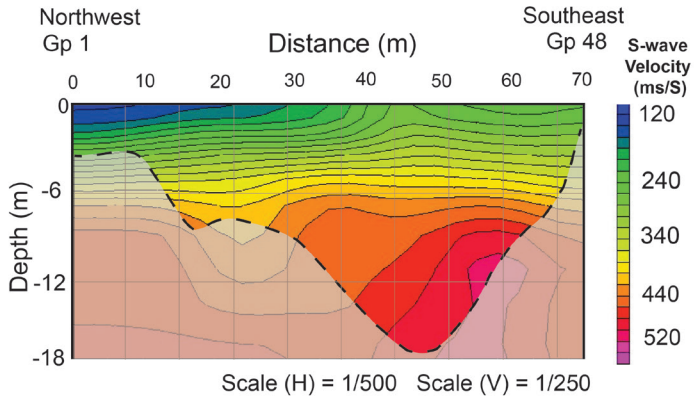
An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 8.3 percent. The inversion was carried out for four iterations and resulted in a final model with an RMSE of 5.5 percent. The final model is unconstrained in the top 1 m (3 ft), below this shows generally increasing velocity to 6 m (20 ft), then shows nearly constant velocity down to 17 m (56 ft), and then has increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 438 m/sec, which places the site solidly in the C site class. Although forward and reverse models do show some heterogeneity, it is not enough to change the site class, and all initial and inverted models place this site in the C site class. This is within the predicted site class of C–D.

GEOLOGY

The 1:24,000-scale geologic map places the school building and seismic array on glacial drift (unit Qvr) with a predicted site class of C–D. Mapped to southeast is alluvium (unit Qoal) with a predicted site class of D–E, and to the northwest is glacial till (unit Qvt) with a predicted site class of C. The 1:100,000-scale geologic map, which is used to predict site class, has slightly different unit contacts. This lower-resolution map places the geologic contact between alluvium and glacial outwash slightly more northwest, and thus the site class boundary crosses through the building. The 2D seismic refraction tomography (SRT) does show heterogeneity across the array, with higher P–wave velocities at shallower depths near geophone 48. The 2D MASW (bottom right) shows this heterogeneity as well, but to a lesser extent. Considering the higher-resolution map moved the geologic contact off the buildings, it is likely the heterogeneity reflects a lateral change within the geologic unit and not a surficial contact with the alluvium. As these lateral changes do not change Vs30 enough to drop it into a site class D, we assign the campus a site class C with reasonable confidence.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.



Pseudo 2D MASW shear-wave velocity model with locations for Geophones (Gp)1 and 48. Dashed line approximately delineates the model's reliability in the vertical extent. Portions of the model at depths below the dashed line are not constrained

CENTRAL PARK ELEMENTARY SCHOOL

ABERDEEN SCHOOL DISTRICT, GRAYS HARBOR COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

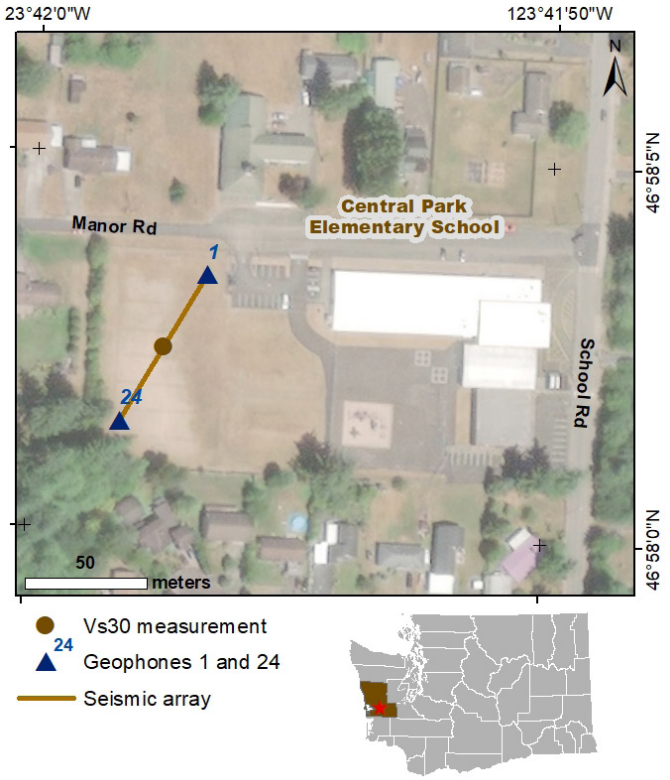
On July 28, 2010, a team from the Washington Geological Survey conducted a seismic survey at Central Park Elementary School. We measured Vs30 by laying out 24 geophones (ground motion sensors) in a 69 m (226 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift, consisting mostly of sand and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

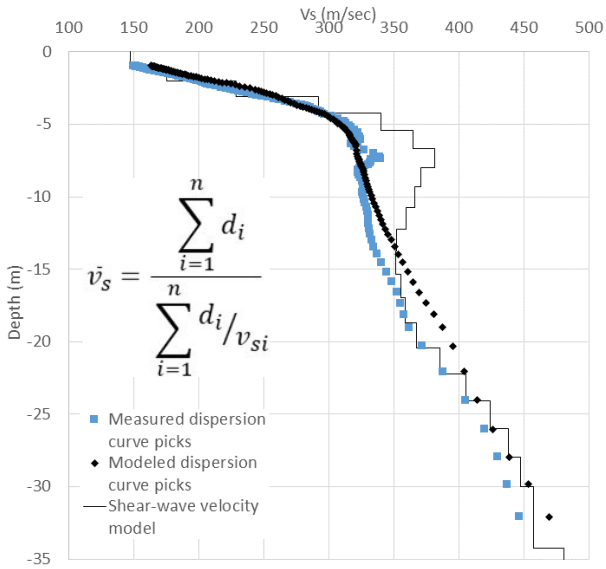
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is excellent quality, and the resulting dispersion curve correlates well with the MASW curves. Therefore, MAM and the forward and reverse MASW are combined into a single final model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 7.7 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.2 percent. The final model shows rapidly increasing velocity to 7 m (23 ft), then a velocity reversal to 15 m (49 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 339 m/sec, which places the site solidly in the D site class. This is within the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

CENTRALIA MIDDLE SCHOOL

CENTRALIA SCHOOL DISTRICT, LEWIS COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

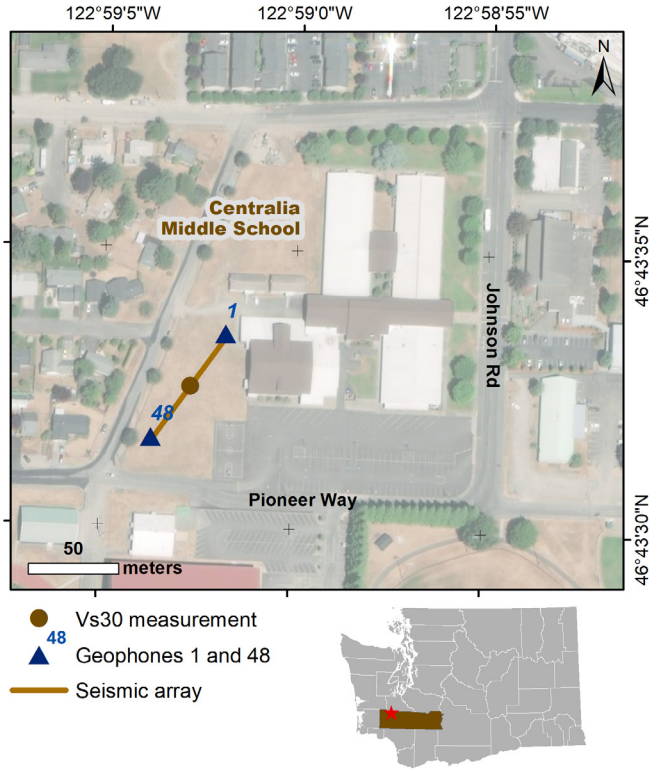
On October 1, 2020, a team from the Washington Geological Survey conducted a seismic survey at Centralia Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (231 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift, comprised mostly of stratified pebble, cobble, and boulder gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

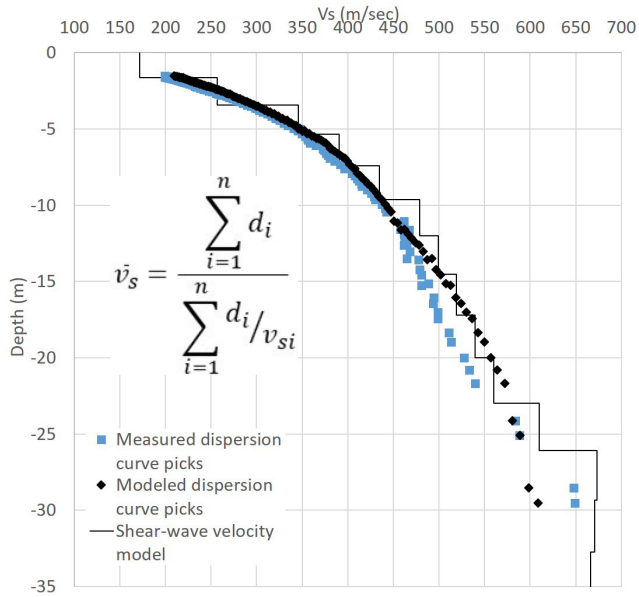
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality so that the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is decent quality, and correlates well with the forward and reverse MASW dispersion curves, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 11.5 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 5.4 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows increasing velocity to 10 m (33 ft), then generally slowly increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 437 m/sec, which places the site solidly in the C site class. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

CHIMACUM HIGH SCHOOL AND MIDDLE SCHOOL

CHIMACUM SCHOOL DISTRICT, JEFFERSON COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

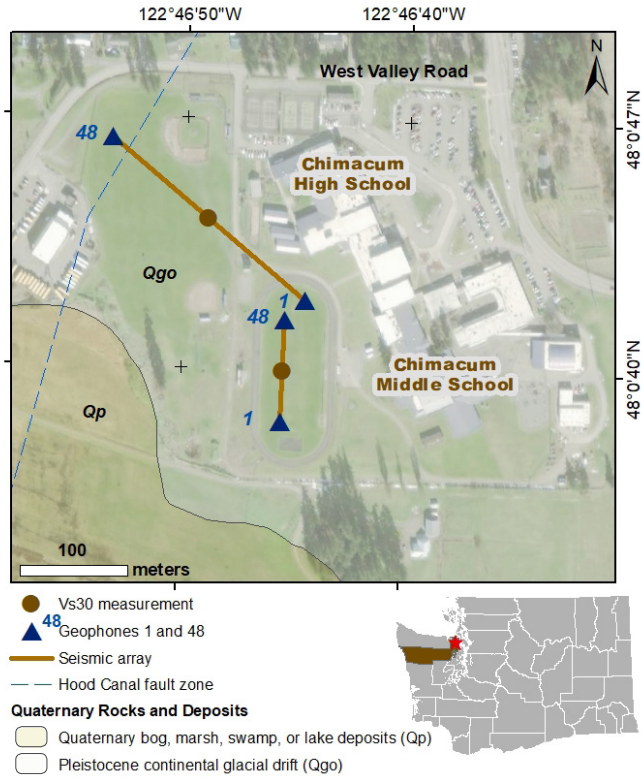
On October 11, 2020, a team from the Washington Geological Survey conducted a seismic survey at Chimacum High School and Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array and a 235 m (771 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic arrays at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial drift (unit Qgo) consisting predominately of pebble to cobble gravel and sand. Mapped to the southeast are marshes and bogs (unit Qp) consisting of peat, muck, silt, and clay.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The dispersion images for the multi-channel analysis of surface wave (MASW) from the forward and reverse directions, and the microtremor analysis method (MAM), are excellent quality for both the NW–SE and N–S so that the fundamental mode can be picked with high confidence. For the N–S line, the MAM and the forward and reverse MASW dispersion curves correlate well and were combined into a single model. For the NW–SE line only the MASW curves were combined, as they sampled to 30 m (100 ft).

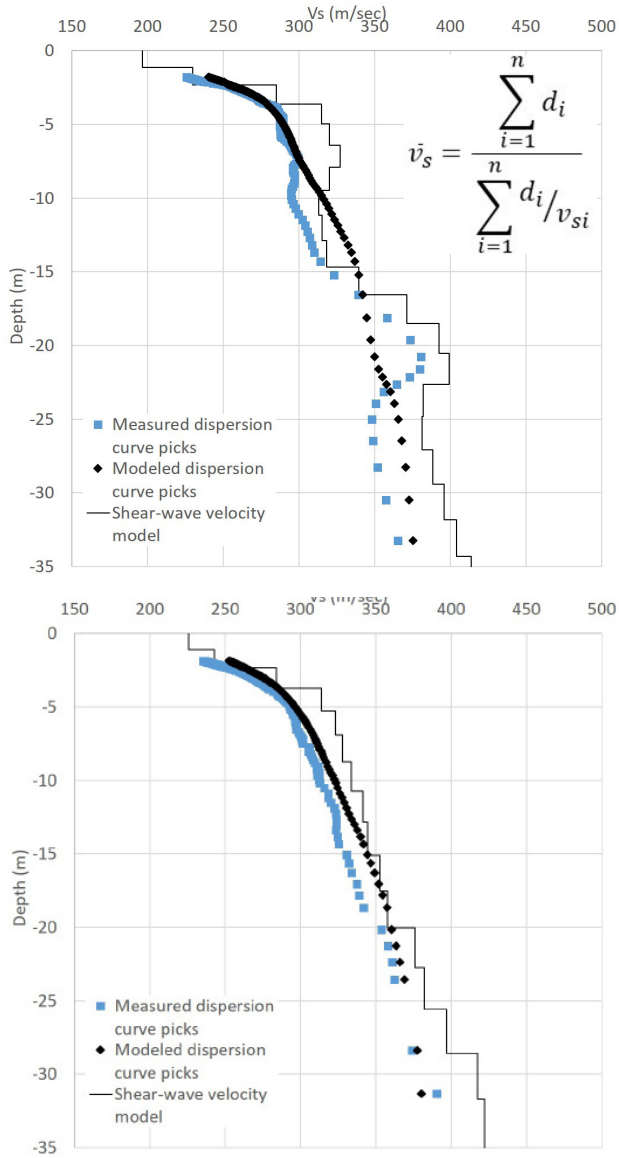
VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves for both arrays. The initial model for the N–S line had an RMSE of 4.8 percent. The inversion was carried out for three iterations and resulted in a final model with an RMSE of 3.6 percent. Our best Vs30 measurement is 332 m/sec. The initial model for the NW–SE line had an RMSE of 6.0 percent. The inversion was carried out for three iterations and resulted in a final model with an RMSE of 4.3 percent. Our best Vs30 measurement is 340 m/sec. All initial and inverted models from both lines place this site in the D class, which is within the predicted site class C–D.

GEOLOGY

The 1:24,000-scale geologic map places both seismic arrays and the school buildings on glacial drift (unit Qgo). The 1:100,000-scale geologic map, which is used to predict site class, also places the buildings and arrays on glacial drift, with a predicted site class of C–D. Nearby boreholes show mostly unconsolidated sediments consistent with a site class D. The velocity models for the two lines are similar save for depths of ~16–23 m, and both lines result in a similar Vs30, so we can confidently assign the campus a site class D.

The map on the front page shows the moderately constrained Hood Canal fault zone (USGS reference ID 552) as a dotted line. The fault trace is mapped at a 1:250,000-scale (Bowman and others, 2019). A detailed study that could confirm the location of the fault is outside the scope of site class assessment. Fault location based primarily on geophysical methods.



Final inverted velocity models with measured dispersion curves and modeled dispersion curves. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner of the top figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer. Top: N–S line; Bottom: NW–SE line.

CHINOOK MIDDLE SCHOOL

HIGHLINE SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

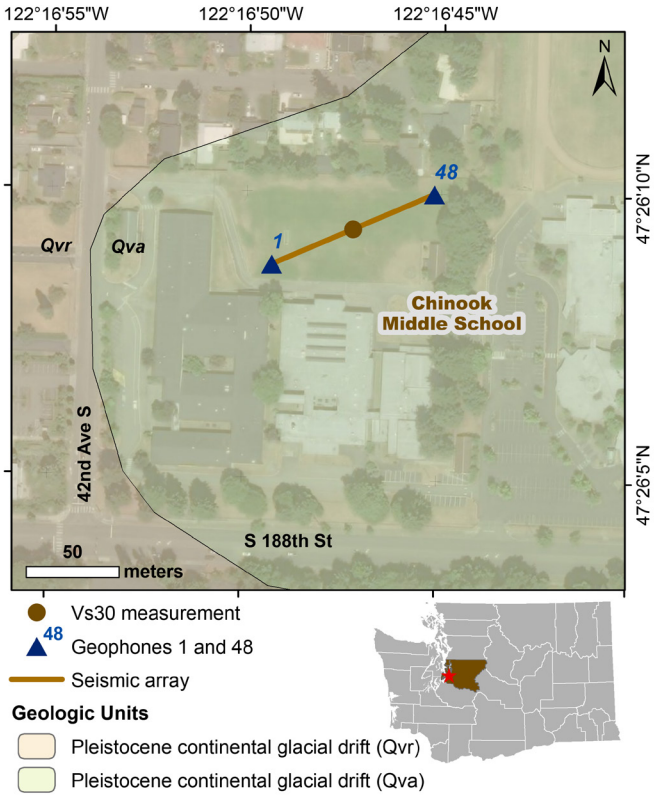
On October 15, 2020, a team from the Washington Geological Survey conducted a seismic survey at Chinook Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial drift consisting mostly of sand and a little gravel (unit Qva), surrounded by glacial drift (unit Qvr) distinct from unit Qva in how it was deposited.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

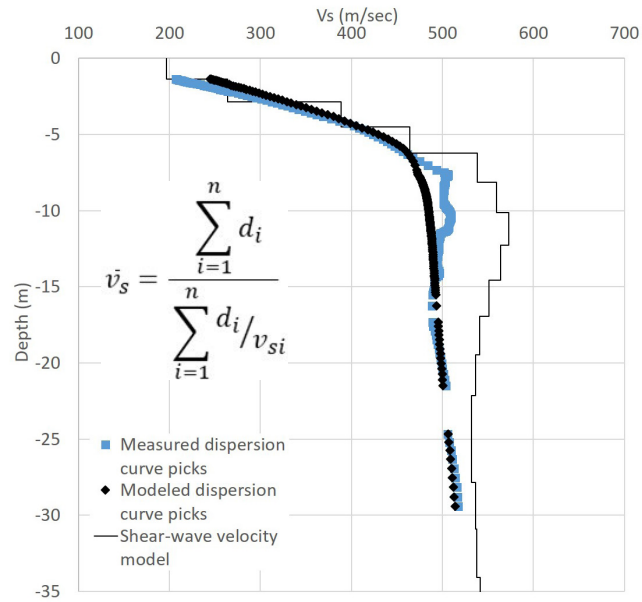
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality so the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is decent quality but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 6.1 percent. The inversion was carried out for three iterations and resulted in a final model with an RMSE of 4.5 percent. The final model shows rapidly increasing velocity to about 10 m (30 ft), then generally constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 469 m/sec, which places the site in the middle of the C site class. All initial and final models are in the C class. This is within the predicted site class of C–D.

GEOLOGY

The 1:24,000-scale geologic map (previous page) places the school buildings and seismic array on Pleistocene continental glacial drift (unit Qva) with more Pleistocene continental glacial drift (unit Qvr) to the west, and places the contact between the two cutting across the southwest and northwest corner of campus. These glacial drifts are distinct in how they were deposited, with sediments of unit Qva deposited during an ice sheet advance, and sediments of unit Qvr deposited during ice sheet retreat. These units roughly correspond to similar units in the 1:100,000-scale geologic map that is used to predict site class, which places the array and most of the school buildings on a predicted site class of C-D with predicted site class C to the west. Nearby boreholes show unsorted, unconsolidated sediments from clay to cobble past 30 m (100 ft). This matches the unit descriptions as well as our velocity model. As we have no evidence for heterogeneity, this site can be confidently classified as a site class C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

CLOVER VALLEY SCHOOL

OAK HARBOR SCHOOL DISTRICT, ISLAND COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

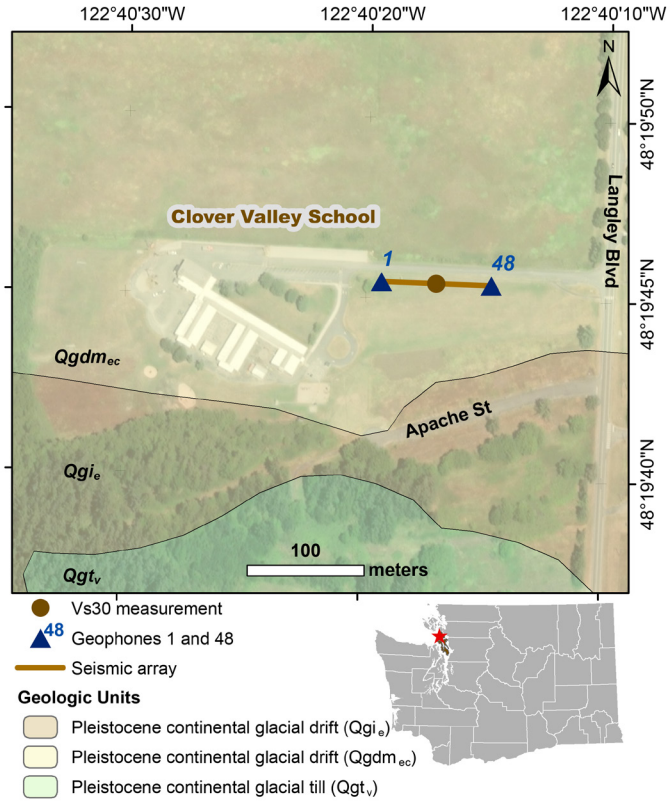
On April 5, 2021, a team from the Washington Geological Survey conducted a seismic survey at Clover Valley School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift., consisting mostly of sand, gravel, and dropstones (unit Qgdm$_{ec}$). South of the school campus is mapped more Pletistocene continental glacial drift (unit Qgi$_e$).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to Moderate

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

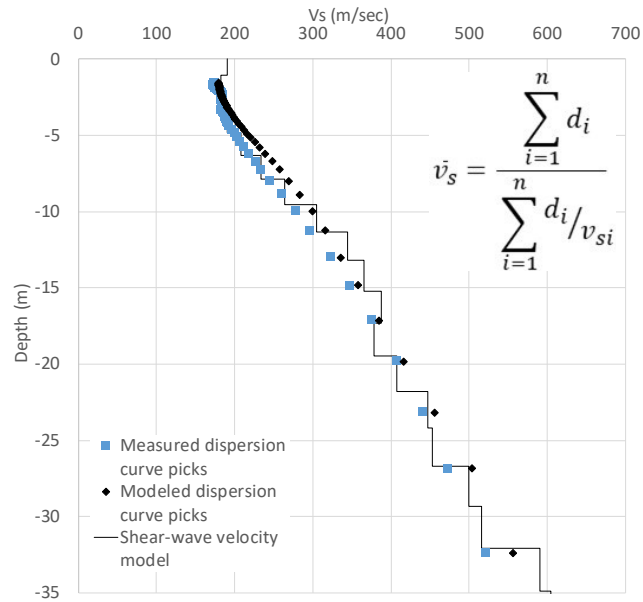
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. The microtremor analysis method (MAM) dispersion image is also excellent quality. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 10.5 percent. The inversion was carried out for nine iterations and resulted in a final model with an RMSE of 4.6 percent. The final model is unconstrained in the top 1.5 m (5 ft), and below this shows generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 311 m/sec, which places the site within the D site class. All initial and inverted models are in the D class. This correlates with the predicted site class of D.

GEOLOGY

The 1:24,000-scale geologic map places the school and seismic array on glacial drift, with more glacial drift and glacial till mapped closely to the south. The 1:100,000-scale geologic map, which is used to predict site class, has slightly different unit contacts. This lower-resolution map shows a contact passing through the school buildings, placing a predicted site class D to the north, and a predicted site class C–D to the south. The lithology of both units is continental glacial drift. Nearby boreholes show mostly unconsolidated sediment, with an occasional dense layer of ~4.5 m (15 ft) thickness, to 24 m (80 ft) depth. As our measured site class is within the predicted site classes of both units, and the higher-resolution mapping places the unit contact away from the buildings, this site can be confidently classified.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

COTTONWOOD ELEMENTARY SCHOOL

CENTRAL KITSAP SCHOOL DISTRICT, KITSAP COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

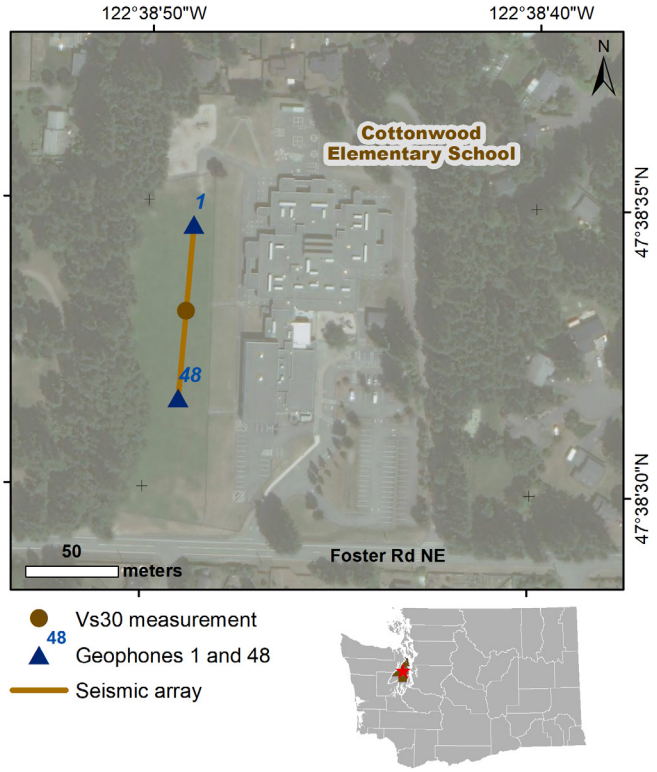
On April 14, 2021, a team from the Washington Geological Survey conducted a seismic survey at Cottonwood Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift, consisting mostly of sand with some pebbles or silt.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low to low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

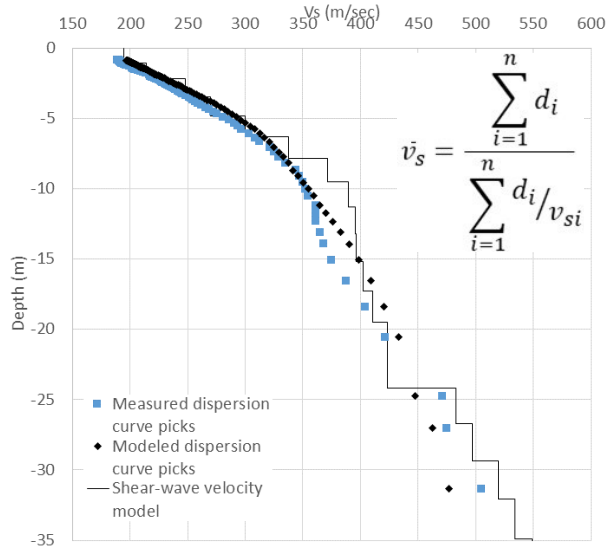
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. The microtremor analysis method (MAM) dispersion image is also excellent quality, and the resulting dispersion curve correlates well with the forward and reverse MASW dispersion curves. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 8.4 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.5 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows generally increasing velocity to 10 m (33 ft), then nearly constant velocity down to 24 m (79 ft), and then steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 364 m/sec, which places the site in the C site class, near the C/D boundary. This is within the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

COWEEMAN MIDDLE SCHOOL

KELSO SCHOOL DISTRICT, COWLITZ COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

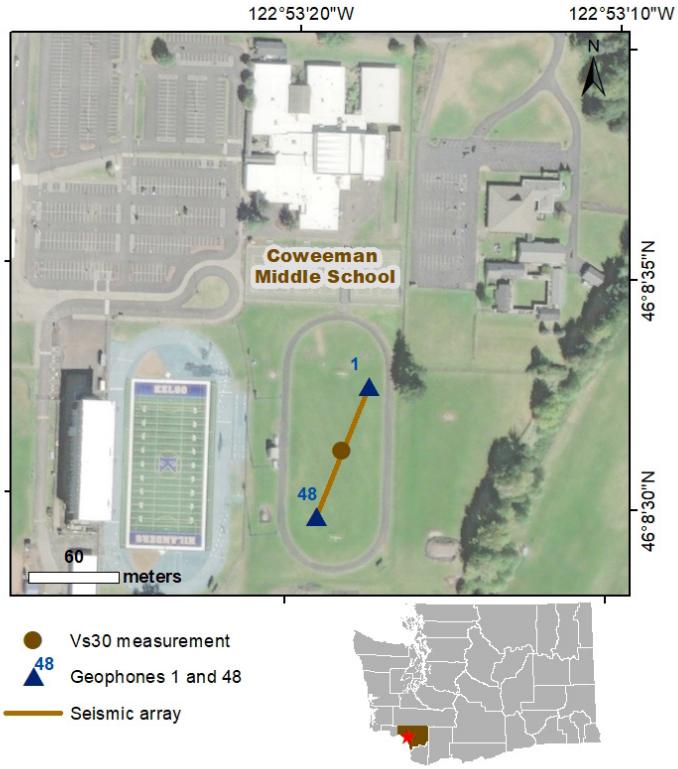
On March 11, 2021, a team from the Washington Geological Survey conducted a seismic survey at Coweeman Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on quaternary alluvium (unit Qa).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

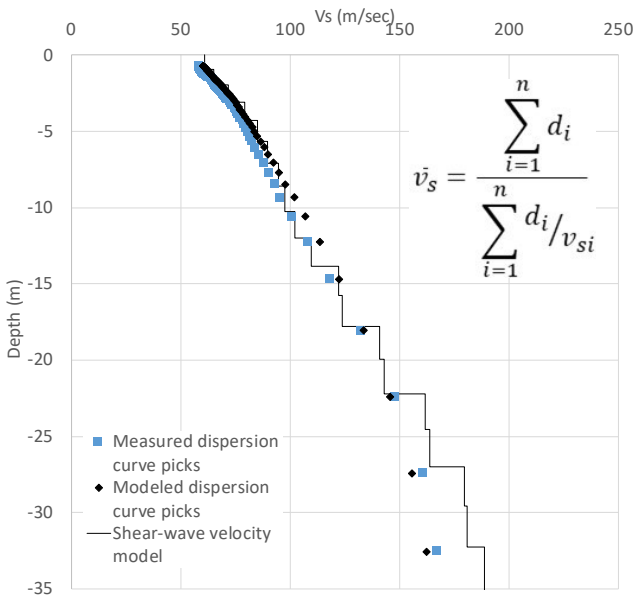
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so the fundamental mode can be picked with high confidence. The microtremor analysis method (MAM) dispersion image is also excellent quality. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 8.2 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.3 percent. The final model shows steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 112 m/sec, which places the site in the E site class. All initial and final models are of the E class, so the site can be confidently classified. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

CROSSROADS HIGH SCHOOL

GRANITE FALLS SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

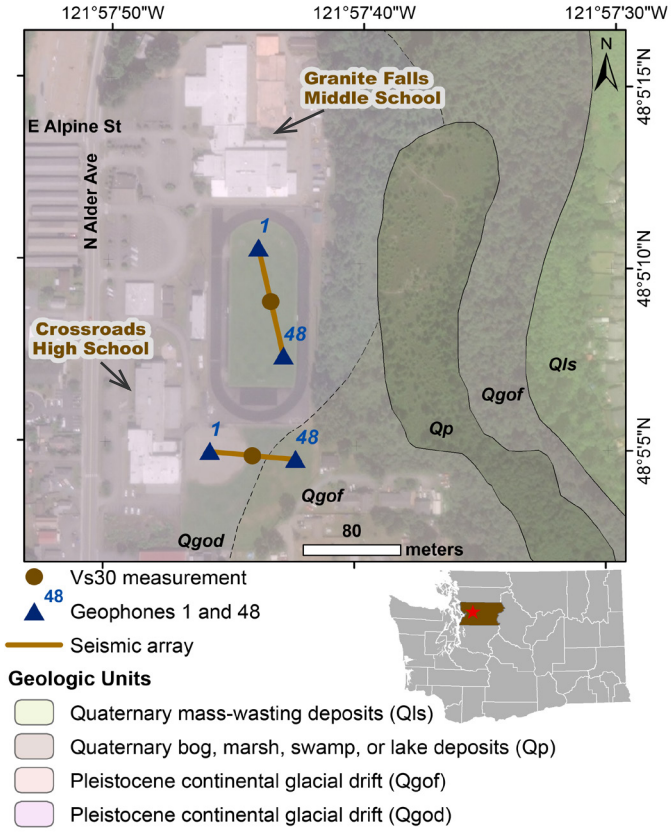
On April 20, 2021, a team from the Washington Geological Survey conducted a seismic survey at Crossroads High School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (231 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift, comprising mostly sand, gravel, and cobbles (unit Qgod). Mapped to the east is more Pleistocene continental glacial drift (unit Qgof), and Quaternary bog, marsh, swamp, or lake deposits (unit Qp).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

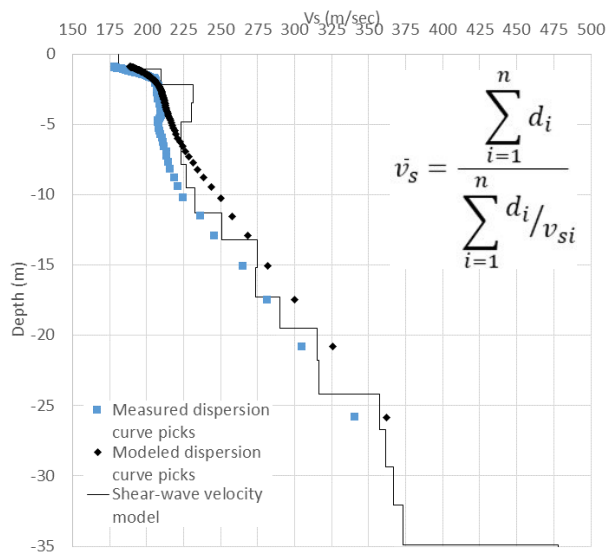
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. The microtremor analysis method (MAM) dispersion image is also excellent quality, and the resulting dispersion curves correlate well with the forward and reverse MASW dispersion curves. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 10.4 percent. The inversion was carried out for three iterations and resulted in a final model with an RMSE of 5.4 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows increasing velocity to 3 m (10 ft), then a slight inversion to 8 m (26 ft), generally increasing velocity to 24 m (79 ft), and then nearly constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 268 m/sec, which places the site solidly in the D site class. With the clear coherence of the dispersion images and all inital and inverted models placing this site in a class D, this site can be confidently classified. This is within the predicted site class of D–E.

GEOLOGY

The 1:24,000-scale geologic map places the school buildings and half of the seismic array on glacial drift (unit Qgod), with the other half of the array lying on more glacial drift (different in sediment size and color from unit Qgod). The 1:100,000-scale geologic map, which is used to predict site class, has different unit contacts, and places the entire campus and surrounding area on a single unit of glacial drift with a predicted site class of D–E. Nearby boreholes show almost exclusively sand and gravel in the top 18 m (60 ft), and boreholes which sample deeper show unconsolidated sand and gravel past 100 ft, consistent with a site class D and the 1D velocity model. The 2D MASW and 2D seismic refraction tomography (SRT) show very little heterogeneity across the length of the seismic array, so we can reasonably assume the high school is on soils similar to the array, even though the array spans a geologic contact. Crossroads High School shares a campus with Granite Falls Middle School, which was also evaluated in this study and has a measured site class of C (see site class assessment for Granite Falls Middle School). The velocity model for Granite Falls Middle School shows a contact with higher velocity materials within the top 30 m, that could be limited in its extent or deeper under the high school.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

CRYSTAL SPRINGS ELEMENTARY SCHOOL

NORTHSHORE SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

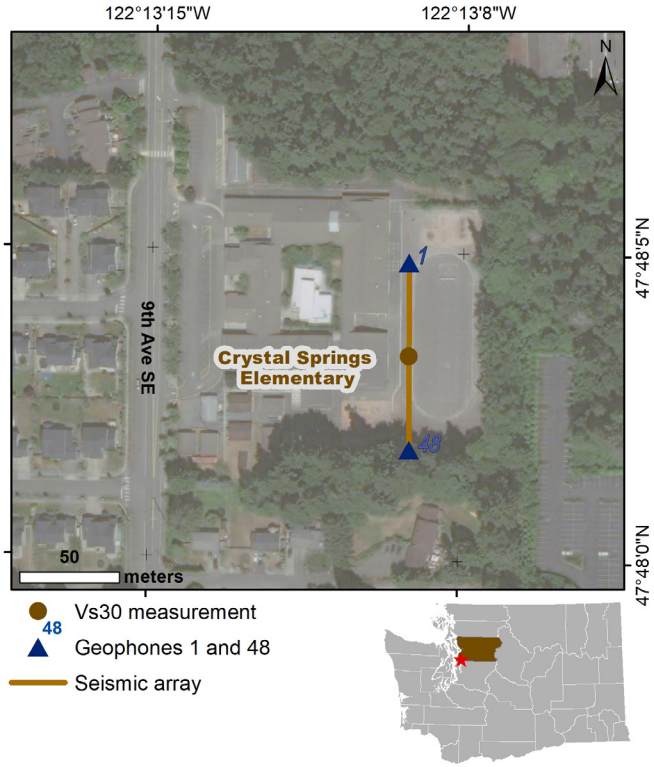
On March 12, 2021, a team from the Washington Geological Survey conducted a seismic survey at Crystal Springs Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene till and outwash dominated by clay, silt, sand, gravel, cobbles, and boulders.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low/bedrock

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

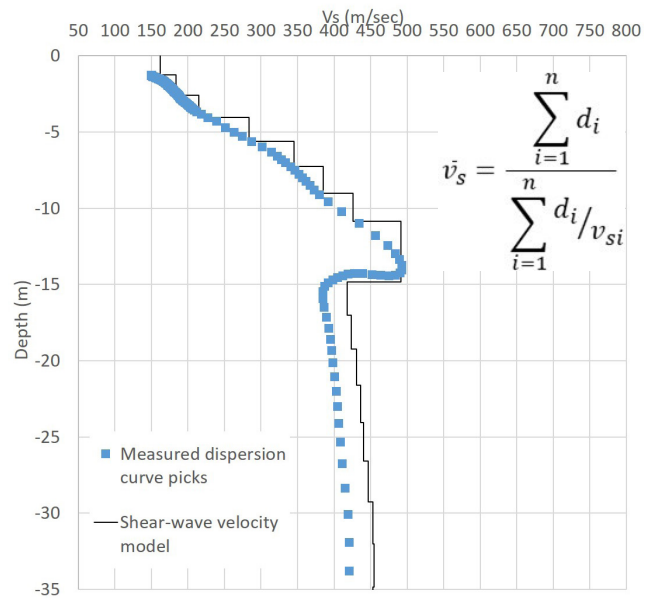
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft) and show some variance between them. The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate fairly well, depicting a similar trend, despite some variance between the MASW. Therefore, the reverse MASW and MAM dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. Although inverted models converge to a reasonable RMSE, they also force unrealistic velocity structure. Therefore, the initial model is used as the final model. The final model is unconstrained in the top 1 m (3 ft) but shows generally increasing velocity to about 15 m (49 ft) where there is a velocity reversal, then generally constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 358 m/sec. All initial and inverted models are around 360 m/sec, firmly placing the site on the C/D site class boundary.

GEOLOGY

The 1:100,000-scale geologic map, which is used to predict site class, shows the school campus and seismic array are sitting on Pleistocene continental glacial drift (unit Qga) with a predicted site class of C-D. This matches the higher-resolution1:24,000-scale geologic map, which also places the school and surrounding area on glacial drift. Nearby boreholes show gravel, clay, and sand down to 30 m (100 ft). These soils are consistent with our final 1D velocity model, but do not show cemented deposits that would help explain the velocity reversal. Regardless of whether the velocity reversal is due to cementation or a layer of more consolidated materials, it is effectively increasing the Vs30 towards the site class boundary, and we cannot verify its lateral extent. Therefore, we take the conservative approach and assign a site class of D, which is within the predicted site class of C–D.



Final velocity model with measured dispersion curve based on the intial model. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

CURTIS SENIOR HIGH SCHOOL

UNIVERSITY PLACE SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

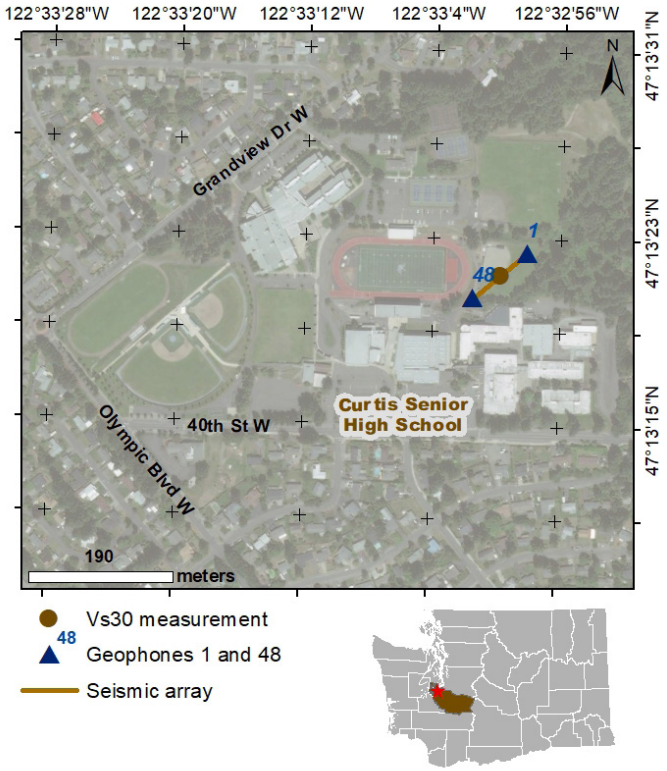
On September 9, 2020, a team from the Washington Geological Survey conducted a seismic survey at Curtis Senior High School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial outwash.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

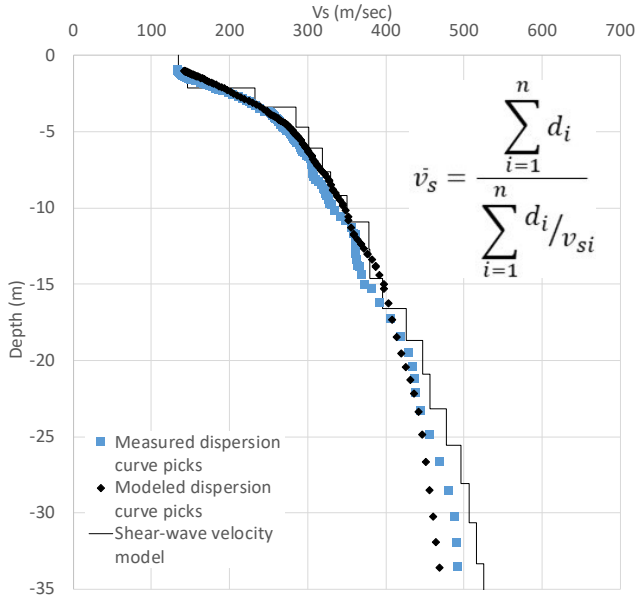
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the shallow layers. MAM and the reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 8.8 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.7 percent. The final model shows generally increasing velocity down to 30 m (100 ft), but is unconstrained in the upper 1 m (3 ft). Our best Vs30 measurement is 343 m/sec, which places the site in the D class, near the D/C boundary. Although the upper 1 m are unconstrained, adjusting them does not change the site class. All initial and final models are of the D class, so the site can be confidently classified. This is different from the predicted site class of C.

GEOLOGY

The 1:100,000-scale geologic map shows the seismic array and the school buildings located on glacial outwash (unit Qgo) with a predicted site class of C, which does not match the measured site class of D. The 1:100,000-scale geologic map also shows unit Qgo mapped further to the east with a predicted site class of C–D instead of C, meaning the site class map does not match the 1:100,000-scale geologic map. Nearby boreholes show a range of sands, gravel, silty sands, and glacial till in the upper 30 m (100 ft). The array was setup at a slightly lower elevation than the school in what appears to be a terraced lot with an unknown amount of artificial fill. However, the 1D velocity profile is similar to what we would expect from the borehole information, so we assume the same conditions persist below the school. Therefore, the change in site class may be due to a subsurface change in the geologic unit or low-resolution mapping.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

CUSTER ELEMENTARY SCHOOL

CLOVER PARK SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

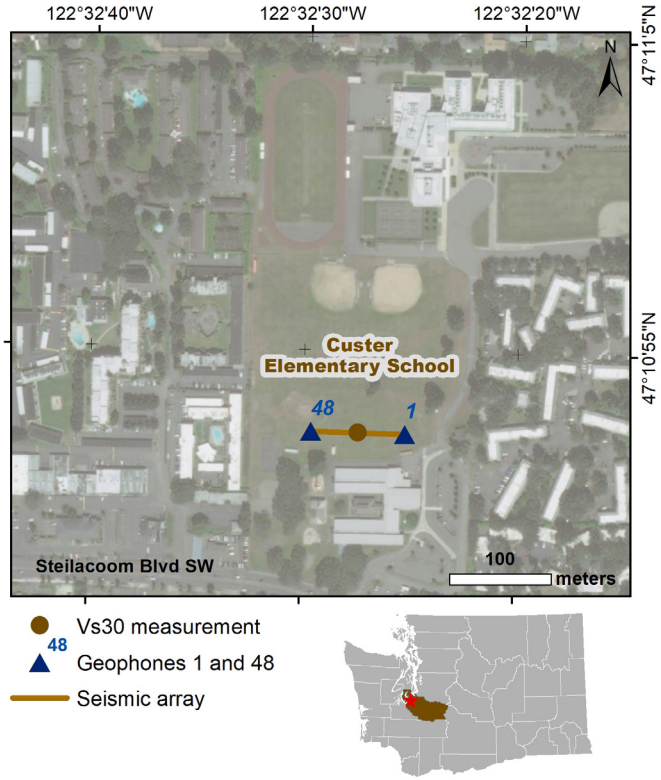
On July 20, 2020, a team from the Washington Geological Survey conducted a seismic survey at Custer Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial outwash.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

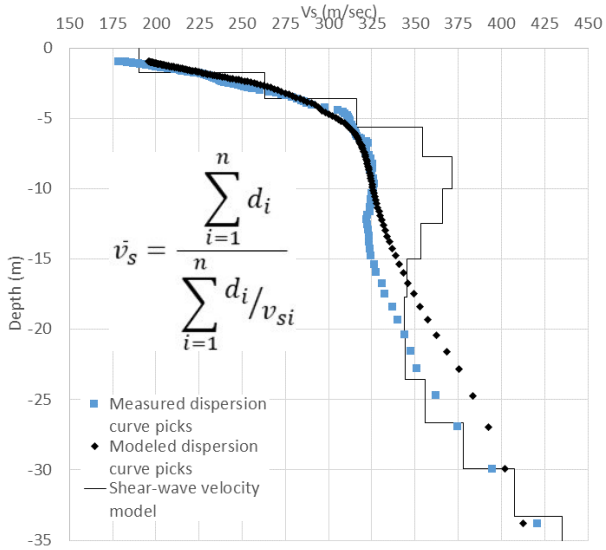
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is also decent quality. The MASW dispersion curves do not sample down to 30 m (100 ft), so they are combined into a single model with the MAM dispersion curve.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model had an RMSE of 8.7 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.7 percent. The final model shows generally increasing velocity to 8 m (26 ft), then a a slight inversion down to 23 m (75 ft), and then again generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 331 m/sec, which places the site solidly in the D site class. This is within the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_S) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

CUSTER ELEMENTARY SCHOOL

FERNDALE SCHOOL DISTRICT, WHATCOM COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

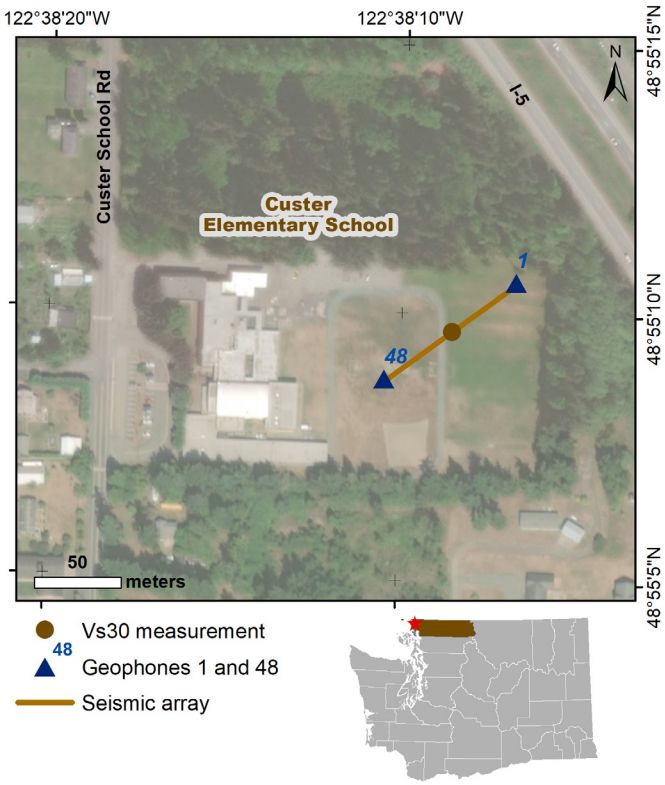
On October 21, 2020, a team from the Washington Geological Survey conducted a seismic survey at Custer Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial outwash.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

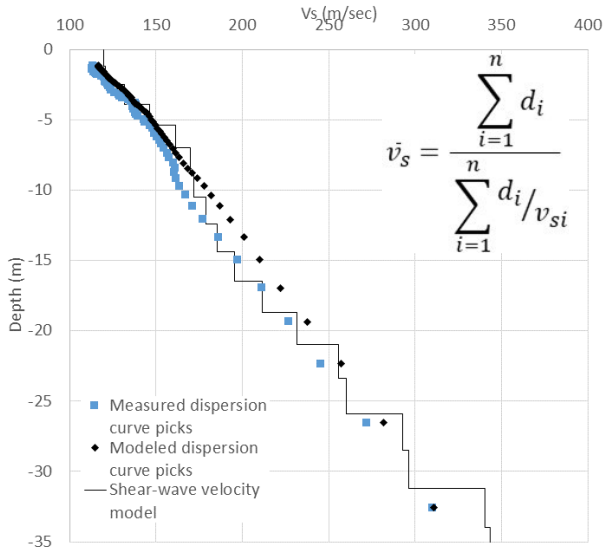
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is excellent quality and the resulting dispersion curve is combined with the forward and reverse direction MASW dispersion curves into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 8.9 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.7 percent. The final model shows generally increasing velocity down to 30 m (100 ft), but is unconstrained in the upper 1 m (6 ft). Our best Vs30 measurement is 191 m/sec, which places the site in the D class, near the D/E boundary. Although the upper 2 m are unconstrained, adjusting them does not change the site class. All the initial and final models place this site in the D class, so the site can be confidently classified. This is the same as the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

DELONG ELEMENTARY SCHOOL

TACOMA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

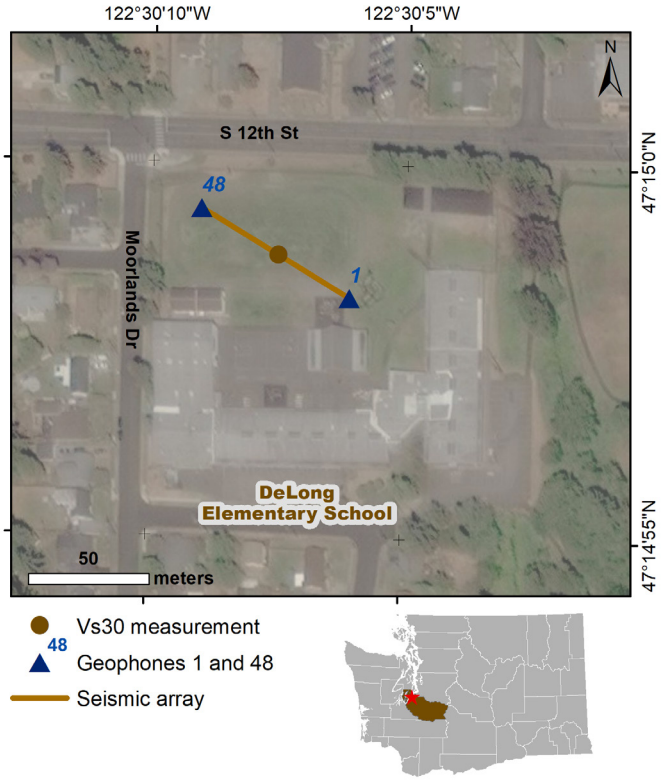
On August 10, 2020, a team from the Washington Geological Survey conducted a seismic survey at DeLong Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (230 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

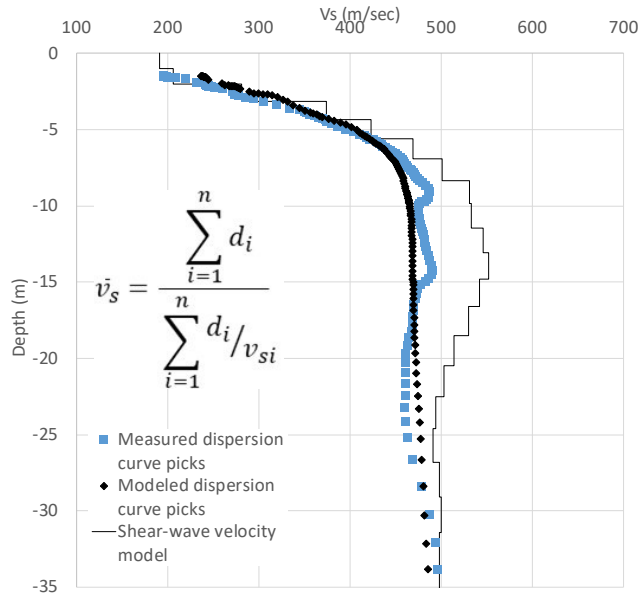
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality so that the fundamental mode is picked with low confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is decent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 7.1 percent. The inversion was carried out for three iterations and resulted in a final model with an RMSE of 5.2 percent. The final model shows rapidly increasing velocity from 1 m (3 ft) to 10 m (30 ft), a strong velocity reversal at around 15 m (50 ft), and then generally constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 443 m/sec, which places the site in the C site class. All initial and inverted models are in the C class, so the site can be confidently classified. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

DISCOVERY ELEMENTARY SCHOOL AND GIG HARBOR HIGH SCHOOL

PENINSULA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

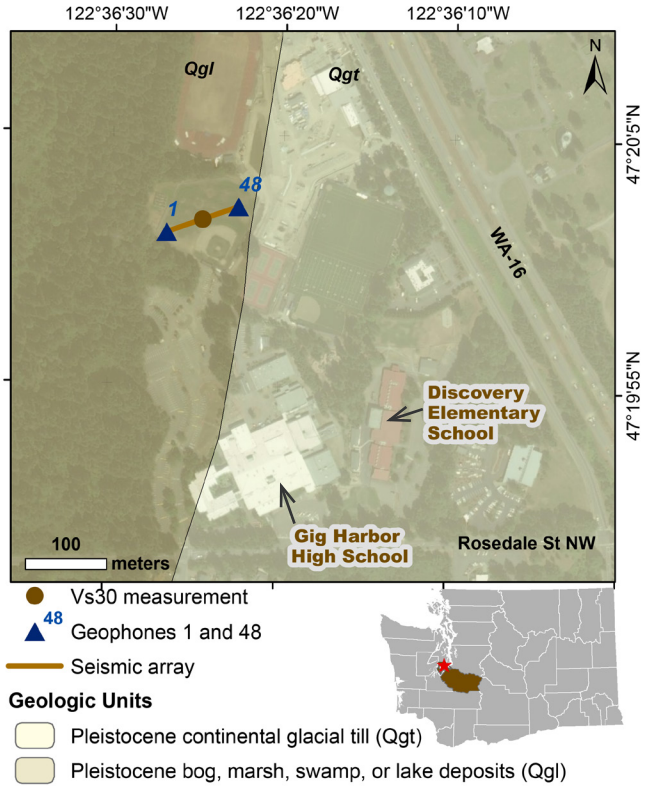
On July 15, 2020, a team from the Washington Geological Survey conducted a seismic survey at Discovery Elementary School and Gig Harbor High School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The schools are built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The schools are sitting on mostly continental glacial till (unit Qgt) and some glaciolacustrine deposits (unit Qgl).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

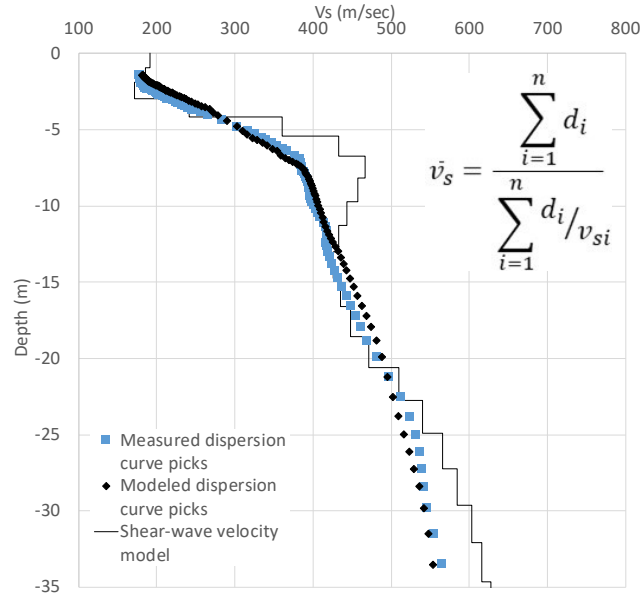
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality so that the fundamental mode can be picked with some confidence. The microtremor analysis method (MAM) dispersion image is decent quality. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 12.8 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 5.1 percent. The final model is unconstrained in the top 1.5 m (5 ft), and below this shows rapidly increasing velocity to 7 m (20 ft), then a slight velocity reversal to 13 m (40 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 397 m/sec, which places the site in the C site class. All initial and inverted models are in the C class, so the site can be confidently classified. This is the same as the predicted site class of C.

GEOLOGY

The site class of C is the same as predicted, but the 1:100,000-scale geologic map on the previous page shows a geologic contact crossing the site. The map indicates the school buildings are primarily located on Pleistocene continental glacial till (unit Qgt) while the seismic array is located on Pleistocene bog, marsh, swamp, or lake deposits (unit Qgl). The contact between units Qgt and Qgl runs along the west side of the campus, cutting through a small portion of the buildings associated with Gig Harbor High School. Nearby boreholes show layers of hardpan interspersed with layers of unconsolidated sediments, which could explain the velocity reversal seen in the 1D velocity model for this site. Regardless, both geologic units that cross through the school buildings have a predicted site class of C, and we do not observe strong heterogeneity across the array, so we can confidently assign a site class of C to the campus.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the top right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

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DOROTHY FOX ELEMENTARY SCHOOL

CAMAS SCHOOL DISTRICT, CLARK COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

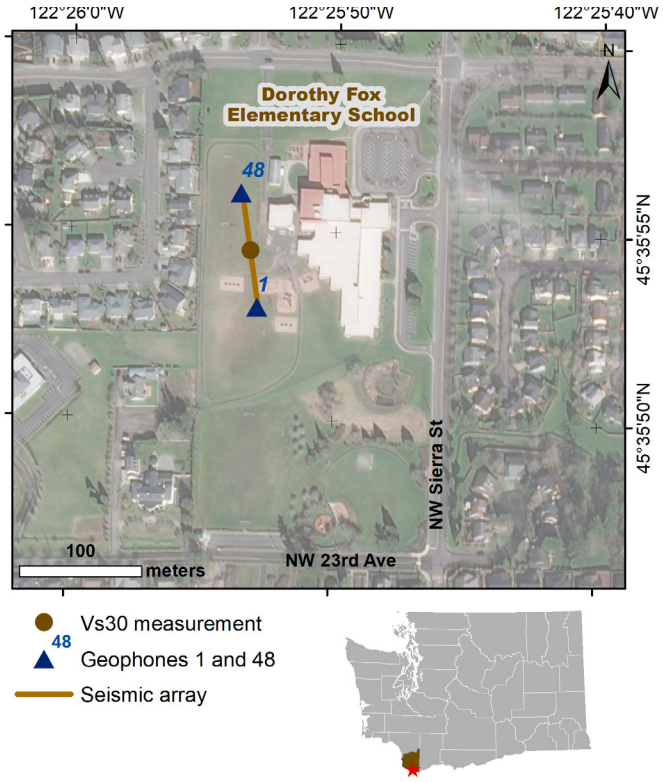
On August 31, 2020, a team from the Washington Geological Survey conducted a seismic survey at Dorothy Fox Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary eolian deposits comprising massive, unconsolidated deposits of silt and fine sand with isolated granules and small pebbles.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Severe

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

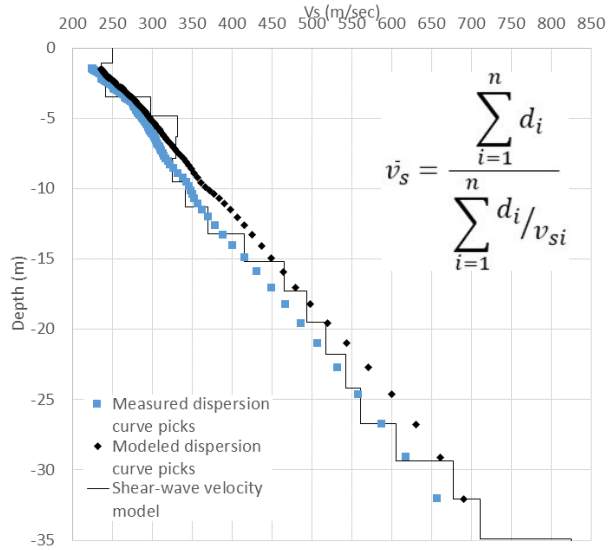
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves depict similar trends, therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 10.8 percent. The inversion was carried out for eight iterations and resulted in a final model with an RMSE of 4.8 percent. The final model is unconstrained in the upper 1.5 m (5 ft), and below this shows generally increasing velocity to 5 m (16 ft), then nearly constant velocity to 10 m (33 ft), and then steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 397 m/sec, which places the site solidly in the C site class. This is within the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = Shear wave velocity in m/sec of the layer.

EDISON ELEMENTARY SCHOOL

TACOMA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

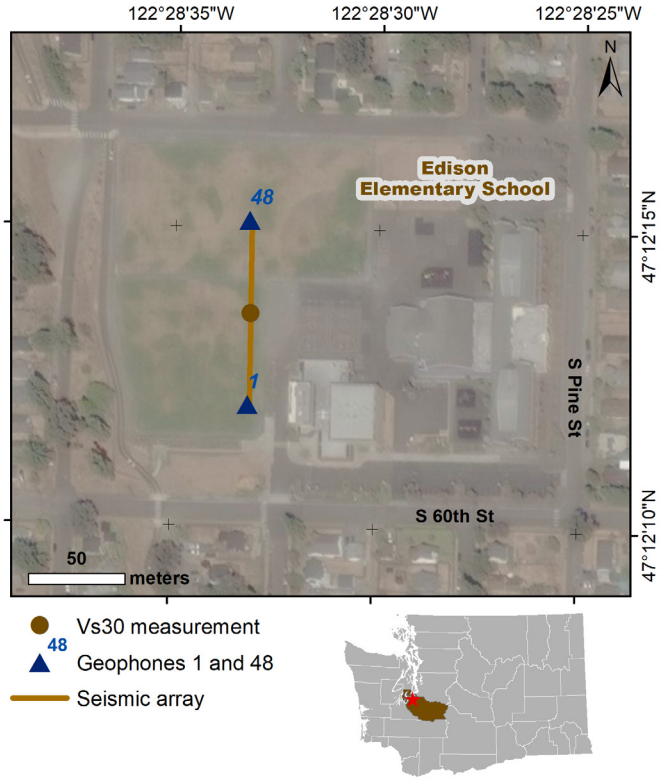
On August 6, 2020, a team from the Washington Geological Survey conducted a seismic survey at Edison Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial outwash.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

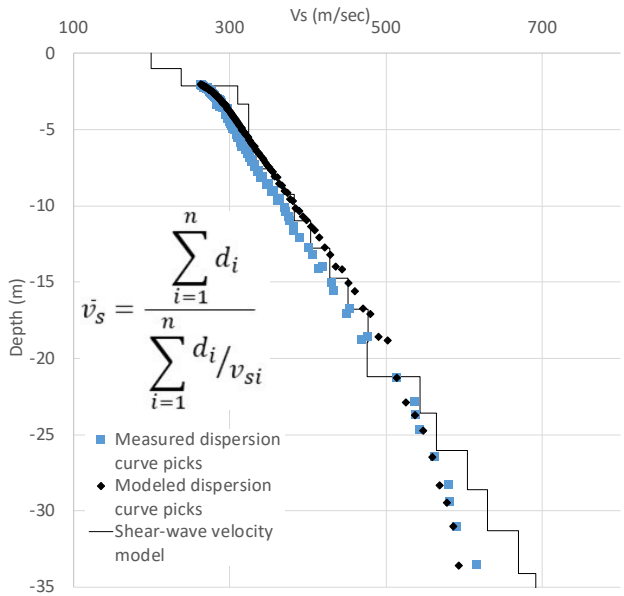
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of excellent quality but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 7.0 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.7 percent. The final model shows generally increasing velocity from 2 m (6 ft) down to 30 m (100 ft). Our best Vs30 measurement is 409 m/sec, which places the site in the C site class. All initial and inverted models are in the C class, so the site can be confidently classified. This is within the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left. d_i = thickness of any layer between 0 and 30 m. V_{si} = Shear wave velocity in m/sec of the layer.

EMERALD HEIGHTS ELEMENTARY SCHOOL

CENTRAL KITSAP SCHOOL DISTRICT, KITSAP COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

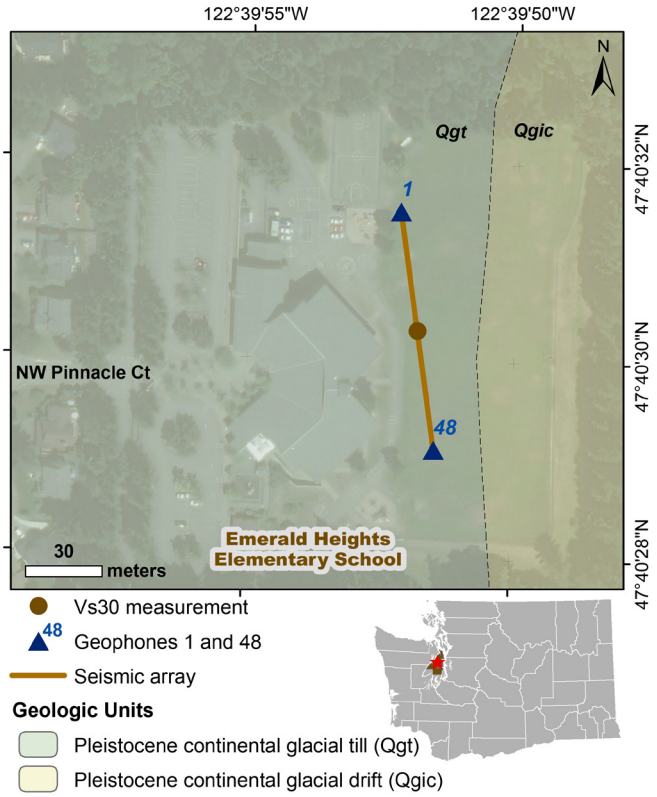
On April 14, 2021, a team from the Washington Geological Survey conducted a seismic survey at Emerald Heights Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental till (unit Qgt) consisting mostly of clay, silt, sand, pebbles, cobbles, and isolated boulders. Mapped on the eastern side of campus is Pleistocene continental drift (unit Qgic) which consists of similar materials.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

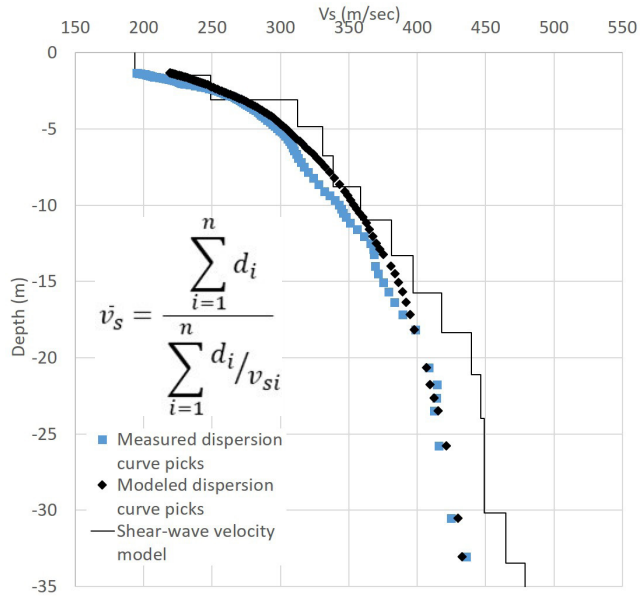
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so the fundamental mode can be picked with high confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is decent quality, but the resulting dispersion curve does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 6.5 percent. The inversion was carried out for three iterations and resulted in a final model with an RMSE of 4.7 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows rapidly increasing velocity to 5 m (18 ft), then gradually increasing velocity to 22 m (72 ft), and then nearly constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 366 m/sec, which places the site near the D/C site class boundary. However, all initial and inverted models are in the the C class, so the site can be confidently classified. This correlates with the predicted site class of C.

GEOLOGY

The 1:24,000-scale geologic map shows both the seismic array and the school buildings are located on Pleistocene glacial till (unit Qgt) while Pleistocene glacial drift (unit Qgic) is mapped on the east side of campus. This is different from the 1:100,000-scale geologic map which places Pleistocene glacial outwash (unit Qga) with a predicted site class of C–D on the northeast corner of campus with the rest of campus being mapped as Pleistocene continental till (unit Qgt) with a predicted site class of C. Nearby boreholes show silt, sand, and gravel past 30 m (100 ft). The 1D velocity model indicates less consolidated materials overlaying more consolidated materials, which become increasingly consolidated with depth past 30 m (100 ft). This is consistent with nearby boreholes, so can we reasonably assign a site class C to the campus.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

EMERSON ELEMENTARY SCHOOL

HOQUIAM SCHOOL DISTRICT, GRAYS HARBOR COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

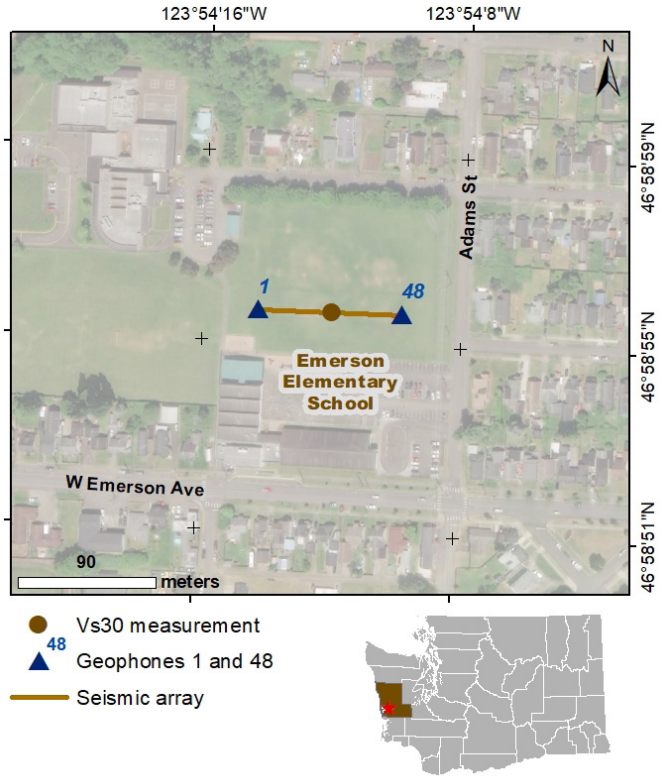
On November 6, 2019, a team from the Washington Geological Survey conducted a seismic survey at Emerson Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on river sediments consisting mostly of boulder, cobble, and pebble gravel and sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Extreme

Tsunami
In a mapped tsunami hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

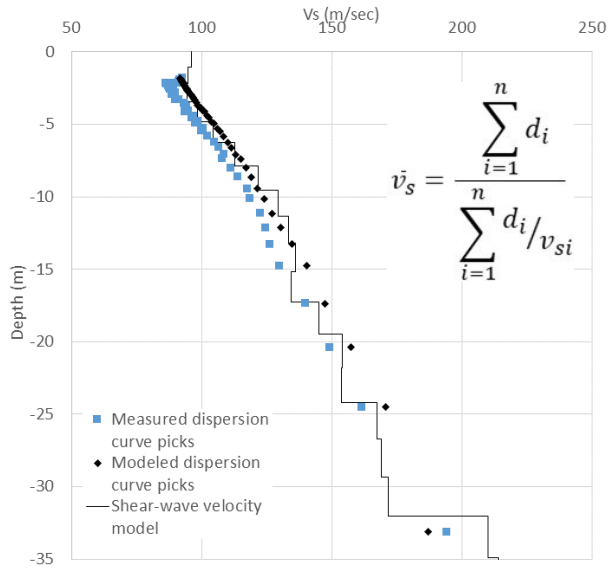
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are of decent quality and the fundamental mode can be picked, but only the reverse direction samples down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of decent quality, and the resulting dispersion curve agrees well with the MASW reverse direction dispersion curve. These curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 6.4 percent. The inversion was carried out for three iterations and resulted in a final model with an RMSE of 4.7 percent. The final model shows generally constant velocity for the top 3 m (10 ft), then gradually increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 131 m/sec, which places the site in the E class. Both initial and inverted models classify this site as below the D/E boundary, so it can be confidently classified. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_S) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

EMERSON ELEMENTARY SCHOOL

SNOHOMISH SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

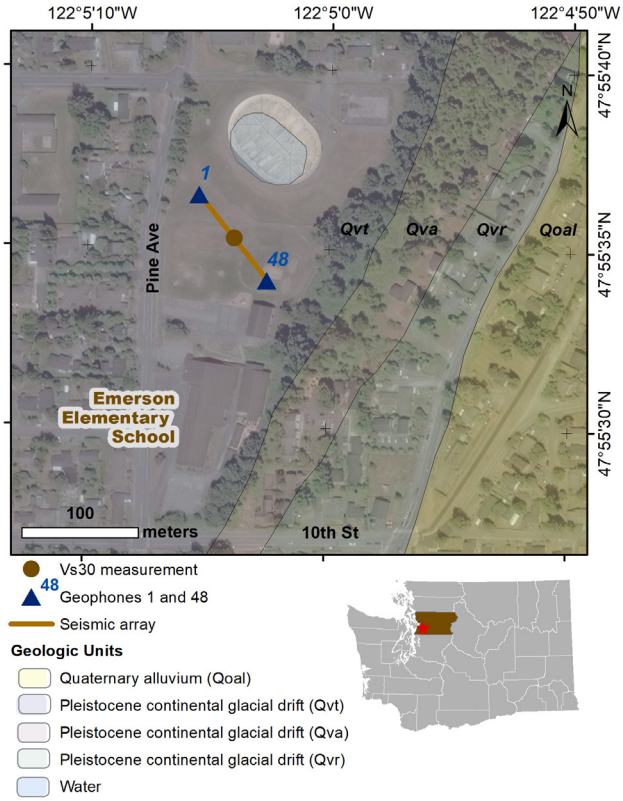
On October 28, 2020, a team from the Washington Geological Survey conducted a seismic survey at Emerson Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

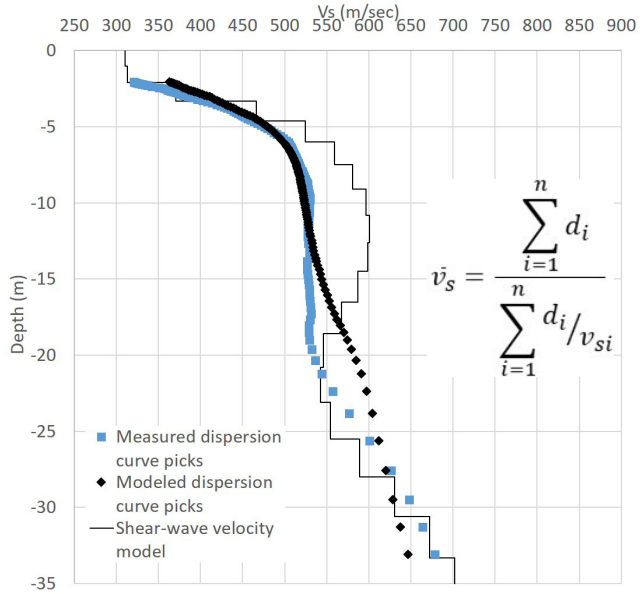
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality but the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is of decent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. The three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 5.85 percent. The inversion was carried out for four iterations and resulted in a final model with an RMSE of 3.64 percent. The final model is unconstrained in the upper 2 m (6 ft), and below this shows generally increasing velocity to 10 m (33 ft), then a significant velocity reversal down to 22 m (72 ft), and then steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 528 m/sec, which places the site in the middle of the C site class. This is within the predicted site class of C–D.

GEOLOGY

The1:100,000-scale geologic map places the school campus mostly Pleistocene continental glacial till (unit Qgt) with a predicted site class of C, but has a contact with Pleistocene glacial drift (unit Qga) with a predicted site class of C–D running roughly northwest/southeast through the buildings. However, the higher resolution 1:24,000-scale geologic map shows this contact is farther east and not directly under the building footprint, placing the entire school and seismic array on glacial till (unit Qvt). Regardless, our measured site class is within the predicted site class for both 1:100,000-scale geologic units. Although the 1D velocity model does depict a velocity reversal, we don't have evidence for significant heterogeneity between the school buildings and the geophone array that could affect Vs30 enough to change the site class. Thus, we can confidently assign site class C to the school buildings.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

EMERSON K–12

LAKE WASHINGTON SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

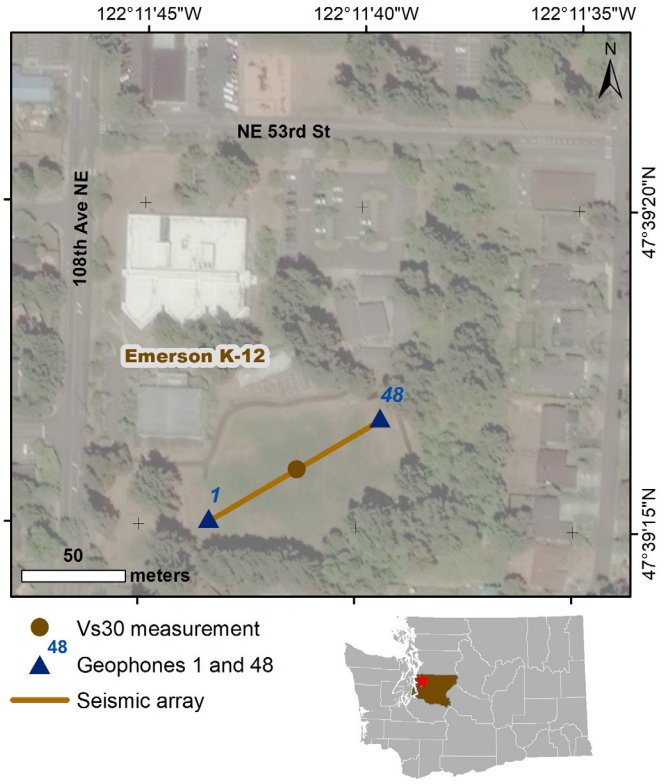
On July 29, 2020, a team from the Washington Geological Survey conducted a seismic survey at Emerson K–12. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift, consisting of well-sorted and fine-grained sandy units with interlayered coarser sand, gravel, and cobbles.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

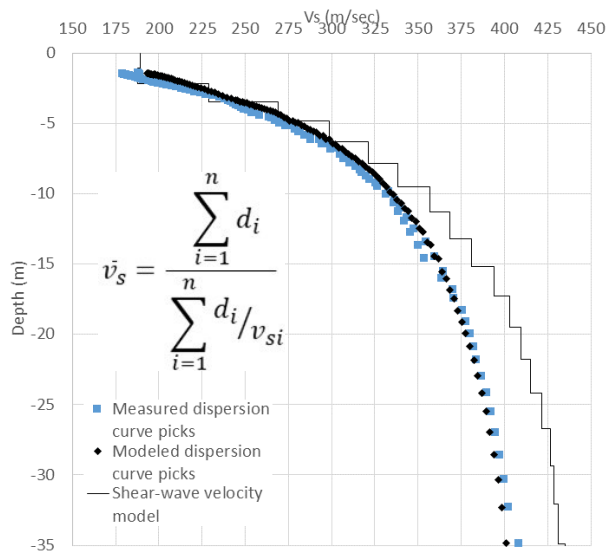
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. However, the MASW dispersion curves don't sample down past 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also excellent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. The three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 7.9 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.1 percent. The final model is unconstrained in the top 1.5 m (5 ft), and below this shows rapidly increasing velocity to 10 m (33 ft), then slowly increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 341 m/sec, which places the site in the D site class. All initial and inverted models place this site in the D class, so the site can be confidently classified. This is within the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

EMILY DICKINSON ELEMENTARY SCHOOL

LAKE WASHINGTON SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

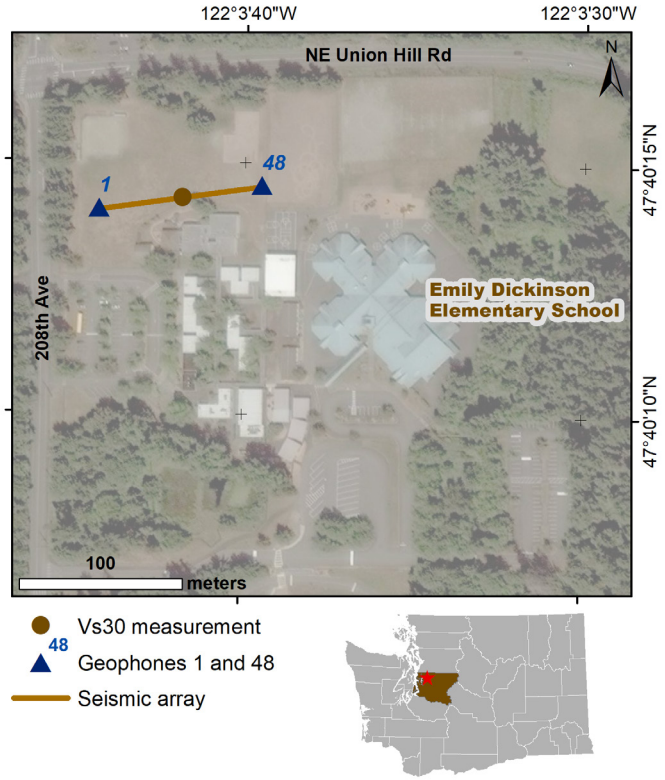
On July 27, 2020, a team from the Washington Geological Survey conducted a seismic survey at Emily Dickinson Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift, consisting mostly of stratified sand and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low/bedrock

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

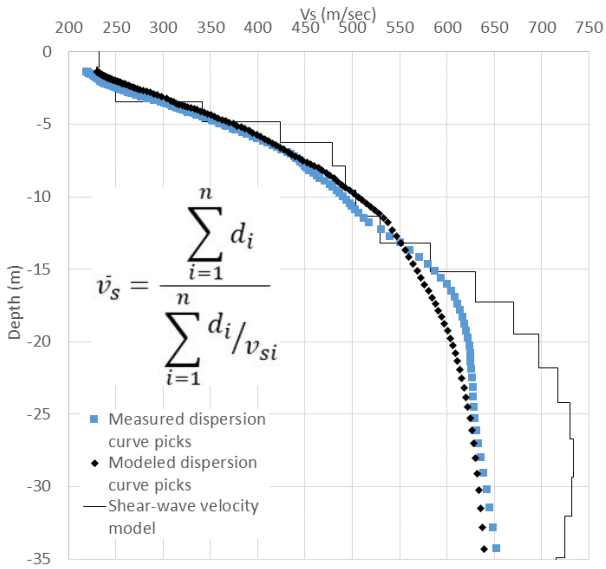
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is excellent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves depict similar trends, therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 10.6 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 4.7 percent. The final model shows generally increasing velocity down to 25 m (82 ft), then nearly constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 499 m/sec, which places the site solidly in the C site class. This is within with the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

EPHRATA HIGH SCHOOL AND GRANT ELEMENTARY SCHOOL

EPHRATA SCHOOL DISTRICT, GRANT COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

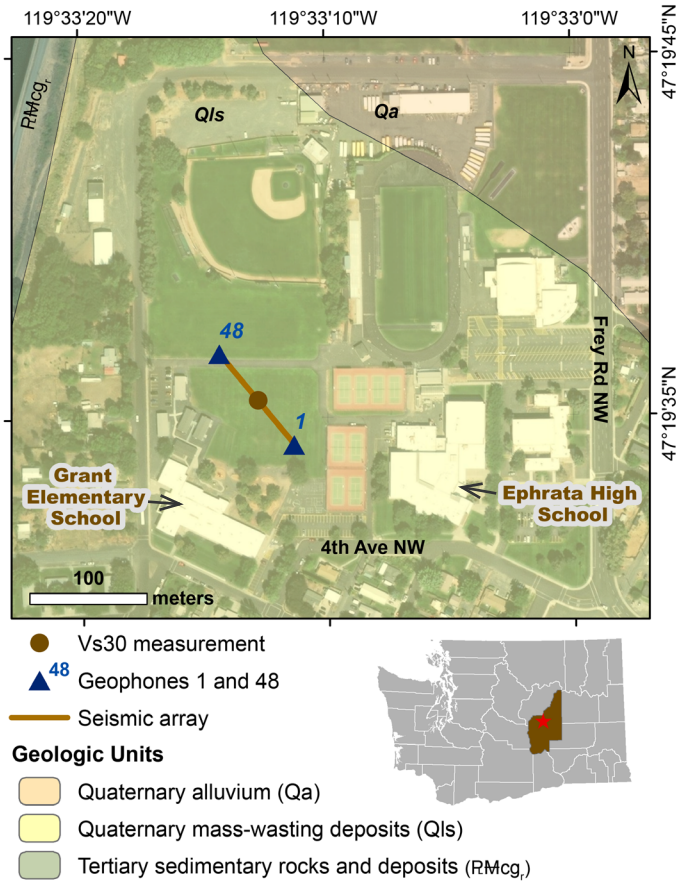
On September 25, 2020, a team from the Washington Geological Survey conducted a seismic survey at Ephrata High School and Grant Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on mass wasting deposits, mostly landslides (unit Qls). Alluvium (unit Qa) is mapped to the northeast while continental sedimentary rocks and deposits (unit RMcg$_r$) are mapped to the northwest.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Very strong

Landslide
Hazard present, based on terrain data

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

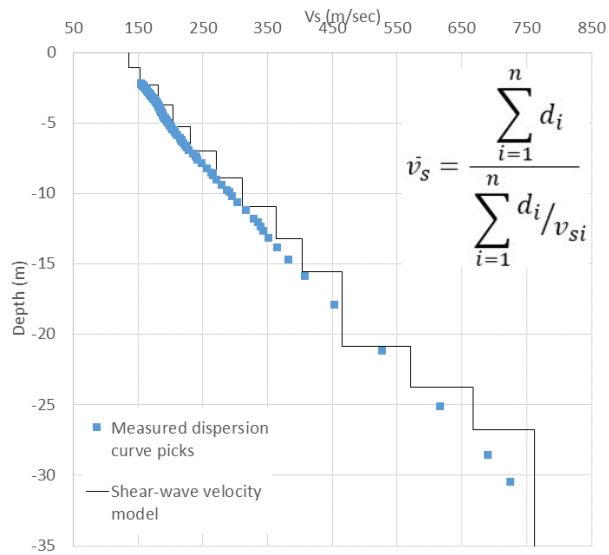
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. The microtremor analysis method (MAM) dispersion image is decent quality above 9 Hz, but poor below, with a drastic increase in phase velocity. However, the MAM and the reverse MASW dispersion curves correlate well and are combined into a single model.

VELOCITY MODEL

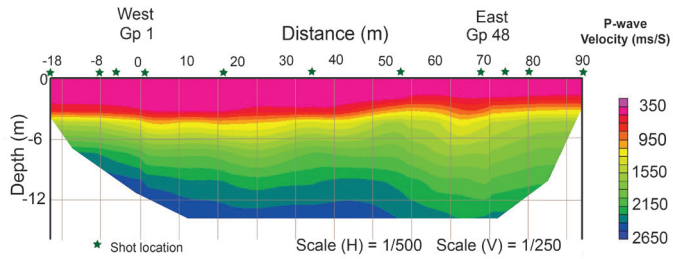
An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. Inverting the model to converge below 5 percent took a considerable number of iterations and forced unrealistic velocity structure. Therefore we base our final model on the initial model. The final model is unconstrained in the top 1 m (3 ft) and below this shows generally increasing velocity to 30 m (100 ft). Our best Vs30 measurement is 338 m/sec, which is solidly in the D site class. All initial and inverted models are in the D class, so this site can be confidently classified.

GEOLOGY

The 1:100,000-scale geologic map (previous page) shows the seismic array and school buildings are sitting on Quaternary mass wasting deposits (unit Qls) with a predicted site class of D. To the northeast is mapped Quaternary alluvium (unit Qa) with a predicted site class of C–D, and to the west is mapped Pliocene–Miocene sedimentary rocks (unit PMcg$_r$) with a predicted site class of B. The 1D velocity model indicates less dense materials in the upper 8 m (26 ft) overlying denser materials, and rock velocity appears around 29 m (97 ft). Nearby boreholes confirm shallow bedrock can be present in the top 30 m (100 ft), and the poor coherency at frequencies that correspond to the depths ~16–26 m is a good indicator of a sharp contact with higher velocity materials. The 2D seismic refraction tomography shows higher velocity materials becoming shallower towards geophone 1, which is nearer the school buildings. These observations suggest shallow bedrock consistent with unit PMcg$_r$ could be present underneath the campus. While this could effectively increase Vs30 into the C class, the Vs30 measured in this study places the site far enough into the D site class that we can reasonably apply a site class D to the soil under the school buildings.



Final velocity model with measured dispersion curve based on the intial model. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.



2D refraction tomography model depicting the lateral variation in P-wave velocity (Vp) with depth in m/sec across the geophone (Gp) array from the farthest off end shot from both ends.

FAIRHAVEN MIDDLE SCHOOL

BELLINGHAM SCHOOL DISTRICT, WHATCOM COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

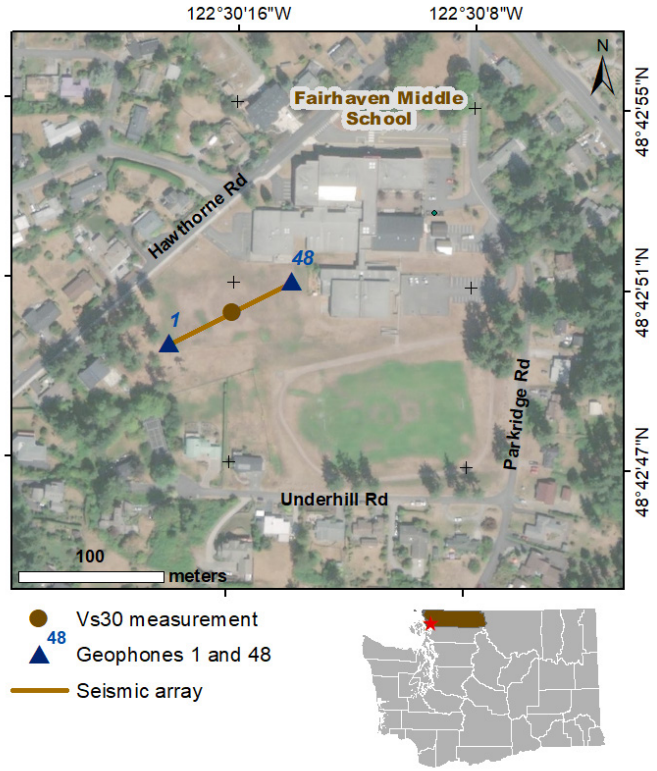
On October 22, 2020, a team from the Washington Geological Survey conducted a seismic survey at Fairhaven Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of B.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Eocene continental sedimentary rocks and deposits.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Unknown, not negligible

Ground Shaking
Severe

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

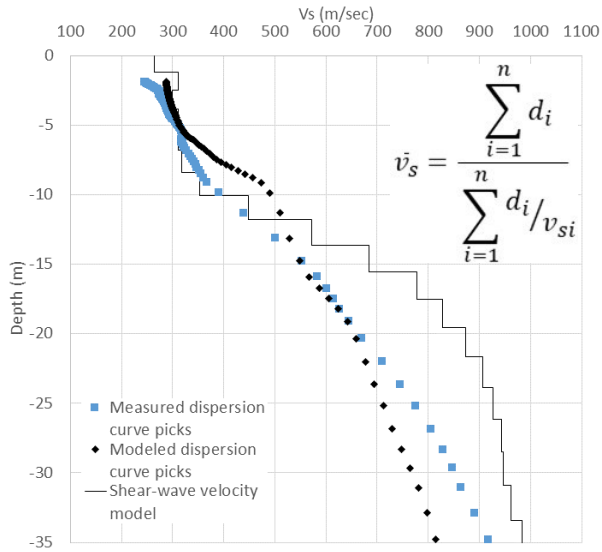
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microwtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the shallow layers. MAM and the reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the two dispersion curves are combined into a single model.

VELOCITY MODEL

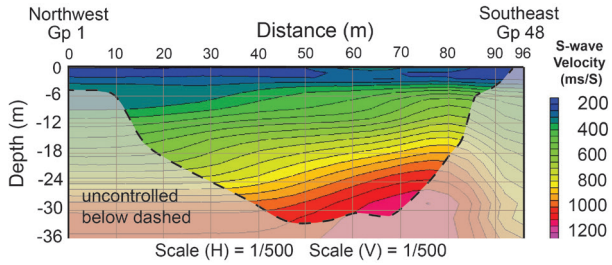
An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 11.1 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 7.3 percent. The final model shows steadily increasing velocity to 10 m (33 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 525 m/sec, which places the site within the C site class. Although the MASW dispersion curves from the reverse and forward directions do show some variability, all inital and inverted models from each are in the C class, so the site can be confidently classified. This is different from the predicted site class of B.

GEOLOGY

The 1:100,000-scale geologic map places the seismic array, school buildings, and the surrounding area on sedimentary rocks and deposits (unit Ec_{cp}), with a predicted site class of B, which does not match our measured site class of C. However, the 1:100,000-scale geology map shows a contact with continental glacial drift (unit Qgd), with a predicted site class of C–D, ~1 km to the east. Nearby boreholes show mostly compact sediments in the top 12 m, then sandstone or siltstone to 20 m. This correlates with the 1D velocity model, which does not show rock velocity expected of unit Ec_{cp} until about 16 m depth. The 2D seismic refraction tomography and 2D MASW indicate rock velocity layers becoming shallower towards the school, reaching the shallowest of ~15 m depth below geophone 45. This confirms bedrock is not at the surface as the 1:100,000-scale geologic map would suggest, and horizontal-to-vertical spectral ratio data corroborates this. Therefore, the change in site class is likely due to low-resolution mapping, and the school is likely on unit Qgd overlaying unit Ec_{cp}.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.



Pseudo 2D MASW shear-wave velocity model with locations for Geophones (Gp) 1 and 48. Dashed line approximately delineates the model's reliability in the vertical extent. Portions of the model at depths below the dashed line (shaded area) are not constrained.

FORKS ELEMENTARY SCHOOL, FORKS INTERMEDIATE SCHOOL, AND FORKS HIGH SCHOOL

QUILLAYUTE VALLEY SCHOOL DISTRICT, CLALLAM COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

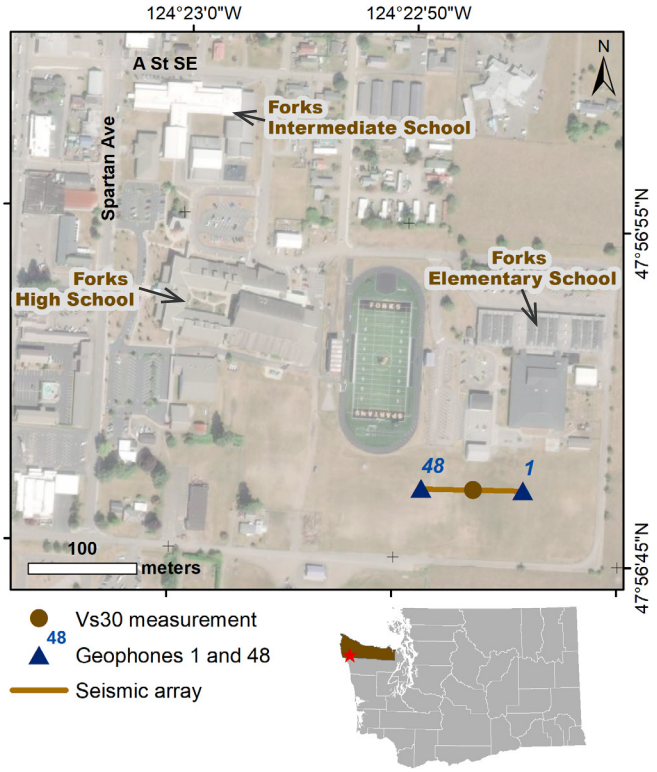
On August 26, 2020, a team from the Washington Geological Survey conducted a seismic survey at Forks Elementary School, Forks Intermediate School, and Forks High School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the schools.

WHAT DID WE LEARN?

- The schools are built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array and the school campuses.

WHAT SOILS ARE UNDER THE SCHOOLS?

All three schools are sitting on Pleistocene continental glacial drift, consisting mostly of stratified sand and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Extreme

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

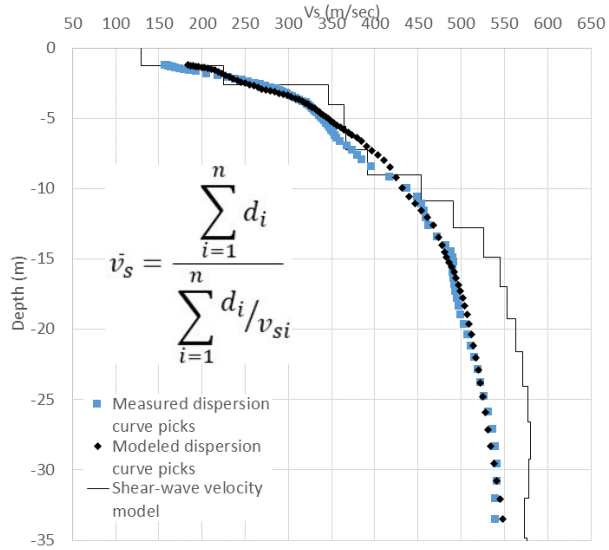
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality, especially at higher frequencies (shallow layers), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is also poor quality at high frequencies, but decent quality at lower frequencies (deeper layers). Despite the shallow layer velocities being somewhat speculative, MAM and the forward and reverse MASW dispersion curves correlate well. The three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 6.7 percent. The inversion was carried out for four iterations and resulted in a final model with an RMSE of 4.4 percent. The final model is unconstrained in the top 1 m (3 ft), below this shows generally increasing velocity to 3 m (10 ft), then nearly constant velocity down to 9 m (30 ft), generally increasing velocity to 15 m (49 ft), and nearly constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 419 m/sec, which places the site solidly in the C site class. All the initial and inverted models are in the C class, so the site can be confidently classified. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

FOSS HIGH SCHOOL

TACOMA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

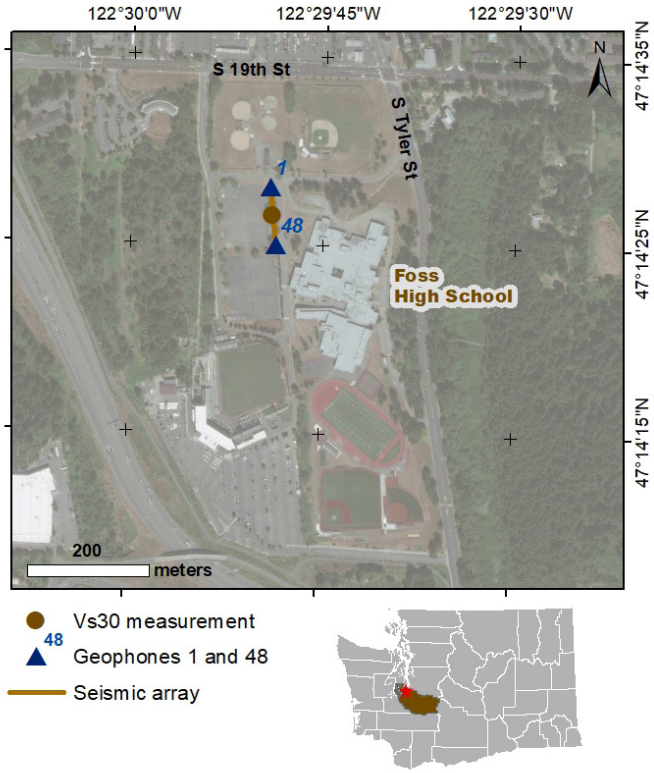
On August 11, 2020, a team from the Washington Geological Survey conducted a seismic survey at Foss High School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

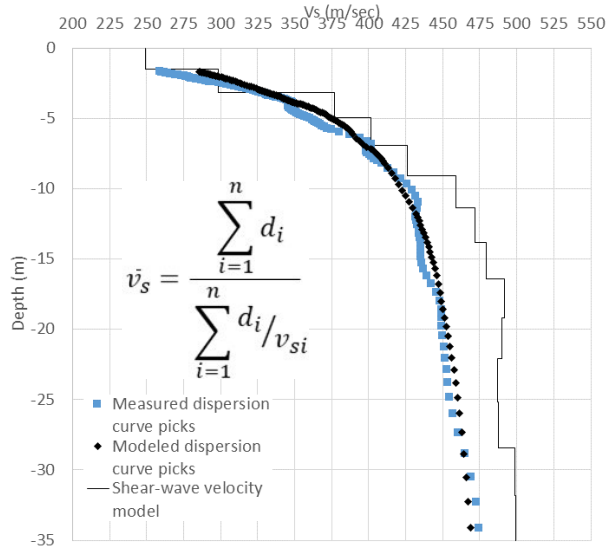
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward direction are decent quality so that the fundamental mode can be picked with confidence. However, the reverse direction images have poor coherency, and are dominated by higher modes. The MASW dispersion curves from both directions do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is poor quality, but the fundamental mode can be picked with some confidence. The MAM dispersion curve does not sample the shallow layers. MAM and the forward MASW dispersion curves correlate well, depicting similar trends. Therefore the two dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 5.8 percent. The inversion was carried out for three iterations and resulted in a final model with an RMSE of 4.3 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows generally increasing velocity to 15 m (49 ft), then nearly constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 432 m/sec, which places the site solidly in the C site class. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = Shear wave velocity in m/sec of the layer.

FRANKLIN ELEMENTARY SCHOOL

TACOMA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

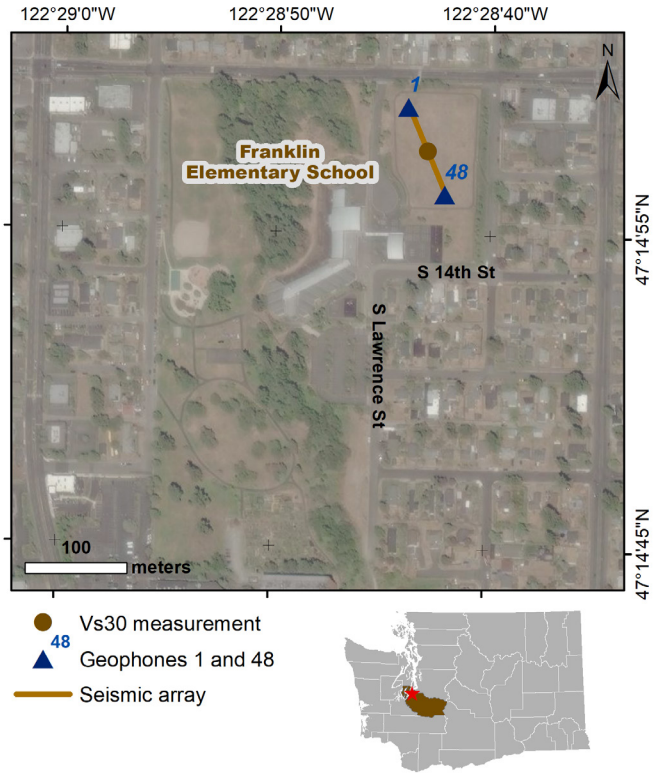
On August 11, 2020, a team from the Washington Geological Survey conducted a seismic survey at Franklin Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

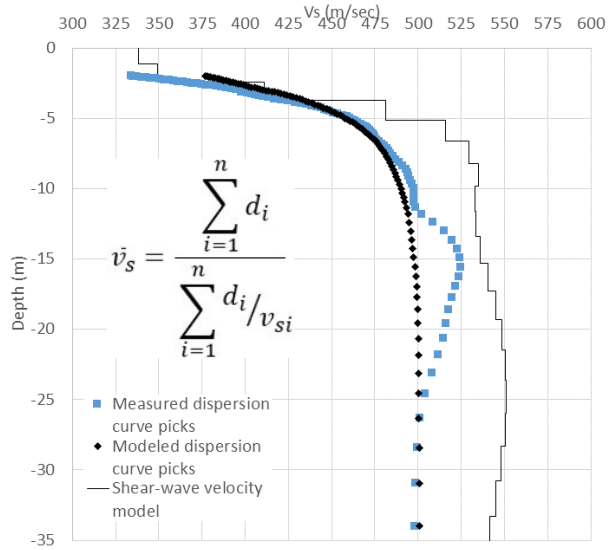
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is excellent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 5.1 percent. The inversion was carried out for three iterations and resulted in a final model with an RMSE of 3.7 percent. The final model is unconstrained in the top 2 m (7 ft), and below this shows rapidly increasing velocity to 7 m (23 ft), then nearly constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 508 m/sec, which places the site in the middle of the C site class. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

GRANITE FALLS MIDDLE SCHOOL

GRANITE FALLS SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

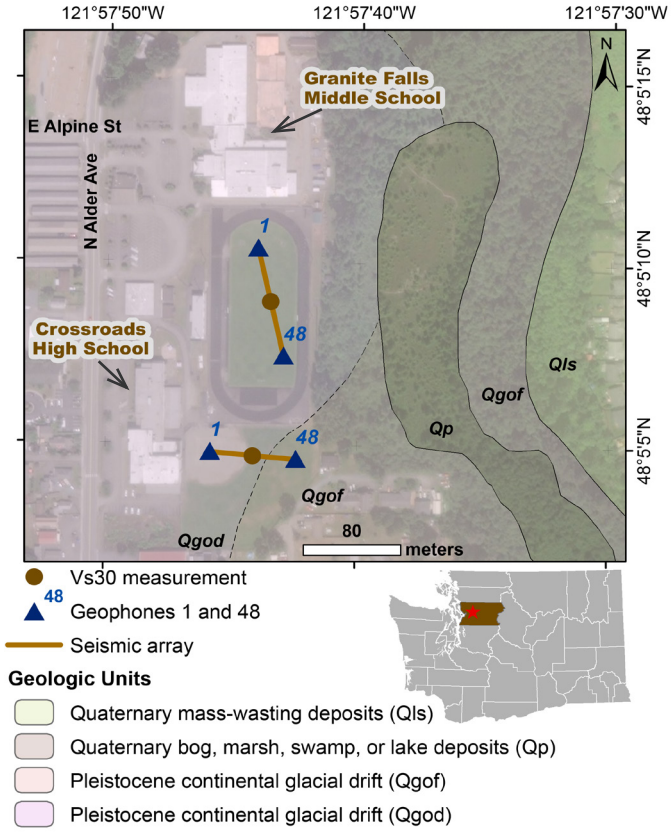
On October 26, 2020, a team from the Washington Geological Survey conducted a seismic survey at Granite Falls Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift, comprising mostly sand, gravel, and cobbles (unit Qgod). Mapped to the east is more Pleistocene continental glacial drift (unit Qgof), and Quaternary bog, marsh, swamp, or lake deposits (unit Qp).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

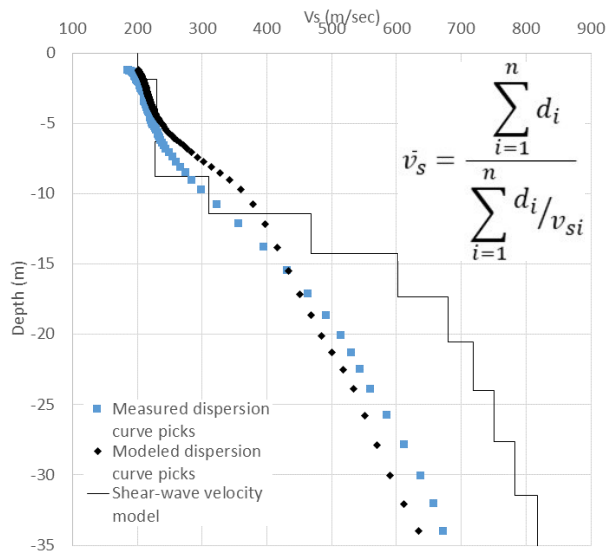
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. The microtremor analysis method (MAM) dispersion image is also excellent quality, and the resulting dispersion curve correlates well with the forward and reverse MASW dispersion curves. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 10.4 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 5.7 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows nearly constant velocity to 9 m (30 ft), then generally increasing velocity 20 m (66 ft), and then more slowly increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 395 m/sec, which places the site solidly in the C site class. With the clear coherence of the dispersion images and all inital and inverted models placing this site in a class C, this site can be confidently classified. This is different from the predicted site class of D–E.

GEOLOGY

The 1:24,000-scale geologic map places the school buildings and the seismic array on glacial drift (unit Qgod), with more glacial drift (different in sediment size and color from unit Qgod) and bog or lake deposits mapped closely to the east and south. The 1:100,000-scale geologic map, which is used to predict site class, has different unit contacts, and places the entire campus and surrounding area on a single unit of glacial drift with predicted site class of D–E. Past this, ~450 m (1500 ft) east of the school in both scale geologic maps, are metasedimentary rocks with predicted site class B. Nearby boreholes show unconsolidated sand and gravel past 100 ft, consistent with site class D. At 11 m (36 ft) depth the 1D velocity model shows a sudden increase in velocity, and rock velocity appears at ~28 m (92 ft). This is consistent with less consolidated material overlying denser materials such as bedrock, which could be fractured or weathered on top. The 2D MASW and 2D seismic refraction tomography (SRT) show very little heterogeneity over the length of the array, so we can reasonably assume the middle school is on materials similar to the array. The change in site class from D–E to C is likely due to denser materials being present in the top 30 m. These could be the metasedimentary rocks mapped to the east, or variability within the glacial drift unit. Granite Falls Middle School shares a campus with Crossroads High School, which was also evaluated in this study and has a measured site class of D (see site class assessment for Crossroads High School). This could indicate the higher velocity material which underlies the middle school is limited in its extent, or slopes down southwards.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

GREEN MOUNTAIN ELEMENTARY

CENTRAL KITSAP SCHOOL DISTRICT, KITSAP COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

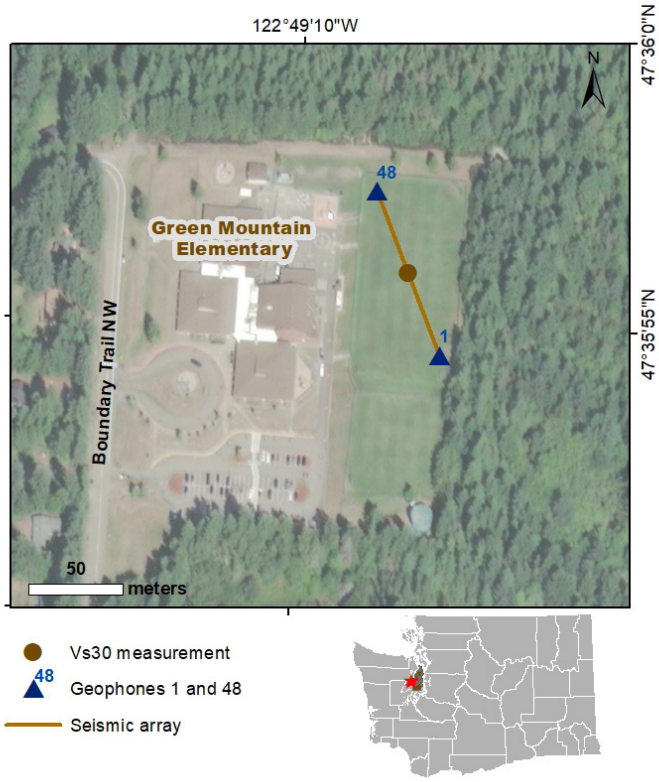
On April 15, 2021, a team from the Washington Geological Survey conducted a seismic survey at Green Mountain Elementary. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

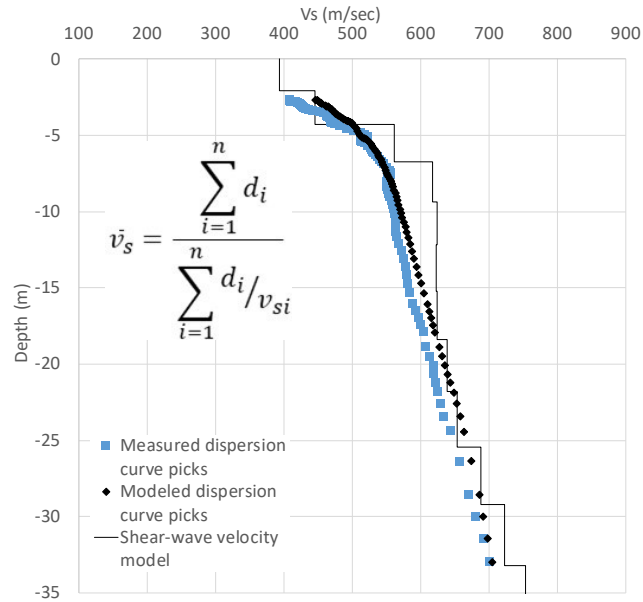
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. The microtremor analysis method (MAM) dispersion image is decent quality. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 5.8 percent. The inversion was carried out for four iterations and resulted in a final model with an RMSE of 3.7 percent. The final model shows generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 592 m/sec, which places the site in the C site class. All initial and final models are of the C class, so the site can be confidently classified. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the image. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

HAZEN HIGH SCHOOL

RENTON SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

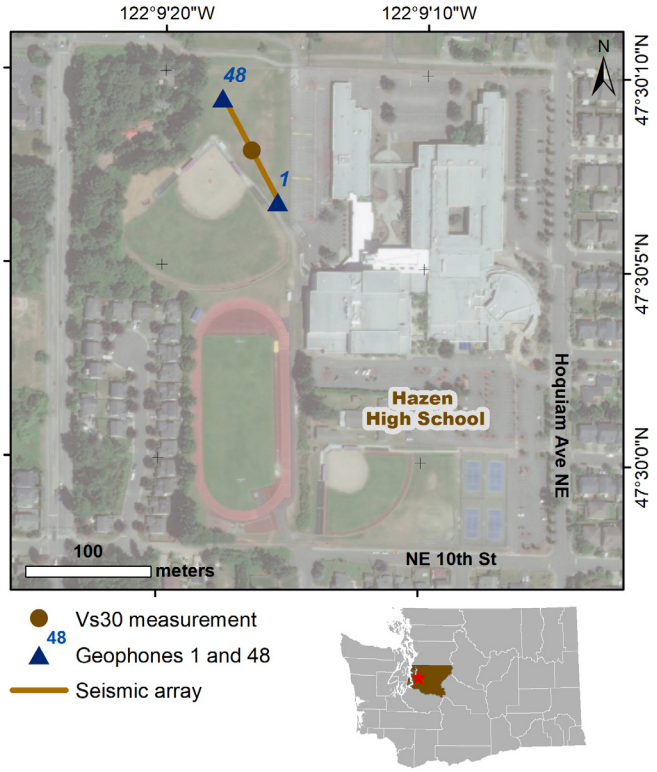
On October 22, 2020, a team from the Washington Geological Survey conducted a seismic survey at Hazen High School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift consisting of well-sorted and fine-grained sandy units with interlayered coarser sand, gravel, and cobbles.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

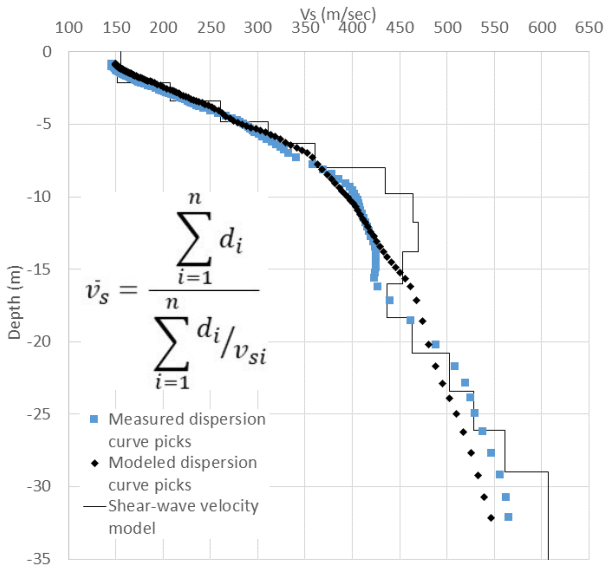
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality so that the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is decent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves depict similar trends, therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 11.1 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.5 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows rapidly increasing velocity to 10 m (33 ft), then a slight velocity reversal down to 17 m (56 ft), and then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 376 m/sec, which places the site in the C site class near the C/D border. This is within the predicted site class of C-D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

HILLTOP ELEMENTARY SCHOOL

HIGHLINE SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

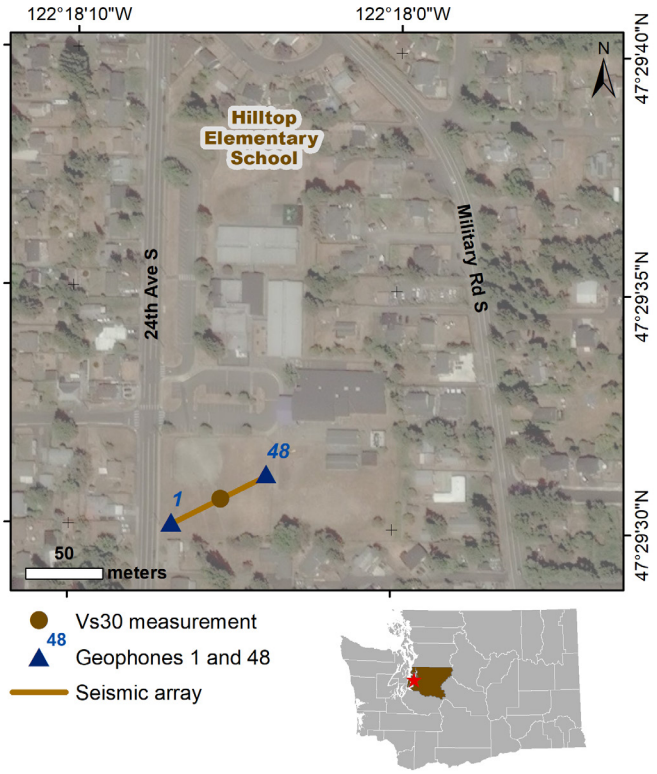
On August 25, 2020, a team from the Washington Geological Survey conducted a seismic survey at Hilltop Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (231 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial till, mostly a compact silt or sand-rich matrix containing sub- to well-rounded clasts.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

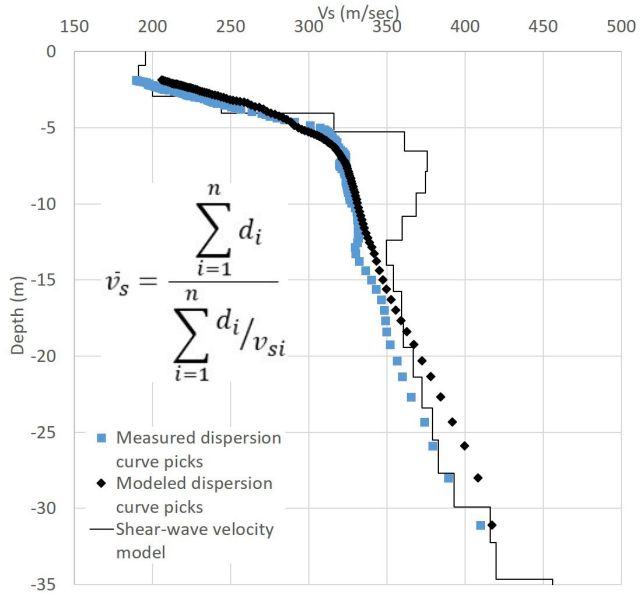
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is excellent quality, and the resulting dispersion curve correlates well with the forward and reverse MASW dispersion curves. MAM and the forward direction MASW dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 8.8 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.8 percent. The final model is unconstrained in the top 2 m (7 ft), and below this shows rapidly increasing velocity to 7 m (23 ft), then a velocity reversal down to 14 m (46 ft), and then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 333 m/sec, which places the site solidly in the D site class. All initial and inverted models are of the D site class, so the site can be confidently classified. This is different from the predicted site class of C.

GEOLOGY

The 1:100,000-scale geologic map, which is used to predict site class, shows the school buildings and seismic array on Pleistocene continental glacial till (unit Qgt) with a predicted site class of C, and maps glacial drift (unit Qgo) ~400 m (1300 ft) to the west with a predicted site class of C–D. However, the 1:24,000-scale geologic map (previous page) places the school and surrounding area on Pleistocene continental glacial drift instead of till. Nearby boreholes show mostly sand, silt, and gravel past 30 m. The velocity inversion in the 1D velocity model around 8 m (26 ft) implies there could be a local change, or a variation within the geologic unit. Thus, the change in site class could be due lateral heterogeneity or low resolution mapping.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

HOCKINSON HEIGHTS ELEMENTARY SCHOOL

HOCKINSON SCHOOL DISTRICT, CLARK COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

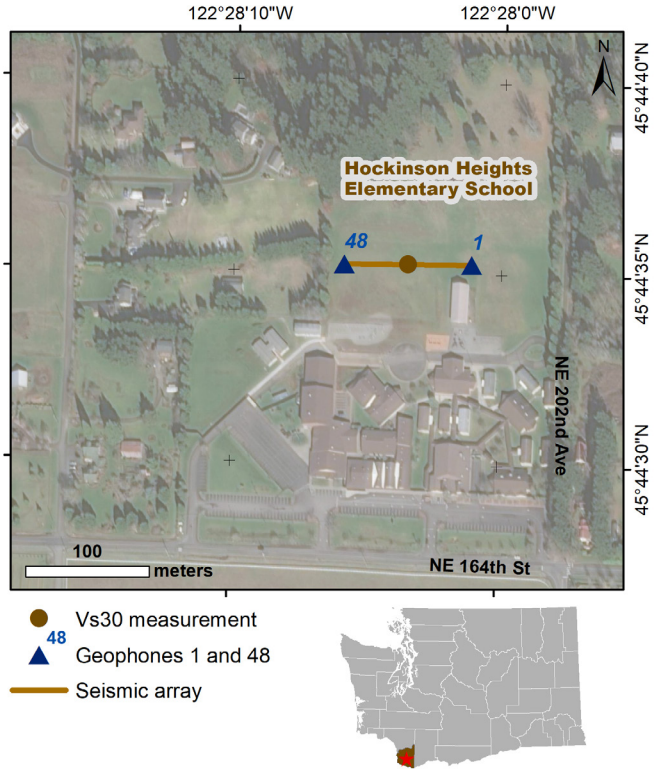
On February 19, 2020, a team from the Washington Geological Survey conducted a seismic survey at Hockinson Heights Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Tertiary sedimentary rocks and deposits, comprising mostly pebbly and cobbly conglomerate with occasional sandstone lenses.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Severe

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

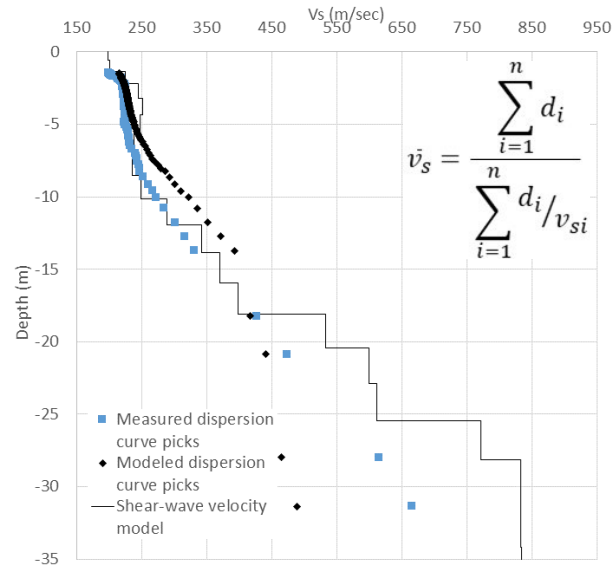
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. The microtremor analysis method (MAM) dispersion image is decent quality, and the resulting dispersion curve correlates well with the forward and reverse MASW dispersion curves, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

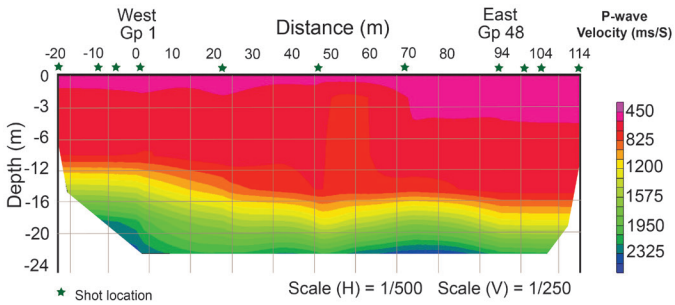
An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 7.6 percent. The inversion was carried out for four iterations and resulted in a final model with an RMSE of 5.0 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows nearly constant velocity to 10 m (33 ft), then increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 359 m/sec, which places the site in the D site class, on the C/D class boundary. While initial models place this site in the D class, inversions can exaggerate shallow and deep layers, creating a less realistic velocity model that shifts into the C class. For the final model we use an inverted model that places Vs30 just shy of this, in class D. This is within the predicted site class of C–D.

GEOLOGY

The 1:24,000-scale geologic map places the school buildings and seismic array on sedimentary rocks and deposits (unit Ttfc), with a predicted site class of C–D. Mapped ~1 km (0.6 mi) to the east is volcanic rocks (unit Tbem), with a predicted site class of B. In the 1D velocity model there is a sudden increase in velocity around 18 m (59 ft), reaching rock velocity by 28 m (92 ft). This could indicate a contact with denser materials at depth. Three other sets of data corroborate this: nearby boreholes show cemented gravel deposits around 17 m (56 ft) and shale around 40 m (131 ft), 2D seismic refraction tomography (SRT) shows rock P-wave velocity around the same depth, and the Horizontal-to-Vertical Spectral Ratio (HVSR) data indicates a contact at this depth. Therefore, it is reasonable to assume subsurface changes in this area that could cause variation in site class, so we choose the most conservative choice that is reasonable and designate this site a D class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.



2D seismic refraction tomography model depicting the lateral variation in P-wave velocity (Vp) with depth across the geophone array from the farthest off end shot from both ends.

HOOVER ELEMENTARY SCHOOL

YAKIMA SCHOOL DISTRICT, YAKIMA COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

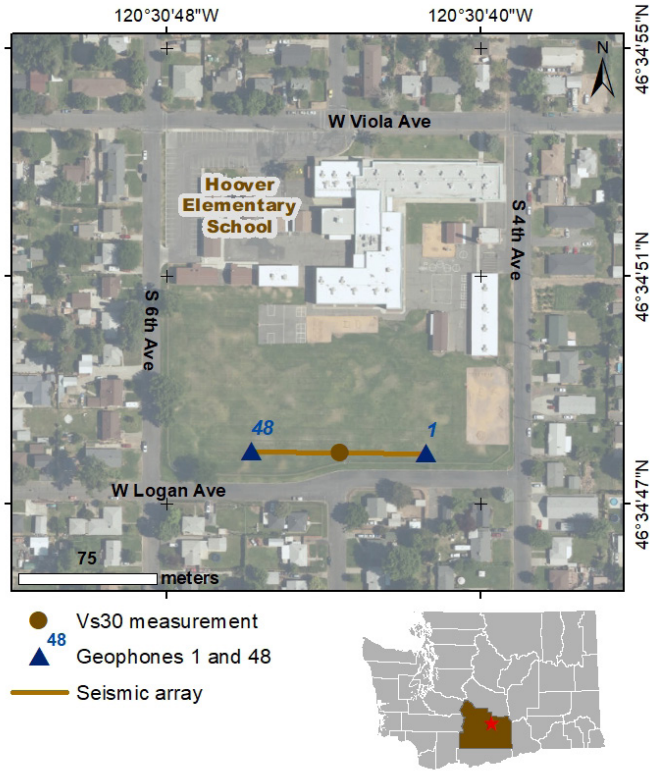
On October 6, 2020, a team from the Washington Geological Survey conducted a seismic survey at Hoover Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary stream terrace deposits, comprising mostly coarse gravel and sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low to low

Ground Shaking
Very strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

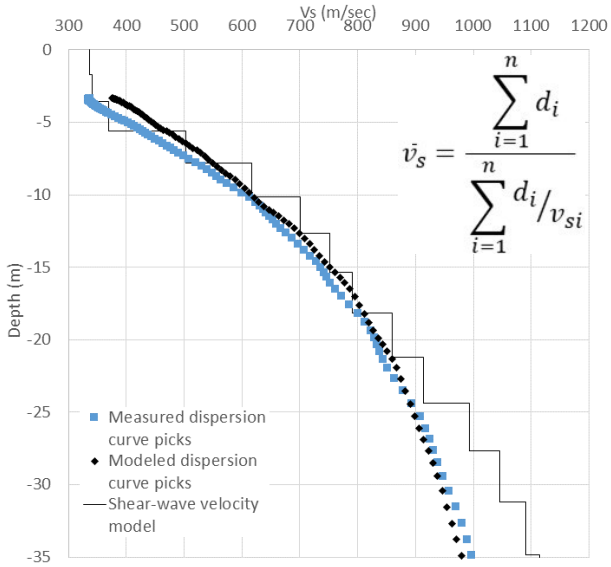
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image from the forward direction is decent quality so that the fundamental mode can be picked with confidence. However, the dispersion image from the reverse direction is very poor and does not add much information. The microtremor analysis method (MAM) dispersion image is excellent quality, and the resulting dispersion curve correlates well with the forward MASW dispersion curve. Therefore the two dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 10.8 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.6 percent. The final model is unconstrained in the top 3 m (10 ft), and below this shows generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 636 m/sec, which places the site solidly in the C site class. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

HOPKINS BUILDING (HARBOR HIGH SCHOOL)

ABERDEEN SCHOOL DISTRICT, GRAYS HARBOR COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

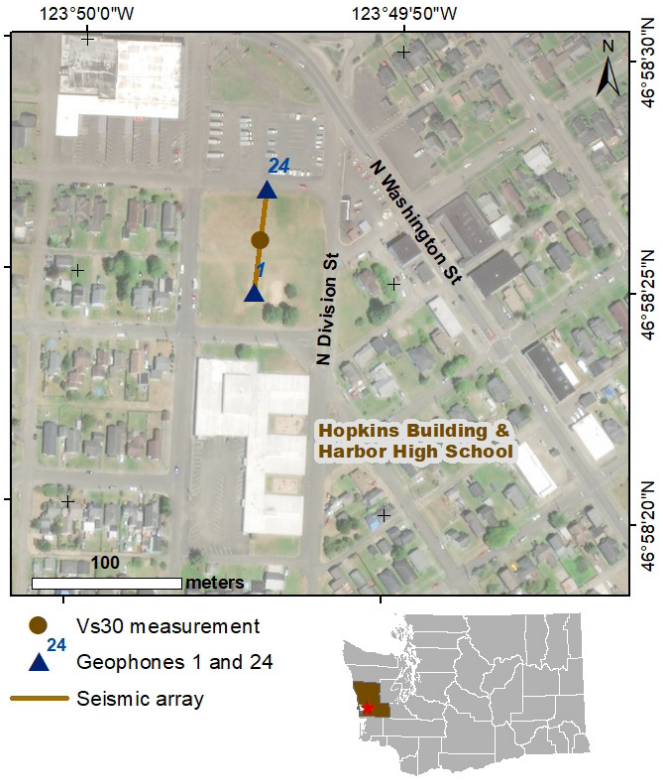
On July 14, 2010, a team from the Washington Geological Survey conducted a seismic survey at the Hopkins Building (Harbor High School). We measured Vs30 by laying out 24 geophones (ground motion sensors) in a 69 m (226 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on river sediments consisting mostly of boulder, cobble, and pebble gravel and sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Extreme

Tsunami
In a mapped tsunami hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

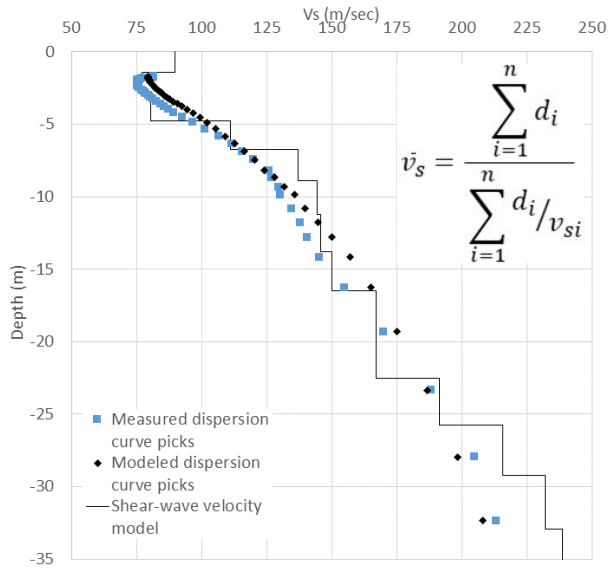
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves only sample the top ~10 m (33 ft). The microtremor analysis method (MAM) dispersion image is excellent quality, so that the fundamental mode can be picked with high confidence. MAM and the forward and reverse MASW dispersion curves depict similar trends, so the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 12.5 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 5.9 percent. The final model is unconstrained in the upper 1.5 m (5 ft) with a slight reversal below, then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 140 m/sec, which places the site in the E site class. All initial and inverted models place this site in the E class, so the site can be confidently classified. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

HOQUIAM HIGH SCHOOL

HOQUIAM SCHOOL DISTRICT, GRAYS HARBOR COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

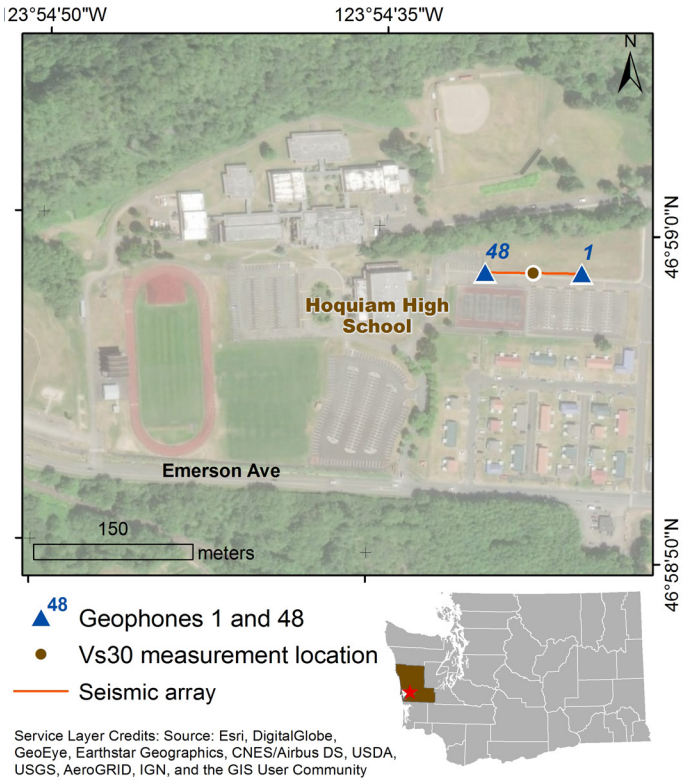
On July 24, 2018, a team from the Washington Geological Survey conducted a seismic survey at Hoquiam High School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Violent

Tsunami
In a mapped tsunami hazard zone

Landslide
Hazard present

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

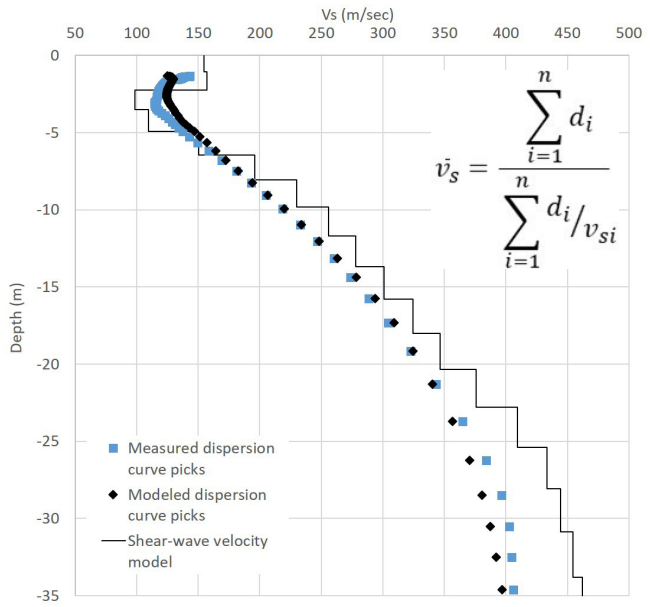
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of good quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (reverse and forward direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 12.3 percent. The inversion was carried out for ten iterations and resulted in a final model with an RMSE of 5.2 percent. The final velocity model shows a small velocity reversal in the top layers of the model, then steadily increasing velocity with depth from 2 m (7 ft) to 30 m (100 ft). Our best Vs30 measurement is 242 m/s, which places the site in the D class. The predicted site class is D or E, which correlates with the measured D site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

ILWACO HIGH SCHOOL AND ILWACO HILLTOP MIDDLE SCHOOL

OCEAN BEACH SCHOOL DISTRICT, PACIFIC COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

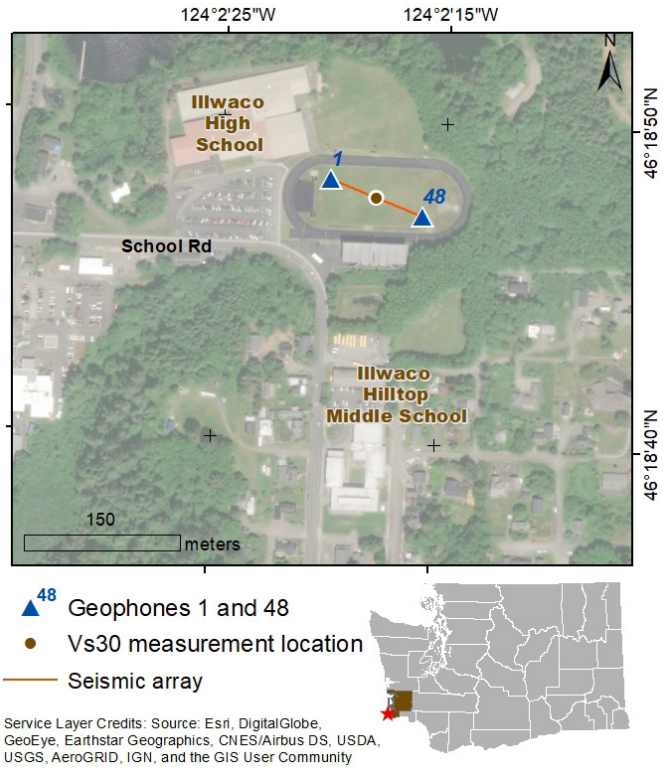
On June 18, 2018, a team from the Washington Geological Survey conducted a seismic survey at Ilwaco High and Hilltop Middle schools. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- This site class differs from the predicted B site class.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on marine sedimentary rocks.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low/bedrock

Ground Shaking
Violent

Tsunami
In a mapped tsunami hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

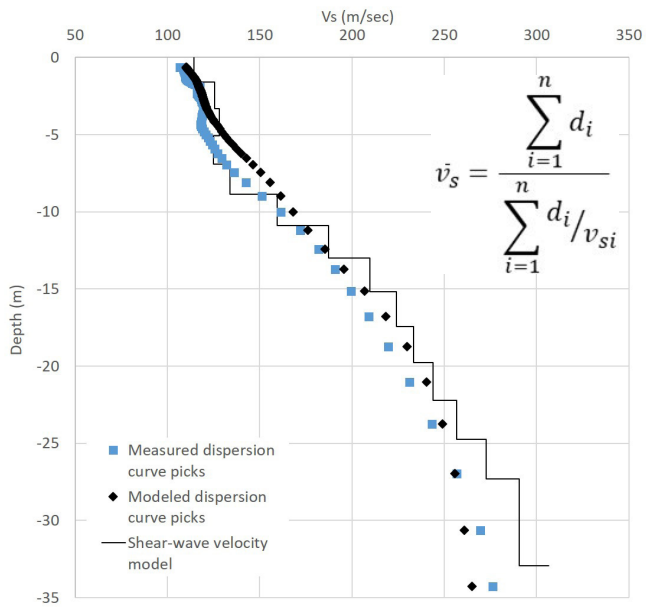
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images contain higher modes but the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of decent quality and the fundamental mode can also be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward and reverse direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model has an RMSE of 6.6 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.5 percent. The final velocity model shows generally increasing velocity with depth from 2 m (7 ft) to 30 m (100 ft) depth. Our best Vs30 measurement is 184 m/s, which places the site near the D to E boundary, at the very low end of the D class. The measured site class is significantly different than the predicted site class of B.

GEOLOGY

The 1:100,000-scale geologic map shows that both school campuses and the geophone array are sitting on the Shoalwater Bay siltstone (unit Em(2sb)) which has a predicted site class of B. Mapped directly to the east of the schools is Quaternary alluvium (unit Qa) which has a predicted site class of D to E. The shear wave velocity profiles show that the measured site class is in the D range, so the location of the geologic contact between the siltstone and alluvium is inaccurate, explaining the discrepancy between the predicted and measured site class. However, this Vs30 measurement is intended to apply to both Ilwaco High school and Hilltop Middle school, which are approximately 300 m (1000 ft) apart. The Vs30 measurement was made at the Iwaco High School playing field, located approximately 200 m (656 ft) away from Ilwaco Middle school. Therefore, horizontal over vertical (H/V) measurements were gathered at both schools as a check for lateral heterogeneity. All H/V measurements show consistent velocity structure, which would indicate that stratigraphy does not change significantly between the school campuses. We therefore confidently assign site class D to both Ilwaco High School and Hilltop Middle School.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

JACKSON ELEMENTARY SCHOOL

EVERETT SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

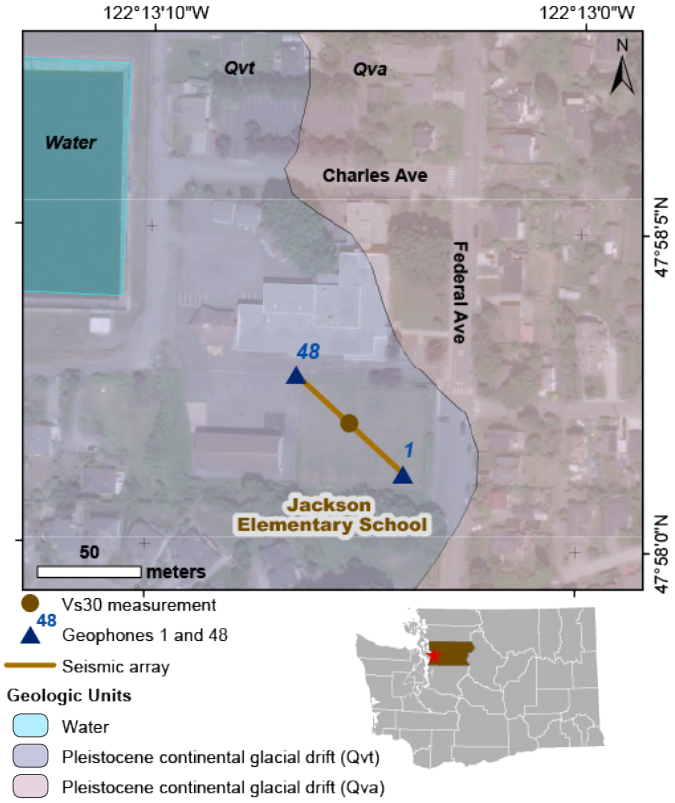
On December 4, 2020, a team from the Washington Geological Survey conducted a seismic survey at Jackson Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (231 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene glacial drift, composed primarily of sand with pebbles and some cobbles (unit Qva). The northeastern side of the school is sitting on a mixture of mud, sand, pebbles, cobbles, and boulders (unit Qvt).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low to low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

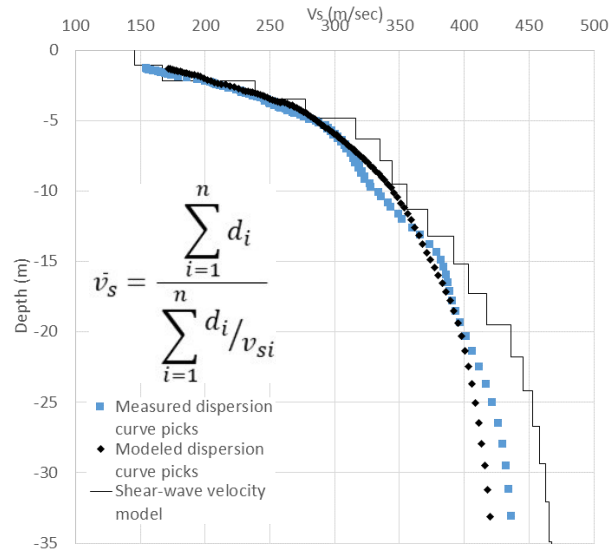
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality so that the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is also poor quality, and does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves depict similar trends, therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

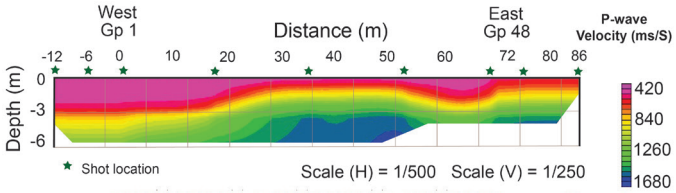
An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 7.6 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.0 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows rapidly increasing velocity to 5 m (16 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 344 m/sec, which places the site in the D site class. While the dispersion images are poor quality, we picked the most conservative model that is reasonable, placing this site in the D class. This is within the predicted site class of C–D.

GEOLOGY

The 1:24,000-scale geologic map places the school buildings and the seismic array on unit Qvt, which has a very limited extent (~400 m diameter). Unit Qva surrounds unit Qvt, and cuts across one building to the northeast. While both of these units are labeled "glacial drift", unit Qvt is described as hills of till, and unit Qva is described as drift which underlies this till. The 1:24,000-scale unit boundaries nearly match the 1:100,000-scale geologic map, which is used to predict site class, and gives the unit of limited extent a predicted site class of C and the unit which surrounds the school a predicted site class of C–D. Nearby boreholes show unconsolidated sediments past 30 m, consistent with a site class D. The 2D seismic refraction tomography (SRT) shows higher velocities at shallower depths near geophone 48 (nearer the buildings), and at deeper depths near geophone 1 (further from the buildings). The 1D velocity model shows rapid increase in the top 5 m, then slowly increasing velocity below. This could indicate the layer of till is not very thick at this location, and thus is likely the cause of the measured site class of D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.



2D seismic refraction tomography model depicting the lateral variation in P-wave velocity (Vp) with depth across the geophone array from the farthest off end shot from both ends.

J. M. WEATHERWAX HIGH SCHOOL

ABERDEEN SCHOOL DISTRICT, GRAYS HARBOR COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

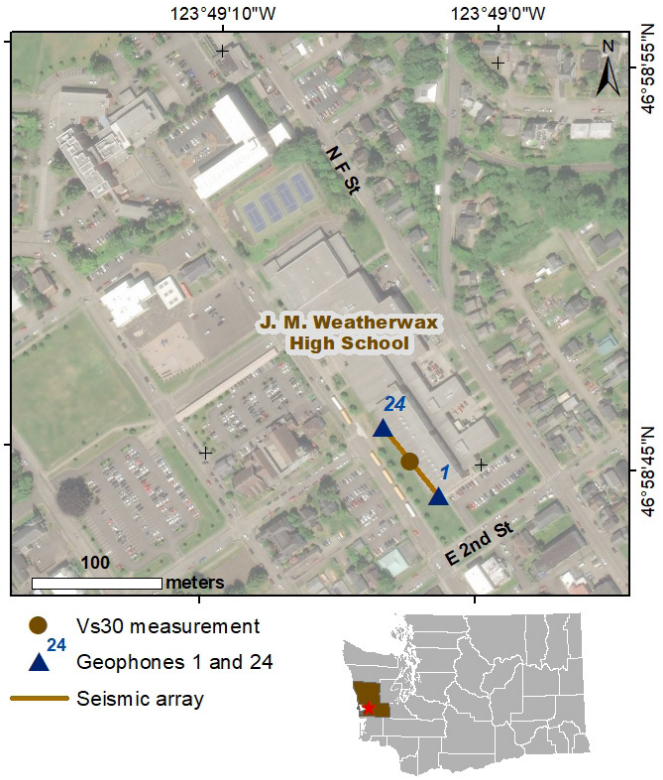
On July 16, 2010, a team from the Washington Geological Survey conducted a seismic survey at J. M. Weatherwax High School. We measured Vs30 by laying out 24 geophones (ground motion sensors) in a 69 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on river sediments consisting mostly of boulder, cobble, and pebble gravel and sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Extreme

Tsunami
In a mapped tsunami hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

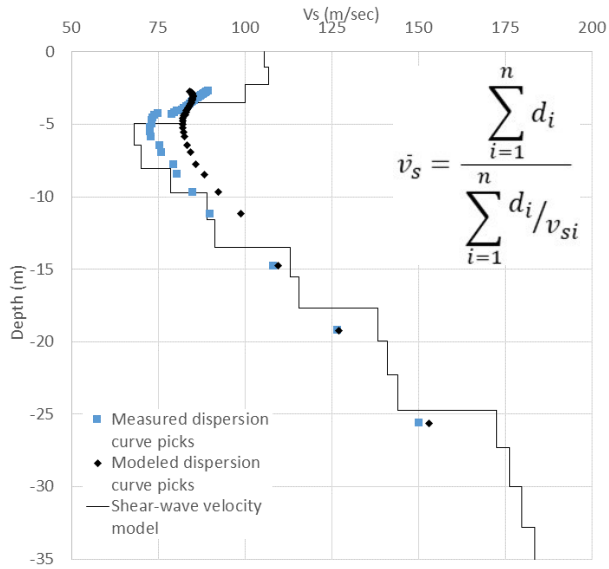
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample below 10 m (33 ft). The microtremor analysis method (MAM) dispersion image is also decent quality and samples from ~ 3 m (10 ft) down past 30 m (100 ft). MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. However, the MASW does not add significant bandwidth, so the final model is based on the MAM dispersion curve.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MAM dispersion curve. The initial model had an RMSE of 9.5 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 6.1 percent. The final model shows a velocity reversal in the top 5 m (16 ft), but is unconstrained in the top 3 m (10 ft). Below this velocity is generally increasing down to 30 m (100 ft). Our best Vs30 measurement is 109 m/sec, which places the site solidly in the E site class. All initial and inverted models are in the E class, so the site can be confidently classified. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_S) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

JULIUS A WENDT ELEMENTARY SCHOOL

WAHKIAKUM SCHOOL DISTRICT, WAHKIAKUM COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

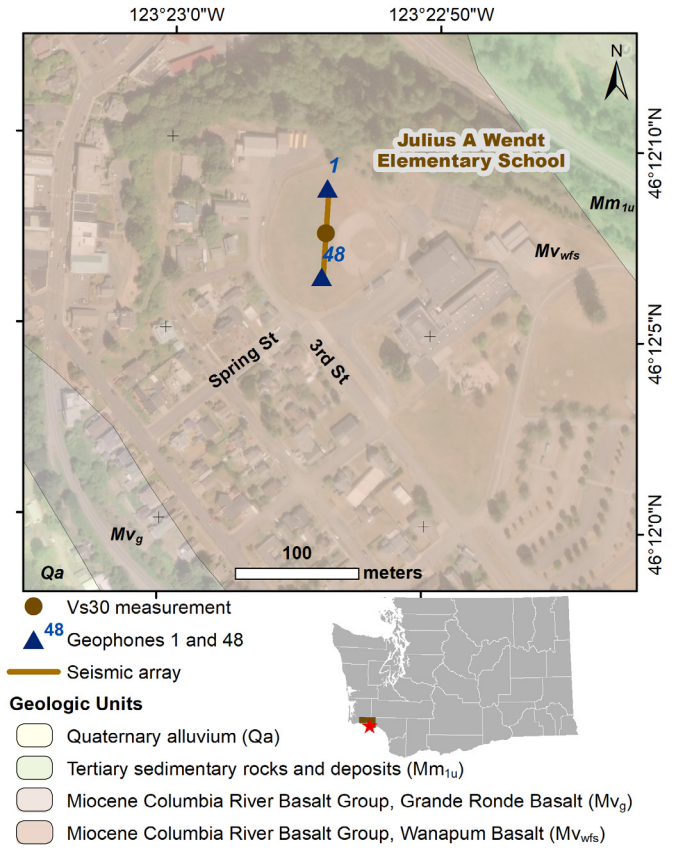
On October 6, 2020, a team from the Washington Geological Survey conducted a seismic survey at Julius A Wendt Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (231 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of B.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Miocene Columbia River Basalt (unit Mv_{wfs}).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Unknown, not negligible

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

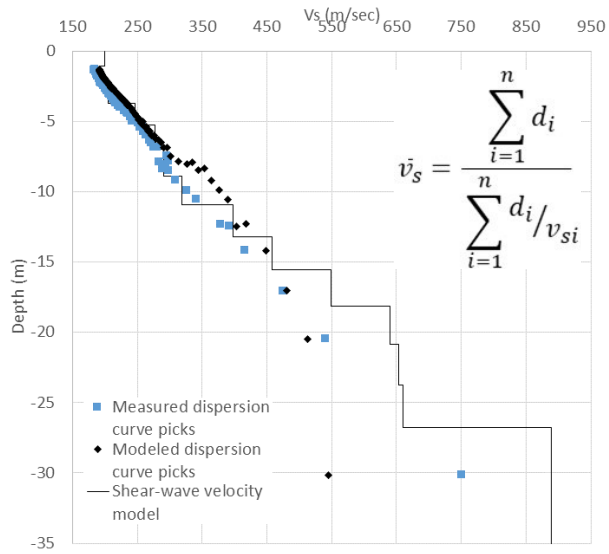
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is poor quality, but the resulting dispersion curve fills in the gaps of the MASW dispersion curve. MAM and the forward MASW dispersion curves correlate well, depicting similar trends. Therefore the two dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 13.1 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 5.9 percent. The final model shows generally increasing velocity to 27 m (89 ft), then a sudden increase in velocity down to 30 m (100 ft). Our best Vs30 measurement is 396 m/sec, which places the site solidly in the C site class. All inital and inverted models place this site in a site class C, so the site can be confidently classified. This is different from the predicted site class of B.

GEOLOGY

The 1:100,000-scale geologic map shown on the previous page places the school and the seismic array on a narrow strip of Columbia River Basalt (unit Mv_{wfs}) with a predicted site class of B. The school is mapped between Quaternary alluvium (unit Qa) to the southwest with a predicted site class D-E and Tertiary sedimentary rock (unit $Mm_{1u)}$ to the northeast with a predicted site class B. However, the 1D velocity model does not reach bedrock velocities until 27 m (89 ft), and nearby boreholes show sand/silt in the upper 15 m (50 ft). This indicates that this site is mismapped, and the surface geology here is likely alluvium or sedimentary rock. Therefore, the site class change is likely due to low-resolution mapping.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

KILO MIDDLE SCHOOL

FEDERAL WAY SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

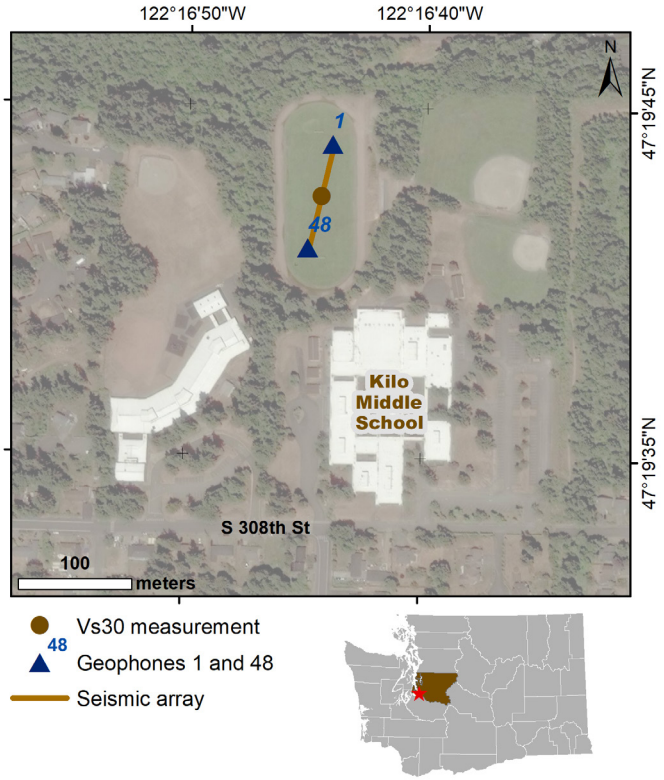
On January 3, 2020, a team from the Washington Geological Survey conducted a seismic survey at Kilo Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial till, mostly a compact silt or sand-rich matrix containing sub- to well-rounded clasts.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

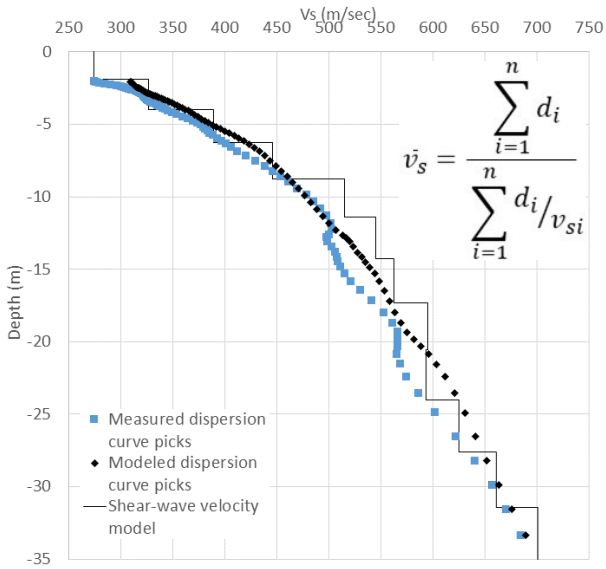
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so the fundamental mode can be picked with high confidence. The microtremor analysis method (MAM) dispersion image is of poor quality, but the fundamental mode can be picked with some confidence. The forward and reverse direction MASW dispersion curves are combined with the MAM dispersion curve to create a single.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 8.5 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.5 percent. The final model shows generally increasing velocity to 9 m (30 ft), then slowly increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 492 m/sec, which places the site in the middle of the C site class. Although the MASW dispersion curves from the reverse and forward directions do show some variability, it is not enough to change the site class, so the site can be confidently classified. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

LA CENTER ELEMENTARY AND MIDDLE SCHOOL

LA CENTER SCHOOL DISTRICT, CLARK COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

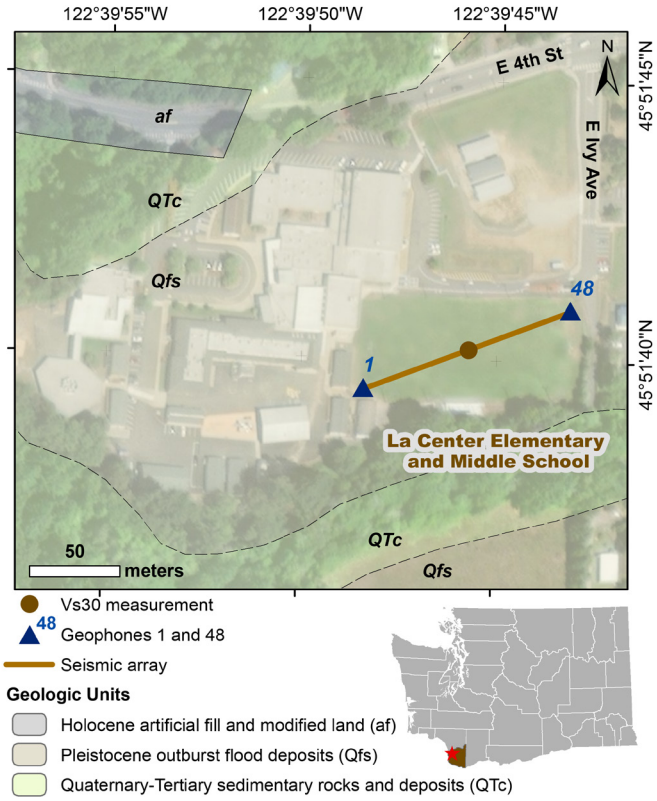
On February 19, 2020, a team from the Washington Geological Survey conducted a seismic survey at La Center Elementary and Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene outburst flood deposits, comprising unconsolidated clay, silt, and fine to medium sand (unit Qfs). To the northwest and looping around to the southeast is mapped Quaternary-Tertiary sedimentary rocks and deposits (unit QTc).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Severe

Landslide
Hazard present, based on terrain data

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

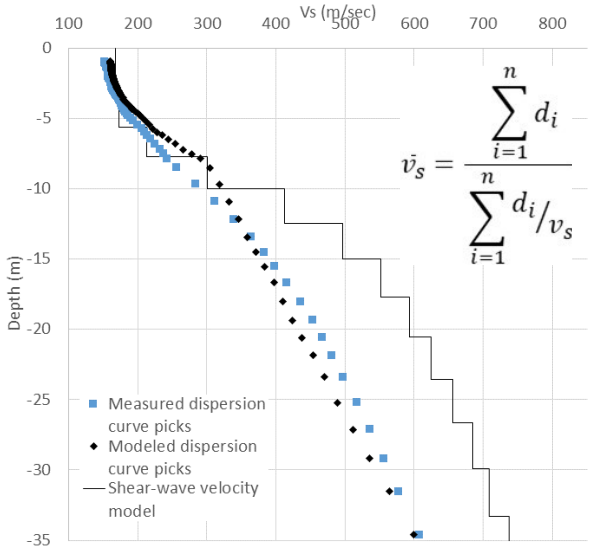
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The dispersion images from both the multi-channel analysis of surface wave (MASW) forward and reverse directions and the microtremor analysis method (MAM) are decent quality so the fundamental mode can be picked with confidence. MAM and the forward and reverse MASW dispersion curves correlate well except at lower frequencies. Therefore the MAM and reverse direction curves are combined into a single model.

VELOCITY MODEL

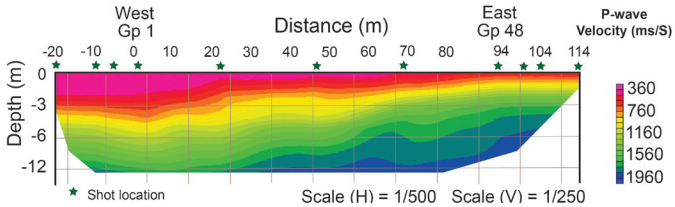
An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 10.1 percent. The inversion was carried out for eight iterations and resulted in a final model with an RMSE of 5.7 percent. The final model is unconstrained in the top 1 m (16 ft), and below this shows nearly constant velocity to 6 m (20 ft), then rapidly increasing velocity to 15 m (49 ft), and then steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 353 m/sec, which places the site just on the D side of the C/D boundary. Each iteration of the inversion forces sharply increasing velocity below 10 m, and with further iterations the Vs30 does reach a site class C while still converging. However, we take the conservative approach and assign this site a site class D. This is different from the predicted site class of C.

GEOLOGY

The 1:100,000-scale geologic map, which is used to predict site class, places the school buildings and seismic array on Pleistocene outburst flood deposits (unit Qfs) with a predicted site class of C, and maps Quaternary alluvial fan deposits (unit Qaf) to the north with a predicted site class of D. This is different from the higher resolution 1:24,000-scale geologic map shown on the previous page, which places the school and array on outburst flood deposits (unit Qfs) surrounded by sedimentary rocks and deposits (unit QTc). Nearby boreholes show gravel, cobbles, and clay to at least 24 m depth, which is consistent with our 1D velocity model. The 2D seismic refraction tomography model shows heterogeneity across the seismic array, depicting a sharp increase in velocity from 300 m/sec to > 2500 m/sec at depths of 10–15 m near geophone 1, and in the top few meters near geophone 48. This suggests that more consolidated materials become shallower towards the northeast (further from the school buildings). These observations support our decision to take the conservative approach and assign a site class D to the campus. The change in site class is could be due to a lateral change within the unit Qfs.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.



2D seismic refraction tomography model depicting the lateral variation in P-wave velocity (Vp) with depth across the geophone array from the farthest off end shot from both ends.

LARCHMONT ELEMENTARY SCHOOL

TACOMA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

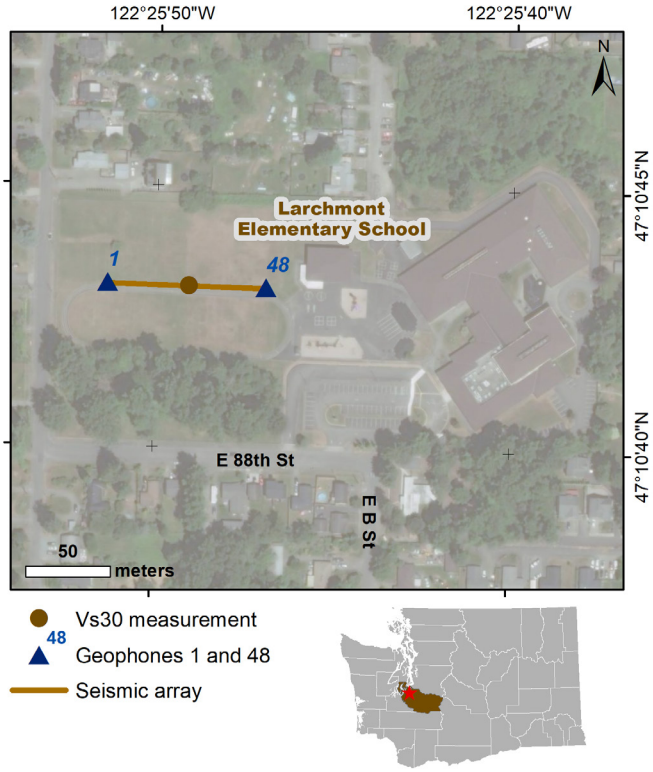
On July 23, 2020, a team from the Washington Geological Survey conducted a seismic survey at Larchmont Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

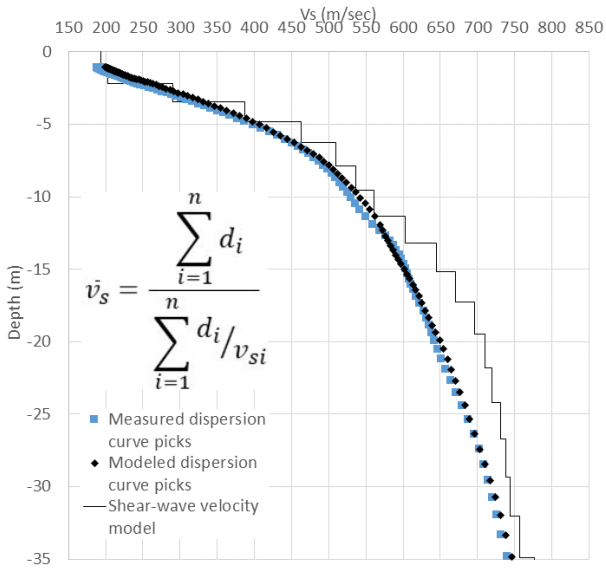
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality so that the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the top 11 m (36 ft). MAM and the forward and reverse MASW dispersion curves depict similar trends, therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 10.0 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 4.4 percent. The final model is unconstrained in the top 1 m (3 ft), then shows generally increasing velocity to 8 m (26 ft), and then more slowly increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 516 m/sec, which places the site in the middle of the C site class. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

LAURA INGALLS WILDER ELEMENTARY SCHOOL

LAKE WASHINGTON SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

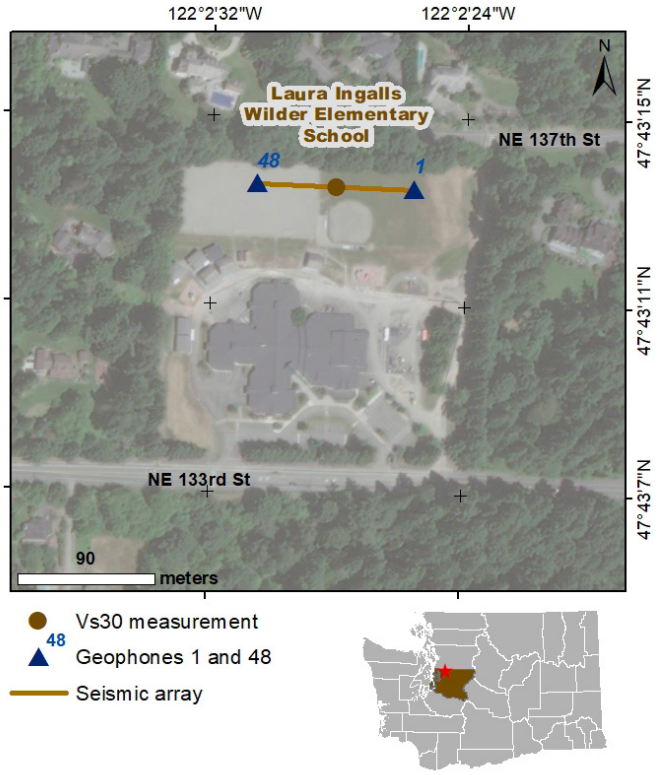
On July 27, 2020, a team from the Washington Geological Survey conducted a seismic survey at Laura Ingalls Wilder Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

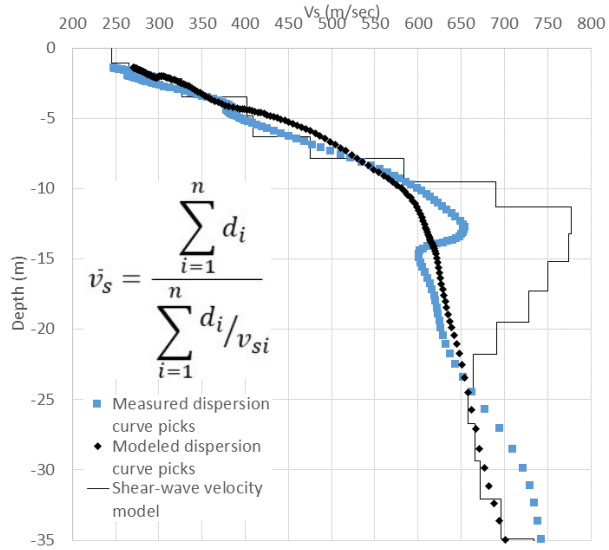
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality so that the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also poor quality, and does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate somewhat, therefore the three dispersion curves are combined and smoothed into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 11.4 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 6.4 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows rapidly increasing velocity to 13 m (43 ft), then a velocity reversal down to 26 m (85 ft), and then slowly increasing velocity to 30 m (100 ft). Our best Vs30 measurement is 550 m/sec, which places the site in the middle of the C site class. Although the dispersion images are all poor quality, several models from different reasonable dispersion curves were created, and all were in site class C so the site can be confidently classified. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

LINDBERGH SENIOR HIGH SCHOOL

RENTON SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

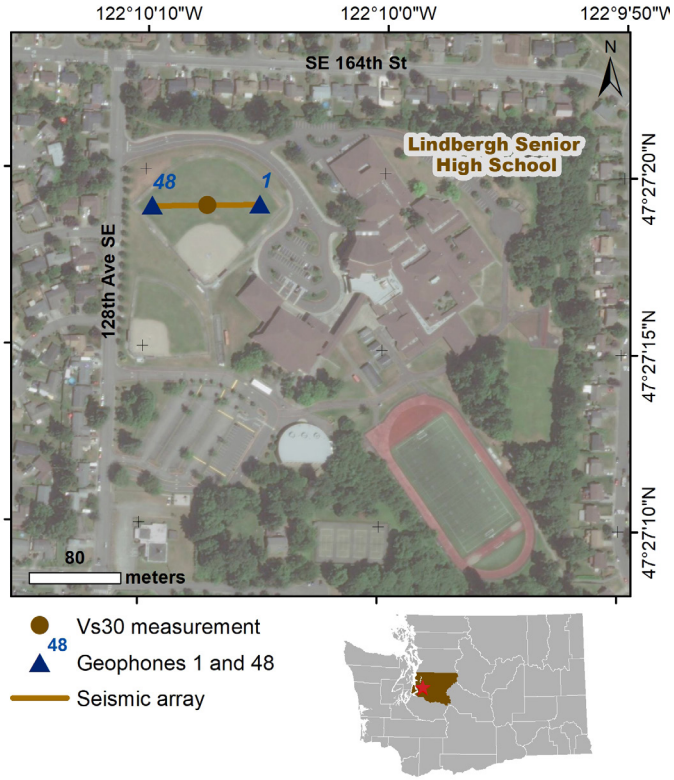
On October 22, 2020, a team from the Washington Geological Survey conducted a seismic survey at Lindbergh Senior High School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

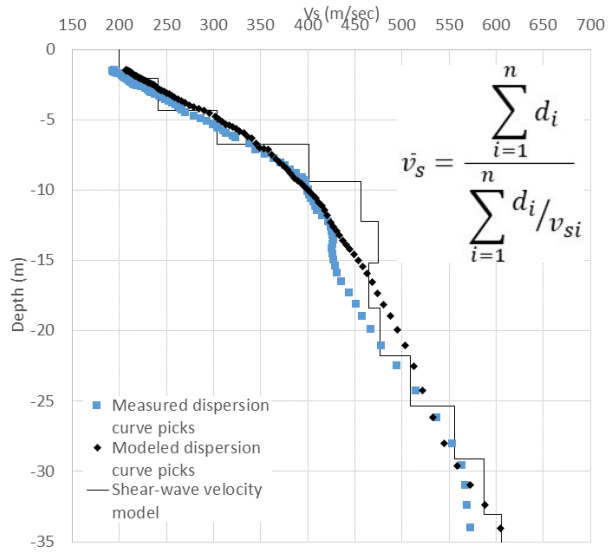
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also decent quality but does not sample the shallow layers. Overall, the MASW and MAM dispersion curves correlate well, so the MASW (forward and reverse direction) and MAM dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 10.4 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.6 percent. The final model is unconstrained in the top 2 m (6 ft), and below this shows rapidly increasing velocity to 10 m (30 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 397 m/sec, which places the site in the C site class. Although the upper 2 m are unconstrained, adjusting them does not change the site class. All initial and final models are in the C class, so the site can be confidently classified. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

LISTER ELEMENTARY SCHOOL

TACOMA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

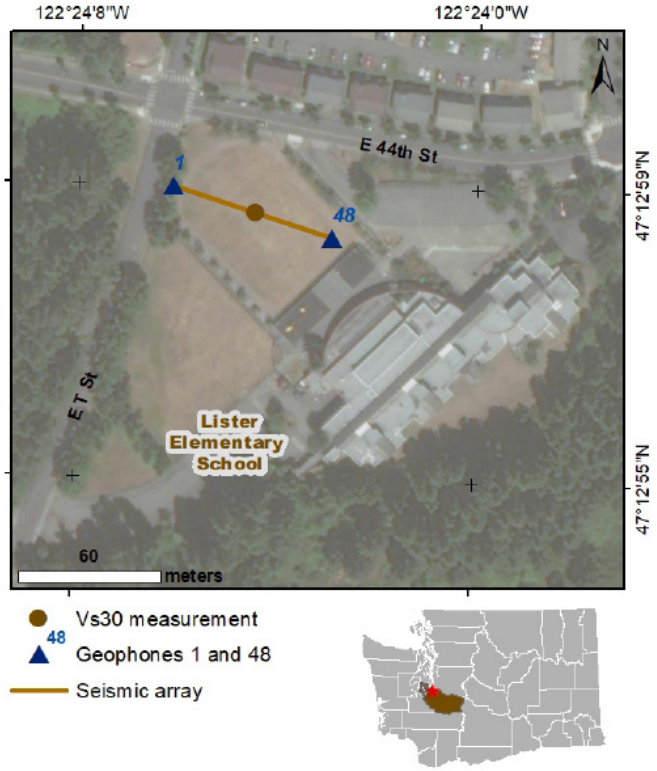
On August 3, 2020, a team from the Washington Geological Survey conducted a seismic survey at Lister Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (231 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial drift which is composed primarily of till and outwash clay, silt, sand, gravel, cobbles, and boulders.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

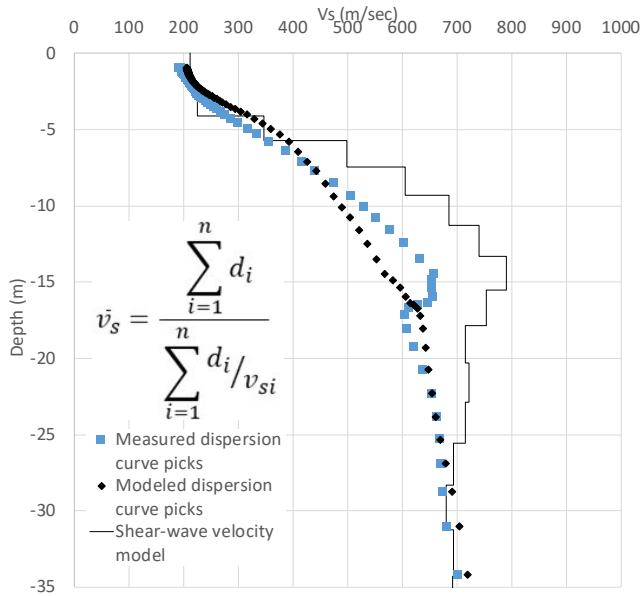
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is also excellent quality. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 10.9 percent. The inversion was carried out for eight iterations and resulted in a final model with an RMSE of 5.7 percent. The final model shows generally increasing velocity to 15 m (45 ft), an inversion to 18 m (60 ft), then generally constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 513 m/sec, which places the site in the middle of the C site class. All initial and inverted models are of the C class, so the site can be confidently classified. This is within the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

LOPEZ MIDDLE/HIGH SCHOOL AND ELEMENTARY SCHOOL

LOPEZ ISLAND SCHOOL DISTRICT, SAN JUAN COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

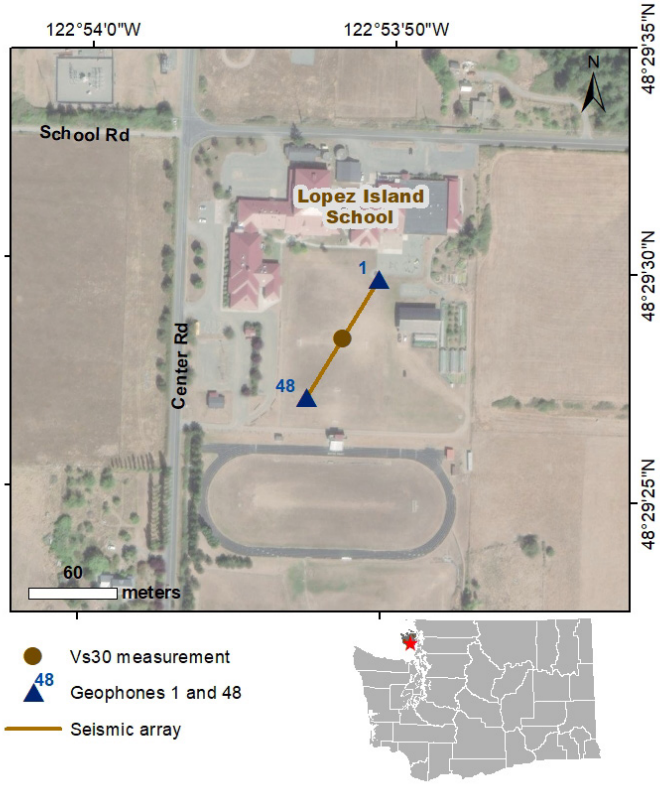
On April 21, 2021, a team from the Washington Geological Survey conducted a seismic survey at Lopez Middle/High School and Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The schools are built on soft rock or very dense soil, which would amplify ground shaking relative to rock.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The schools are sitting on continental glacial till.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

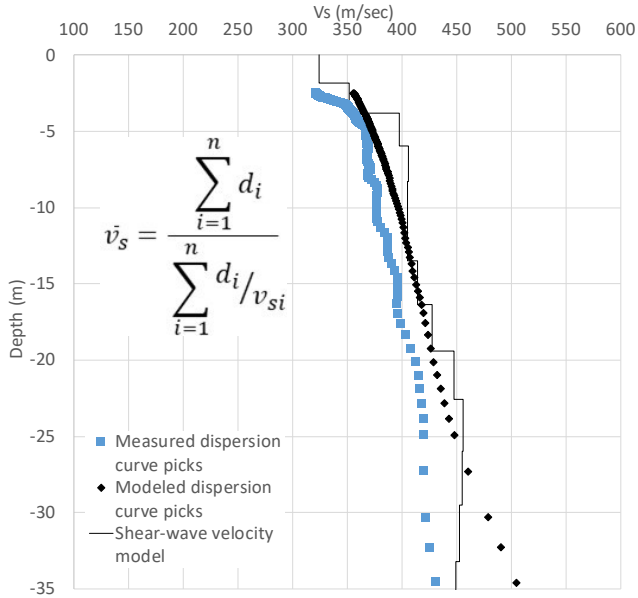
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. The microtremor analysis method (MAM) dispersion image is also excellent quality. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 4.8 percent. The inversion was carried out for three iterations and resulted in a final model with an RMSE of 3.5 percent. The final model is unconstrained in the top 2 m (6 ft), then shows steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 413 m/sec, which places the site in the C site class. All initial and final models are of the C class, so the site can be confidently classified. This is the same the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

MADISON ELEMENTARY SCHOOL

EVERETT SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

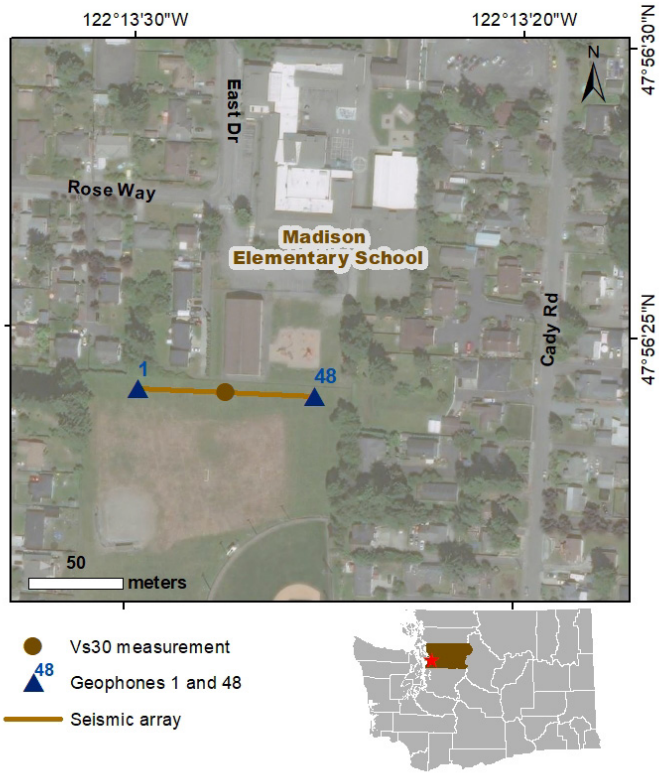
On December 4, 2020, a team from the Washington Geological Survey conducted a seismic survey at Madison Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial drift (unit Qvt).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

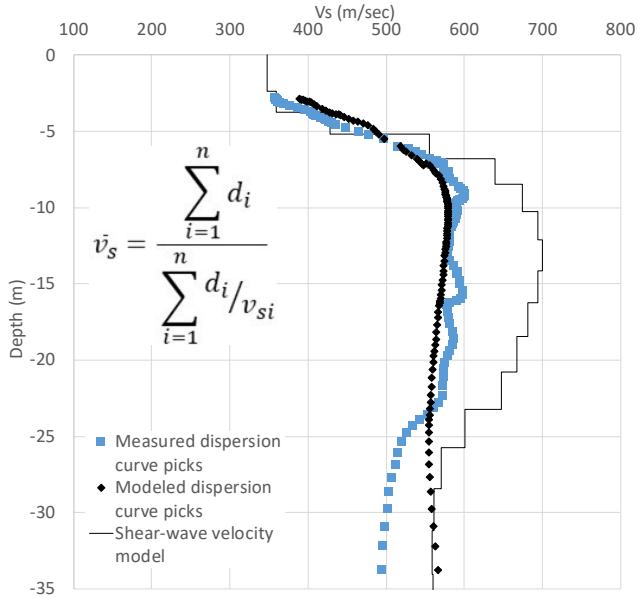
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is excellent quality. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 9.0 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.7 percent. The final model shows generally increasing velocity to about 15 m (45 ft), then steadily decreasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 566 m/sec, which places the site in the C site class. All initial models are of the C class, so the site can be confidently classified. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

MADISON ELEMENTARY SCHOOL

SPOKANE SCHOOL DISTRICT, SPOKANE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

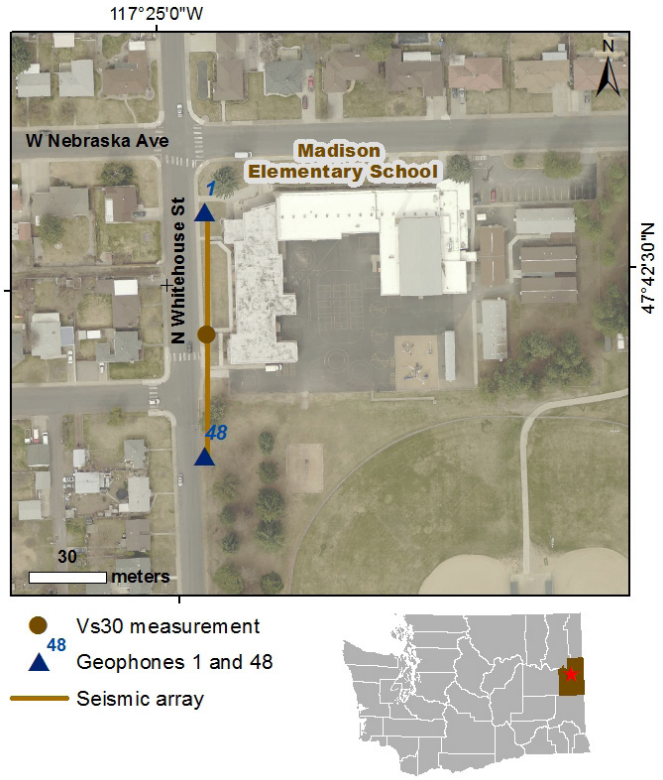
On September 30, 2020, a team from the Washington Geological Survey conducted a seismic survey at Madison Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is on glaical outburst flood deposits consisting mostly of pebbles, cobbles, and boulders in a sand and gravel matrix.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Very Strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

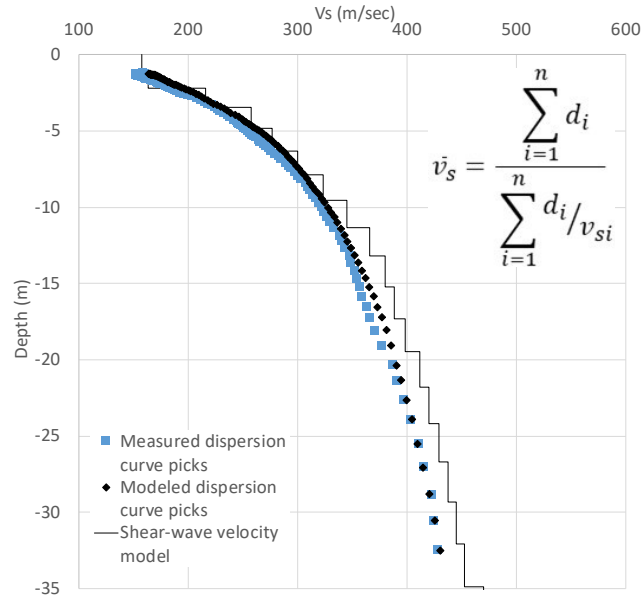
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is of excellent quality and is combined with the MASW forward and reverse directions into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 8.9 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.6 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows rapidly increasing velocity in the upper 6 m (20 ft), which transitions into more steadily increasing velocity below, down to 30 m (100 ft). Our best Vs30 measurement is 329 m/sec, which places the site in the D site class. All initial and inverted models are of the D class, so the site can be confidently classified. This is different from the predicted site class of C.

GEOLOGY

The 1:24,000-scale geologic map shows the seismic array and the school buildings are located on Pleistocene outburst flood deposits (unit Qfcg), which matches the 1:100,000-scale geologic map unit with a predicted site class of C. However, the 1:100,000-scale geology map also shows a contact ~500 m (1500 ft) to the north with Quaternary dune sand (unit Qd) with a predicted site class of D. Nearby boreholes show sand in the upper 30 m (100 ft), consistant with unit Qd. The 1D velocity model shows velocities that correlate well with these boreholes, indicating less consolidated materials in the upper 6 m (20 ft) transitioning into more consolidated with depth as confining pressure increases. These observations suggest that the change in site class could be due to low resolution mapping.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

MANITOU PARK ELEMENTARY SCHOOL

TACOMA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

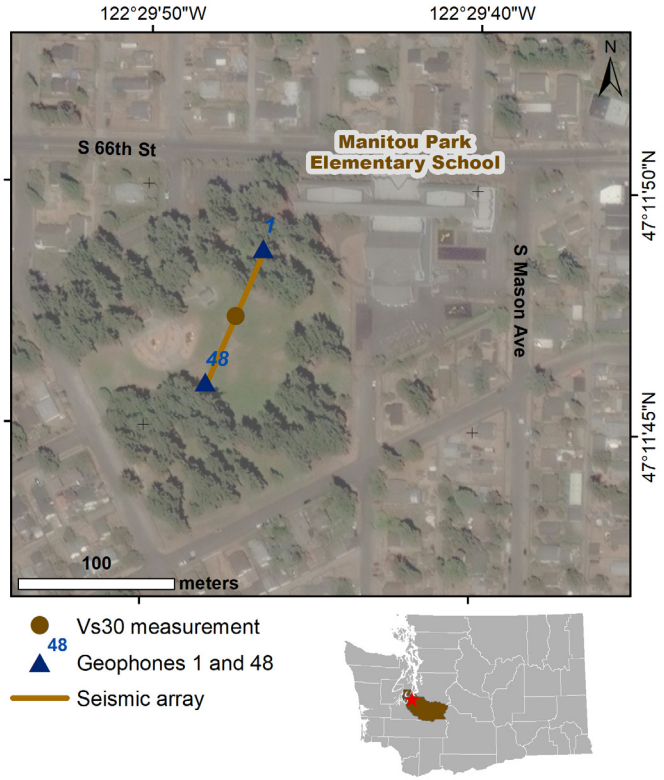
On August 4, 2020, a team from the Washington Geological Survey conducted a seismic survey at Manitou Park Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial outwash.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

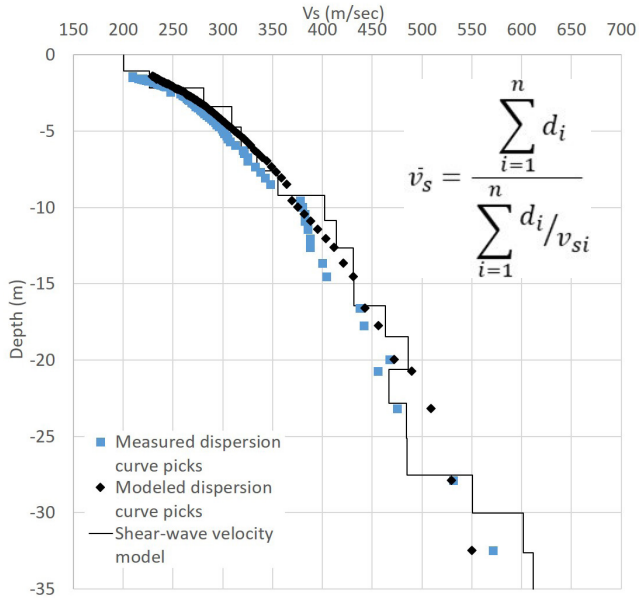
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. The microtremor analysis method (MAM) dispersion image is not needed because the forward direction MASW adequately samples below 30 m (100 ft).

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the dispersion curve from the MASW forward direction (located off end geophone 1). The initial model had an RMSE of 8.7 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.7 percent. The final model shows generally increasing velocity down to 30 m (100 ft), but is unconstrained in the upper 2 m (7 ft). Our best Vs30 measurement is 391 m/sec, which places the site near the C/D site class boundary. Although the upper 2 meters are unconstrained, adjusting them does not change the site class. All initial and final models are in the C class, so the site can be confidently classified. This is the same as the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

MANN ELEMENTARY SCHOOL

TACOMA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

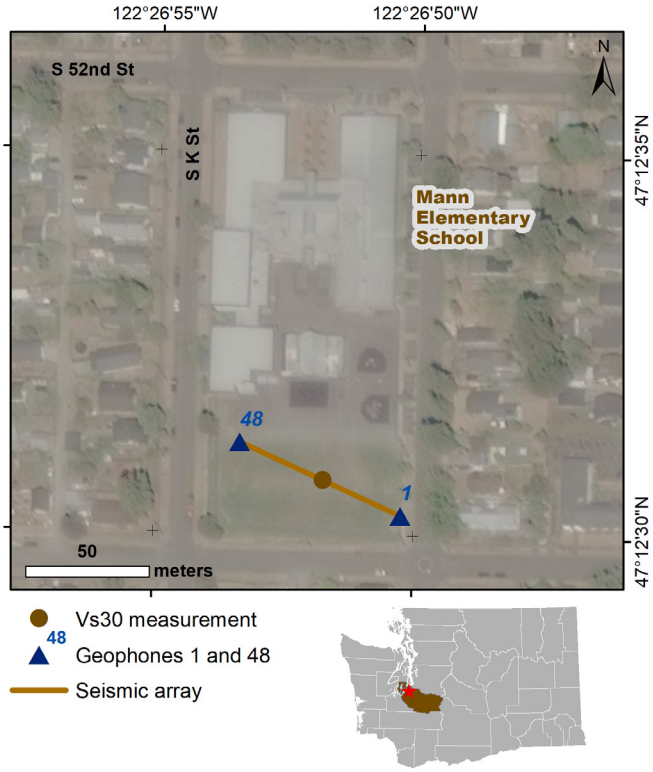
On August 17, 2020, a team from the Washington Geological Survey conducted a seismic survey at Mann Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 72 m (235 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

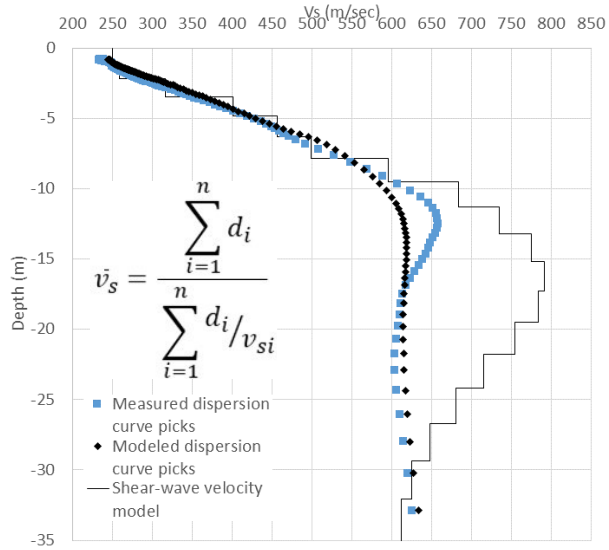
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also decent quality, and the MAM dispersion curve correlates well with the forward and reverse MASW dispersion curves. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 11.5 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.5 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows generally increasing velocity to 16 m (52 ft), then a significant velocity reversal down to 30 m (100 ft). Our best Vs30 measurement is 561 m/sec, which places the site in the middle of the C site class. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

MARY M KNIGHT SCHOOL

MARY M KNIGHT SCHOOL DISTRICT, GRAYS HARBOR COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

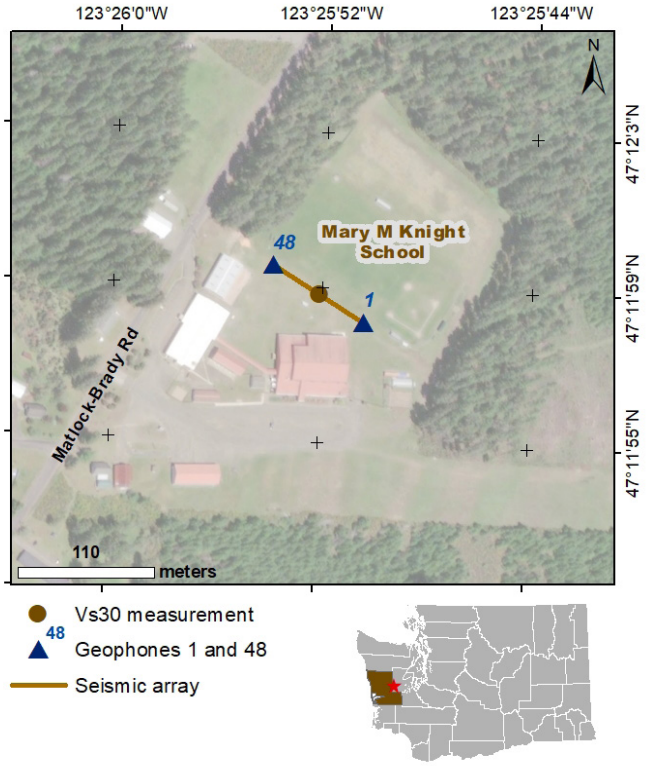
On July 16, 2020, a team from the Washington Geological Survey conducted a seismic survey at Mary M Knight School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 85 m (282 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial outwash.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

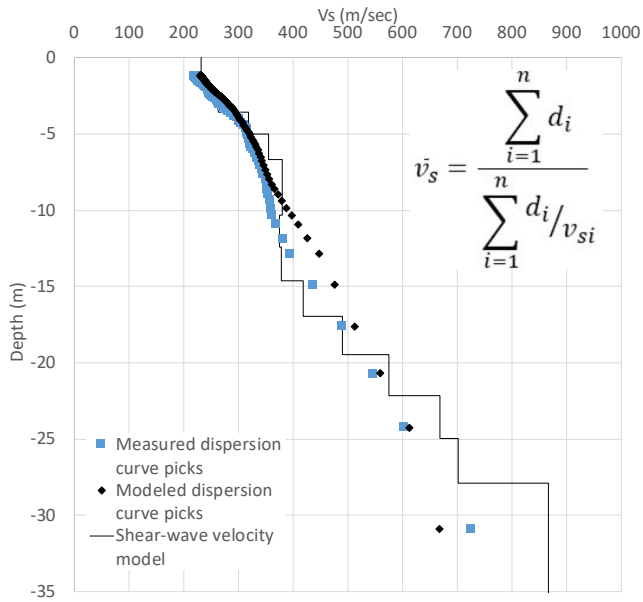
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is excellent quality. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 9.9 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.2 percent. The final model shows steadily increasing velocity to about 15 m (45 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 427 m/sec, which places the site in the C site class. All initial and final models are of the C class, so the site can be confidently classified. This is within the predicted site class of C-D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = hear wave velocity in m/sec of the layer.

MARYSVILLE PILCHUCK SENIOR HIGH SCHOOL

MARYSVILLE SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

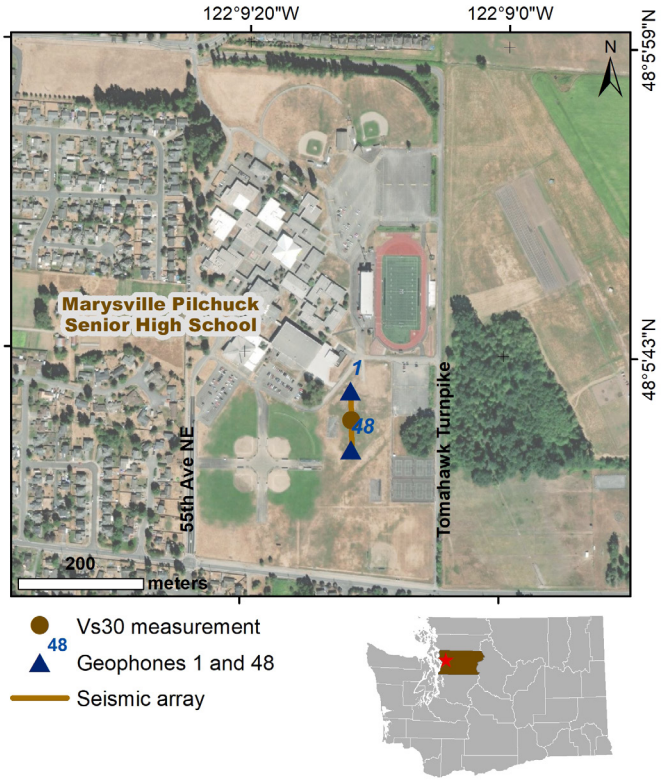
On October 27, 2020, a team from the Washington Geological Survey conducted a seismic survey at Marysville Pilchuck Senior High School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on glacial meltwater deposits consisting of well-drained, stratified-to-massive outwash sand, a little fine gravel, and some beds of silt and clay.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

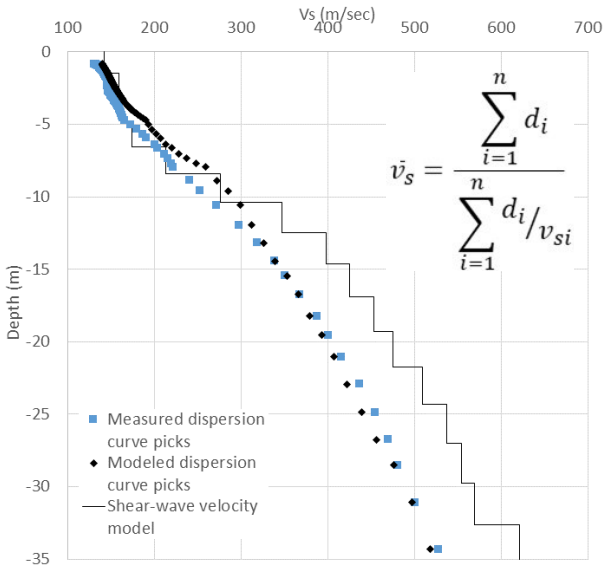
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are of decent quality so the fundamental mode can be picked. The microtremor analysis method (MAM) dispersion image is also of decent quality and the fundamental mode can be picked. Each dispersion curve samples down to 30 m (100 ft), and forward and reverse MASW and MAM curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.8 percent. The final model shows generally constant velocity to 6 m (20 ft), then steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 304 m/sec, which places the site firmly in the D class. All the initial and inverted models are in the middle of the D class, so the site can be confidently classified. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_S) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

MCDERMOTH ELEMENTARY SCHOOL

ABERDEEN SCHOOL DISTRICT, GRAYS HARBOR COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

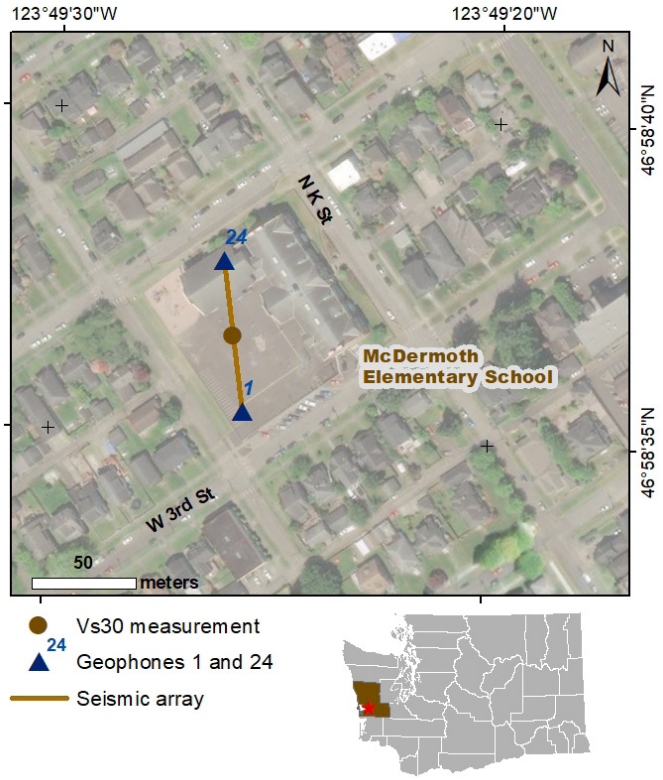
On July 14, 2010, a team from the Washington Geological Survey conducted a seismic survey at McDermoth Elementary School. We measured Vs30 by laying out 24 geophones (ground motion sensors) in a 69 m (226 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on river sediments consisting mostly of boulder, cobble, and pebble gravel and sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Extreme

Tsunami
In a mapped tsunami hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

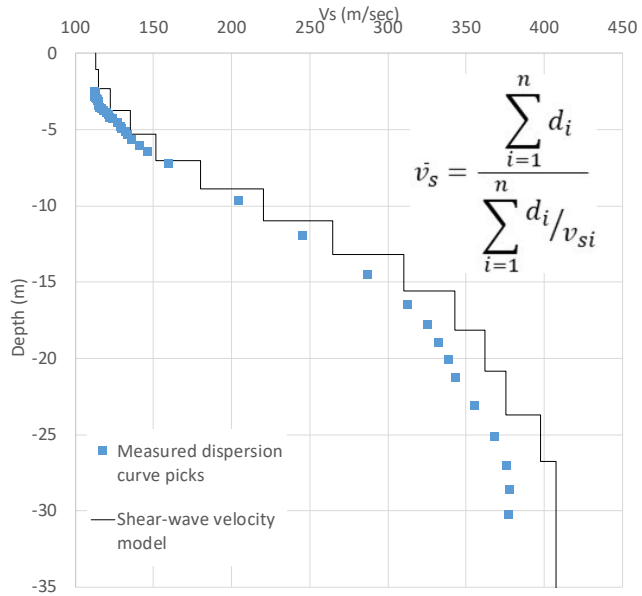
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality so that the fundamental mode can be picked with some confidence. However, the MASW dispersion curves only sample down to 16 m (52 ft) and there is some variability between the forward and reverse MASW. The microtremor analysis method (MAM) dispersion image is also poor quality and does not sample the upper 12 m (39 ft). MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inverted models do not converge, therefore we use the initial model as our final velocity model. This velocity model is unconstrained in the top 3 m (10 ft), then shows rapidly increasing velocity from 3 m (10 ft) to 15 m (49 ft), then generally increasing velocity down to 26 m (85 ft), with constant velocity down past 30 m (100 ft). Our best Vs30 measurement is 234 m/sec, which places the site solidly in the D site class. This is within the predicted site class of D–E. Although the MASW dispersion curves from the reverse and forward directions do show some variability, it is not enough to change the site class, so the site can be confidently classified.



Final velocity model based on the initial model with measured dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

MEEKER ELEMENTARY SCHOOL

PUYALLUP SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

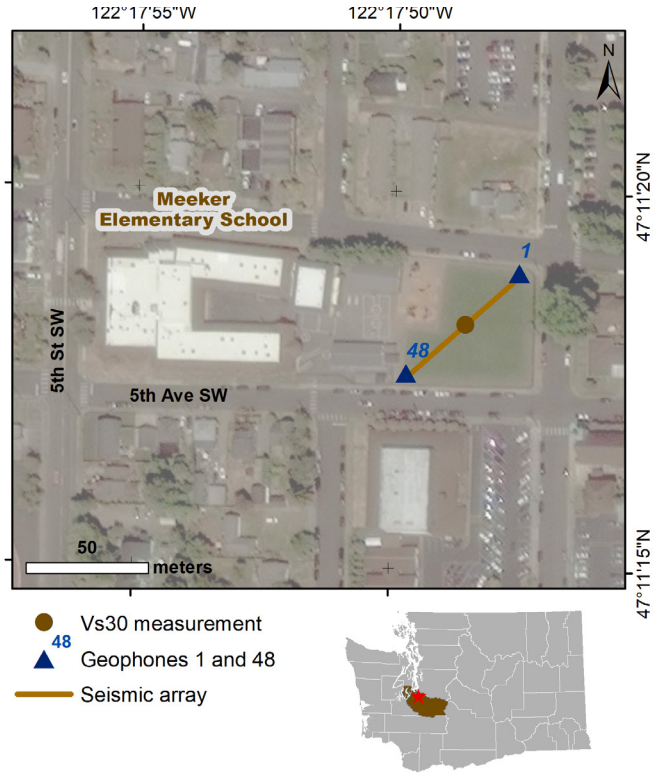
On July 21, 2020, a team from the Washington Geological Survey conducted a seismic survey at Meeker Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (231 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium; river sediments consisting mostly of boulder, cobble, and pebble gravel and sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
High

Ground Shaking
Violent

Lahar
In a mapped lahar hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

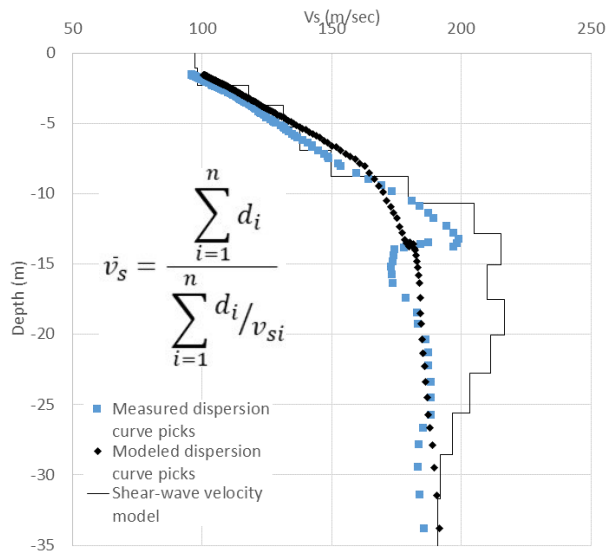
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is excellent quality. The MAM and the forward and reverse MASW dispersion curves correlate well, however the MASW does not contribute much in terms of sampling, and is used only as a check for consistency. Therefore, only the MAM dispersion curve is used.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the MAM dispersion curve. The initial model had an RMSE of 8.7 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.9 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows generally increasing velocity to 15 m (49 ft), then nearly constant velocity to 20 m (66 ft), then a velocity reversal down to 30 m (100 ft). Our best Vs30 measurement is 171 m/sec, which places the site in the E class. All initial and inverted models place this site in the E class, so the site can be confidently classified. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

MINT VALLEY ELEMENTARY SCHOOL

LONGVIEW SCHOOL DISTRICT, COWLITZ COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

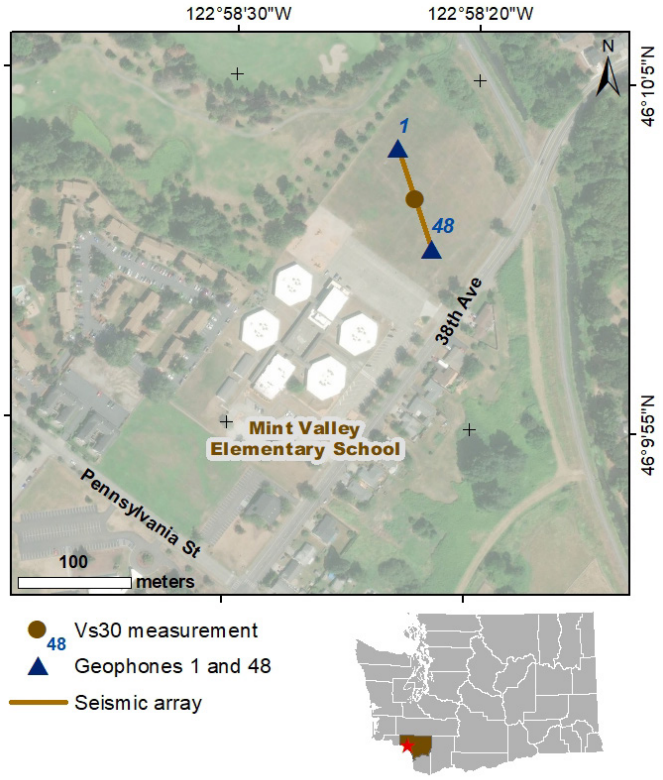
On August 26, 2019, a team from the Washington Geological Survey conducted a seismic survey at Mint Valley Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on river sediments consisting mostly of boulder, cobble, and pebble gravel and sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Violent

Tsunami
In a mapped tsunami hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

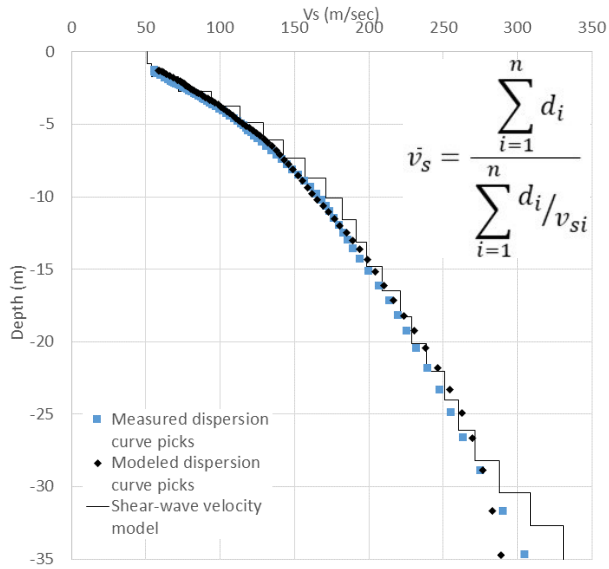
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down past 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is excellent quality and samples much deeper. The forward and reverse direction MASW and MAM are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 12.9 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 5.8 percent. The final model shows rapidly increasing velocity in the top 5 m (16 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 159 m/sec, which places the site in the E site class. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_S) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = Shear wave velocity in m/sec of the layer.

MINTER CREEK ELEMENTARY SCHOOL

PENINSULA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

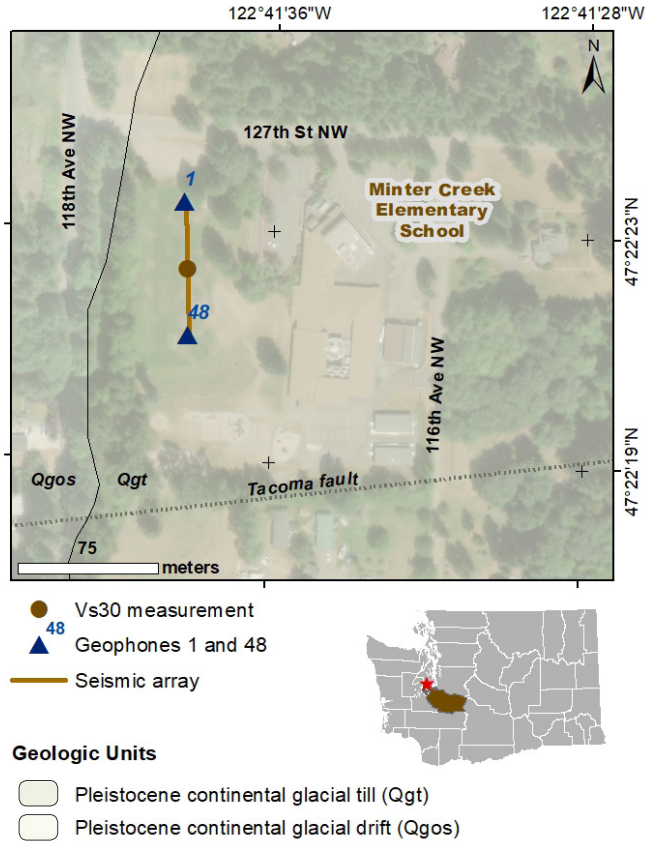
On July 14, 2020, a team from the Washington Geological Survey conducted a seismic survey at Minter Creek Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 73.2 m (240 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till (unit Qgt) consisting primarily of an unsorted mixture of clay, silt, sand, and gravel. To the west of the school is continental glacial drift (unit Qgos) which is dominated by loose sand and silt with minor gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality so that the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is decent quality, but does not sample the shallow layers. MAM and the reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the two dispersion curves are combined into a single model.

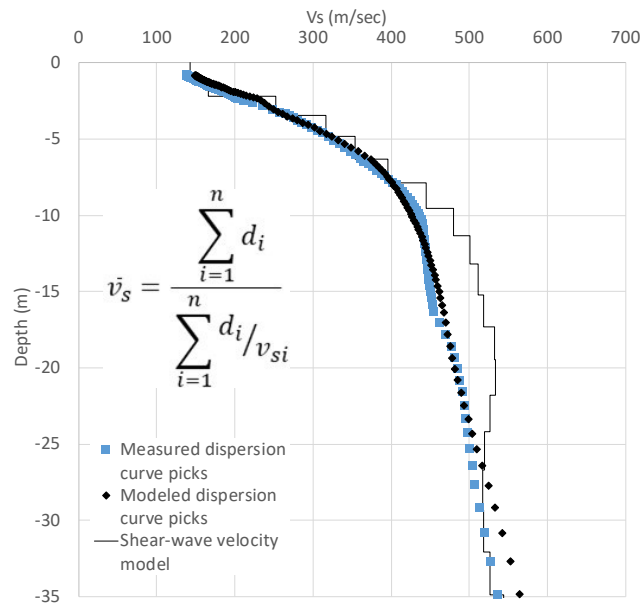
VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 9.7 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 4.6 percent. The final model shows rapidly increasing velocity to 10 m (30 ft), and then steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 401 m/sec, which places the site in the C class near the D/C boundary. All of the initial and inverted models are of the C class, so the site can be confidently classified. This is within the predicted site class of C–D.

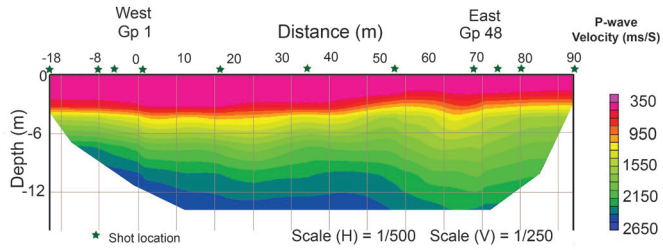
GEOLOGY

The site class of C is within the predicted site class of C–D, but the 1:100,000-scale geologic map on the previous page shows a contact crossing the site. The 1:100,000-scale geologic map indicates the seismic array and the school buildings are mapped on glacial till (unit Qgt). The contact with glacial drift (unit Qgos) runs along the west of the campus, but does not pass through any of the school buildings. However, both units are predicted to have a site class of C–D. We also model 2D seismic refraction tomography (2D SRT) in order to confirm the 1D velocity structure. The model (figure to the right) shows laterally continuous velocity structure in the upper 3–4 m, but a 3 m lateral drop around 80 m at a depth of 9 m, putting higher Vp to the north and lower Vp to the south.

The map on the front page shows the moderately constrained Tacoma fault (USGS reference ID 581) as a dotted line. The fault trace is mapped at a 1:250,000 scale by Brocher and others (2016) who project it directly south of the campus. A detailed study that could confirm the location of the fault is outside the scope of site class assessment.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.



2D seismic refraction tomography model depicting the lateral variation in P-wave velocity (Vp) with depth across the geophone array from the farthest off end shot from both ends.

MOUNT ERIE ELEMENTARY SCHOOL

ANACORTES SCHOOL DISTRICT, SKAGIT COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

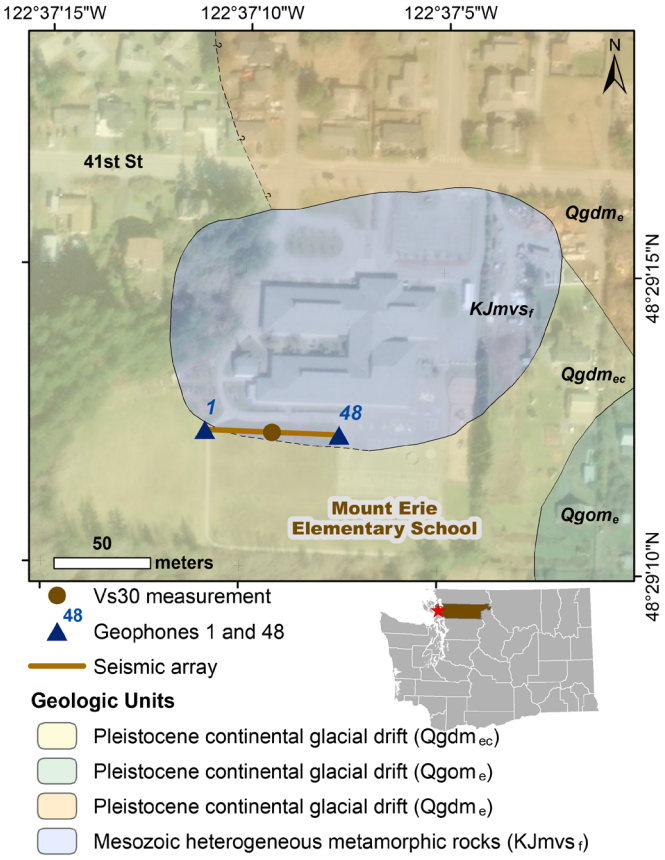
On April 05, 2021, a team from the Washington Geological Survey conducted a seismic survey at Mount Erie Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (231 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Mesozoic (Cretaceous–Jurassic) heterogeneous metamorphic rocks (unit KJmvs$_f$) and surrounded by Pleistocene continental glacial drift (units Qgdm$_{ec}$, Qgdm$_e$, and Qgom$_e$).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

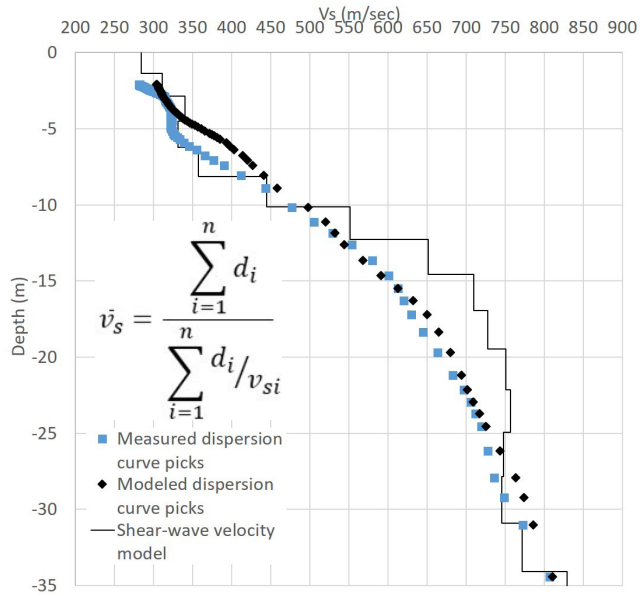
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality, but the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is also poor quality, and does not sample the shallow layers. MAM and the reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the two dispersion curves are combined into a single model.

VELOCITY MODEL

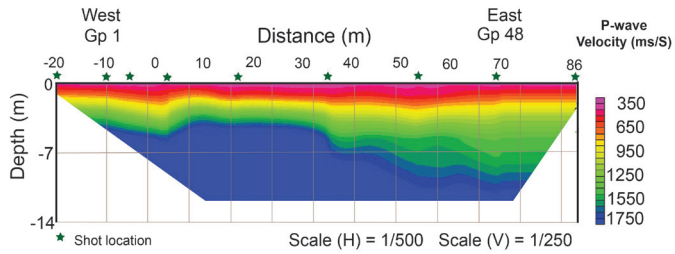
An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 10.9 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.8 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows gradually increasing velocity to 6 m (20 ft), then rapidly increasing velocity down to 18 m (59 ft), and nearly constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 523 m/sec, which places the site in the C site class. All initial and inverted models are in the middle of the C class. This correlates with the predicted site class of C.

GEOLOGY

The 1:24,000-scale geologic map shows both the seismic array and the school buildings are located on Cretaceous–Jurassic heterogeneous metamorphic rocks (unit $KJmvs_f$) and surrounded by Pleistocene glacial drift (units $Qgdm_{ec}$, $Qgdm_e$, and $Qgom_e$). This is different from the 1:100,000-scale geologic map which places Cretaceous–Jurassic volcanic rocks (unit $KJvc_f$) with a predicted site class of B on the northwest corner of campus and shows the rest of campus underlain by Pleistocene continental till (unit Qgt) with a predicted site class of C. The 1D velocity model indicates weaker, unconsolidated materials in the upper 10 m (33 ft) underlain by much denser materials that approach rock velocity around 20 m (66 ft). 2D seismic refraction tomographic models show laterally discontinuous velocity structure in the upper 12 m (39 ft), which could relate to the 1:24,000-scale $Qgdm_{ec}/KJmvs_f$ mapped contact. However, the lateral change in velocity is not significant enough to alter site class, which is in the middle C range, so we can confidently assign this site a site class C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.



2D refraction tomography model depicting lateral variation in P-wave velocity (Vp) in m/sec with depth across the geophone (Gp) array from the farthest off end shot from both ends. For this model, Vp shows heterogeneity, placing higher Vp at shallower depths to the west.

MOUNT SOLO MIDDLE SCHOOL

LONGVIEW SCHOOL DISTRICT, COWLITZ COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

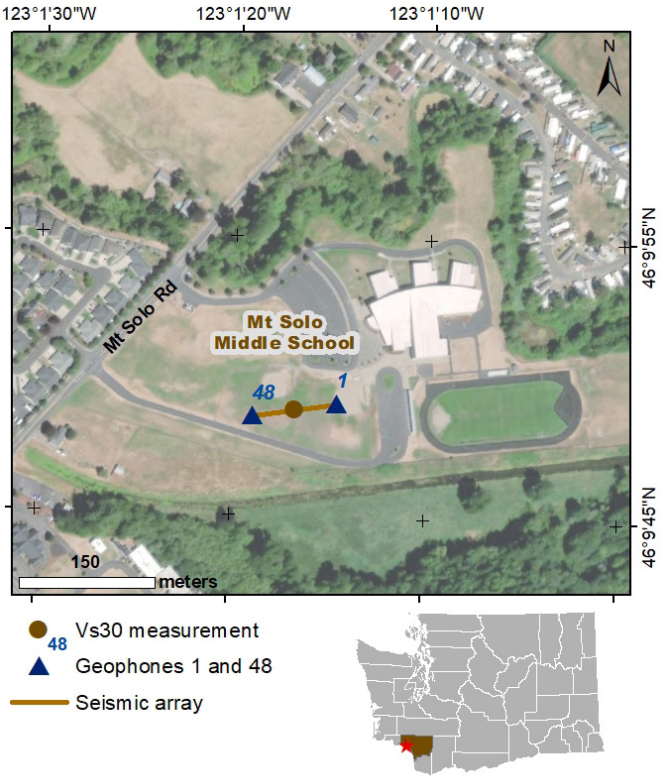
On August 26, 2019, a team from the Washington Geological Survey conducted a seismic survey at Mount Solo Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on river sediments consisting mostly of boulder, cobble, and pebble gravel and sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Violent

Tsunami
In a mapped tsunami hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

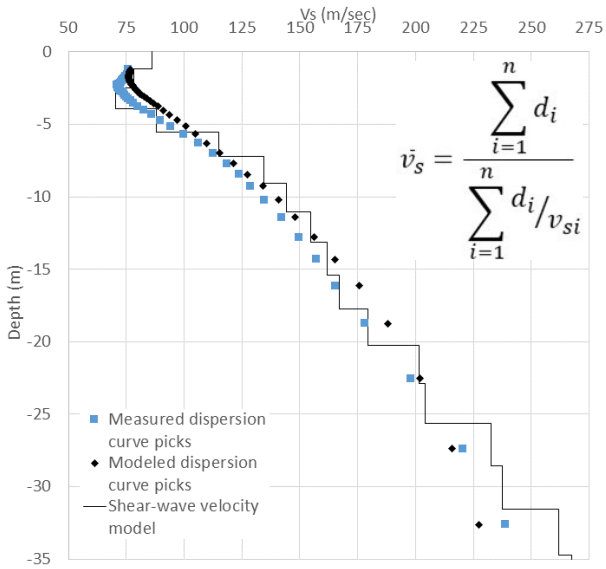
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so the fundamental mode can be picked with high confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also excellent quality and samples deeper, and the resulting dispersion curve correlates well with the MASW dispersion curves. The three curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 11.5 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 6.0 percent. The final model shows a slight velocity reversal in the top 4 m (13 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 142 m/sec, which places the site solidly in the E site class. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

MOUNTAIN MEADOW ELEMENTARY SCHOOL

WHITE RIVER SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

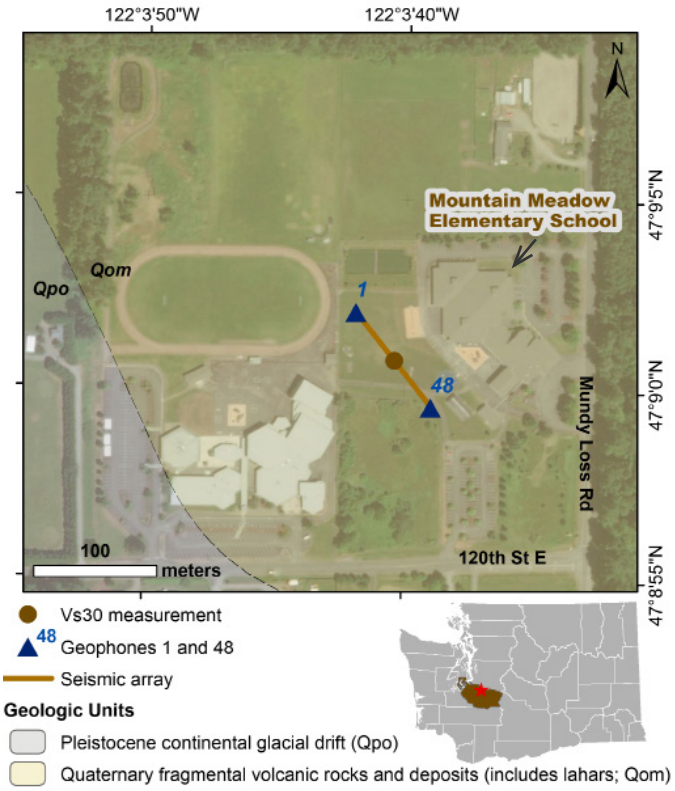
On July 8, 2020, a team from the Washington Geological Survey conducted a seismic survey at Mountain Meadow Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in an 86 m (282 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary fragmental volcanic rocks and deposits, consisting of an unsorted mixture of andesitic rock fragments in a clayey sand matrix (unit Qom). To the southwest is Pleistocene continental glacial drift consisting of sand and pebble to cobble gravel (unit Qpo).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

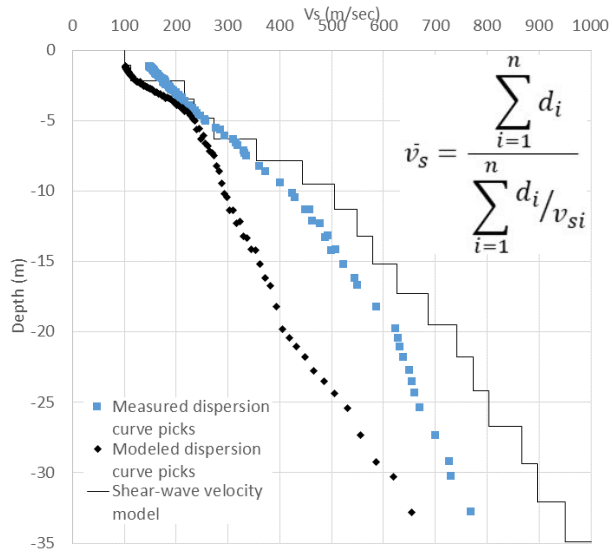
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also excellent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. The three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 13.2 percent. The inversion was carried out for nine iterations and resulted in a final model with an RMSE of 5.7 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 399 m/sec, which places the site solidly in the C site class. The dispersion images are excellent quality and all initial and inverted models place this site in the C site class, so the site can be confidently classified. This is different from the predicted site class of D–E.

GEOLOGY

The 1:24,000-scale geologic map places both the seismic array and the school buildings on fragmental volcanic rocks and deposits (unit Qom), with a predicted site class of D–E. The southwest edge of the school is in contact with glacial drift (unit Qpo), with a predicted site class of C–D. Nearby boreholes on unit Qom show silt, sand, and gravel down to ~15 m (50 ft), and below this more consolidated sediments. This indicates harder materials (typical of unit Qpo) underlaying less consolidated materials (typical of volcaniclastic lahar materials such as unit Qom), and the site class change could be due to a contact with unit Qpo within the top 30 m (100 ft).



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the top right corner of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

MOUNTAIN VIEW ELEMENTARY SCHOOL

PUYALLUP SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

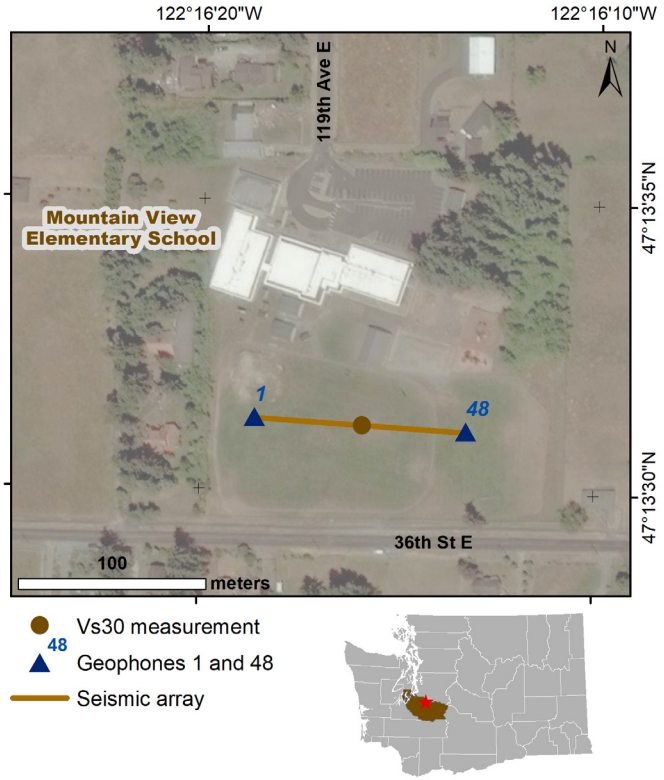
On July 22, 2020, a team from the Washington Geological Survey conducted a seismic survey at Mountain View Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till, comprising of compact and unsorted mixture of sand, silt, clay, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

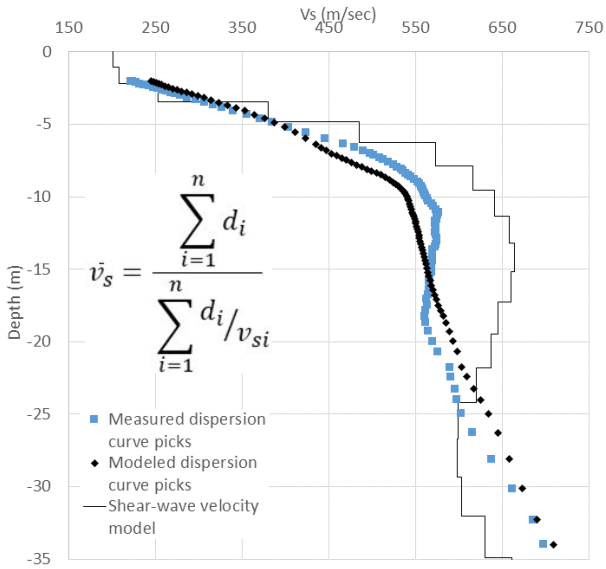
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. The three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 9.4 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 4.6 percent. The final model shows rapidly increasing velocity from 2 to 10 m (7 to 33 ft), a velocity reversal down to 25 m (82 ft), then steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 500 m/sec, which places the site in the middle of the C site class. All initial and inverted models place this site in the C class, so the site can be confidently classified. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

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MOUNTAIN WAY ELEMENTARY SCHOOL

GRANITE FALLS SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

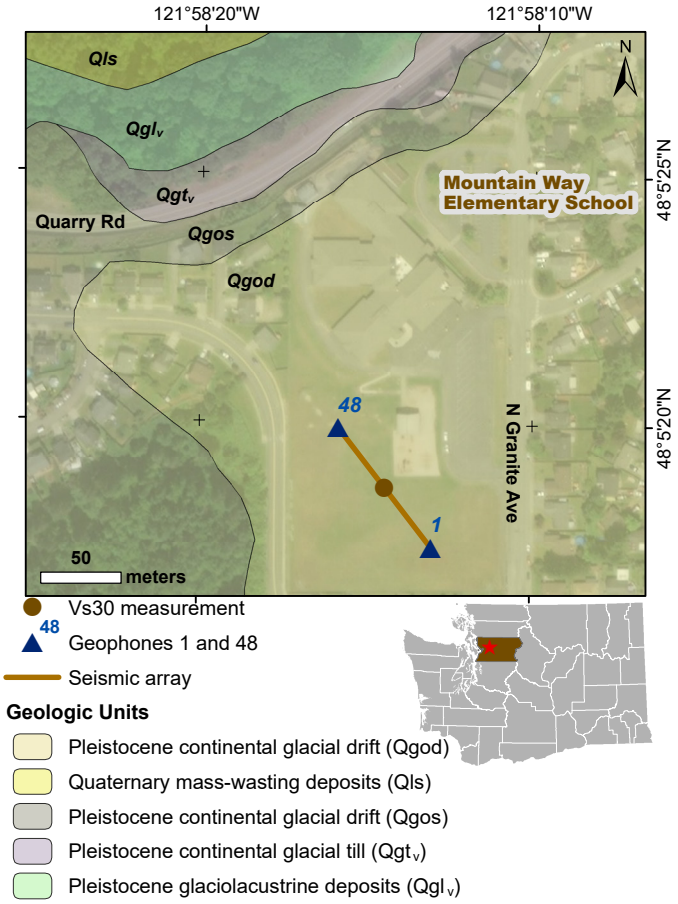
On October 29, 2020, a team from the Washington Geological Survey conducted a seismic survey at Mountain Way Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift, comprising mostly sand, gravel, and cobbles (unit Qgod).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

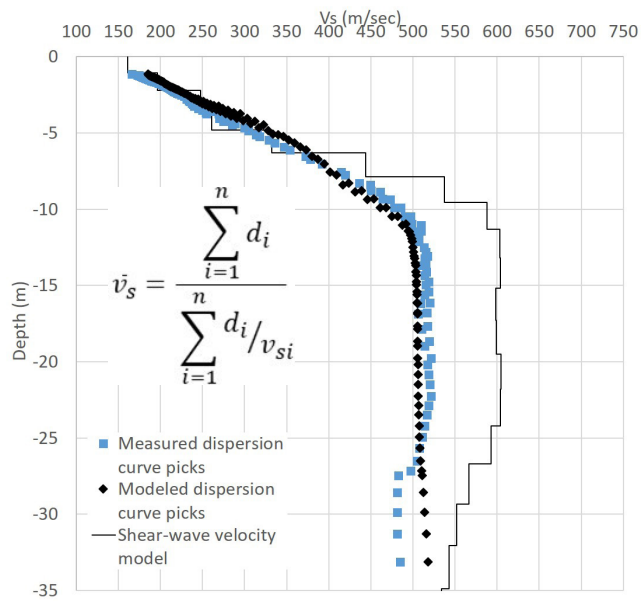
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality so the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 11.4 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.9 percent. The final model is unconstrained in the top 1 m (3 ft), but below this shows generally increasing velocity to 10 m (33 ft), then generally constant velocity down to 25 m (82 ft), and finally a slight velocity reversal below down to 30 m (100 ft). Our best Vs30 measurement is 441 m/sec, which places the site in the middle of the C site class. All initial and inverted models place this site in the C class, so the site can be confidently classified. This is different than the predicted site class of D–E.

GEOLOGY

The 1:24,000-scale geologic map shows the seismic array and most of the buildings are sitting on Pleistocene continental glacial drift (unit Qgod), which is similar to the 1:100,000-scale mapped unit $Qgos_S$. The 1:24,000-scale geologic map also shows Pleistocene glacial till (unit Qgt_V) and Pleistocene glaciolacustrine deposits (unit Qgl_V) to the north and west of campus. Unit Qgos is mapped as crossing through the northern portion of campus, just inside the footprint of a few buildings. While all of the above units have a predicted site class of D–E, there are also marine medisedimentary rocks (unit KJms(w)) mapped closely to the east with a predicted site class of B. The 1D velocity model depicts velocities consistent with more consolidated materials below 10 m (33 ft) depth that underlay weakly to moderately consolidated lower velocity materials. Nearby boreholes show clay, sands, silty sands, and gravels down to 30 m depth, which are consistent with the lower velocity materials. Therefore, the higher velocities below 10 m (33 ft), which have the effect of increasing Vs30 into the C class, are likely due to either lateral variations in unit Qgod, or unit KJms(w) underlying unit Qgod. Regardless, we do not see evidence for heterogeneity along the array and can assign a site class with confidence.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

NAPAVINE ELEMENTARY AND JUNIOR/SENIOR HIGH SCHOOL

NAPAVINE SCHOOL DISTRICT, LEWIS COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

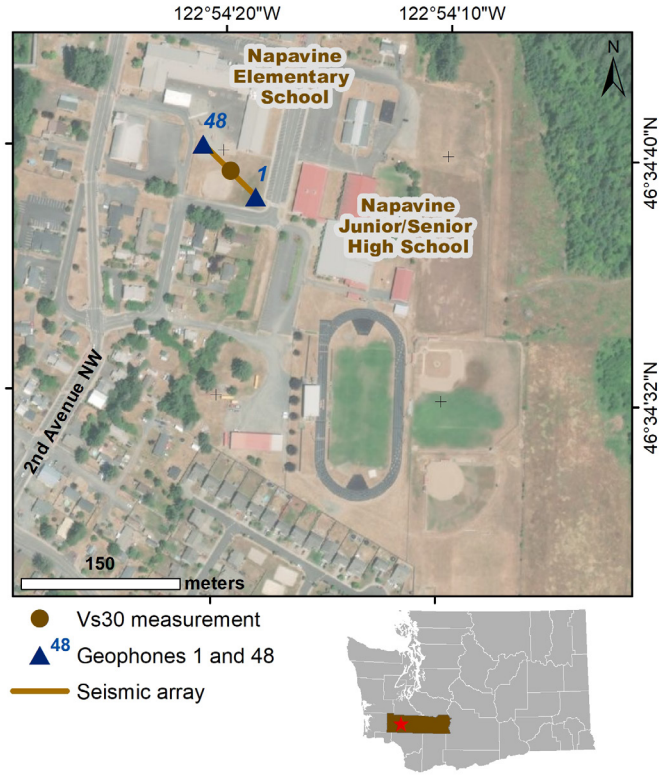
On October 6, 2020, a team from the Washington Geological Survey conducted a seismic survey at Napavine Elementary School and Napavine Junior/Senior High School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (231 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The schools are built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The schools are sitting on alpine glacial drift consisting predominately of sands, silts, and gravels.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

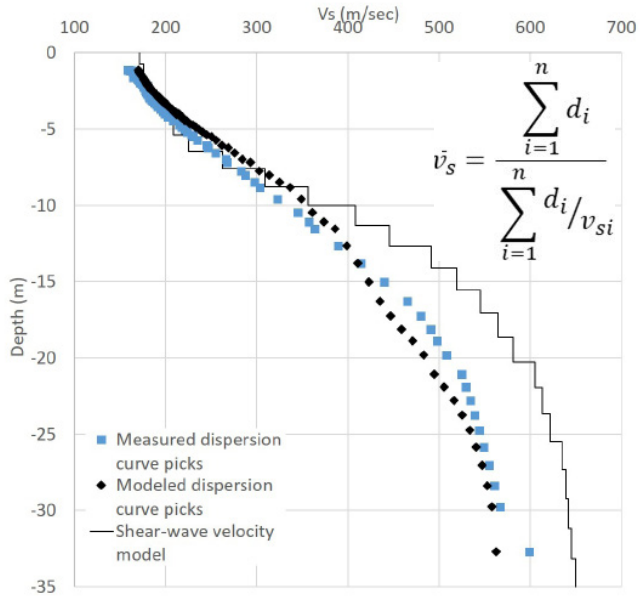
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so the fundamental mode can be picked with high confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is decent quality and can also be picked with confidence. The forward and reverse direction MASW show little variability and correlate well with the MAM, so they are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 12.1 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.9 percent. The final model is unconstrained in the top 1 m (3 ft), then shows gradually increasing velocity to 5 m (16 ft), with steadily increasing velocity from 5 m (16 ft) to 20 m (60 ft), and gradually increasing velocity below 20 m. Our best Vs30 measurement is 375 m/sec, which places the site near the C/D boundary on the low end of the C site class. All the initial and inverted models are in the C class, so the site can be confidently classified. This is within the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

NASELLE-GRAYS RIVER VALLEY SCHOOLS

NASELLE–GRAYS RIVER DISTRICT, PACIFIC COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

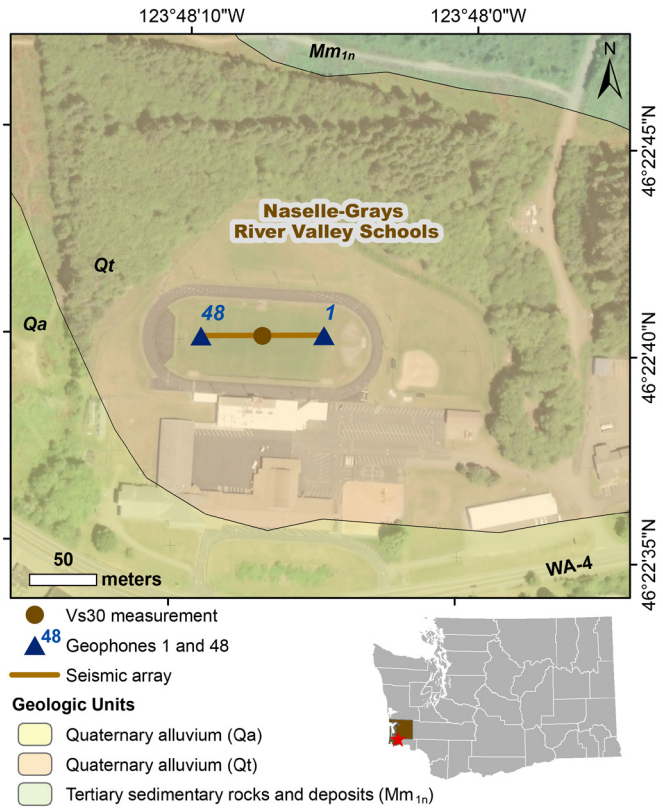
On February 27, 2020, a team from the Washington Geological Survey conducted a seismic survey at Naselle-Grays River Valley Schools. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is different than the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting partially on Quaternary alluvium (unit Qa) and Quaternary alluvium terrace deposits (unit Qt), which consist predominately of silts, sand, and gravels. Just north of the school are Tertiary sedimentary rocks (unit Mm_{1n}).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low to low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

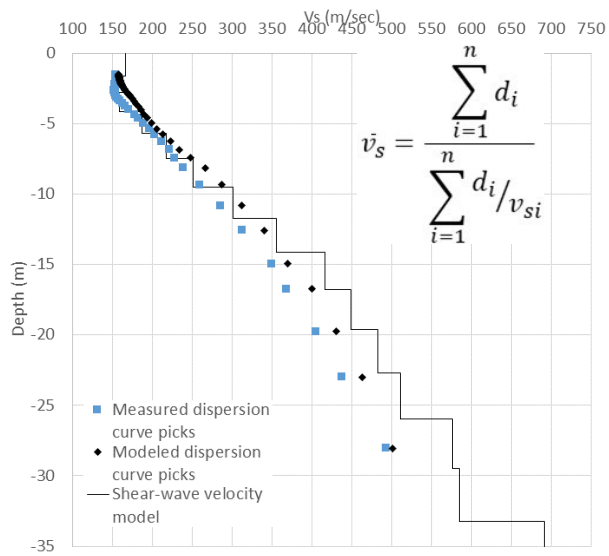
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. The forward and reverse direction MASW show little variability and sample below 30 m (100 ft) depth. The microtremor analysis method (MAM) dispersion image is decent quality, and the resulting dispersion curve correlates well with the MASW dispersion curves. However, combining the MAM does not improve the accuracy of the model, so our analysis is based on the combined dispersion curves from the forward and reverse direction MASW.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 11.8 percent. The inversion was carried out for eight iterations and resulted in a final model with an RMSE of 5.6 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows generally constant velocity to 5 m (16 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 301 m/sec, which places the site solidly in the D site class. All the initial and inverted models are in the D class, so the site can be confidently classified. This is different from the predicted site class of C.

GEOLOGY

The 1:100,000-scale geologic map shows the school buildings are partially sitting on Quaternary alluvium terrace deposits (unit Qt) with a predicted site class of C, and partially on Quaternary alluvium (unit Qa), with a predicted site class of D–E. The seismic array is located entirely on unit Qt. Mapped just north of campus are Tertiary sedimentary rocks (unit Mm_{1n}), with a predicted site class of B. The velocity model depicts low velocities consistent with weakly consolidated sediments in the upper 5 m (16 ft), underlain by gradually increasing velocities with depth that do not reach rock velocity. Although boreholes from the area only reach maximum depths of 4.5 m (15 ft), they do confirm that these shallow layers are soft clay. The Horizontal-to-Vertical Spectral Ratio (HVSR) seismic data corroborates a site class D. We do not have strong evidence for a subsurface geologic contact in the upper 30 m (100 ft) between the location of the array and the school buildings that would cause a significant change in the measured Vs30. Therefore, we assign the measured site class of D to the school. The site class change is likely due to low-resolution mapping.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

NAUTILUS ELEMENTARY SCHOOL

FEDERAL WAY SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

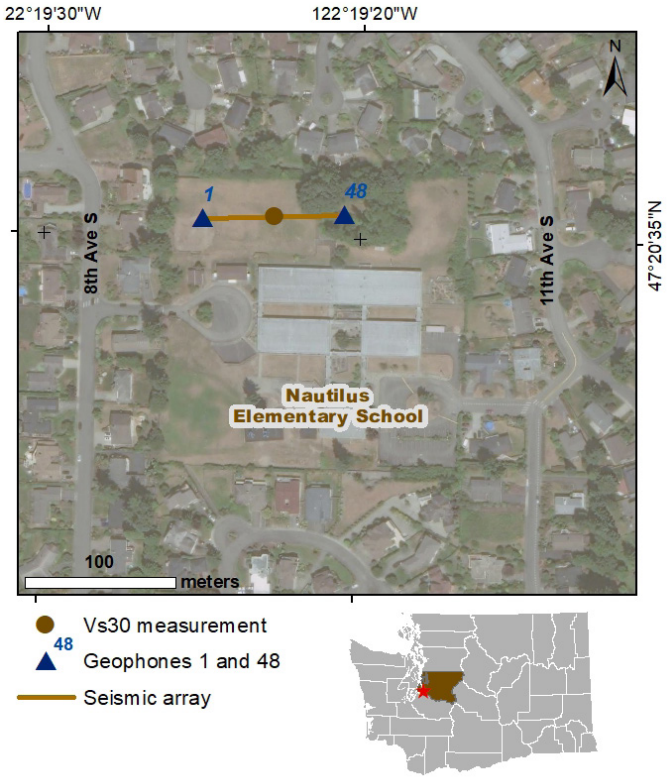
On January 9, 2020, a team from the Washington Geological Survey conducted a seismic survey at Nautilus Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift consisting mostly of sand and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

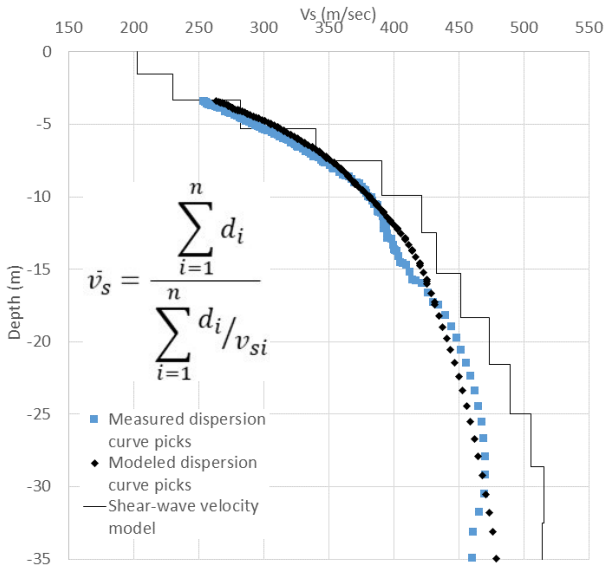
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. However, the MASW does not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is decent quality, so the fundamental mode can be picked with confidence. Forward and reverse direction MASW dispersion curves are combined with the MAM dispersion curve to create a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 8.4 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 3.9 percent. The final model is unconstrained in the top 3 m (10 ft) , then shows generally increasing velocity to 10 m (33 ft), with slowly increasing velocity below down to 30 m (100 ft). Our best Vs30 measurement is 386 m/sec, which places the site in the C site class. Although this is near the site class boundary C/D, all initial and inverted models place this site in the C class, so it can be confidently classified. This is within the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

NOB HILL ELEMENTARY SCHOOL

YAKIMA SCHOOL DISTRICT, YAKIMA COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

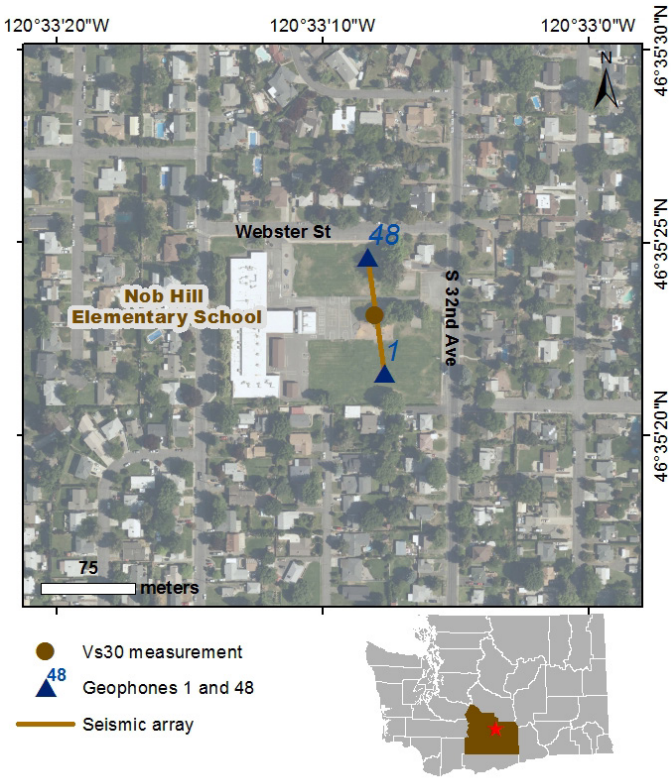
On October 6, 2020, a team from the Washington Geological Survey conducted a seismic survey at Nob Hill Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of B.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Ellensburg Formation consisting of gravel and coarse sand with pumice and andesite (unit Teug).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Unknown, not negligible

Ground Shaking
Very strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

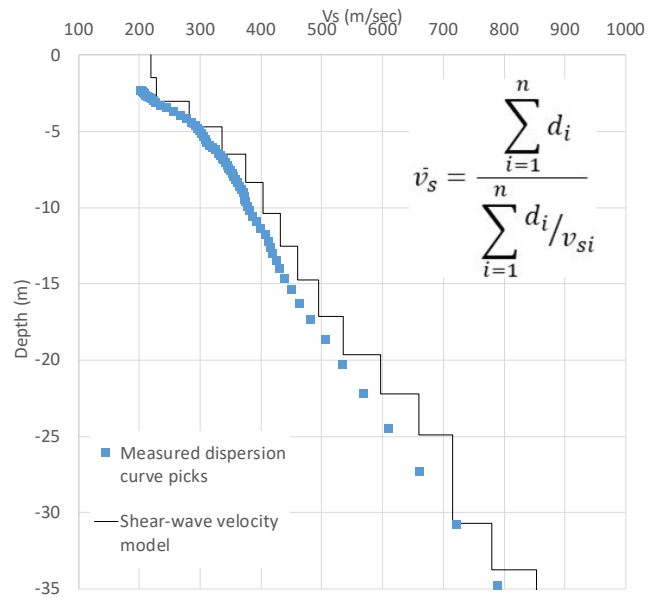
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is excellent quality. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inverted model does not converge to an acceptable RMSE, therefore the initial model is used as the final model. The final model shows generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 434 m/sec, which places the site solidly in the C site class. All of the initial and final models are of the C class, so the site can be confidently classified. This is different from the predicted site class of B.

GEOLOGY

The 1:24,000-scale geologic map shows the seismic array and school buildings are on Ellensburg Formation (unit Teug), which matches the 1:100,000-scale geologic map that predicts a seismic site class of B. Nearby boreholes indicate mostly sands and gravels with some clays in the upper 30 m (100 ft), similar to what is expected of the Ellensburg Formation. The 1D velocity structure on the right shows a generally increasing, smooth velocity structure that reaches bedrock velocities around 25 m (80 ft) depth. Ellensburg Formation tends to consist of a variety of lithologies such as interbedded volcanic and sedimentary deposits, and may not always fall into a site class B. Therefore, the change in site class is likely due to an internal change in the lithology of the geologic unit.



Final velocity model based on the initial model with measured dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

NORMAN ROCKWELL ELEMENTARY SCHOOL

LAKE WASHINGTON SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

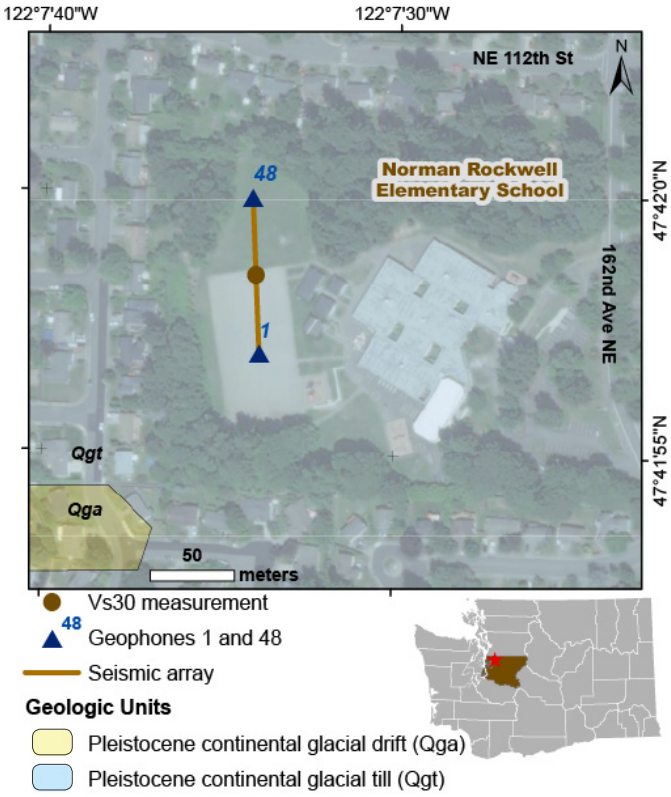
On July 28, 2020, a team from the Washington Geological Survey conducted a seismic survey at Norman Rockwell Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel (unit Qgt). To the west is mapped Pleistocene continental glacial drift (unit Qga).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

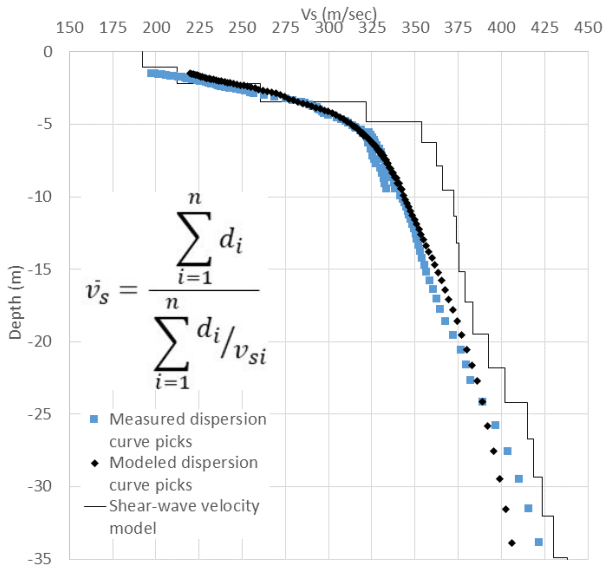
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward direction are poor quality, but the dispersion images from the reverse direction are decent quality so that the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the top 5 m (16 ft). MAM and the reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the two dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 5.4 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 2.9 percent. The final model is unconstrained in the top 1.5 m (5 ft), and below this shows rapidly increasing velocity to 5 m (16 ft), then more slowly increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 353 m/sec, which places the site in the D site class, near the C/D site class border. This is different from the predicted site class of C.

GEOLOGY

The 1:100,000-scale geologic map places the school buildings and seismic array on glacial till (unit Qgt), with a predicted site class of C. Located 150 m (500 ft) to the south is glacial drift (unit Qga), with a predicted site class of C–D. Nearby boreholes to the east and west show sand, clay, and gravel in the top 30 m (100 ft), with an unclear amount of consolidation (for example, "till" vs. "drift"). The 2D seismic refraction tomography (SRT) shows no shallow heterogeneity, and validates the 1D velocity structure in the top 6 m (20 ft). The Vs30 for this location is near the site class boundary with the predicted site class, so the change could be due to either a subsurface change within the unit, or low resolution mapping.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

NORTH BEACH JUNIOR/SENIOR HIGH SCHOOL

NORTH BEACH SCHOOL DISTRICT, GRAYS HARBOR COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

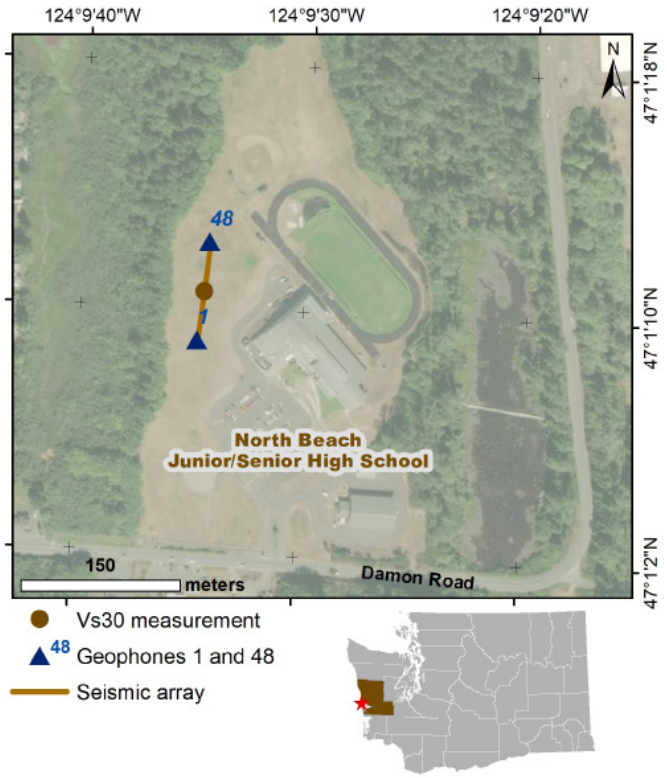
On November 13, 2019, a team from the Washington Geological Survey conducted a seismic survey at North Beach Junior/Senior High School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on beach deposits of fine to coarse sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Extreme

Active Fault Proximity
Within 5 miles of an active mapped fault

Tsunami
In a mapped tsunami hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

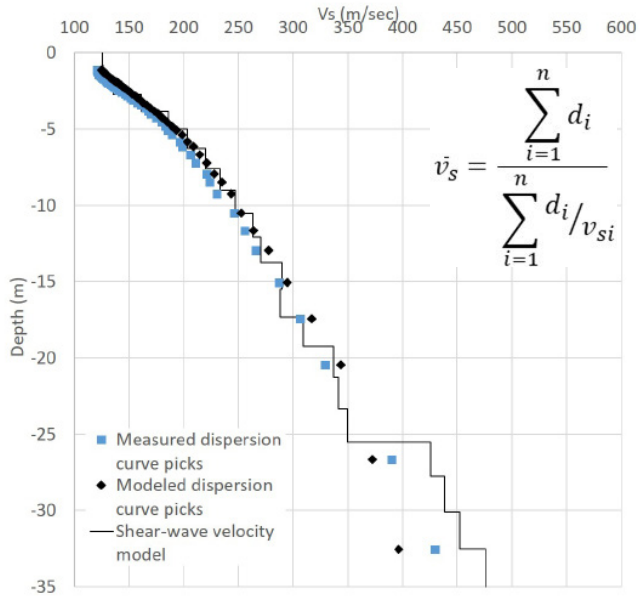
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of decent quality so the fundamental mode can be picked with confidence. The MAM and forward and reverse direction MASW correlate well, depicting similar trends. The three dispersion images are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 12.1 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 5.4 percent. The final model shows velocity steadily increasing with depth from 1 m (3 ft) to 25 m (82 ft) with a sharp jump in velocity at 25 m (82 ft), then a steady increase below. Our best Vs30 measurement is 256 m/sec, which places the site in the middle of the D site class. All of the initial models are in the middle of the D class as well, so the site can be confidently classified. This is the same as the predicted site class of D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

NORTH RIVER SCHOOL

NORTH RIVER SCHOOL DISTRICT, GRAYS HARBOR COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

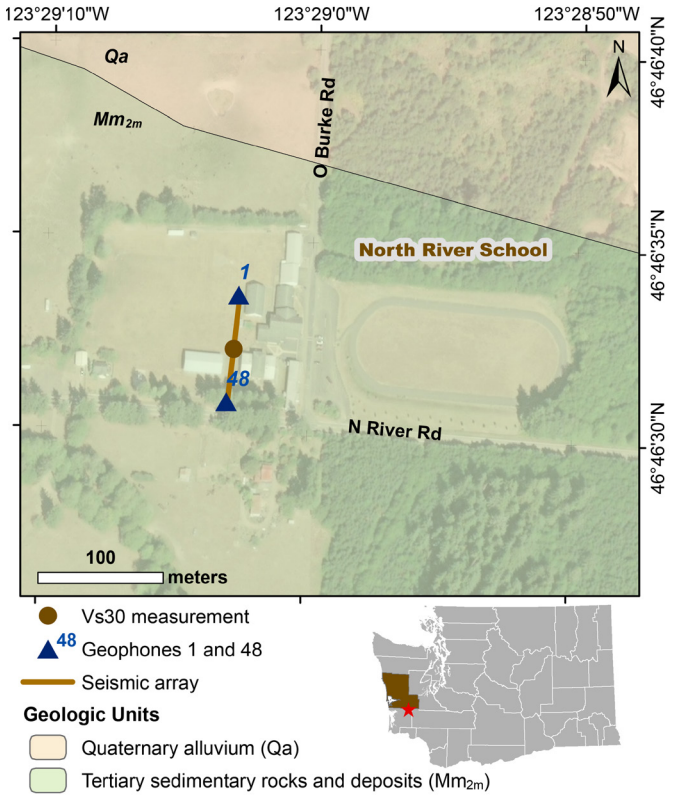
On July 15, 2020, a team from the Washington Geological Survey conducted a seismic survey at North River School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 86 m (282 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of B.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is mapped as sitting on marine sedimentary rocks (unit Mm_{2m}).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Unknown, not negligible

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

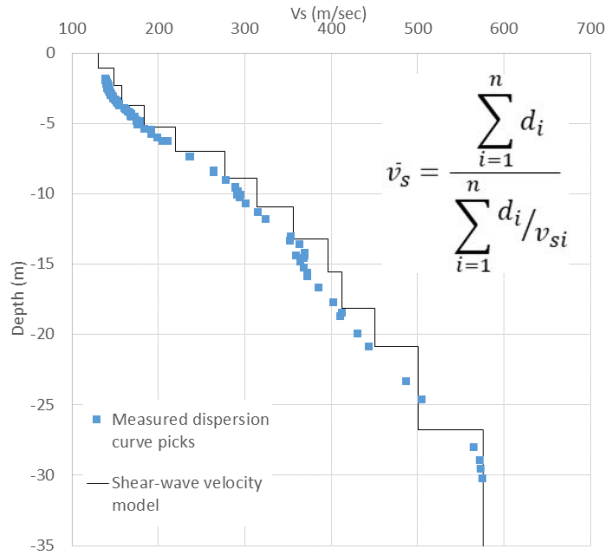
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is also of decent quality and the resulting dispersion curve is combined with the MASW reverse direction dispersion curve into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model is used as the final model because the inverted models force unrealistic velocity structure and don't converge to a reasonable RMSE. The final model shows generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 311 m/sec, which places the site in the D site class. This is different from the predicted site class of B.

GEOLOGY

The 1:100,000-scale geologic map shows the seismic array and the school buildings are located on geologic unit Mm_{2m}, sedimentary rocks. The contact with Quaternary alluvium (unit Qa) is mapped ~100 m (330 ft) to the north. Nearby boreholes on the same geologic unit as the school show sandstone in the top 15 m (50 ft), and boreholes to the east of campus on unit Mm_{2m} show sandstone much shallower, generally in the top 3 m (10 ft). Horizontal-to-Vertical Spectral Ratio (HVSR) analysis performed on the campus indicates a stratigraphic contact at around 13 m (43 ft) depth and does not indicate bedrock is at the surface. Both the boreholes and HVSR correlate well with our final 1D velocity model. The predicted site class of B is based on the 1:100,000-scale geology map which places the school on sedimentary rocks, however, the 1D velocity model correlates with the geology of unit Qa. Thus, the change in site class from the predicted is likely due to low resolution mapping and we can confidently classify the site as a site class D.



Final inital velocity model based on the initial modle with measured dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

NORTH TAPPS MIDDLE SCHOOL

DIERINGER SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

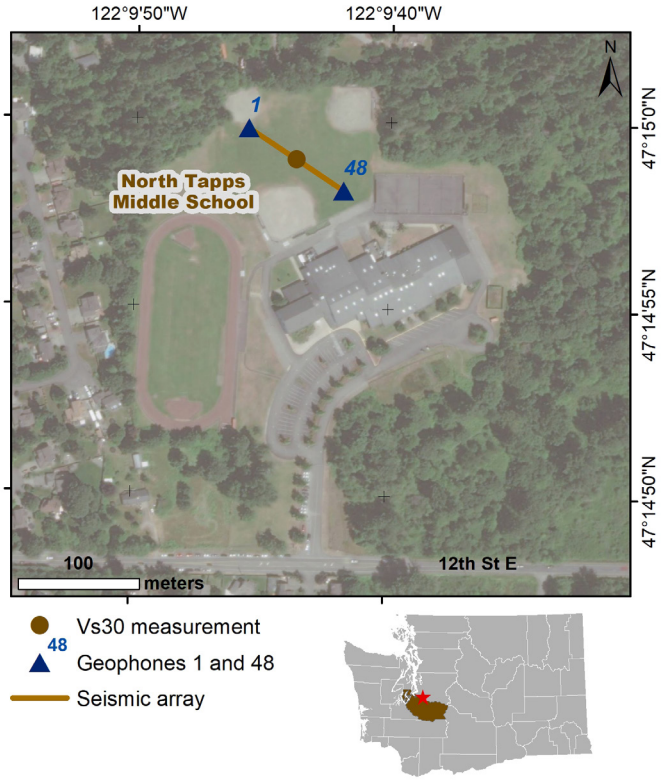
On September 22, 2020, a team from the Washington Geological Survey conducted a seismic survey at North Tapps Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Plesitocene continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

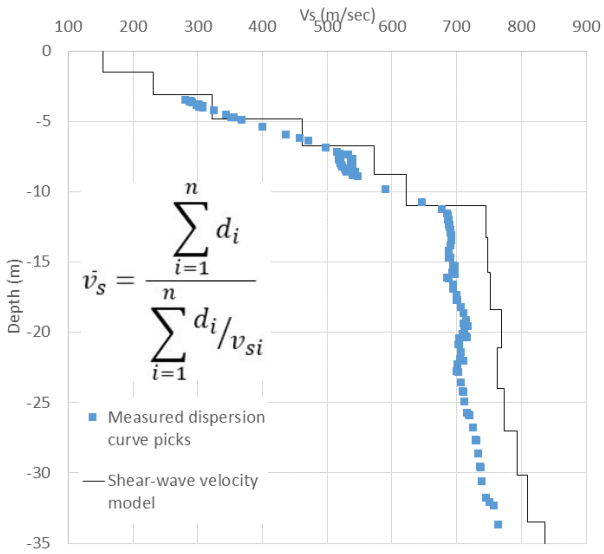
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality so that the fundamental mode can be picked with some confidence. The microtremor analysis method (MAM) dispersion image is decent quality and is combined with the MASW to adequately sample below 30 m (100 ft).

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inverted model converges well above 5 percent and forces unrealistic velocity structure, therefore the initial model is used as the final model. The final model is unconstrained in the top 1 m (3 ft), and below this shows rapidly increasing velocity to 10 m (30 ft), then generally constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 519 m/sec, which places the site solidly in the C site class. All initial and inverted models are in the C class, so the site can be confidently classified. This is the same as the predicted site class of C.



Final velocity model based on the initial model with measured dispersion curve. The equation used to calculate the average shear wave velocity (V_S) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

NORTHEAST TACOMA ELEMENTARY SCHOOL

TACOMA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

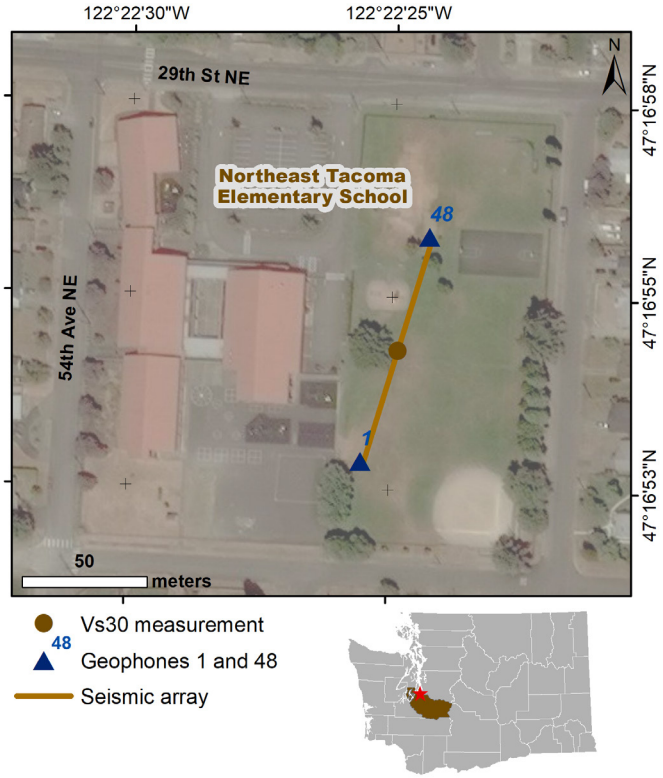
On August 13, 2020, a team from the Washington Geological Survey conducted a seismic survey at Northeast Tacoma Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

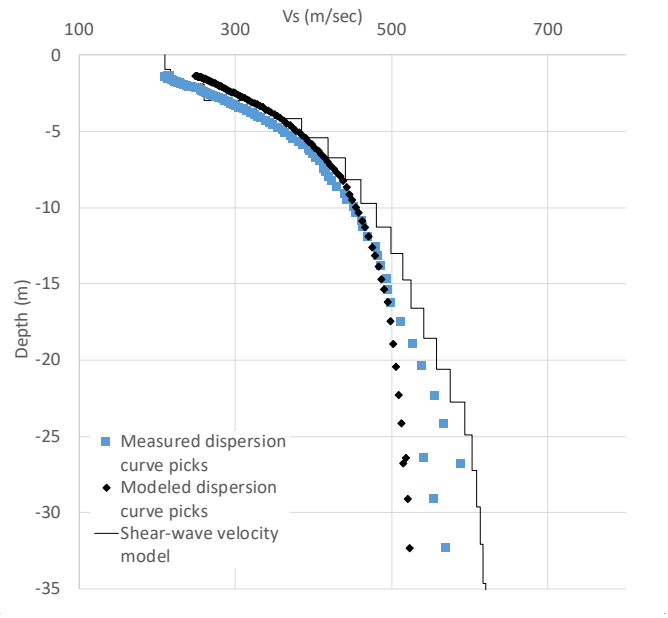
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. The microtremor analysis method (MAM) dispersion image is of decent quality but is not needed because the forward and reverse direction MASW adequately samples below 30 m (100 ft).

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the dispersion curves. The initial model had an RMSE of 10.5 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.4 percent. The final model shows generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 453 m/sec, which places the site in the middle of the C site class. All initial and inverted models are in the C class, so the site can be confidently classified. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_S) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{Si} = shear wave velocity in m/sec of the layer.

OAK HARBOR INTERMEDIATE SCHOOL

OAK HARBOR SCHOOL DISTRICT, ISLAND COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

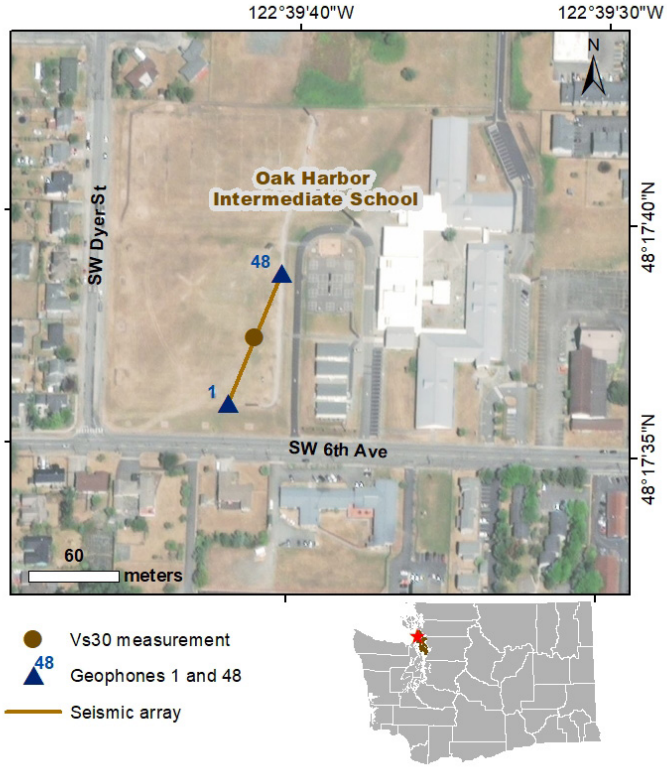
On April 6, 2021, a team from the Washington Geological Survey conducted a seismic survey at Oak Harbor Intermediate School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial drift.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

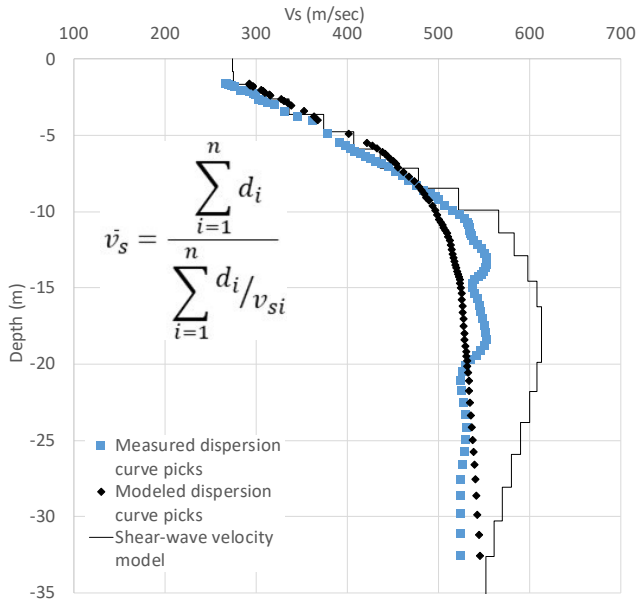
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is also decent quality. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 6.9 percent. The inversion was carried out for three iterations and resulted in a final model with an RMSE of 4.9 percent. The final model shows rapidly increasing velocity to about 15 m (50 ft) then generally constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 499 m/sec, which places the site in the C site class. All initial and final models are of the C class, so the site can be confidently classified. This is within the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

OAKBROOK ELEMENTARY SCHOOL

CLOVER PARK SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

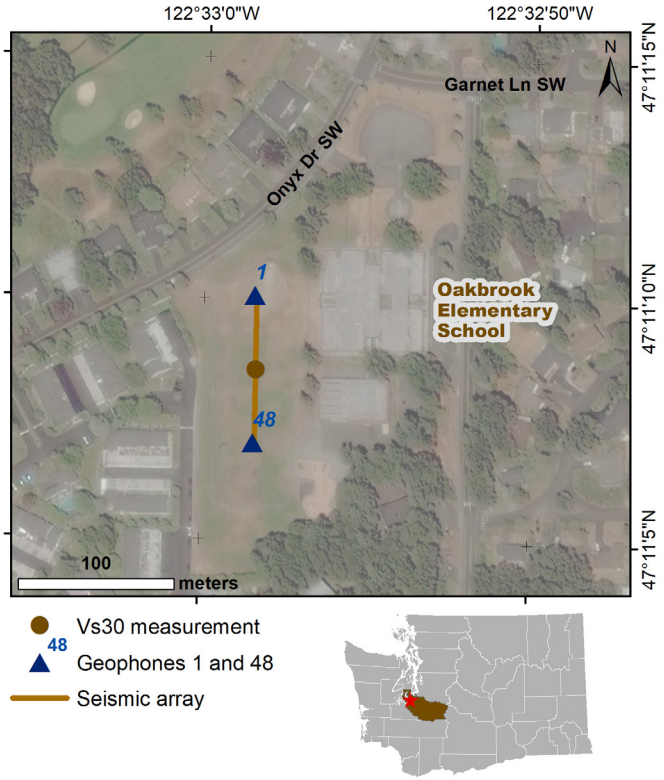
On July 20, 2020, a team from the Washington Geological Survey conducted a seismic survey at Oakbrook Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

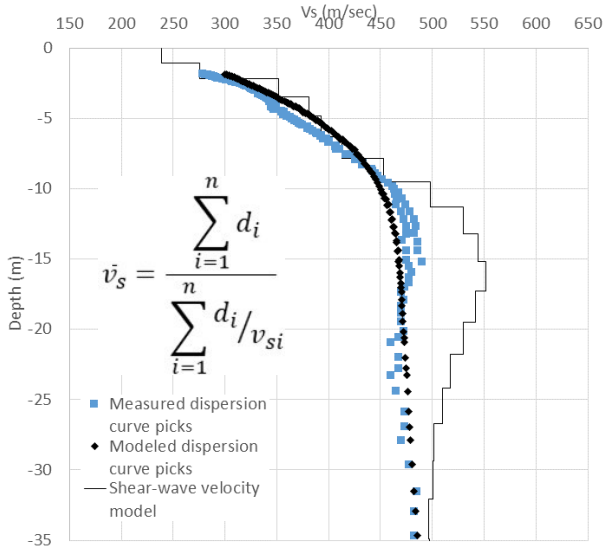
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also excellent, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves depict similar trends, therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 6.6 percent. The inversion was carried out for three iterations and resulted in a final model with an RMSE of 4.7 percent. The final model is unconstrained in the top 1.5 m (5 ft), below this shows generally increasing velocity to 16 m (52 ft), and then shows a velocity inversion down to 30 m (100 ft). Our best Vs30 measurement is 455 m/sec, which places the site solidly in the C site class. This is within the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

OAKVIEW ELEMENTARY SCHOOL

CENTRALIA SCHOOL DISTRICT, LEWIS COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

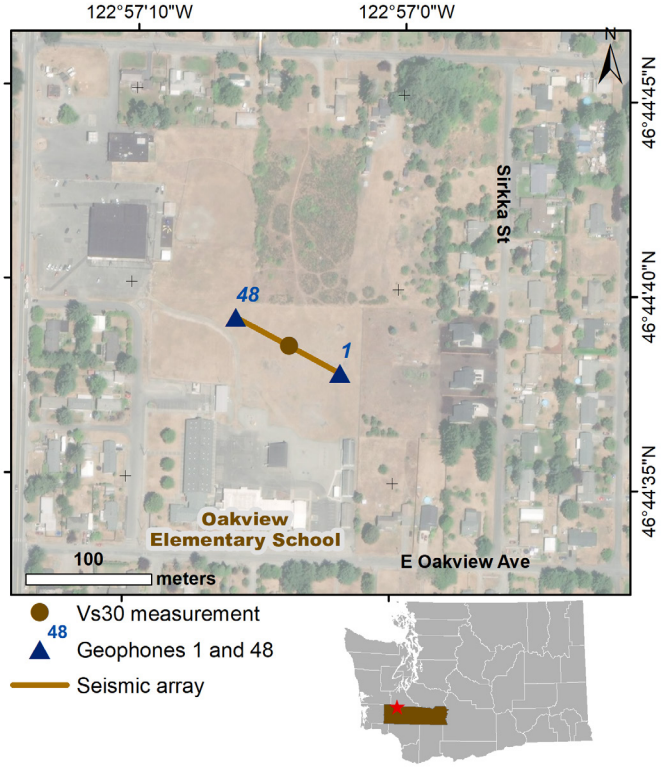
On October 1, 2020, a team from the Washington Geological Survey conducted a seismic survey at Oakview Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift, comprised mostly of stratified pebble, cobble, and boulder gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

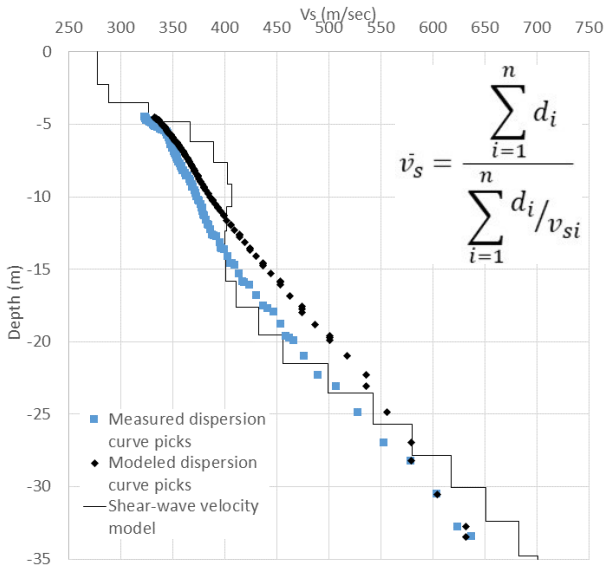
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also excellent quality. MAM and the forward and reverse MASW dispersion curves depict similar trends, therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 9.1 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 4.0 percent. The final model is unconstrained in the upper 4 m (13 ft), but below this shows generally increasing velocity to 8 m (26 ft), then a slight reversal down to 16 m (52 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 415 m/sec, which places the site solidly in the C site class. All initial and inverted models place this site in the C class, so the site can be confidently classified. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_S) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

OLYMPIC ELEMENTARY SCHOOL

LONGVIEW SCHOOL DISTRICT, COWLITZ COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

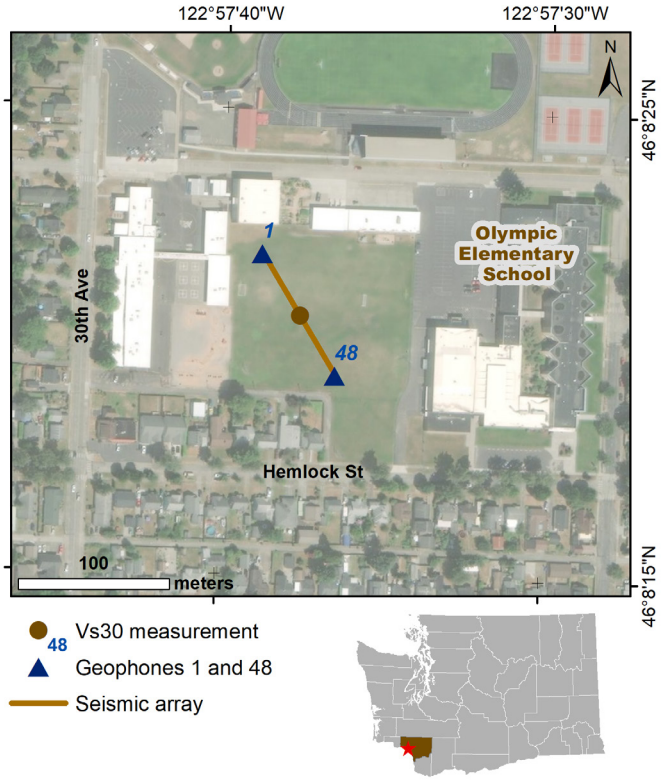
On August 27, 2019, a team from the Washington Geological Survey conducted a seismic survey at Olympic Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on river sediments consisting mostly of boulder, cobble, and pebble gravel and sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

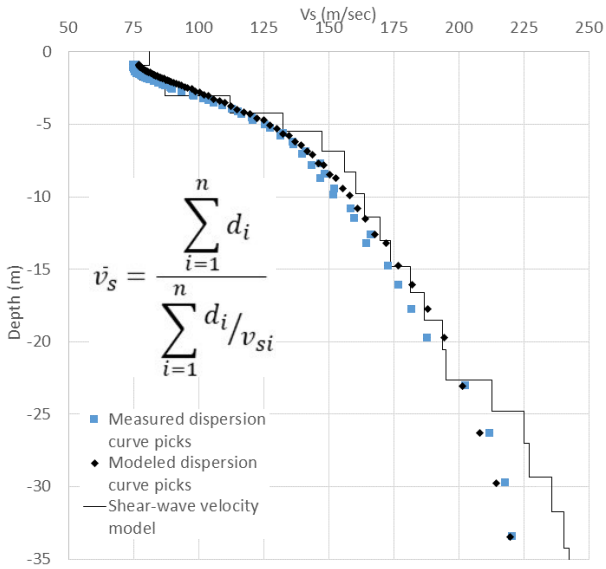
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample past 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is excellent quality and samples deeper, and the resulting dispersion curve correlates well with the MASW dispersion curves. The three curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 10.6 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 4.7 percent. The final model shows rapidly increasing velocity in the top 6 m (20 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 159 m/sec, which places the site in the E site class. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the graph. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

ORTING PRIMARY SCHOOL

ORTING SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

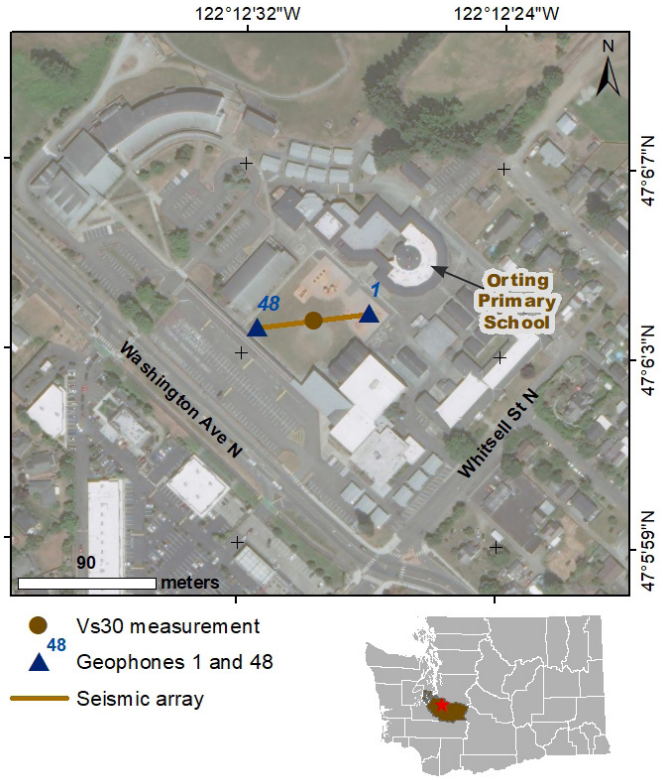
On July 8, 2020, a team from the Washington Geological Survey conducted a seismic survey at Orting Primary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on predominantly an unsorted mixture of andesitic rock fragments in a clayey sand matrix.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Violent

Lahar
In a mapped lahar hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

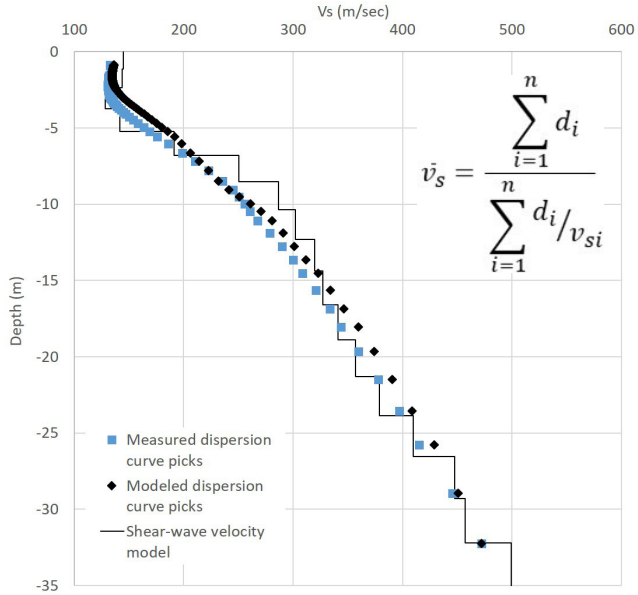
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images are of decent quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of excellent quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward and reverse direction) and MAM dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 9.9 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 4.4 percent. The final velocity model shows a slight velocity reversal around 3 m (10 ft) and rapidly increasing velocity to around 8 m (26 ft), then steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 267 m/sec, which places the site in the middle of the D class. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_S) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

PARKWAY SCHOOL

EPHRATA SCHOOL DISTRICT, GRANT COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

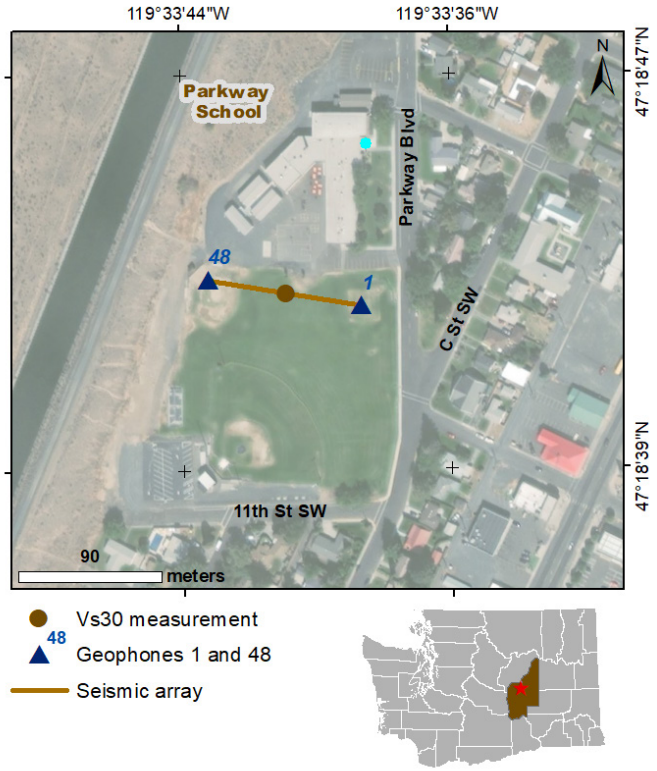
On October 1, 2020, a team from the Washington Geological Survey conducted a seismic survey at Parkway School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on mass wasting deposits, mostly landslides.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Very strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

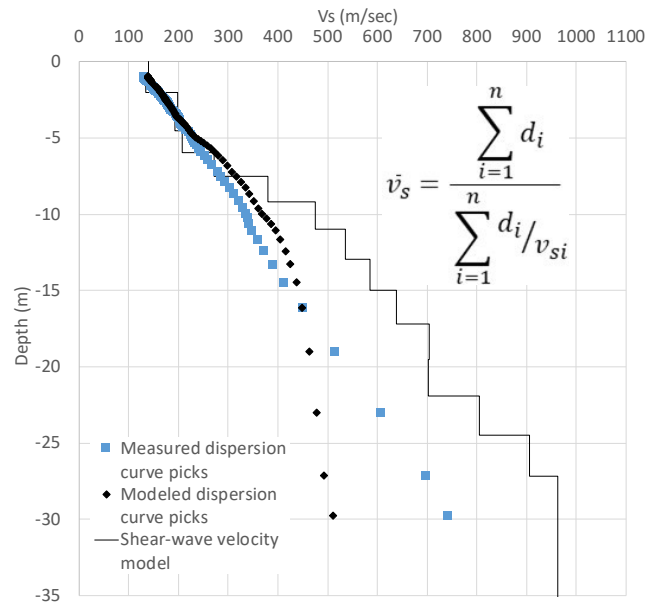
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality so that the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is decent quality. MAM and the forward MASW dispersion curves correlate well, depicting similar trends. Therefore the two dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 13.7 percent. The inversion was carried out for fifteen iterations and resulted in a final model with an RMSE of 5.8 percent. The final model shows steadily increasing velocity in the upper 7 m (22 ft), then rapidly increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 405 m/sec, which places the site in the C site class near the D/C boundary. All combined models are in the C class, so the site can be confidently classified. This is different from the predicted site class of D.

GEOLOGY

The 1:100,000-scale geologic map shows the seismic array and the school buildings are located on mass wasting deposits (unit Qls) with a predicted site class of D, which does not match our measured site class of C. However, the 1:100,000-scale geology map shows a contact to the west with unit $Mv_{(gN2)}$, or Grande Ronde Basalt, that predicts a site class of B. Nearby boreholes indicate sandy silt in the upper 7 m (22 ft), then basalt similar to unit $Mv_{(gN2)}$. The 1D velocity structure and additional 2D seismic refraction tomography, show shallow bedrock velocities underlying lower velocity materials. These shallow high velocities effectively increase Vs30. Therefore, the change in site class is likely due to a subsurface change in geology.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

PE ELL SCHOOL

PE ELL SCHOOL DISTRICT, LEWIS COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

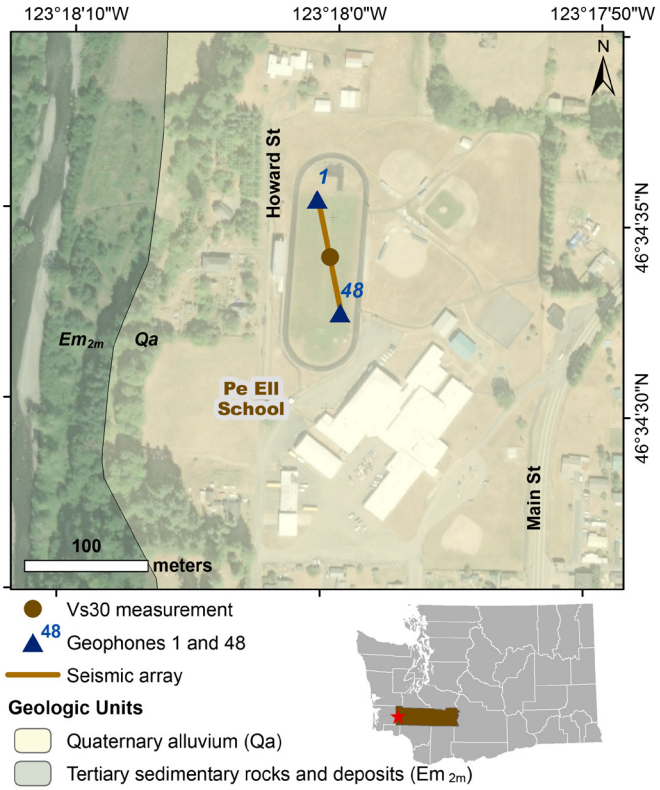
On September 30, 2020, a team from the Washington Geological Survey conducted a seismic survey at Pe Ell School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium; river sediments consisting mostly of boulder, cobble, and pebble gravel and sand (unit Qa). Just west of the school is Eocene marine sedimentary rocks and deposits (unit Em_{2m}).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

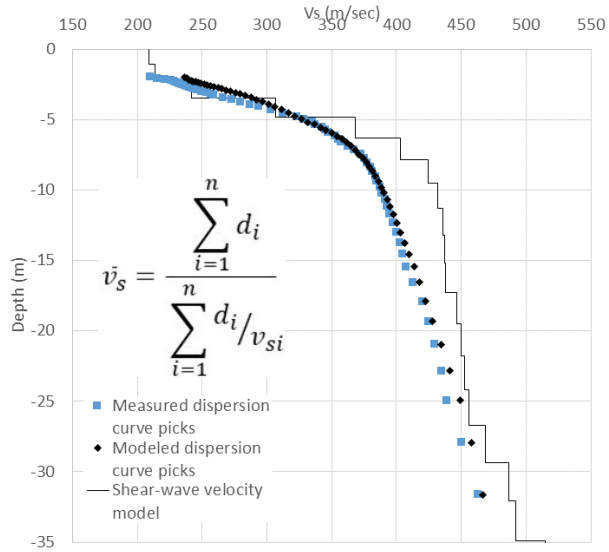
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is also decent quality, but does not have information at lower frequencies. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 5.3 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.1 percent. The final model is unconstrained in the top 2 m (7 ft), and below this shows generally increasing velocity to 8 m (26 ft), then nearly constant velocity down to 27 m (89 ft), and then generally increasing velocity down to 30 m (100 ft). Inversions led to an unrealistic top layer; however, manually adjusting this layer did not change the site class. Our best Vs30 measurement is 388 m/sec, which places the site solidly in the C site class. Although the MAM coherence cuts out at lower frequencies and thus does not sample the deeper layers, there are no reasonable picks in the MASW dispersion image that would lead to Vs30 outside class C, so the site can be confidently classified. This is different from the predicted site class of D–E.

GEOLOGY

The 1:100,000-scale geologic map places the school and seismic array on Quaternary alluvium (unit Qa), which is comprised mostly of uncosolidated or semiconsolidated clay-gravel, with a predicted site class of D–E. Approximately 100 m (330 ft) to the west is mapped Tertiary marine sedimentary rocks and deposits (unit Em_{2m}), consisting mostly of sandstone and shale with a predicted site class of B. Nearby boreholes on unit Qa show clay, sand, and some gravel in the top ~5 m (16 ft), and below this sandstone or siltstone. Our velocity model indicates soft rock velocities starting around 8 m (26 ft), which is consistent with the boreholes. Therefore it is likely the site class change is due to a subsurface change, with unit Qa overlying unit Em_{2m}.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

PENINSULA HIGH SCHOOL

PENINSULA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

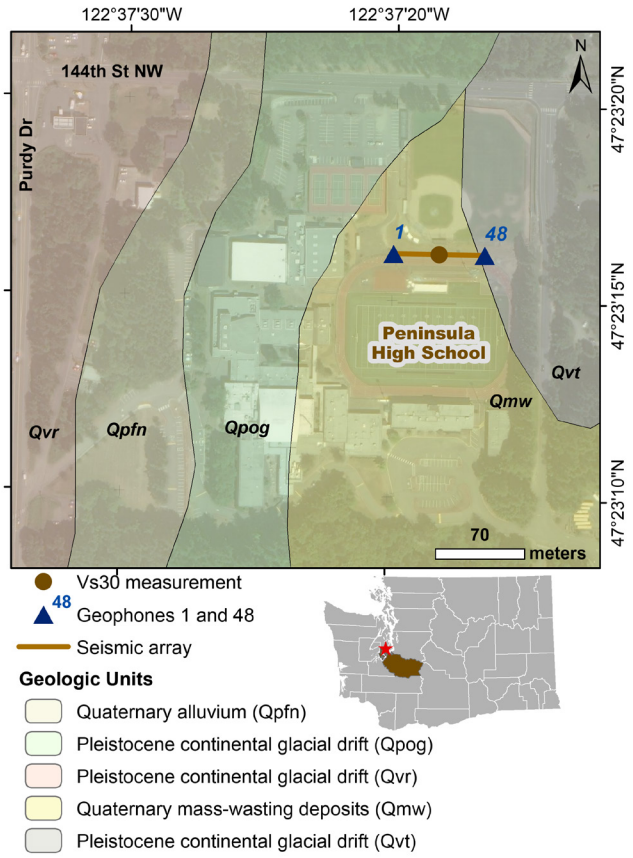
On July 14, 2020, a team from the Washington Geological Survey conducted a seismic survey at Peninsula High School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 73 m (240 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school buildings are sitting primarily on two units: (1) mass wasting deposits (unit Qmw), consisting mostly of landslides and colluvium; and (2) Pleistocene glacial drift (unit Qpog) which are dominated by silt, sand, and gravels.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

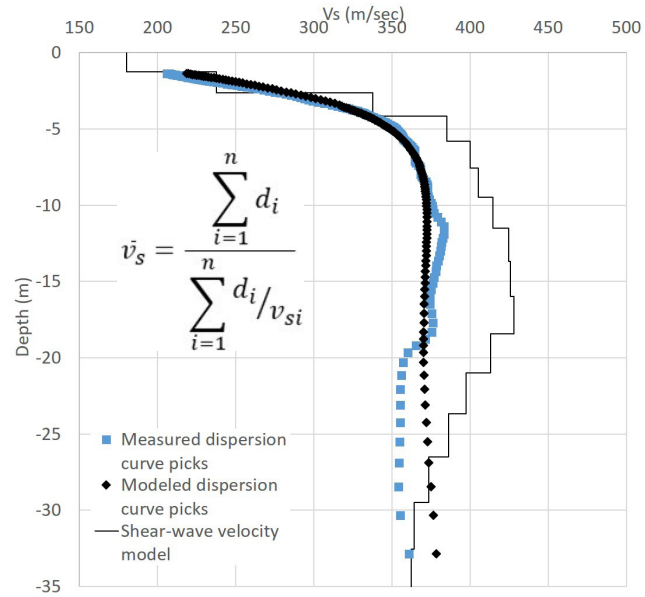
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well and are combined into a single model.

VELOCITY MODEL

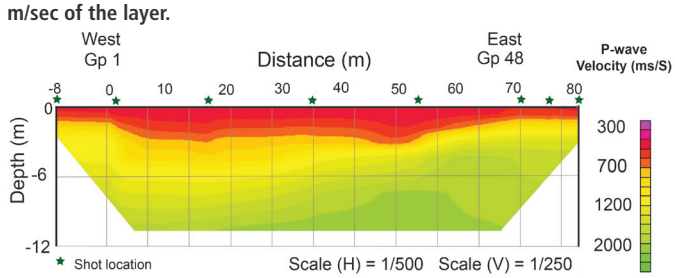
An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 7.1 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.8 percent. The final model is unconstrained in the upper 2 m (6 ft), but below this shows rapidly increasing velocity from 1 m (3 ft) to 5 m (16 ft), steadily increasing velocity to 19 m (62 ft), and then a velocity reversal down to 30 m (100 ft). Our best Vs30 measurement is 368 m/sec. All initial and inverted models are slightly higher than 360 m/s, putting the site on the site class C/D boundary. This is the same as the predicted site class of C.

GEOLOGY

The 1:24,000-scale geologic map on the previous page shows Pleistocene continental glacial drift (unit Qpog) and till (unit Qvt) occupying the western and eastern portions of the campus, with Quaternary mass wasting deposits (unit Qmw) mapped between them. The seismic array is mostly on unit Qmw and partially over unit Qvt. All of the above units have a predicted site class of C. The 1D velocity model indicates softer materials in the upper 5 m (16 ft) overlying generally denser materials down to 20 m (60 ft). 2D seismic refraction tomography indicates softer materials in the top 4 m (12 ft), but shows slight lateral variation in velocity structure, with higher velocities eastward from geophone 36. This could mark the mapped contact between the less consolidated unit Qmw to the west and the more consolidated unit Qvt to the east, or localized cementation. Although located too far to be directly correlated to the site, boreholes suggest the latter, showing hardpan from 15 to 21 m (50 to 70 ft). Regardless, verifying the extent of cementation across the campus is beyond the scope of the project and the observed heterogeneity isn't significant enough to lower the Vs30 into the D class, so we apply the site class C to the site with reasonable confidence.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper left corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.



2D refraction tomography model depicting the lateral variation in P-wave velocity (Vp) with depth in m/sec across the geophone array from the farthest off-end shot from both ends.

PINECREST ELEMENTARY SCHOOL

CENTRAL KITSAP SCHOOL DISTRICT, KITSAP COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

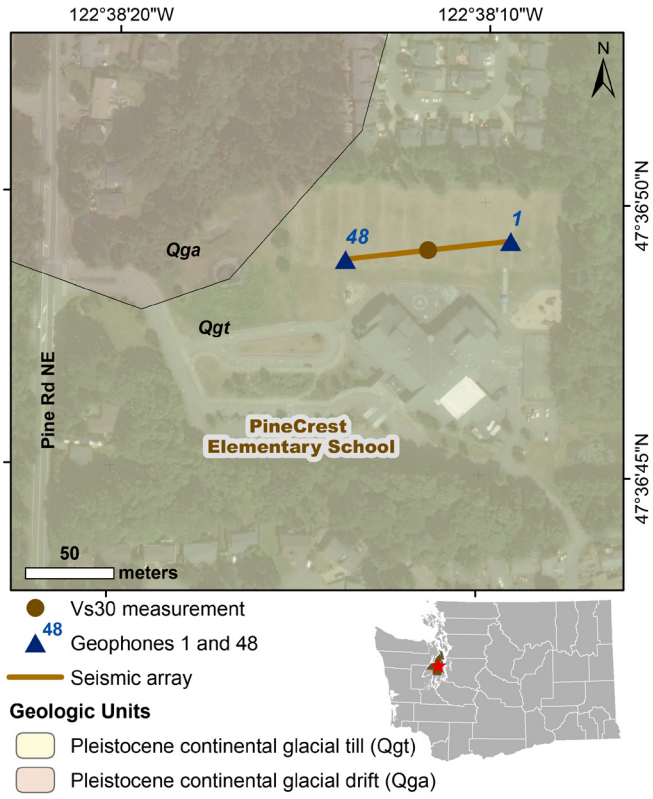
On April 15, 2021, a team from the Washington Geological Survey conducted a seismic survey at PineCrest Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial till (unit Qgt), comprising a compact and unsorted mixture of sand, silt, clay, and gravel. The northwestern edge of the campus is on Pleistocene continental glacial drift (unit Qga).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

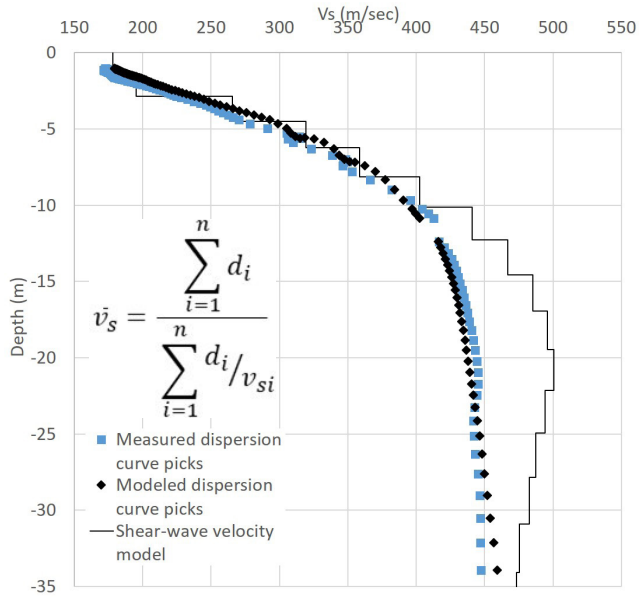
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality, but the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is also poor quality, and does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 9.4 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.1 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows generally increasing velocity to 20 m (60 ft), then a slight velocity reversal down to 30 m (100 ft). Our best Vs30 measurement is 384 m/sec, which places the site on the low side of the C site class. All initial and inverted models are in the C class, so the site can be confidently classified. This correlates with the predicted site class of C.

GEOLOGY

The 1:100,000-scale geologic map shows both the seismic array and the school buildings are on Pleistocene glacial till (unit Qgt) with a predicted site class of C. Mapped over the northwest corner of the campus is Pleistocene glacial drift (unit Qga) with a predicted site class of C–D. The 1D velocity model indicates less consolidated material in the upper 5 m (16 ft) underlain by more consolidated and denser materials, which is consistent with nearby boreholes that show silt, sand, and clay past 30 m (100 ft). Therefore we assign the campus a site class C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

PINEWOOD ELEMENTARY SCHOOL

MARYSVILLE SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

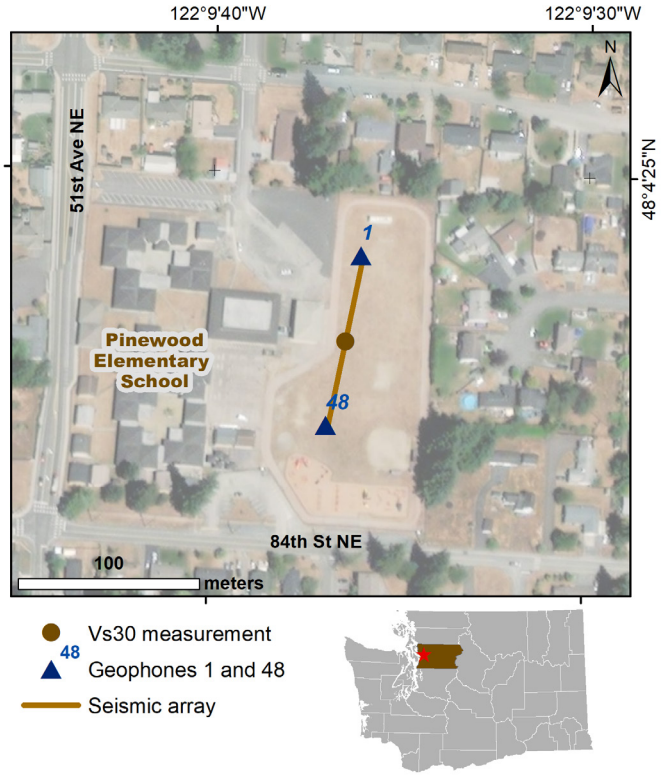
On July 13, 2020, a team from the Washington Geological Survey conducted a seismic survey at Pinewood Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on glacial meltwater deposits consisting of well-drained, stratified-to-massive outwash sand, a little fine gravel, and some beds of silt and clay.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

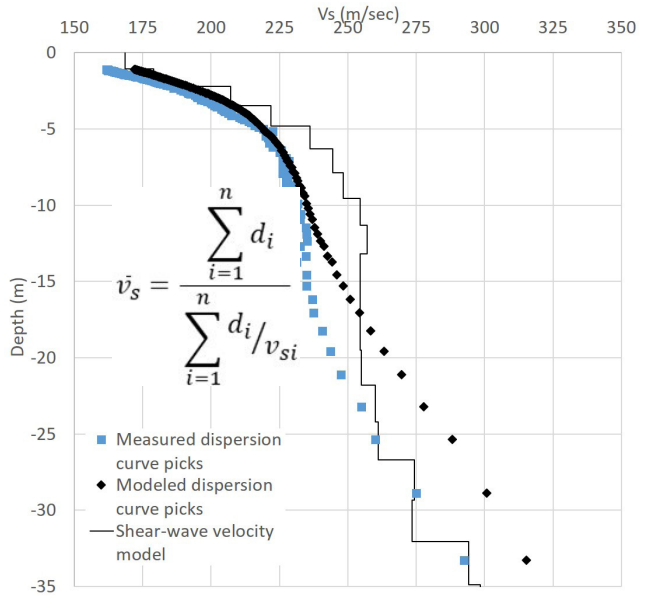
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so the fundamental mode can be picked with high confidence. However, the MASW does not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is decent quality, and the fundamental mode can be picked with confidence. The forward and reverse direction MASW and MAM are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curve. The initial model had an RMSE of 5.8 percent. The inversion was carried out for three iterations and resulted in a final model with an RMSE of 4.3 percent. The final model shows rapidly increasing velocity in the top 10 m (33 ft), then nearly constant velocity down to 22 m (72 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 243 m/sec, which places the site in the middle of the D site class. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

POINT DEFIANCE ELEMENTARY SCHOOL

TACOMA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

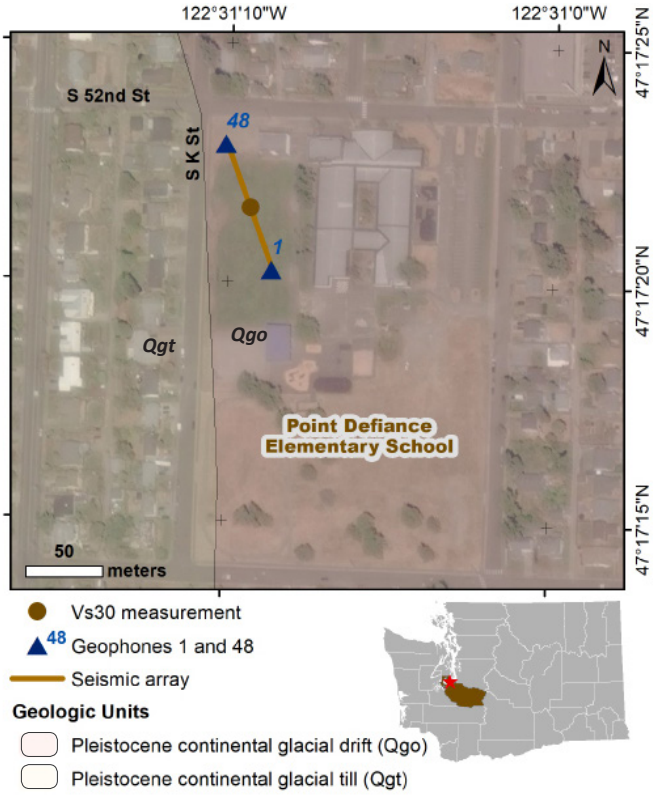
On August 17, 2020, a team from the Washington Geological Survey conducted a seismic survey at Point Defiance Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in an 86 m (282 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift, consisting mostly of stratified sand and gravel (unit Qgo). The western edge of the school is on continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel (unit Qgt).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

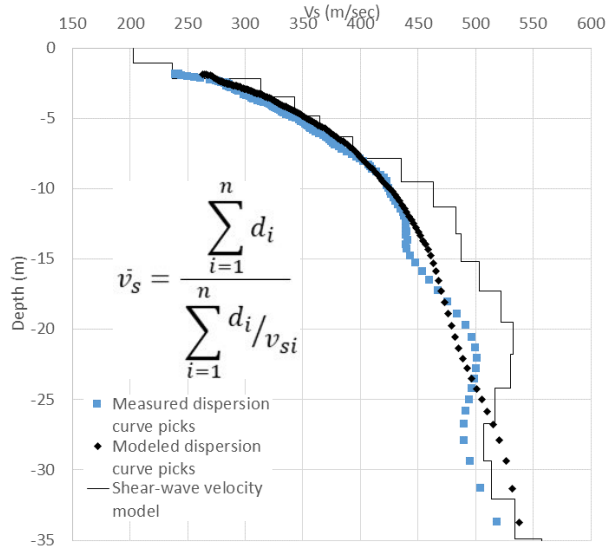
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 7.2 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.0 percent. The final model is unconstrained in the top 2 m (7 ft), and below this shows generally increasing velocity down to 20 m (66 ft), then a slight velocity reversal down to 30 m (100 ft). Our best Vs30 measurement is 428 m/sec, which places the site solidly in the C site class. This is the same as the predicted site class of C.

GEOLOGY

The 1:100,000-scale geologic map shows the school and the seismic array sitting on Pleistocene continental glacial drift (unit Qgo). The contact with Pleistocene continental glacial till (unit Qgt) roughly parallels the western edge of the field of the school, but does not pass through any school buildings. Both units are predicted to have a site class of C and we do not see evidence for heterogeneity along the array, so the site can confidently be classified as a site class C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the image. d_i = thickness of any layer between 0 and 30 m. V_{si} = Shear wave velocity in m/sec of the layer.

QUIL CEDA TULALIP ELEMENTARY SCHOOL

MARYSVILLE SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

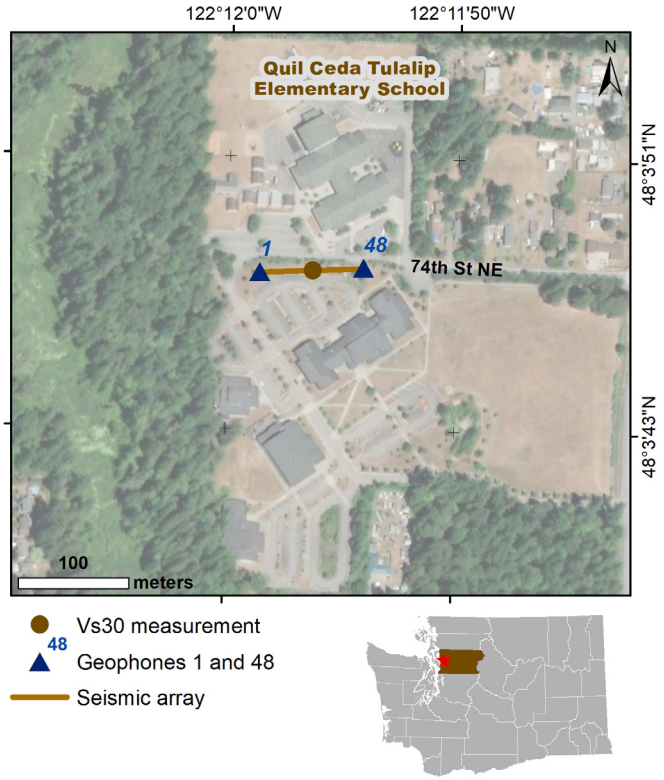
On October 11, 2019, a team from the Washington Geological Survey conducted a seismic survey at Quil Ceda Tulalip Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium composed predominantly of unconsolidated silt, sand, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

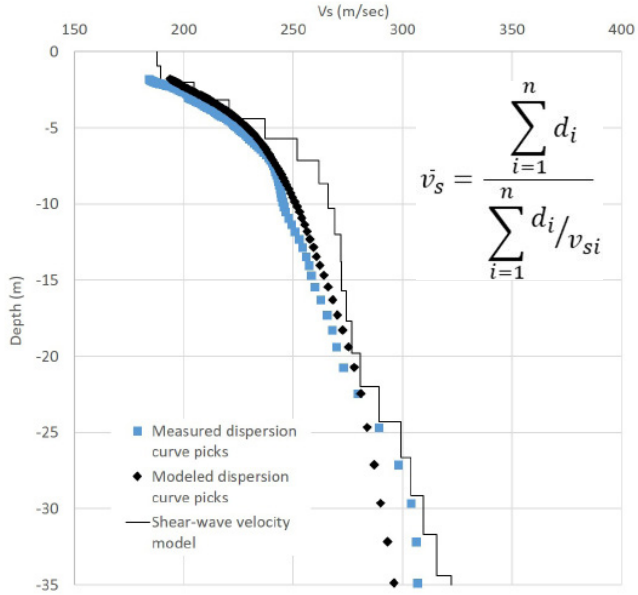
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves contain strong higher modes but are of decent quality so the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of excellent quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree over a broad frequency band, so the MASW (forward and reverse direction) and MAM dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 5.72 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.03 percent. The final velocity model shows rapidly increasing velocity in the upper 8 m, then mostly constant velocity to 20 m, and steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 263 m/sec, which places the site in the D class. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_S) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

REED ELEMENTARY SCHOOL

TACOMA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

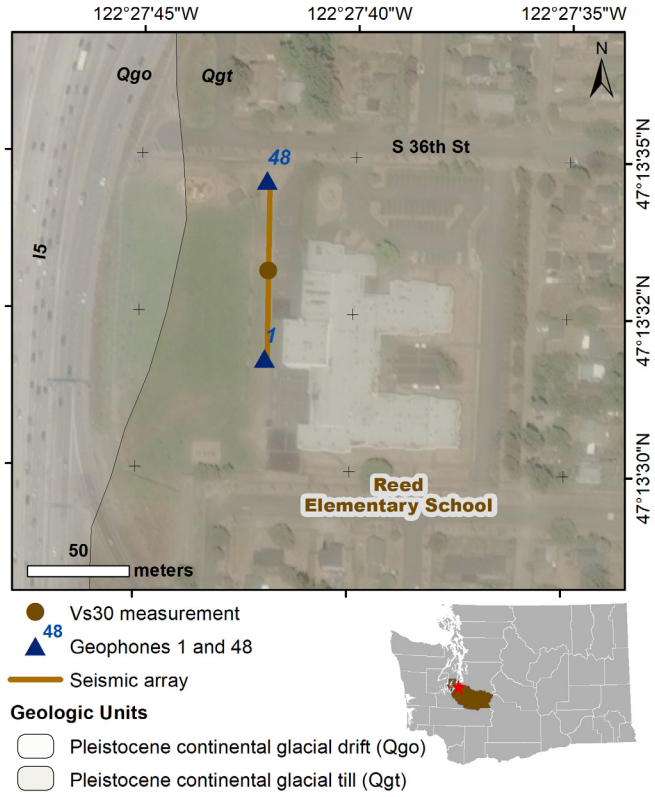
On August 12, 2020, a team from the Washington Geological Survey conducted a seismic survey at Reed Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in an 86 m (282 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

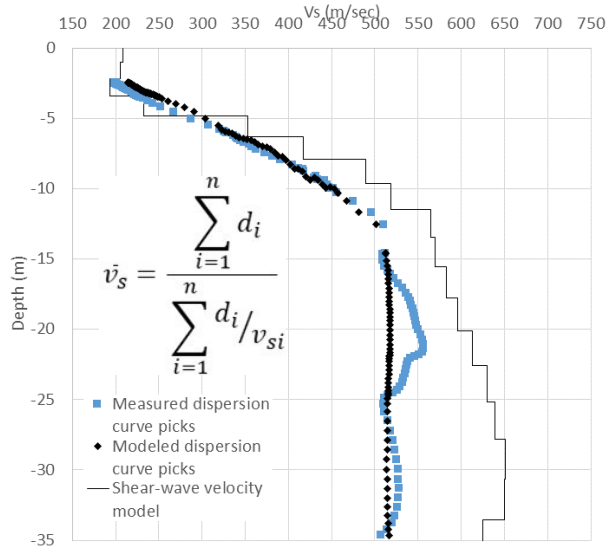
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is decent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 11.9 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 5.2 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows generally increasing velocity to 11 m (36 ft), then more slowly increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 439 m/sec, which places the site solidly in the C site class. This is the same as the predicted site class of C.

GEOLOGY

The 1:100,000-scale geologic map places the array and the school on Pleistocene continental glacial till (unit Qgt). Just west of the school there is a contact with unit Qgo, which consists of Pleistocene continental glacial drift. Both units have a predicted site class of C, which matches the measured site class, so this site can be confidently classified.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

RENTON HIGH SCHOOL

RENTON SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

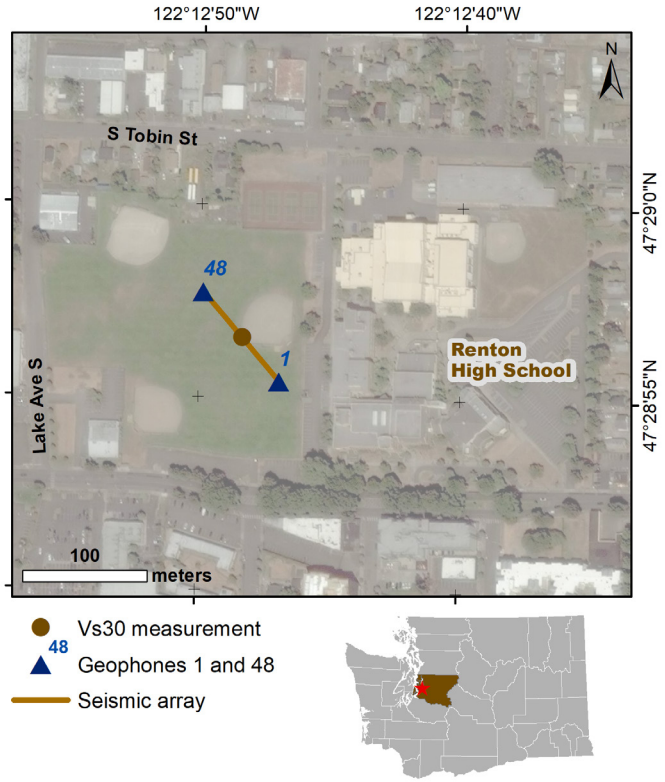
On October 15, 2020, a team from the Washington Geological Survey conducted a seismic survey at Renton High School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on urban or industrial land modified by widespread or discontinuous artificial fill.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

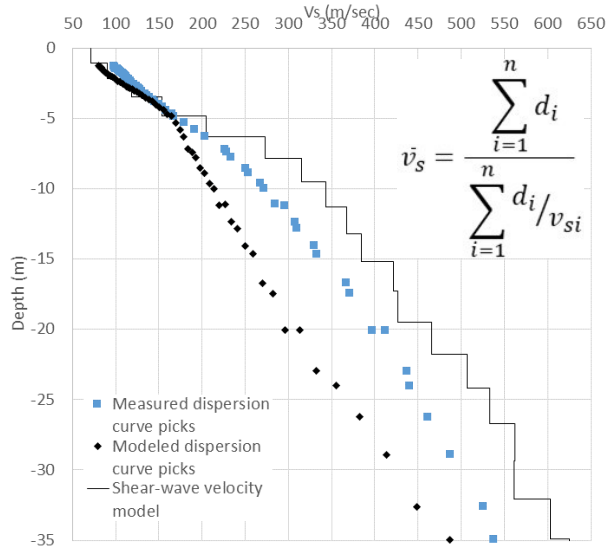
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality, but the fundamental mode can be picked with some confidence. However, the microtremor analysis method (MAM) dispersion image is excellent quality, so that the fundamental mode can be picked with high confidence. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 12.9 percent. The inversion was carried out for ten iterations and resulted in a final model with an RMSE of 4.7 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows rapidly increasing velocity to 6 m (20 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 272 m/sec, which places the site solidly in the D site class. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

ROBERT GRAY ELEMENTARY SCHOOL

LONGVIEW SCHOOL DISTRICT, COWLITZ COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

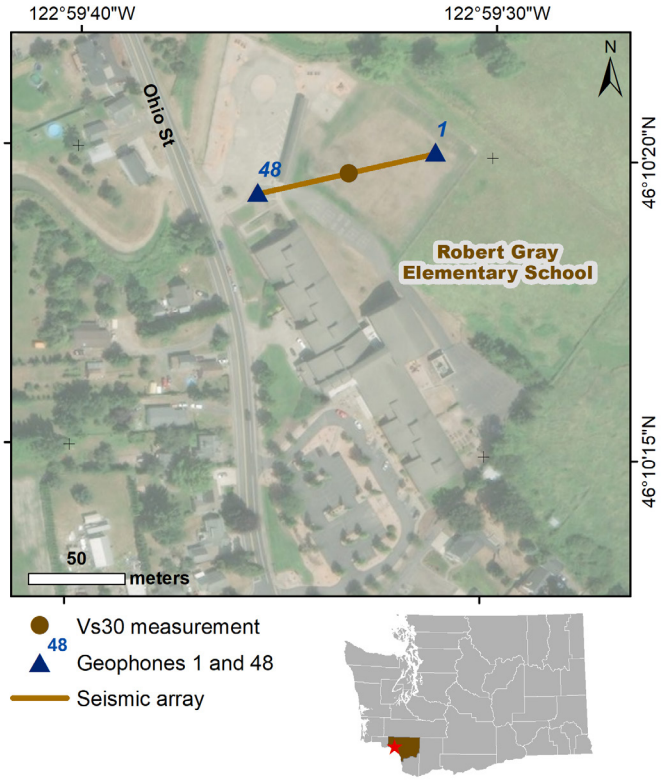
On August 27, 2019, a team from the Washington Geological Survey conducted a seismic survey at Robert Gray Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Violent

Tsunami
In a mapped tsunami hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

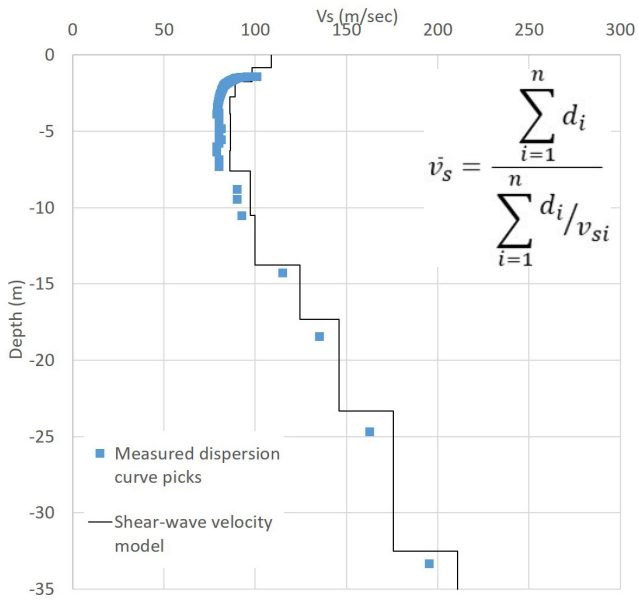
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward direction are decent quality so that the fundamental mode can be picked with confidence. The MASW dispersion curves are more coherent in the forward direction compared to the reverse. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of excellent coherency, and adequately samples from the shallow layers down to below 30 m (100 ft) and correlate well with the MASW.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the dispersion curve from the MAM. The inverted model converges with an RMSE below 5.0 percent, however it forces unrealistic velocity structure so the initial model is used instead. The final model shows a velocity reversal in the upper 5 m and then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 119 m/sec, which places the site solidly in the E site class. This is within the predicted site class of D–E.



Final velocity model based on the initial model with measured dispersion curve. The equation used to calculate the average shear wave velocity (V_S) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

ROBERTSON ELEMENTARY SCHOOL

YAKIMA SCHOOL DISTRICT, YAKIMA COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

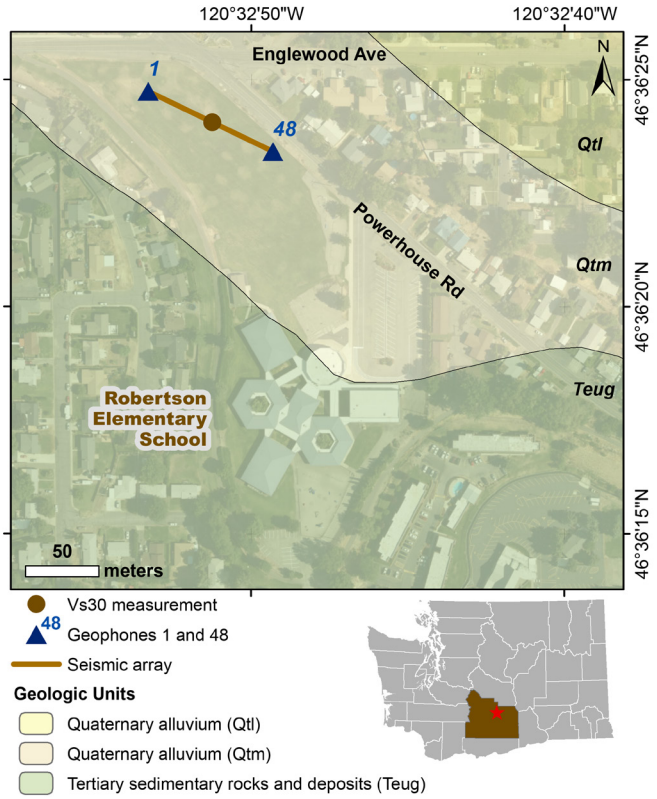
On October 7, 2020, a team from the Washington Geological Survey conducted a seismic survey at Robertson Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of B.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The southern part of the school is sitting on Tertiary volcanic and sedimentary gravels and coarse sands consisting mostly of pumice and andesite (unit Teug). The northern part of the school is sitting on Quaternary stream terrace deposits with mostly coarse gravel and sand (unit Qtm).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Unknown, not negligible

Ground Shaking
Very Strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

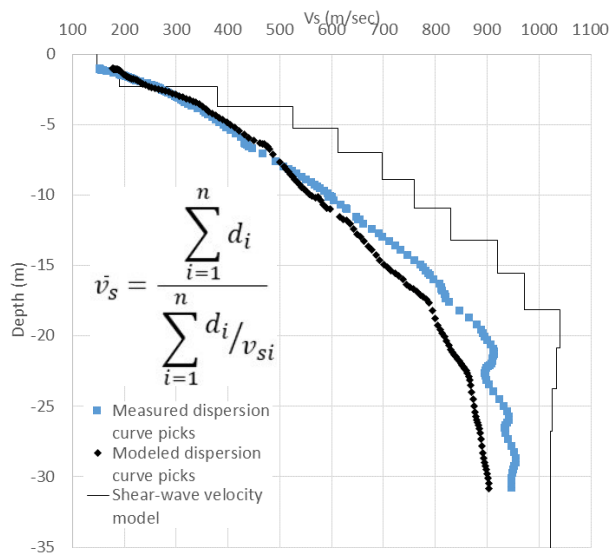
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality so that the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is also poor quality, and does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 13.9 percent. The inversion was carried out for nine iterations and resulted in a final model with an RMSE of 5.4 percent. The final model is unconstrained in the upper 1 m (3 ft), and below this shows generally increasing velocity to 18 m (59 ft), then nearly constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 627 m/sec, which places the site in the middle of the C site class. Although the MASW dispersion curves from the reverse and forward directions are poor quality, all initial and inverted models place this site solidly in the C class, so the site can be confidently classified. This is different from the predicted site class of B.

GEOLOGY

The 1:24,000-scale geologic map places the school buildings on a contact between two geologic units. To the south are Tertiary volcanic and sedimentary rocks (unit Teug), and to the north are Quaternary stream deposits (unit Qtm). The seismic array is on unit Qtm, while most of the school buildings are on unit Teug. The 1:100,000-scale geologic map, which is used to predict site class, has slightly different unit contacts, and places the school buildings completely on Tertiary sedimentary rocks and deposits with a predicted site class B and the array on Quaternary alluvium with predicted site class C. Nearby boreholes on both units show gravel, sand, clay, and occasional boulders down to ~20 m (70 ft), then sandstone. The reverse direction MASW, nearer the school buildings, creates a velocity model nearly identical to the forward MASW, so there is no indication of a velocity increase over the distance the array covers. The array is only 135 m (450 ft) from the school buildings, and while it is possible for ground velocity to increase enough over this distance to change site class, there is no indication this is likely. We assume the school is on materials similar to the array, and therefore assign it a site class C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

ROCKY RIDGE ELEMENTARY SCHOOL

BETHEL SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

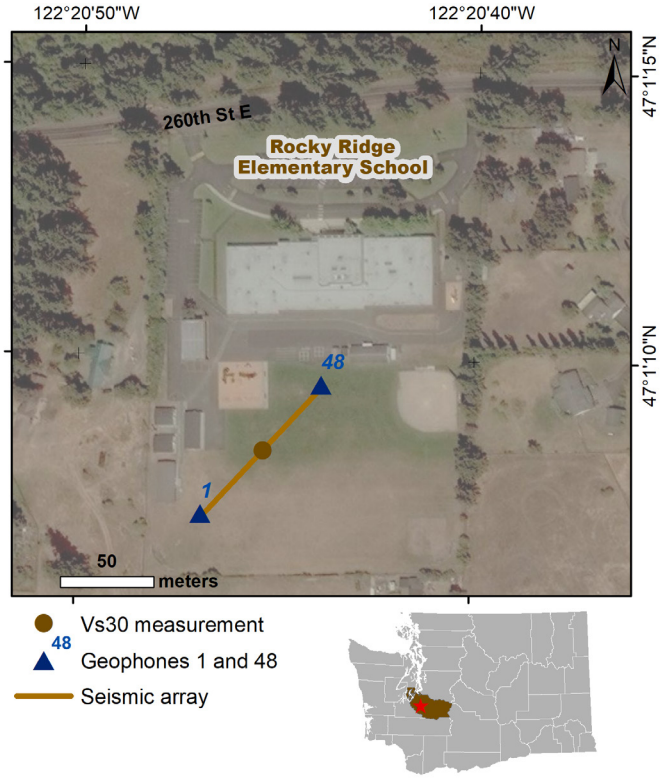
On March 11, 2020, a team from the Washington Geological Survey conducted a seismic survey at Rocky Ridge Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial outwash.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low to low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

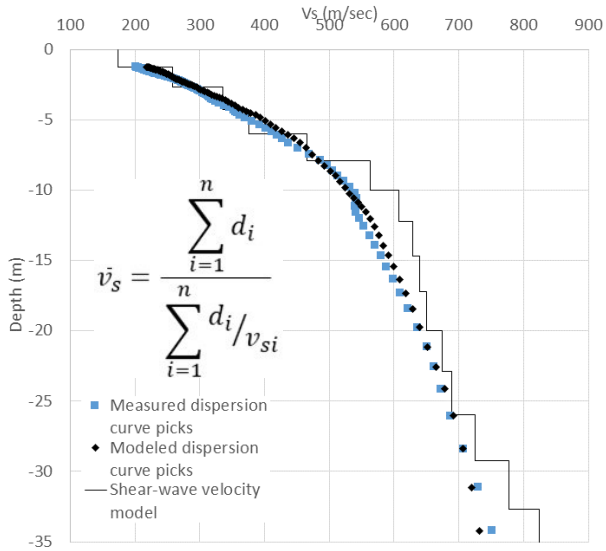
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is of poor quality but is not needed because the forward and reverse direction MASW adequately samples below 30 m (100 ft). The two MASW dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 9.6 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 4.3 percent. The final model shows generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 503 m/sec, which places the site near the middle of the C site class. All initial and inverted models are in the C class, so the site can be confidently classified. This is within the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

ROOSEVELT ELEMENTARY SCHOOL

BELLINGHAM SCHOOL DISTRICT, WHATCOM COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

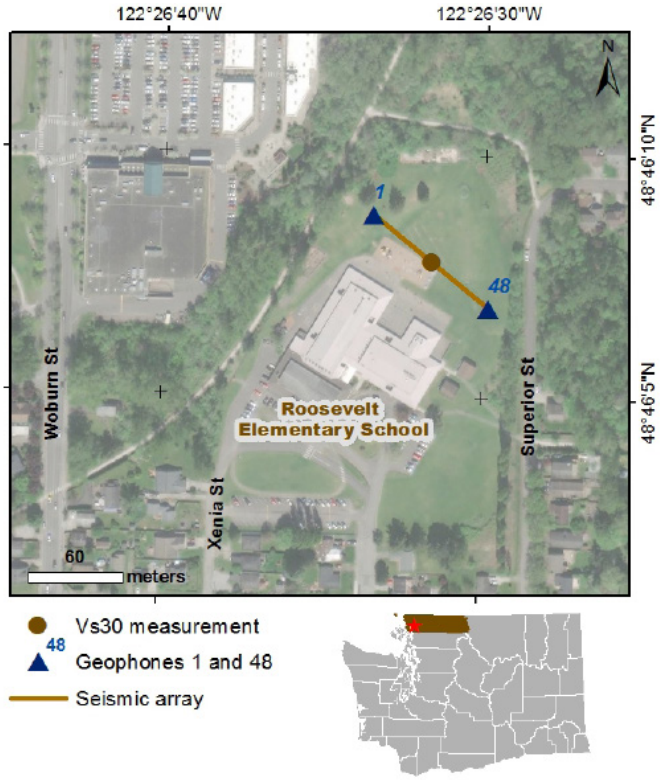
On October 22, 2020, a team from the Washington Geological Survey conducted a seismic survey at Roosevelt Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift, consisting mostly of gravelly silt with dropstones and layers of gravel, sand, silt, and clay.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

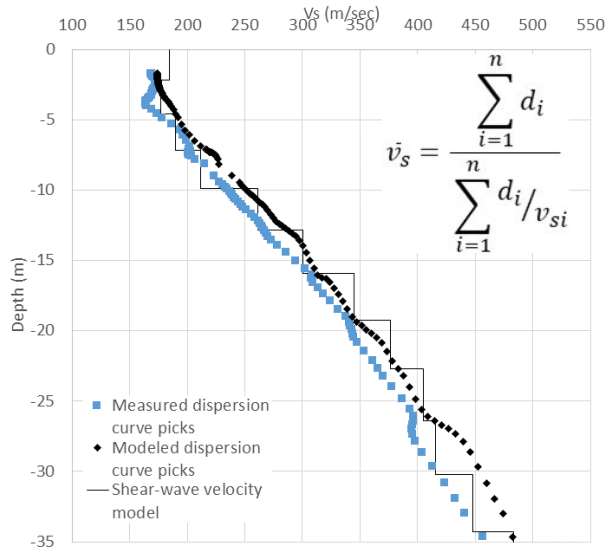
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image from the forward direction is excellent quality so that the fundamental mode can be picked with high confidence. However, the MASW reverse direction dispersion image is unusable and the forward direction does not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of decent quality, but does not sample the shallow layers. Overall, the forward direction MASW and MAM dispersion curves correlate well, so they are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 10.8 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.7 percent. The final model is unconstrained in the top 1.5 m (5 ft), and below this shows generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 274 m/sec, which places the site solidly in the D site class. All initial and inverted models are in the D class, so the site can be confidently classified. This is the same as the predicted site class of D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

ROOSEVELT ELEMENTARY SCHOOL

TACOMA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

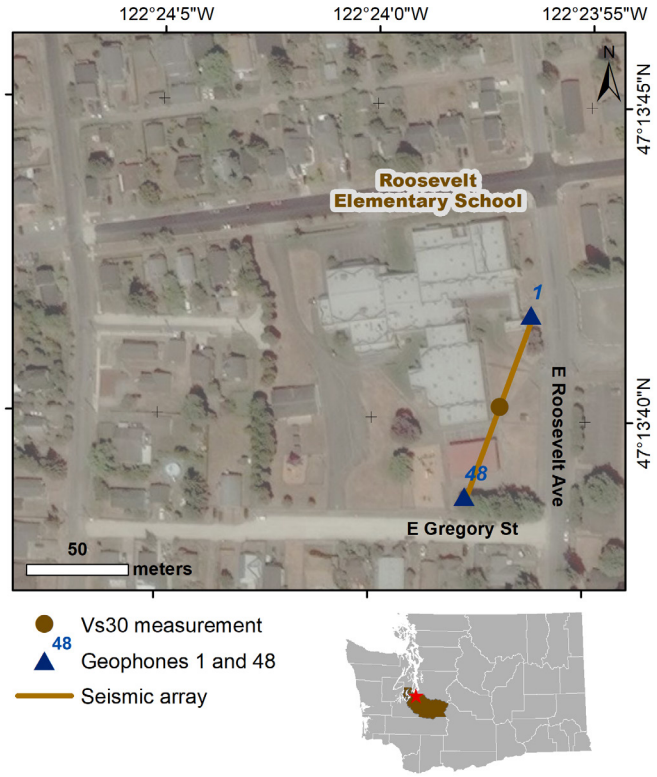
On August 3, 2020, a team from the Washington Geological Survey conducted a seismic survey at Roosevelt Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

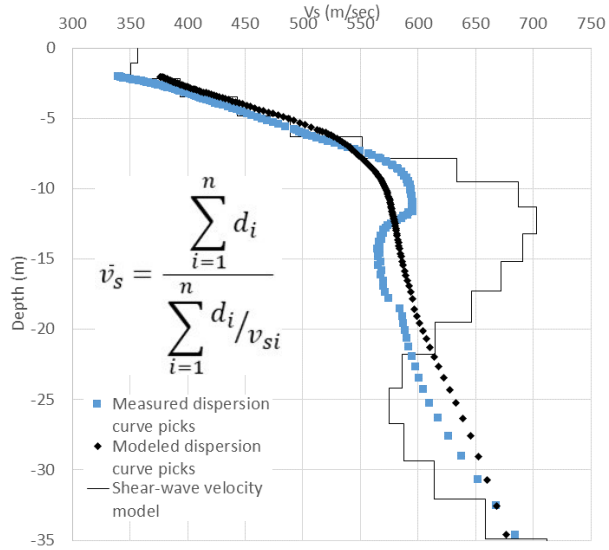
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the upper 6 m (20 ft). MAM and the forward and reverse MASW dispersion curves depict similar trends, therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 8.1 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.6 percent. The final model is unconstrained in the top 2 m (7 ft), and below this shows generally increasing velocity to 12 m (39 ft), then a significant velocity reversal down to 25 m (82 ft), and then steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 562 m/sec, which places the site in the middle of the C site class. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = Shear wave velocity in m/sec of the layer.

ROSE VALLEY ELEMENTARY SCHOOL

KELSO SCHOOL DISTRICT, COWLITZ COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

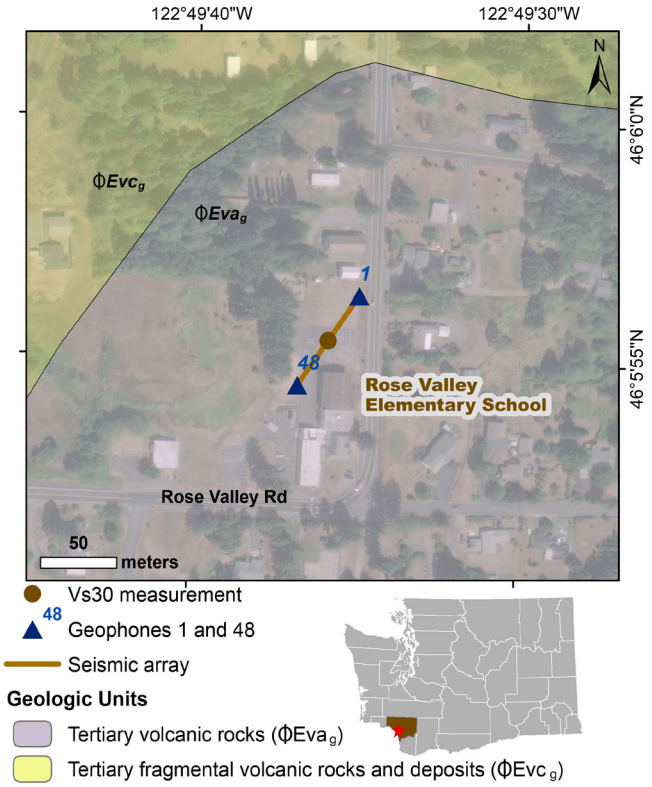
On March 11, 2021, a team from the Washington Geological Survey conducted a seismic survey at Rose Valley Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (231 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of B.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Oligocene–Eocene andesite basalt flows and flow breccia (unit ΦEva$_g$). Northwest of the school is mapped Oligocene–Eocene fragmental volcanic rocks and deposits (includes lahars), such as tuff, volcanic sandstone, and matrix-supported conglomerate interbedded with thin basalt flows (unit ΦEvc$_g$).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Unknown, not negligible

Ground Shaking
Severe

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

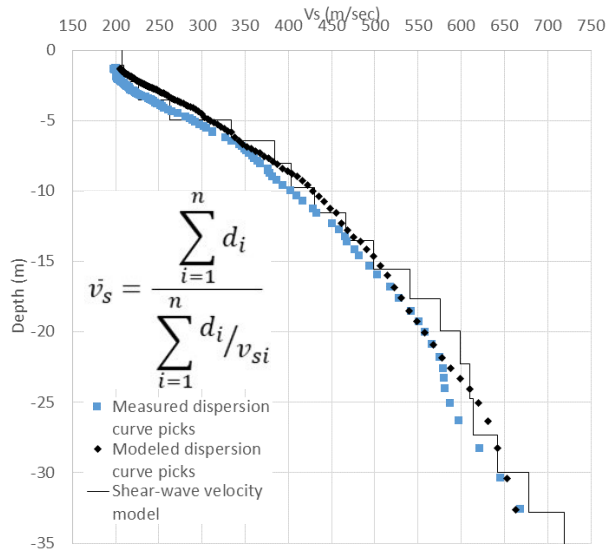
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward direction are decent quality so that the fundamental mode can be picked with confidence. However, the dispersion images from the reverse direction are unuseable. The microtremor analysis method (MAM) dispersion image is excellent quality, and the resulting dispersion curve depicts trends similar to the forward MASW dispersion curves. Therefore two forward MASW and the MAM dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 12.4 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 5.5 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 423 m/sec, which places the site solidly in the C site class. All initial and inverted models place this site in the C class, so the site can be confidently classified. This is different from the predicted site class of B.

GEOLOGY

The 1:100,000-scale geologic map places the school buildings and seismic array on basalt flows (unit ΦEva_g). Mapped ~100 m (300 ft) to the north and west is fragmented volcanic rocks and volcanic deposits (unit ΦEvc_g). Both units have a predicted site class of B. Nearby boreholes on the same unit as the school indicate clay to about 9 m (30 ft), then shale, rock, or alternating layers of the two past 30 m (100 ft). This matches the description of the unit, which mentions layers of shale and volcanic sandstone are common. While there is a strip of lower predicted site classes around the river to the west of the school, Rose Valley Elementary is in the middle of a large area (diameter of 20 km or 12 miles) with a predicted site class of B. The description of the unit is more in line with a site class C, however, so it is unlikely there is a change in geology and we suspect that higher resolution mapping would place this site on a C site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

SACAJAWEA MIDDLE SCHOOL

FEDERAL WAY SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

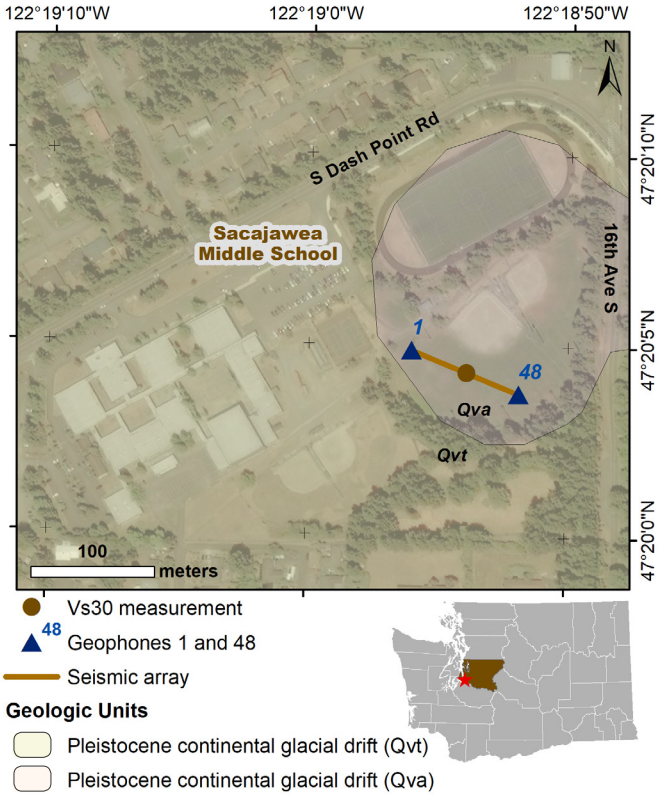
On October 2, 2020, a team from the Washington Geological Survey conducted a seismic survey at Sacajawea Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school buildings sit on Pleistocene continental glacial till, mostly a compact silt or sand-rich matrix containing sub- to well-rounded clasts (unit Qvt). The eastern part of the school campus sits on Pleistocene continental glacial drift consisting mostly of sand, and a little gravel (unit Qva).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

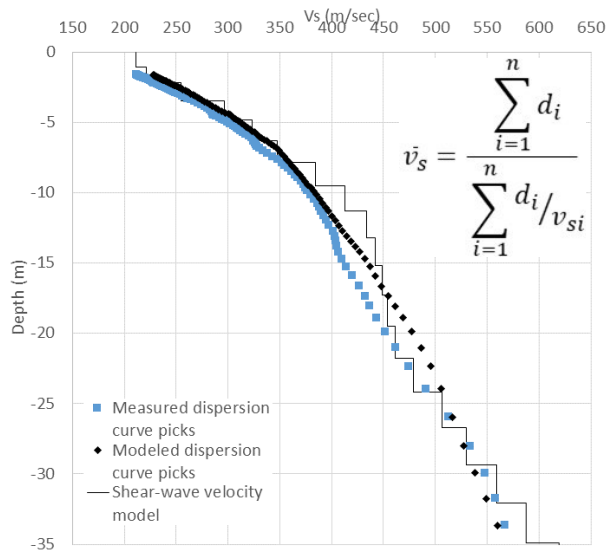
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward direction are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion images from the reverse direction are poor quality, and neither the forward nor reverse direction MASW dispersion curves sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is decent quality, but does not sample the top 4.5 m (15 ft). MAM and the forward MASW dispersion curve depict similar trends, therefore the two dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 9.4 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.9 percent. The final model is unconstrained in the top 2 m (7 ft), and below this shows generally increasing velocity to 13 m (43 ft), then a nearly constant velocity to 22 m (72 ft), and then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 392 m/sec, which places the site solidly in the C site class. This correlates with the predicted site class of C.

GEOLOGY

The 1:24,000-scale geologic map places the school on glacial till (unit Qvt) and the seismic array on glacial drift (unit Qva). The predicted site class map has slightly different boundaries, placing the school buildings on a predicted site class C and the seismic array spanning this and a predicted site class C–D. Nearby boreholes indicate the soil surrounding the school is generally unconsolidated sediments of thicknesses ranging from 1.5 m (5 ft) to 18 m (60 ft) overlaying till. The borehole on the school campus near the array shows unconsolidated sediments to 18 m, consistent with the 1D velocity model. We see no evidence for significant heterogeneity, so this site can be confidently classified as a site class C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

SEAHURST ELEMENTARY SCHOOL

HIGHLINE SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

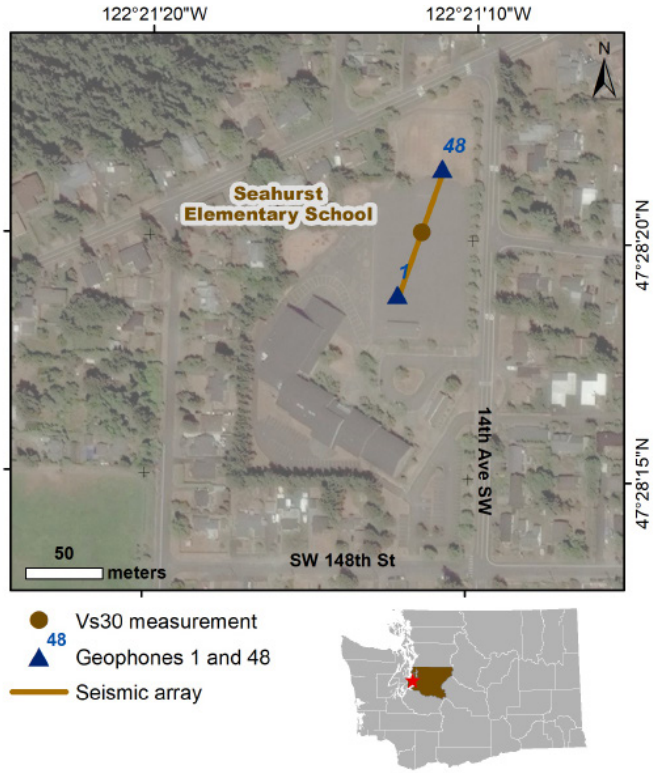
On August 18, 2020, a team from the Washington Geological Survey conducted a seismic survey at Seahurst Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial till, mostly a compact silt or sand-rich matrix containing sub- to well-rounded clasts.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

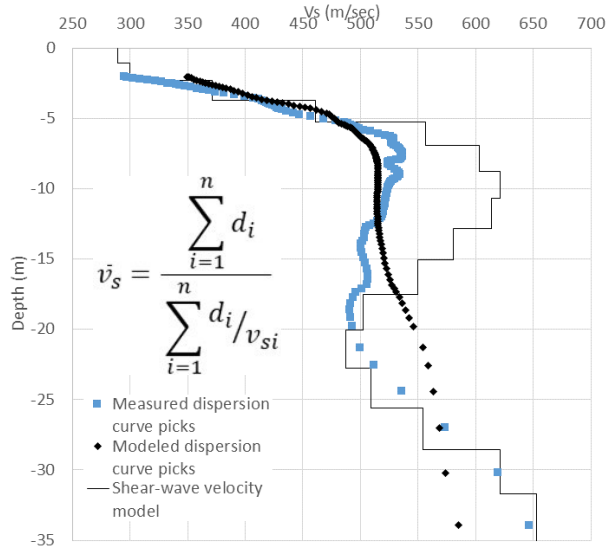
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence, despite noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the top 5 m (16 ft). MAM and the forward MASW dispersion curves correlate well, depicting similar trends, so the two dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 7.6 percent. The inversion was carried out for four iterations and resulted in a final model with an RMSE of 5.0 percent. The final model is unconstrained in the top 2 m (7 ft), and below this shows rapidly increasing velocity to 10 m (33 ft), then a significant velocity reversal down to 20 m (66 ft), and then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 504 m/sec, which places the site in the middle of the C site class. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

SHELTON VIEW ELEMENTARY SCHOOL

NORTHSHORE SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

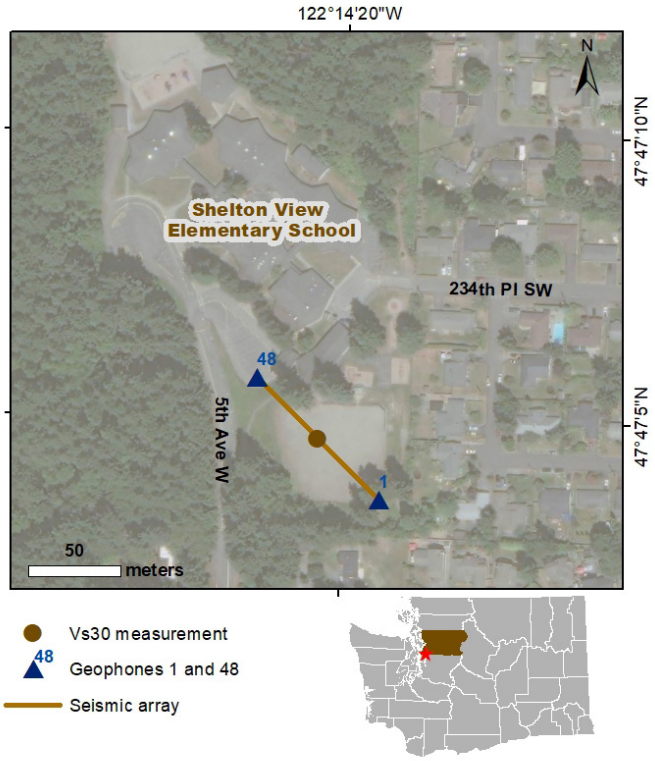
On March 17, 2021, a team from the Washington Geological Survey conducted a seismic survey at Shelton View Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

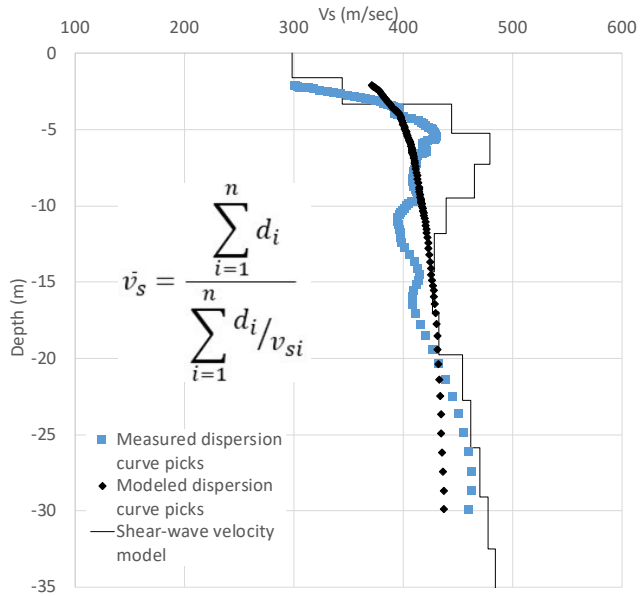
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward direction are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is excellent quality. MAM and the forward MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 4.5 percent. The inversion was carried out for two iterations and resulted in a final model with an RMSE of 3.9 percent. The final model shows generally increasing velocity to 5 m (15 ft), then generally constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 432 m/sec, which places the site in the C site class. All initial and final models are of the C class, so the site can be confidently classified. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the image. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

SHERIDAN ELEMENTARY SCHOOL

TACOMA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

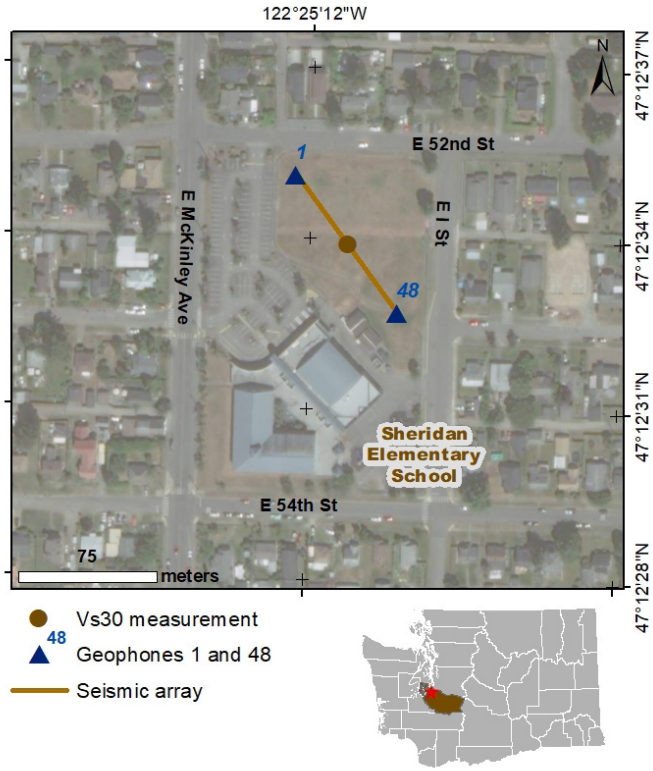
On August 4, 2020, a team from the Washington Geological Survey conducted a seismic survey at Sheridan Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

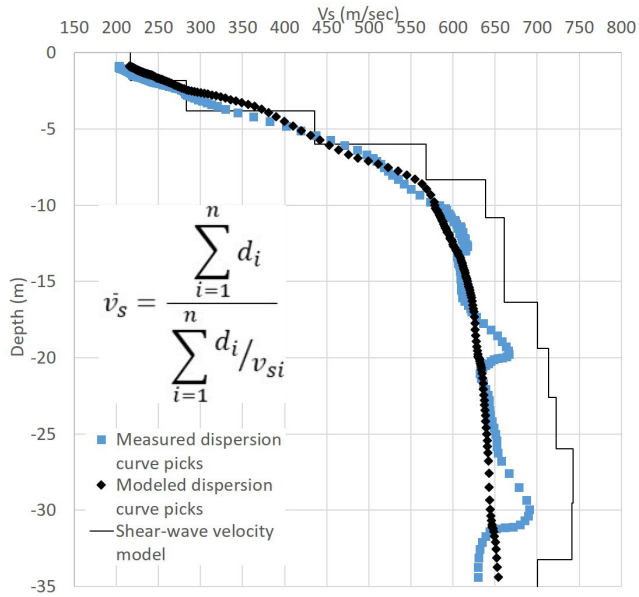
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion image from the forward direction is decent quality so that the fundamental mode can be picked with confidence, while the reverse MASW dispersion image is poor quality with noticeable interference from higher modes. Neither the forward or reverse direction MASW sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is decent quality, but does not sample the top 10 m (33 ft). MAM and the forward MASW dispersion curves correlate well, depicting similar trends where they overlap. Therefore the two dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 8.4 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.0 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows rapidly increasing velocity to 8 m (20 ft), then slowly increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 541 m/sec, which places the site in the middle of the C site class. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

SHOULTES ELEMENTARY SCHOOL

MARYSVILLE SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

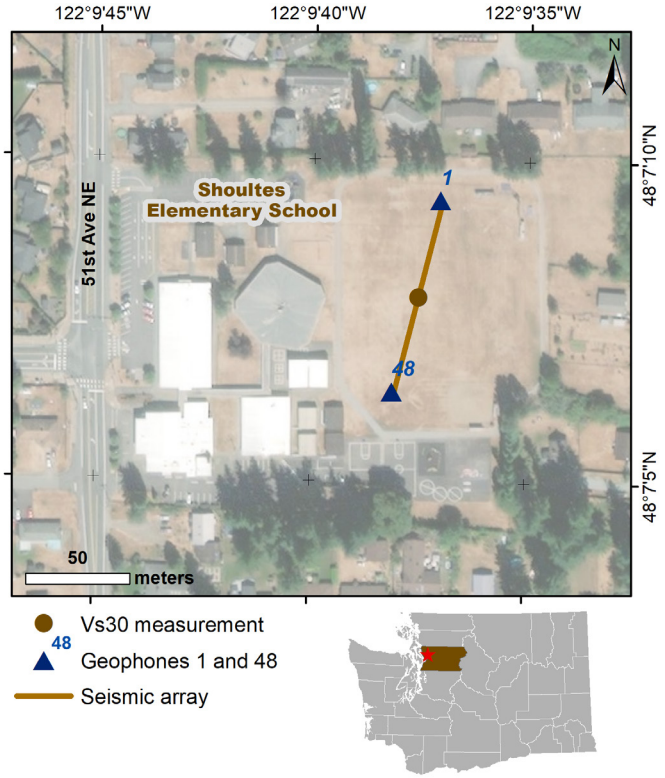
On July 10, 2020, a team from the Washington Geological Survey conducted a seismic survey at Shoultes Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on glacial meltwater deposits consisting of well-drained, stratified-to-massive outwash sand, fine gravel, and some beds of silt and clay.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

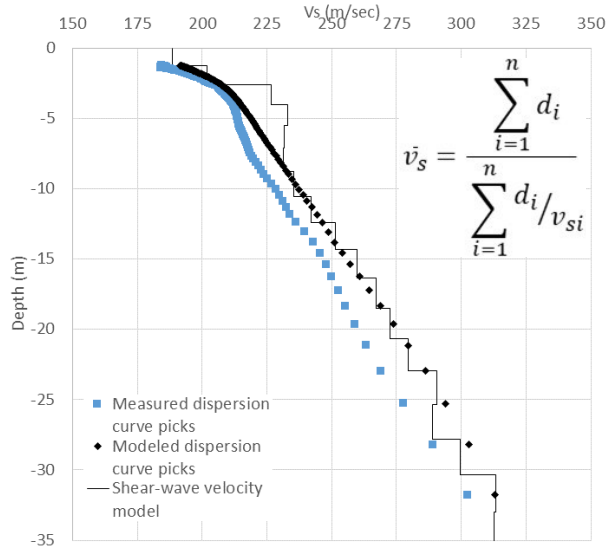
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is poor quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves depict similar trends, therefore the three curves are combined into a single final model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 5.3 percent. The inversion was carried out for four iterations and resulted in a final model with an RMSE of 3.3 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows increasing velocity to 4 m (20 ft), then nearly constant velocity to 9 m (30 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 253 m/sec, which places the site in the middle of the D site class. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

SKAMANIA ELEMENTARY SCHOOL

SKAMANIA SCHOOL DISTRICT, SKAMANIA COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

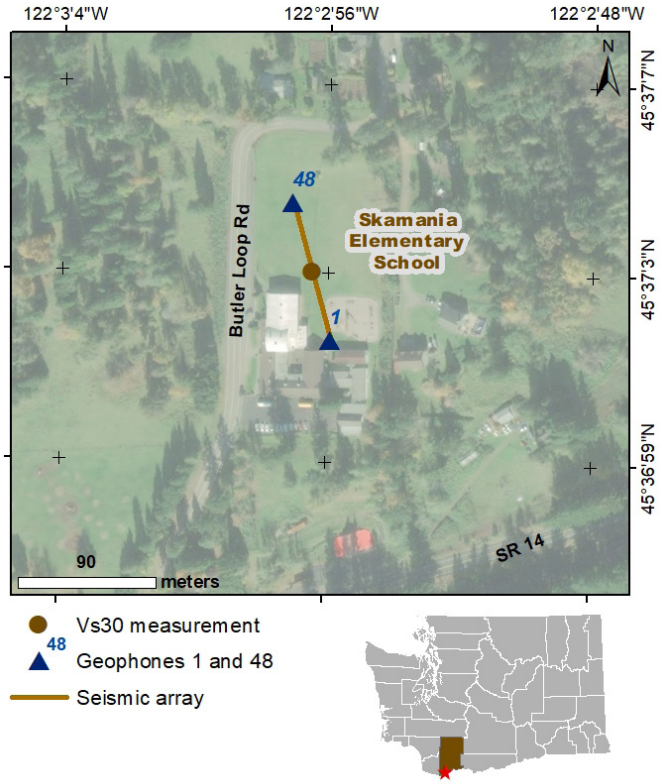
On March 9, 2020, a team from the Washington Geological Survey conducted a seismic survey at Skamania Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	
D	Stiff soil	180–360	
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on mass-wasting deposits from landslides.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Severe

Landslide
Hazard present, based on terrain data

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

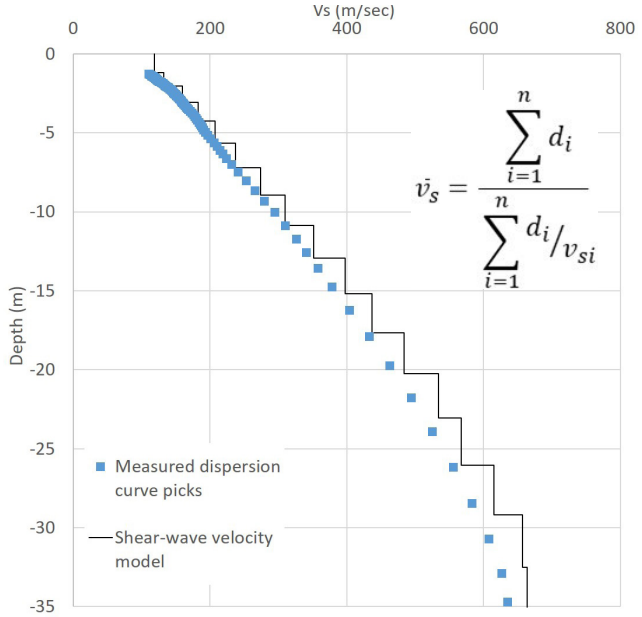
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality and the fundamental mode can be picked, but neither sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also decent quality, and the resulting dispersion curve correlates well with the MASW dispersion curves. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inital model had an RMSE of 14.7 percent. The inversion was carried out for nine iterations and resulted in a final model with an RMSE of 7.0 percent. The final model is unconstrained in the top 1 m (3 ft), then shows gradually increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 319 m/sec, which places the site solidly in the D class. Although the combined models fail to converge below 5 percent, all initial and inverted models are in the D site class, so the site can be confidently classified. This is the same as the predicted site class of D.



Final velocity model based on the initial model with the measured dispersion curve. The equation used to calculate the average shear wave velocity (V_S) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

SOUTH BEND JUNIOR AND SENIOR HIGH SCHOOL

SOUTH BEND SCHOOL DISTRICT, PACIFIC COUNTY, WA

WASHINGTON 2017–2019 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

To assess school seismic safety we must identify soil site class. Site class is a measure of ground shaking potential, and is based on how fast shear waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been estimated for the entire State of Washington, but these predictions aren't always accurate in places where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore very accurate.

HOW DID WE MEASURE SITE CLASS?

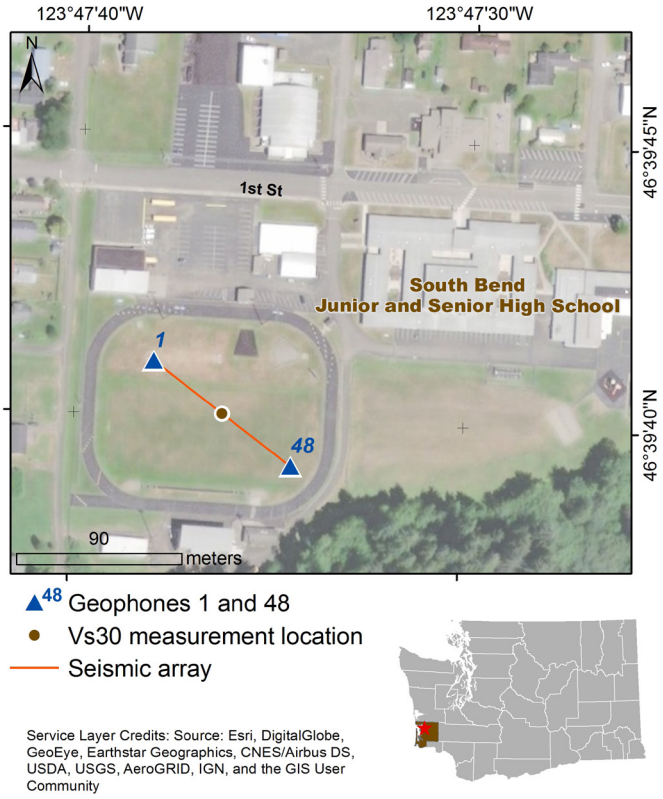
On June 19, 2018, a team from the Washington Geological Survey conducted a seismic survey at South Bend Junior and Senior High School. We measured shear wave velocity of the upper 30 m (100 ft) by laying out 48 geophones (ground motion sensors) in a 308-ft line. Then we conducted (1) an active survey in which a sledge hammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school, but this may not be appropriate in some areas.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is similar to what was predicted.

Site class	Description	Vs30 (m/sec)	Ground shaking potential
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on silt, sand, and gravel deposited in streambeds.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high hazard

Ground Shaking
Violent

Tsunami
In a mapped tsunami hazard zone

Landslide
Hazard present

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

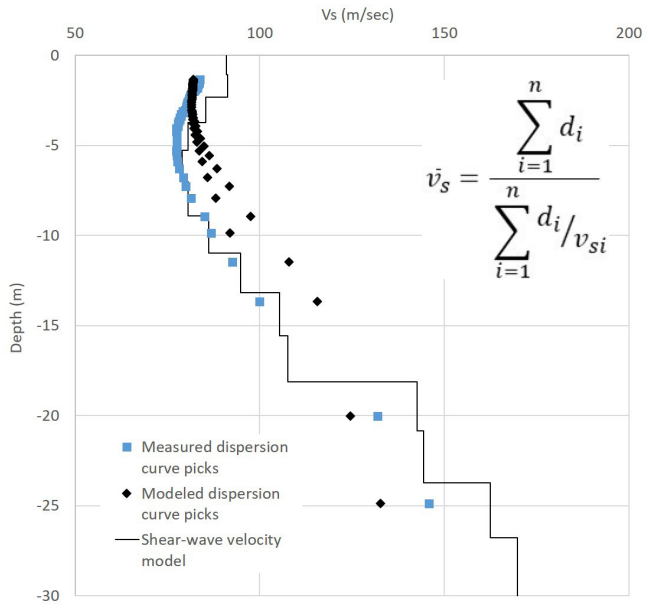
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves are of good quality and the fundamental mode can be picked. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of good quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band so the MASW (forward a direction) and MAM dispersion curves are averaged together.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The model has an RMSE of 6.3 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 3.7 percent. The velocity models shows a slight velocity inversion above 5 m (16 ft) and increasing velocities below that down to 30 m (100 ft). The best estimate for Vs30 is 109 m/s, which places the site in the site class E. The predicted site class is D or E, which correlates with the measured E site class.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. di = thickness of any layer between 0 and 30 m. Vsi = Shear wave velocity in (m/s) of the layer.

SOUTH RIDGE ELEMENTARY SCHOOL

RIDGEFIELD SCHOOL DISTRICT, CLARK COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

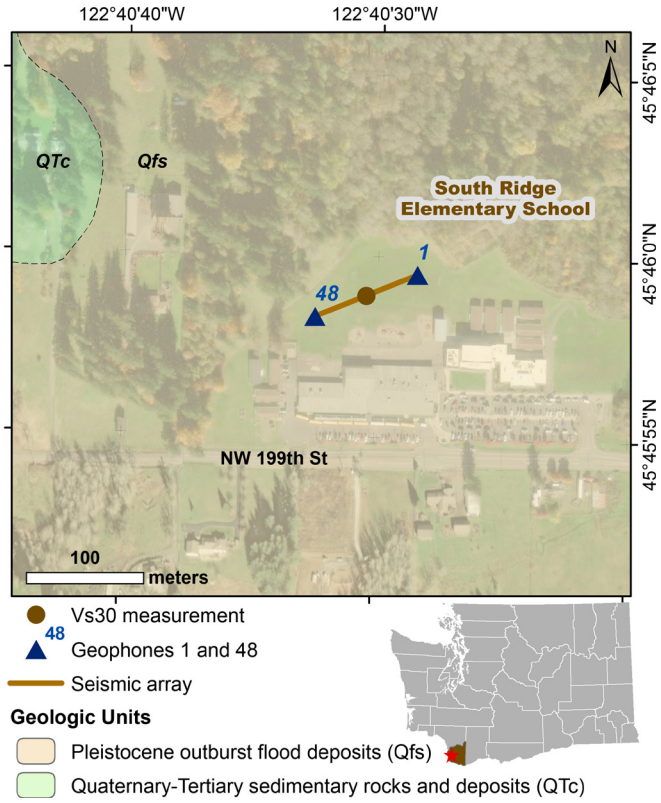
On April 29, 2021, a team from the Washington Geological Survey conducted a seismic survey at South Ridge Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene outburst flood deposits (unit Qfs) consisting of clay, silt, and fine- to medium-grained sand. Mapped northwest of campus are Quaternary–Tertiary sedimentary rocks and deposits (unit QTc).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Severe

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

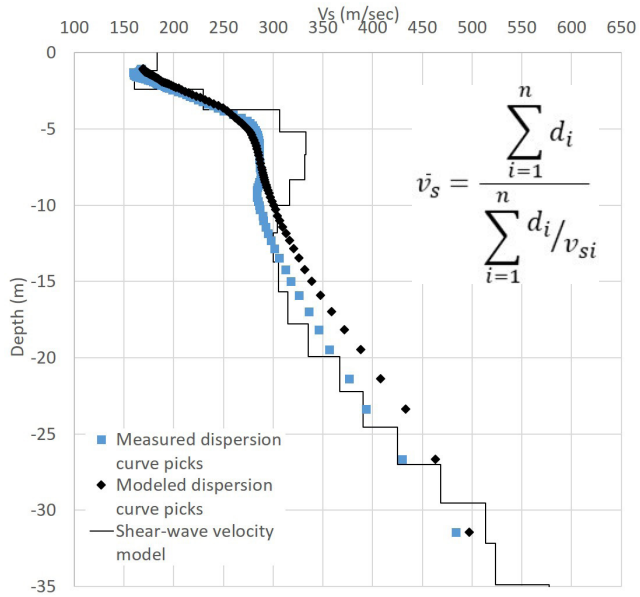
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality, but the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is decent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 11.5 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 5.2 percent. The final model shows rapidly increasing velocity to 6 m (20 ft), then a significant velocity reversal down to 18 m (59 ft), and then generally increasing velocity past 30 m (100 ft). Our best Vs30 measurement is 316 m/sec, which places the site solidly in the D site class. All initial and inverted models are in the D class, so the site can be confidently classified. This is different from the predicted site class of C.

GEOLOGY

The 1:24,000-scale geologic map shows that both the seismic array and the school buildings are located on Pleistocene outburst flood deposits (unit Qfs), which is the same as the 1:100,000-scale geologic map with a predicted site class of C. Mapped just off campus to the northwest, both the 1:100,000-scale and 1:24,000-scale geologic maps show similar mapped units of Tertiary sedimentary rocks and deposits (unit PMc$_t$) and Quaternary–Tertiary sedimentary rocks and deposits (unit QTc), respectively. Unit PMc$_t$ has a predicted site class of C–D. Nearby boreholes show clay, sand, conglomerates, and gravel with intermittent cementation past 30 m (100 ft). The 1D velocity model indicates weak consolidated materials in the upper 4 m (13 ft) sitting on top of a 5-m-thick (16 ft) layer of more consolidated material, which is underlain by weaker materials that become denser with depth. This more consolidated 5-m-thick (16 ft) layer could be a result of cementation, or just represent a localized pocket of more consolidated or denser material. Nearby boreholes show layers of both cementation and conglomerates, so either explanation could be valid. Thus, the change in site class could be due to a lateral change within the unit or low-resolution mapping. Regardless, there is no strong evidence for heterogeneity between the array and the buildings, so we can reasonably assign a site class D to the campus.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

SOUTH WHIDBEY ELEMENTARY - SOUTH CAMPUS 5–6

SOUTH WHIDBEY SCHOOL DISTRICT, ISLAND COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

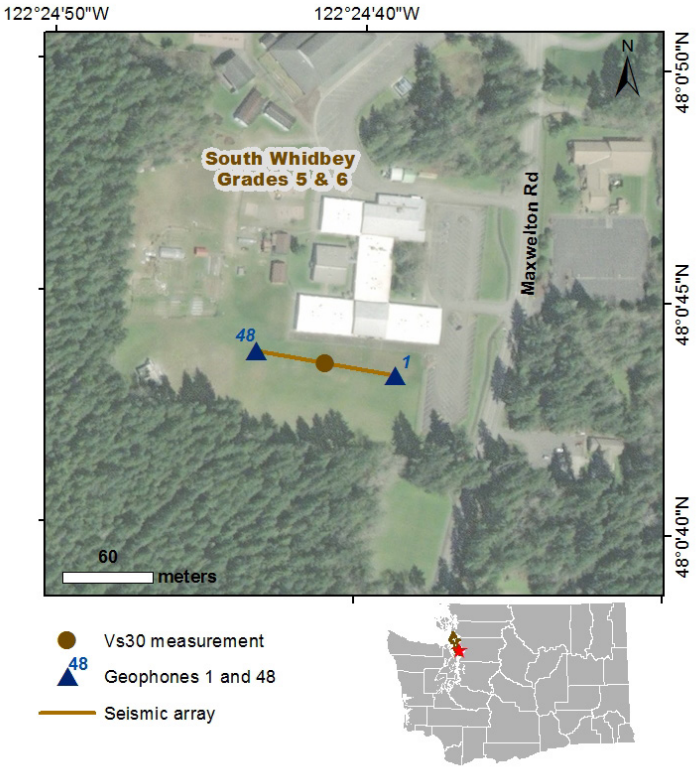
On April 6, 2021, a team from the Washington Geological Survey conducted a seismic survey at South Whidbey Elementary - South Campus 5–6. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

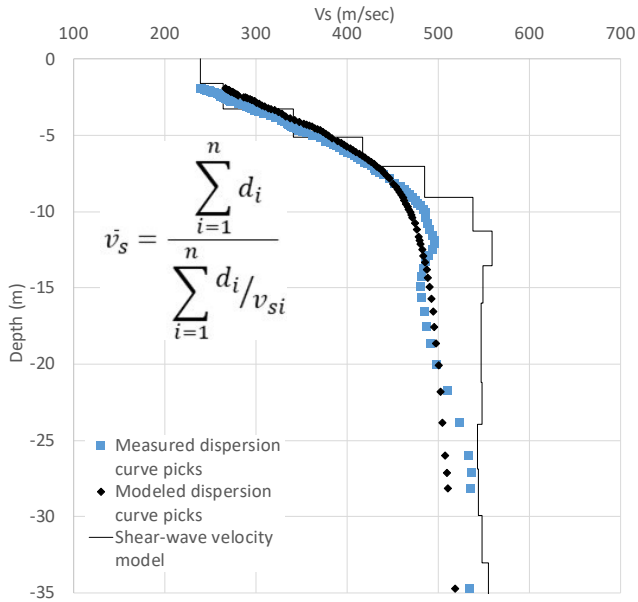
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is also decent quality. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 9.2 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.0 percent. The final model shows generally increasing velocity down to 15 m (50 ft), then generally constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 460 m/sec, which places the site solidly in the C site class. All initial and final models are of the C class, so the site can be confidently classified. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = Shear wave velocity in m/sec of the layer.

SOUTHERN HEIGHTS ELEMENTARY SCHOOL

HIGHLINE SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

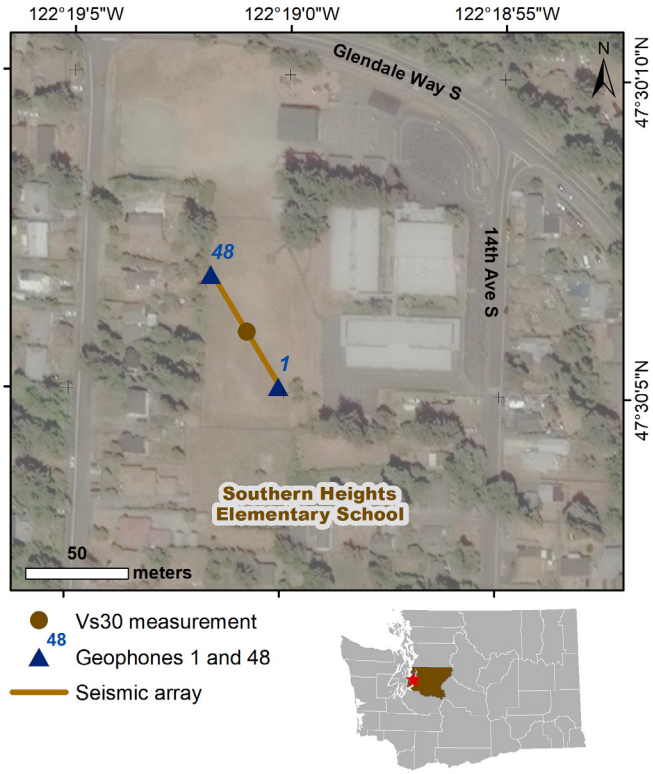
On August 19, 2020, a team from the Washington Geological Survey conducted a seismic survey at Southern Heights Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (231 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift, consisting mostly of stratified sand and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

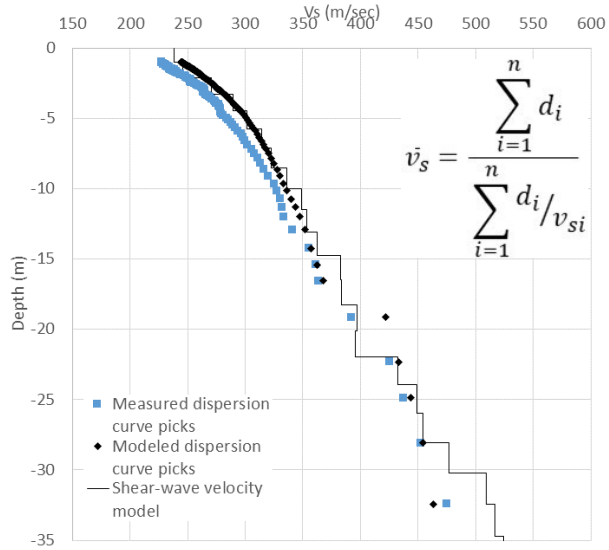
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also excellent quality, but does not sample the shallow layers. MAM and the reverse MASW dispersion curves correlate well, depicting similar trends, so the two dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 7.1 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.7 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 358 m/sec, which puts the site on the D/C site class boundary, just barely on the D side. However, all the initial and inverted models are in the D site class and we do not see an indication of significant heterogeneity across the array. Thus, taking the conservative approach, we can confidently classify the site as a site class D. This is within the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

SPOKANE PUBLIC MONTESSORI

SPOKANE SCHOOL DISTRICT, SPOKANE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

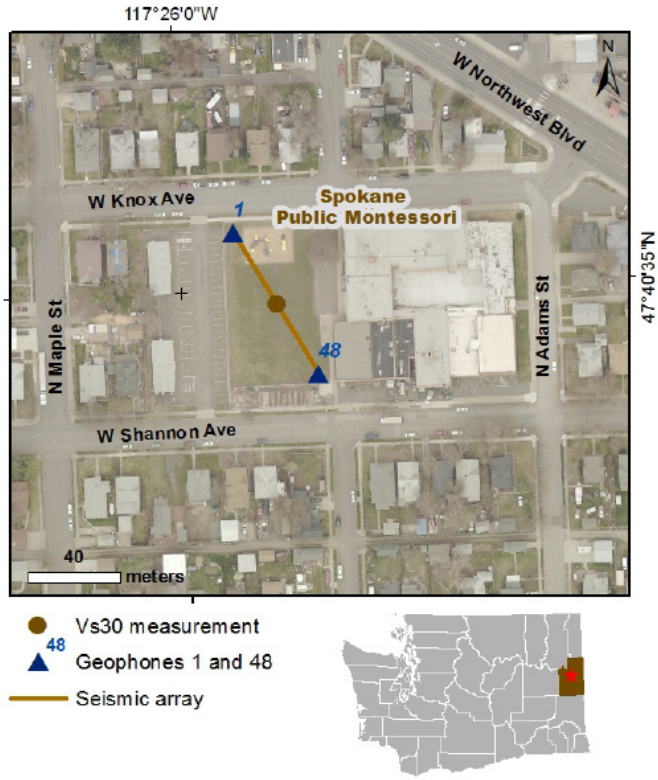
On September 30, 2020, a team from the Washington Geological Survey conducted a seismic survey at Spokane Public Montessori. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (230 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on glacial outburst flood deposits.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Very strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

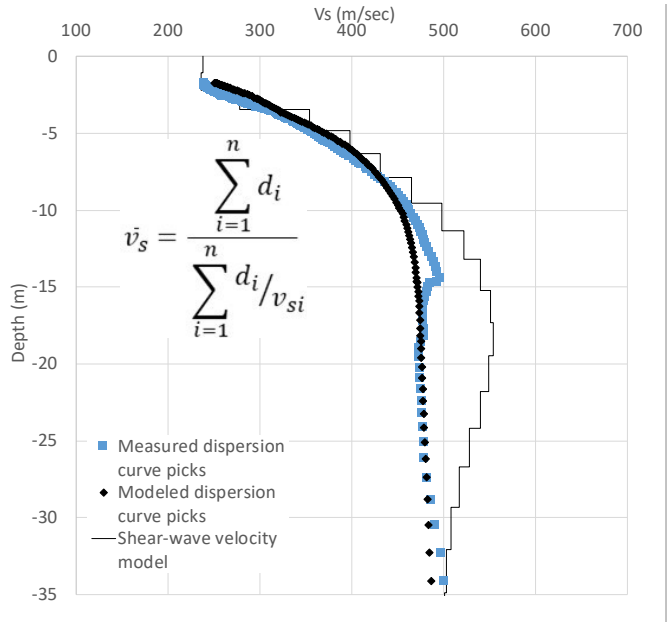
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also decent quality but does not sample the shallow layers. Overall, the MASW and MAM dispersion curves correlate well, so the MASW (forward and reverse direction) and MAM dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 9.0 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.7 percent. The final model shows generally increasing velocity to 20 m (70 ft) and then steadily decreasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 449 m/sec, which places the site solidly in the C site class. All initial and inverted models are in the C class, so the site can be confidently classified. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper left corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

STANLEY ELEMENTARY SCHOOL

TACOMA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

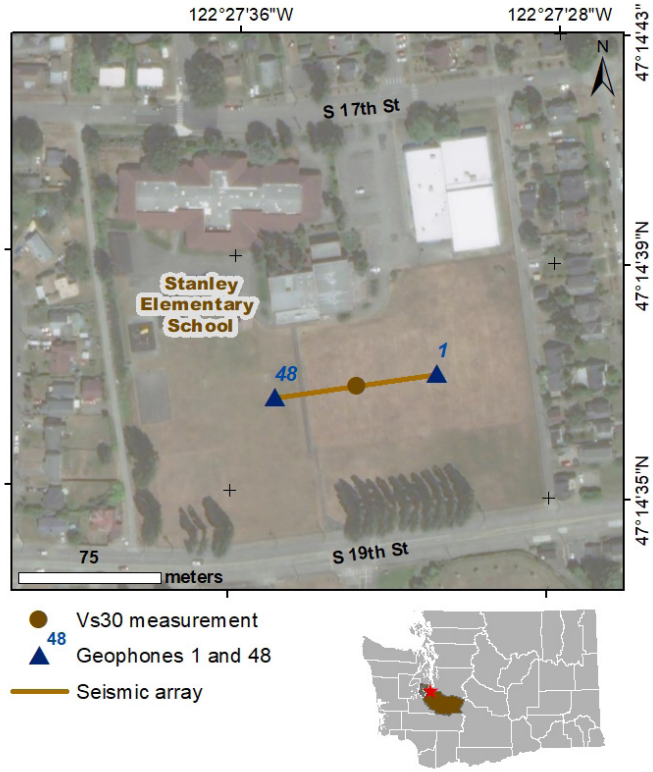
On August 12, 2020, a team from the Washington Geological Survey conducted a seismic survey at Stanley Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 86 m (282 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene till and outwash clay, silt, sand, gravel, cobbles, and boulders.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

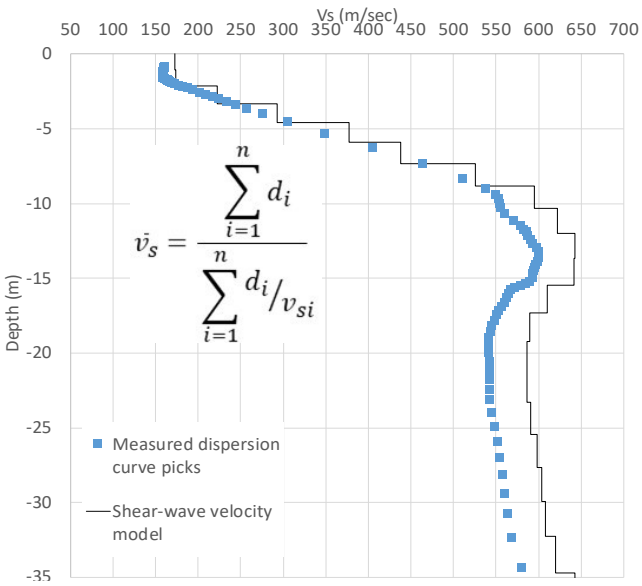
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality so that the fundamental mode can be picked with some confidence. The microtremor analysis method (MAM) dispersion image is decent quality. MAM and the reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the two dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The inverted model does not converge to an acceptable RMSE, therefore the initial model is used as the final model. The final model shows rapidly increasing velocity to about 15 m (50 ft), a slight velocity reversal to 20 m (70 ft), then steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 452 m/sec, which places the site solidly in the C site class. All initial and final models are of the C class, so the site can be confidently classified. This is the same as the predicted site class of C.



Final velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the left corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

STANWOOD ELEMENTARY SCHOOL

STANWOOD–CAMANO SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

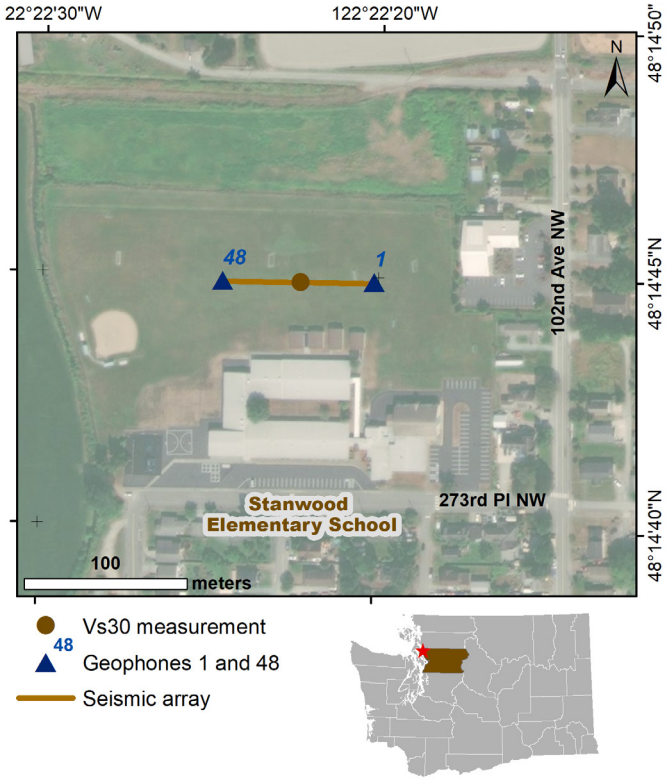
On October 17, 2019, a team from the Washington Geological Survey conducted a seismic survey at Stanwood Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Holocene alluvial and estuarine deposits, with sediments consisting mostly of stream-laid stratified sand and gravel or fine to very fine sand, silt, and clay with some organic matter.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Violent

Lahar
In a mapped lahar hazard zone

Tsunami
In a mapped tsunami hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

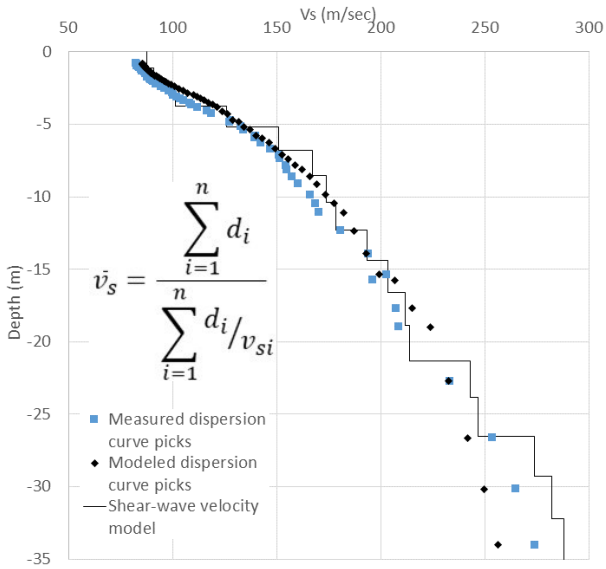
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is excellent quality so that the fundamental mode can be picked with high confidence. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. The three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 9.8 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.2 percent. The final model shows generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 176 m/sec, which places the site in the E site class near the D/E boundary. Although some initial models are just within the D site class, when inverted, they consistently result in a site class E, while converging to an acceptable RMSE of around 5 percent. Furthermore, we do not see strong variance between the forward and reverse MASW that could be indicative of heterogeneity, so the site can be confidently classified. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

STANWOOD MIDDLE SCHOOL

STANWOOD–CAMANO SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

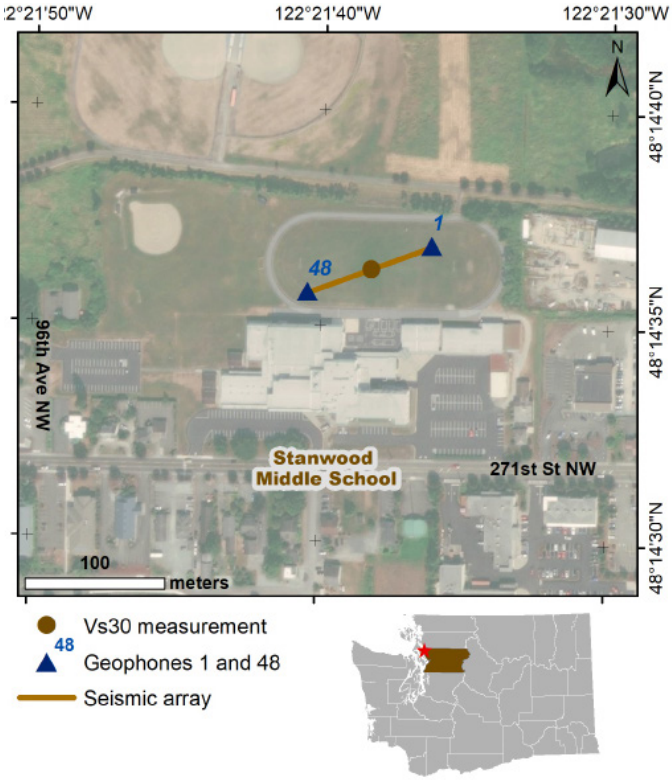
On October 17, 2019, a team from the Washington Geological Survey conducted a seismic survey at Stanwood Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Holocene alluvial and estuarine deposits, with sediments consisting mostly of stream-laid stratified sand and gravel or fine to very fine sand, silt, and clay with some organic matter.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Violent

Lahar
In a mapped lahar hazard zone

Tsunami
In a mapped tsunami hazard zone

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

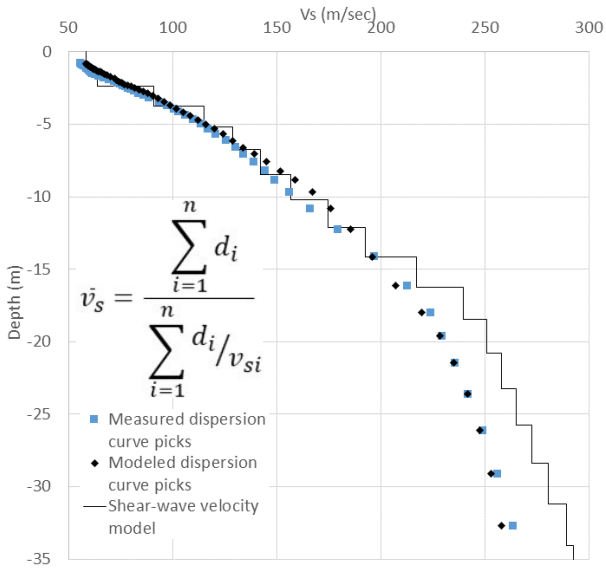
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality but the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is excellent quality, so that the fundamental mode can be picked with high confidence. MAM and the forward and reverse MASW dispersion curves correlate well and the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 11.8 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.5 percent. The final model shows generally increasing velocity to 16 m (52 ft), then steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 163 m/sec, which places the site solidly in the E site class. This is within the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

STEVENSON HIGH SCHOOL

STEVENSON-CARSON SCHOOL DISTRICT, SKAMANIA COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

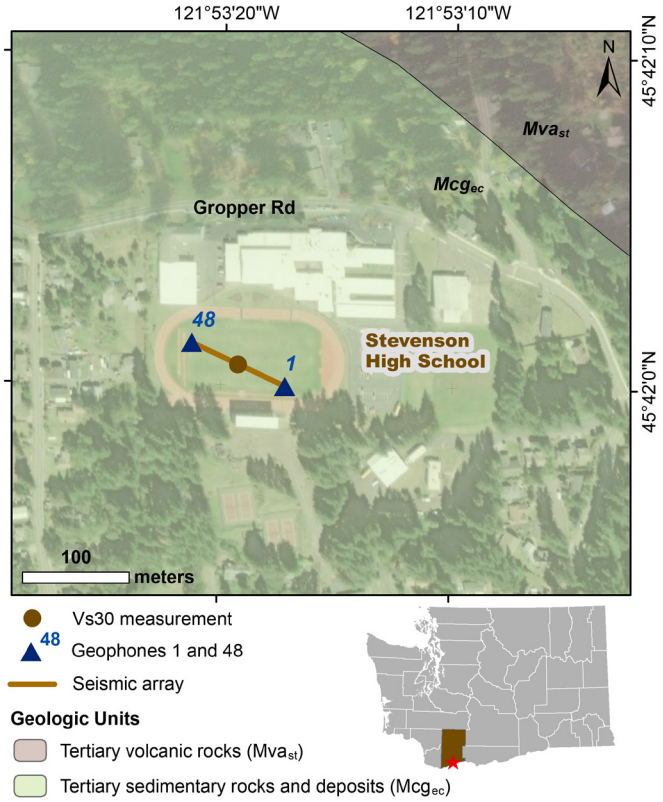
On August 31, 2020, a team from the Washington Geological Survey conducted a seismic survey at Stevenson High School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of B.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on sedimentary rocks and deposits, which are described as interstratified conglomerates and volcaniclastic deposits, predominantly of fluvial origin, and consisting mostly of boulders, cobbles, and clay (unit Mcg$_{ec}$). To the northeast of the school are andesite flows (unit Mva$_{st}$).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Unknown, not negligible

Ground Shaking
Severe

Landslide
Hazard present, based on terrain data

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

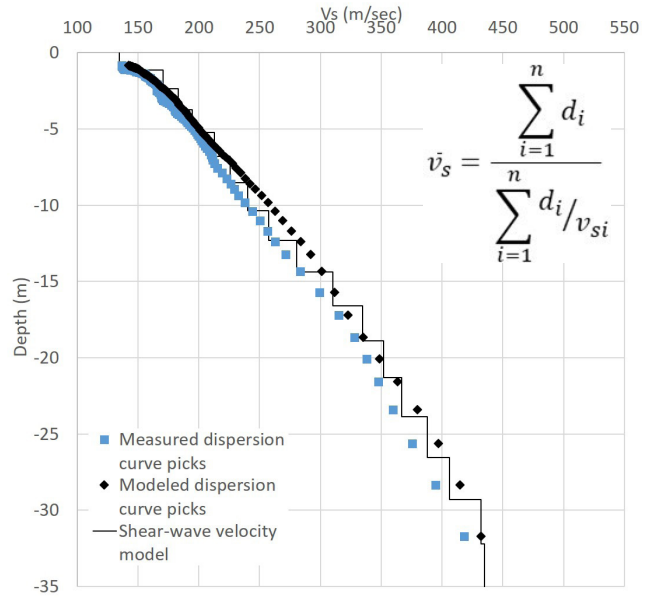
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, only the forward MASW dispersion curve samples down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the shallow layers. The forward and reverse MASW dispersion curves diverge somewhat at shallow depths but depict similar trends below, therefore the three curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 9.0 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.8 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows a steady increase in velocity down to 30 m (100 ft). Our best Vs30 measurement is 270 m/sec, which places the site in the middle of the D site class. This is different from the predicted site class of B.

GEOLOGY

The 1:100,000-scale geologic map places the seismic array and the school buildings on sedimentary rocks and deposits (unit Mcg_{ec}), with a predicted site class of B. Andesite flows (unit Mva_{st}) are mapped just north of campus and mass wasting deposits (unit Qls) about 1 km to the southwest, with predicted site classes of B and D, respectively. Nearby boreholes to the north show clay layers ~3–17 m thick (10–55 ft) on top of basalt, which indicates hard rock is not at the surface. The 1D velocity model is consistent with softer soils and does not indicate a contact with bedrock within the top 30 m (100 ft). Therefore, the change in site class is likely due to low resolution mapping. Although it is possible bedrock is shallower under the school than under the array, the array was placed very near the school buildings, and no initial or inverted models result in a Vs30 near the C site class boundary, so we can reasonably apply the measured site class of D to the campus.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

SUNSET PRIMARY SCHOOL

UNIVERSITY PLACE SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

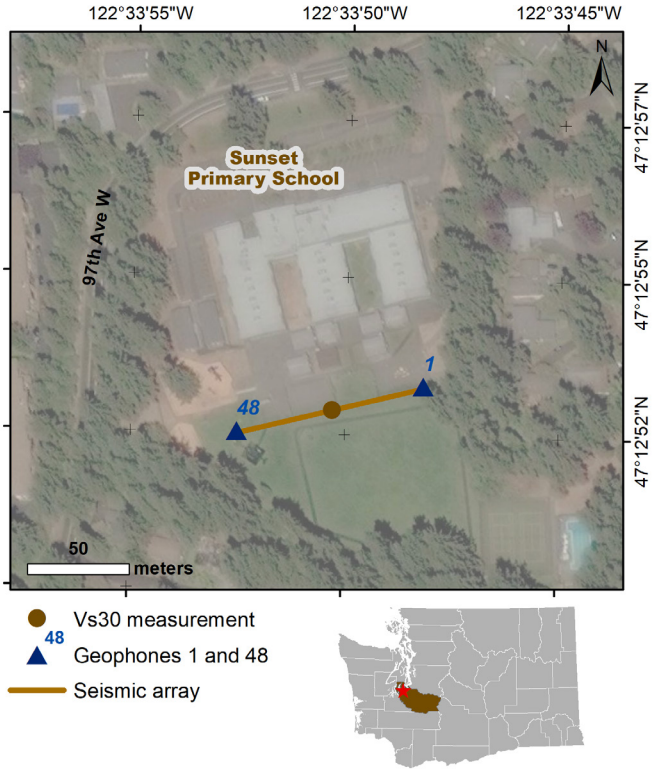
On September 9, 2020, a team from the Washington Geological Survey conducted a seismic survey at Sunset Primary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift consisting mostly of stratified sand and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

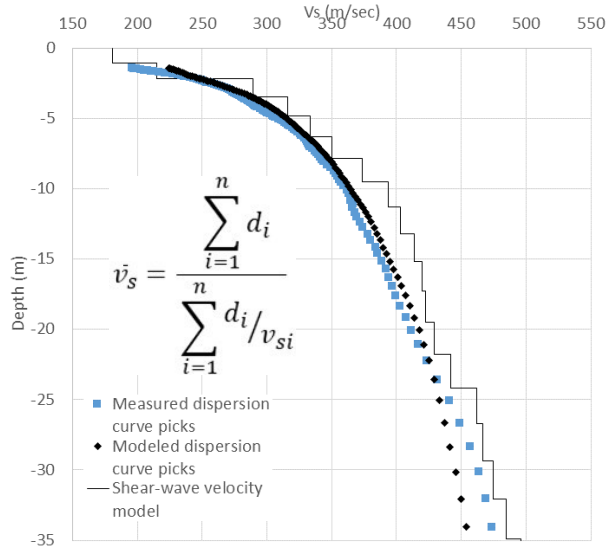
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 6.1 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.2 percent. The final model is unconstrained in the top 1.5 m (5 ft), and below this shows generally increasing velocity to 10 m (33 ft), then more slowly increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 373 m/sec, which places the site in the C site class, near the C/D boundary. All initial and inverted models classify this in the C site class, so the site can be confidently classified. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

SYLVESTER MIDDLE SCHOOL

HIGHLINE SCHOOL DISTRICT, KING COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

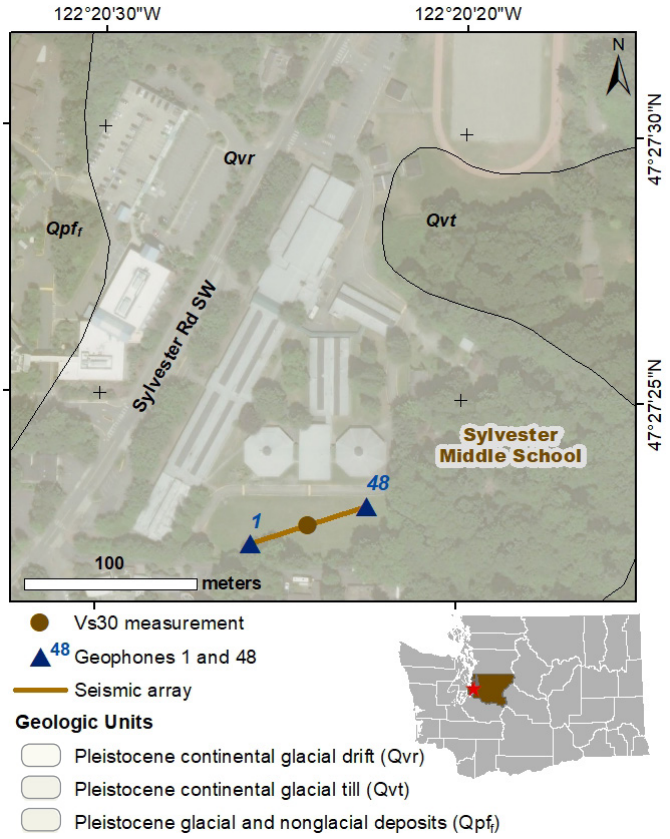
On August 18, 2020, a team from the Washington Geological Survey conducted a seismic survey at Sylvester Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (231 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of F.

Site class	Description	Vs30 (m/sec)	Ground shaking Amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	↓
F	Liquefiable soil, peat, or clay	N/A	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift (unit Qvr) consisting mostly of sand and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also excellent quality. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

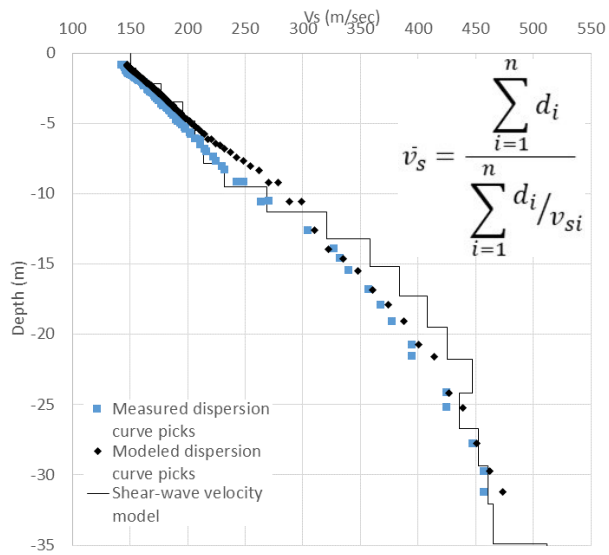
VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 9.6 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 4.3 percent. The final model is unconstrained in the top 1 m (3 ft), but below this shows steadily increasing velocity to 9 m (30 ft), then generally increasing velocity to 22 m (72 ft), then nearly constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 293 m/sec, which places the site in the middle of the D site class. With the excellent coherence of the dispersion images, and all inital and inverted models placing this site in the D class, the site can be confidently classified. This is different from the predicted site class of F.

GEOLOGY

The 1:24,000-scale geologic map on the previous page shows the line and the buildings are sitting on Pleistocene continental glacial drift (unit Qvr), which is similar to the 1:100,000-scale mapped unit Qgo, also a Pleistocene continental glacial drift. Within the campus, much of the unit has a predicted site class F, while outside the campus, this unit has a predicted site class of C–D. In fact, the F/C–D site class boundary crosses directly under the seismic line and a portion of the building on the east side of campus.

The 1D shear wave velocity model indicates softer, less consolidated materials in the upper 9 m (10 ft) grading into more dense and consolidated materials below. 2D seismic refraction tomography also shows softer materials in the upper 4 to 8 m (12 to 26 ft), transitioning into denser, more consolidated materials below. Although low shear wave velocities that could be peat (which is usually associated with site class F) are present in the 1D model, they are limited to the upper 2 m (6 ft) and could not be verified through ground truthing. Thus, the discrepancy between the predicted and measured site class is most likely due to mis-mapping and we can assign the site class of D to the site with reasonable certainty.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

TACOMA SCHOOL OF THE ARTS

TACOMA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

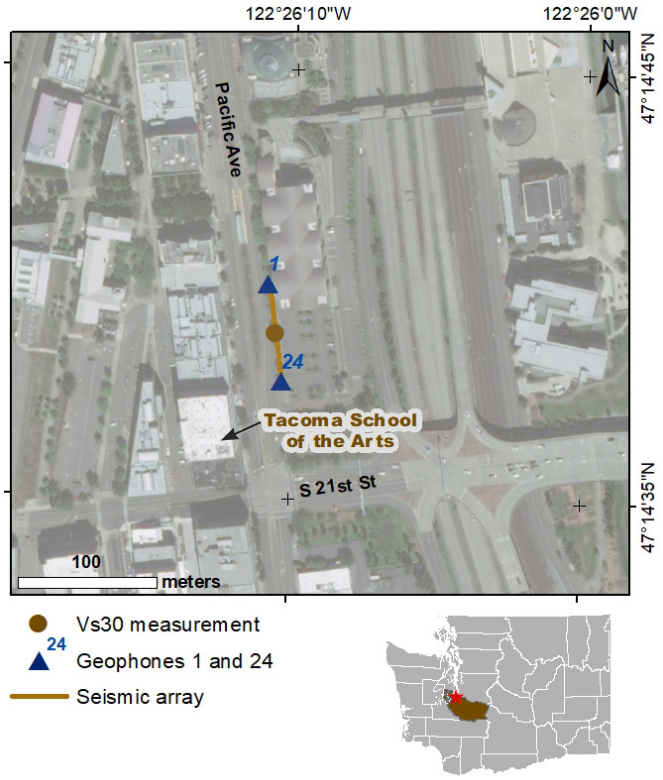
On September 3, 2019, a team from the Washington Geological Survey conducted a seismic survey at Tacoma School of the Arts. We measured Vs30 by laying out 24 geophones (ground motion sensors) in a 69 m (226 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial outwash.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

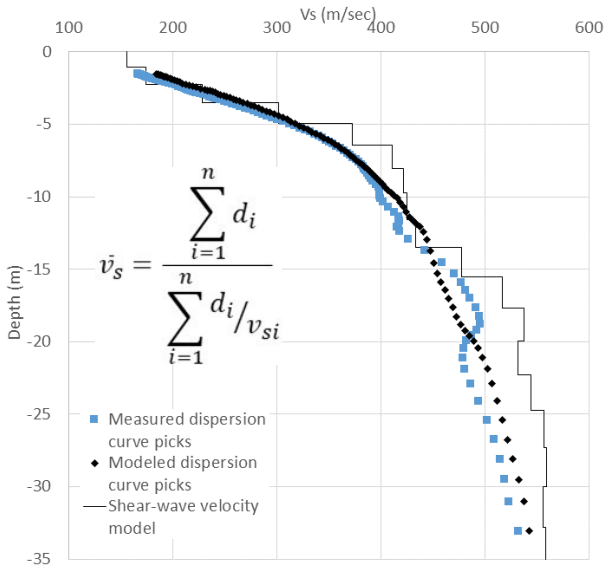
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of decent quality. MAM and the forward MASW dispersion curves correlate well, depicting similar trends. Therefore the dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 9.6 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 4.7 percent. The final model shows rapidly increasing velocity from 2 m (7 ft) down to 7 m (23 ft), then generally increasing velocity down to 25 m (82 ft), then nearly constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 399 m/sec, which places the site in the C site class. The initial and inverted models from each dispersion curve also place this site solidly in the C class, so the site can be confidently classified. This is within the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_S) for the upper 30 m is shown in the middle left of the image. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

THURGOOD MARSHALL MIDDLE SCHOOL

OLYMPIA SCHOOL DISTRICT, THURSTON COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

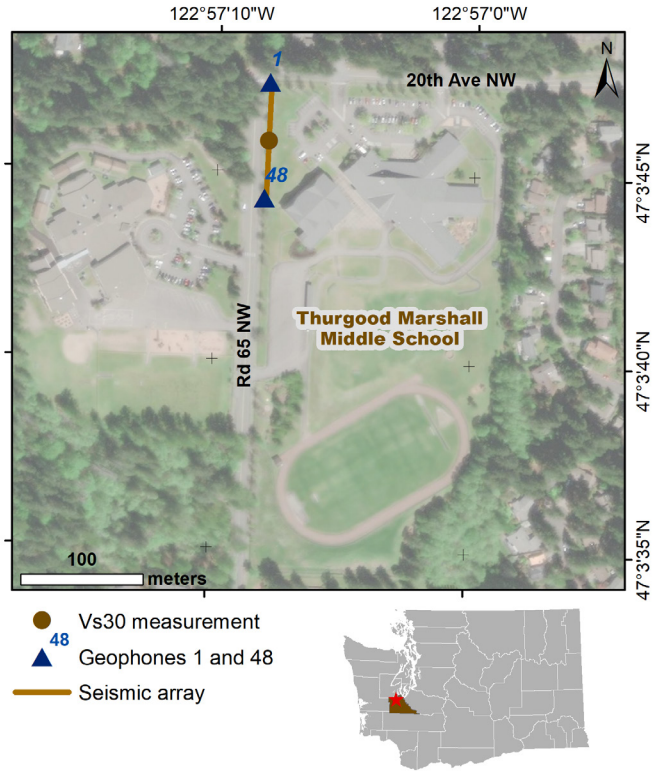
On August 5, 2020, a team from the Washington Geological Survey conducted a seismic survey at Thurgood Marshall Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

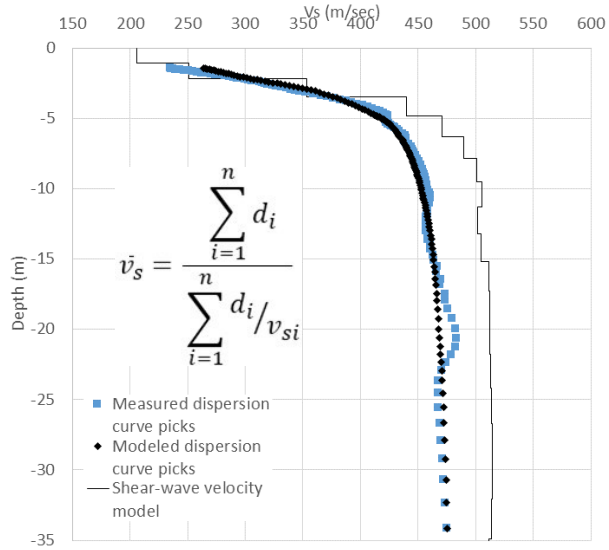
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the top 5 m (16 ft). MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 5.8 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.1 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows rapidly increasing velocity to 6 m (20 ft), then nearly constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 454 m/sec, which places the site solidly in the C site class. This is the same as with the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = Shear wave velocity in m/sec of the layer.

TILLICUM ELEMENTARY SCHOOL

CLOVER PARK SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

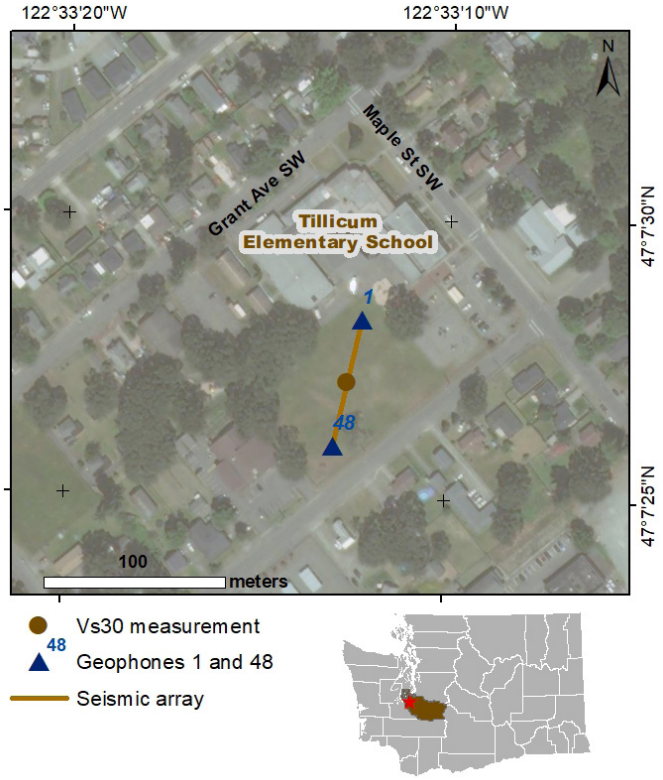
On July 20, 2020, a team from the Washington Geological Survey conducted a seismic survey at Tillicum Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (231 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

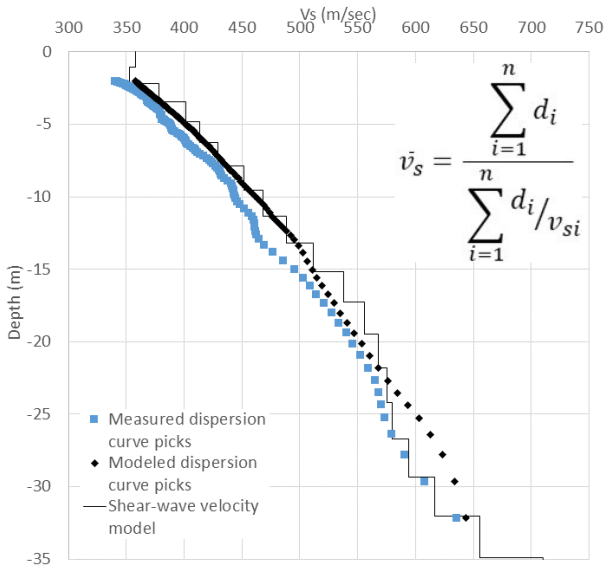
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also excellent quality, and the resulting dispersion curve correlates well with the MASW dispersion curves. The three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 7.5 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.0 percent. The final model is unconstrained in the upper 2 m (7 ft), but below this shows generally increasing velocity down to 20 m (66 ft), then nearly constant velocity down to 27 m (89 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 491 m/sec, which places the site solidly in the C site class. All initial and inverted models place this site in the C class, so the site can be confidently classified. This is within the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

TOLEDO ELEMENTARY SCHOOL

TOLEDO SCHOOL DISTRICT, LEWIS COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

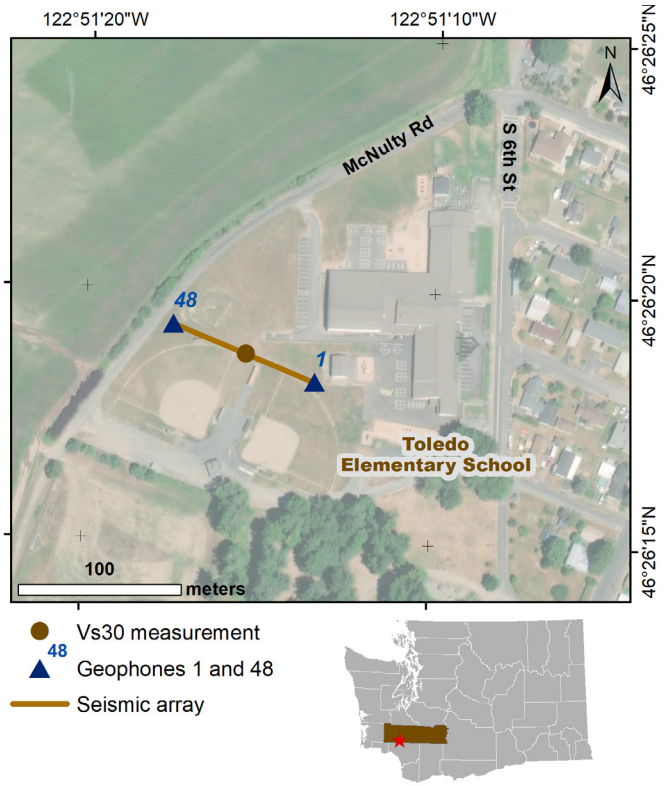
On March 12, 2020, a team from the Washington Geological Survey conducted a seismic survey at Toledo Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on river sediments consisting mostly of boulder, cobble, and pebble gravel and sand.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

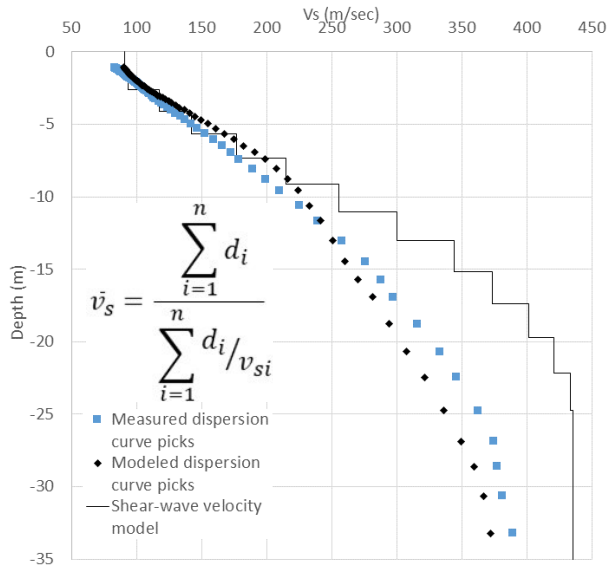
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft) and do show some interference from higher modes. The microtremor analysis method (MAM) dispersion image is excellent quality so the fundamental mode can be picked with high confidence. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. The three dispersion curves are combined into a single final model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 12.9 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 6.6 percent. The final model shows generally increasing velocity to 20 m (66 ft), then nearly constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 241 m/sec, which places the site in the middle of the D site class. This is within with the predicted site class of D–E.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

TOLEDO MIDDLE SCHOOL

TOLEDO SCHOOL DISTRICT, LEWIS COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

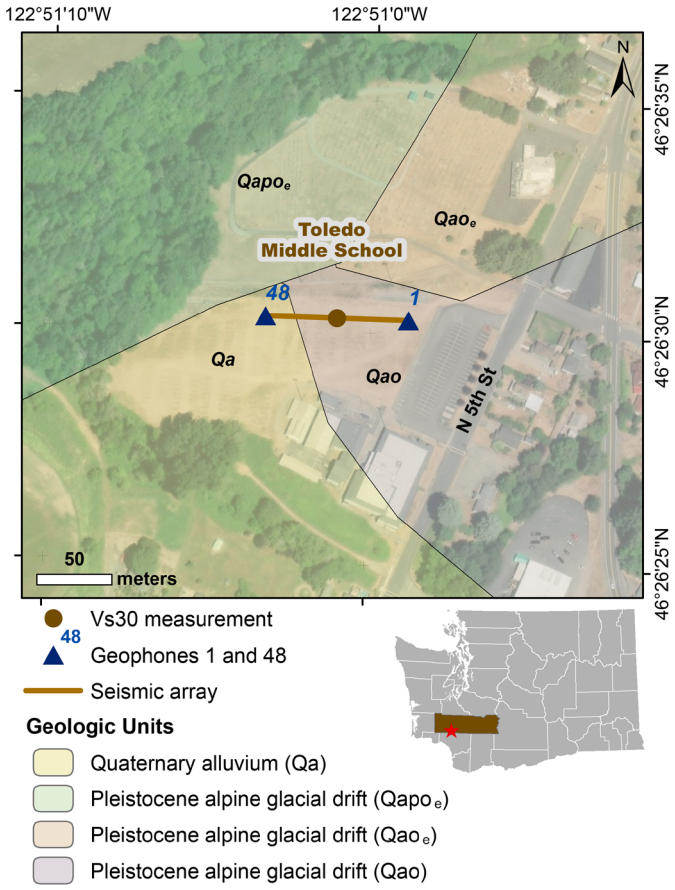
On March 12, 2020, a team from the Washington Geological Survey conducted a seismic survey at Toledo Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on a contact between Quaternary alluvium (unit Qa) and Pleistocene alpine glacial drift (units Qao, Qao$_e$, Qapo$_e$).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

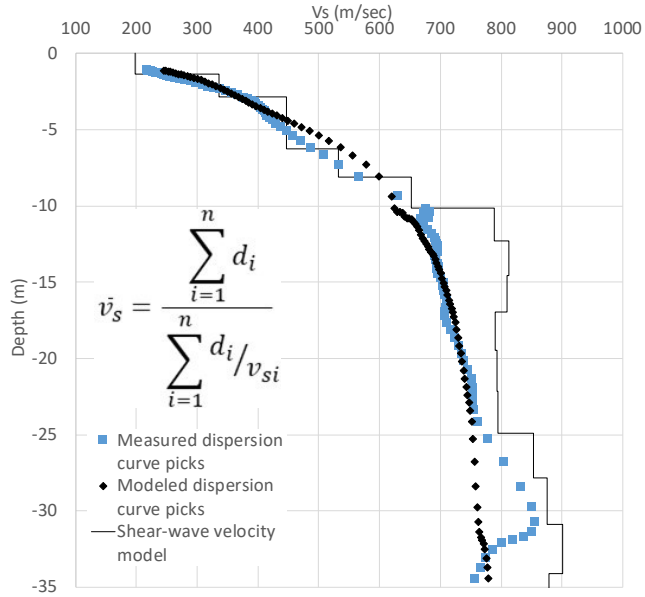
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward direction are poor quality so that the fundamental mode can be picked with some confidence, but the reverse direction MASW dispersion images are too low quality to be useable. The microtremor analysis method (MAM) dispersion image is decent quality, and the resulting dispersion curve is combined with the forward MASW dispersion curve to create a single model that adequately samples below 30 m (100 ft).

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 7.4 percent. The inversion was carried out for three iterations and resulted in a final model with an RMSE of 4.6 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows rapidly increasing velocity to about 10 m (30 ft), then nearly constant velocity to 25 m (82 ft), then steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 603 m/sec, which places the site in the middle of the C site class. All initial and inverted models are in the C class, so the site can be confidently classified. This correlates with the predicted site class of C.

GEOLOGY

The site class of C is the same as predicted, but the 1:100,000-scale geologic map on the previous page shows a geologic contact crossing the site. The map indicates the seismic array and the school buildings span both Quaternary alluvium (unit Qa) with a predicted site class of D–E and glacial drift with a predicted site class of C. Mapped closely to the north are more glacial drift units, all with a predicted site class of C. Nearby boreholes show mostly unconsolidated sediment, occasionally on top of sedimentary rock at 9–15 m (30–50 ft) depth. This is consistent with the 1D velocity model, which reaches rock velocity around 10 m (33 ft), and below this indicates material that does not compress much further with depth. Because most of the units are predicted to have a site class of C which matches our final site class, and we observe very little heterogeneity across the array, we confidently assign a site class C to the campus.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

TWIN CITY ELEMENTARY SCHOOL

STANWOOD-CAMANO SCHOOL DISTRICT, SNOHOMISH COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

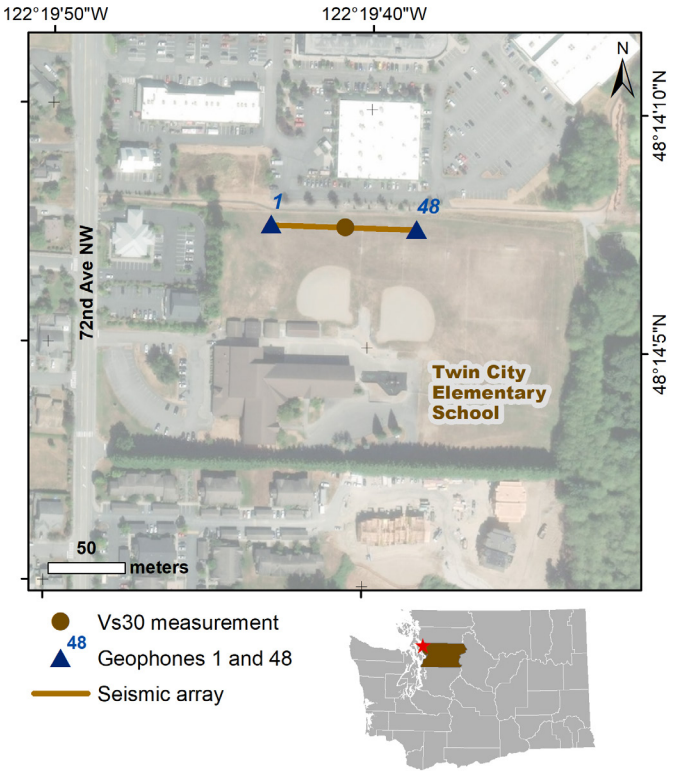
On December 2, 2020, a team from the Washington Geological Survey conducted a seismic survey at Twin City Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary alluvium consisting of well-bedded to lensing sand and gravel grading up into fine flood-plain sand, silt, and clay.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

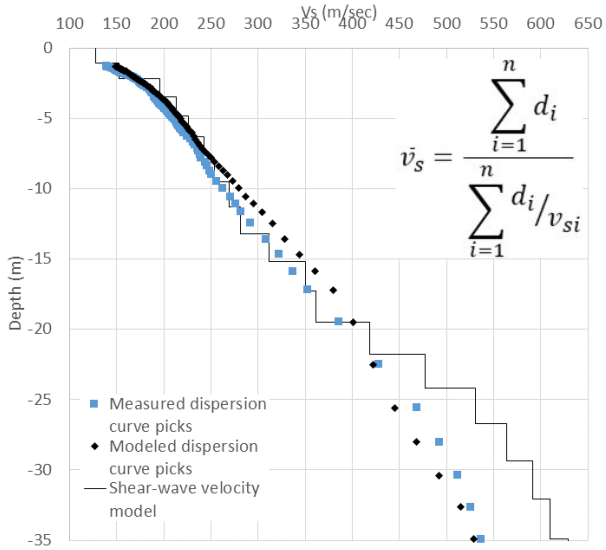
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the top 4 m (13 ft). MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. The three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 11.4 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.5 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 300 m/sec, which places the site solidly in the D site class. This is the same as the predicted site class of D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

VOYAGER ELEMENTARY SCHOOL

PENINSULA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

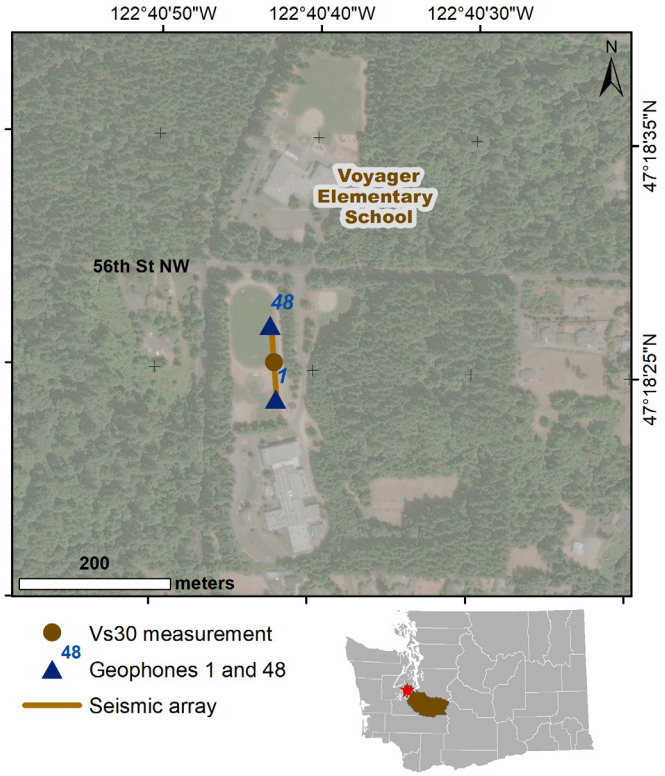
On July 15, 2020, a team from the Washington Geological Survey conducted a seismic survey at Voyager Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift consisting of sand and minor gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

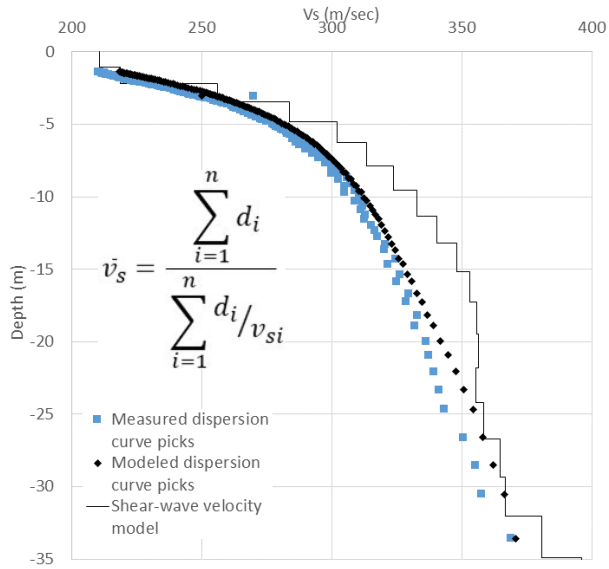
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are excellent quality so that the fundamental mode can be picked with high confidence. However, the MASW does not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also excellent quality, and the fundamental mode can be picked with high confidence. The forward and reverse direction MASW and MAM are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curve. The initial model had an RMSE of 6.0 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 3.2 percent. The final model shows rapidly increasing velocity in the top 5 m (16 ft), then generally increasing velocity down to 15 m (49 ft), and nearly constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 323 m/sec, which places the site solidly in the D site class. This is within the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

WALLER ROAD ELEMENTARY SCHOOL

PUYALLUP SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

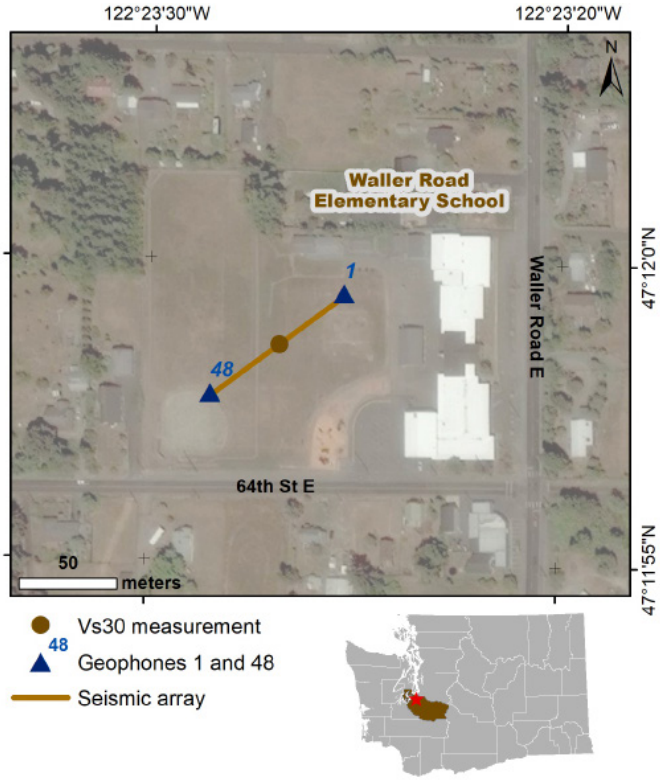
On July 22, 2020, a team from the Washington Geological Survey conducted a seismic survey at Waller Road Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial till, comprising a compact and unsorted mixture of sand, silt, clay, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

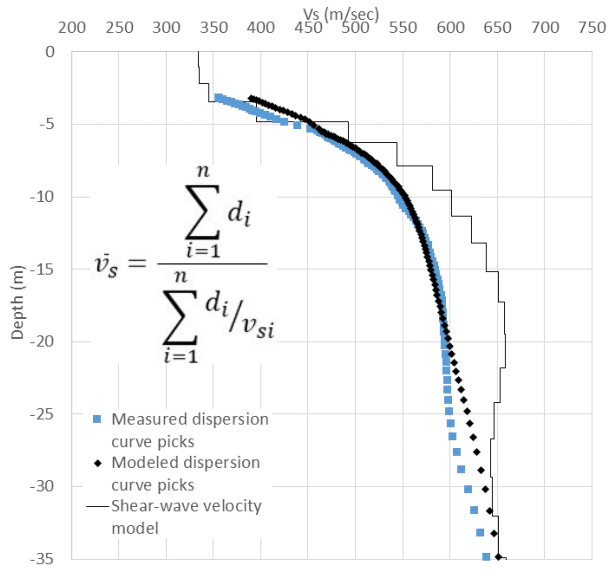
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is decent quality, but does not sample the top 6 m (20 ft). MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. The three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 4.5 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 2.5 percent. The final model is unconstrained in the top 3 m (10 ft), but below that shows rapidly increasing velocity down to 12 m (39 ft), then nearly constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 554 m/sec, which places the site in the middle of the C site class. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

WASHINGTON ELEMENTARY SCHOOL

CENTRALIA SCHOOL DISTRICT, LEWIS COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

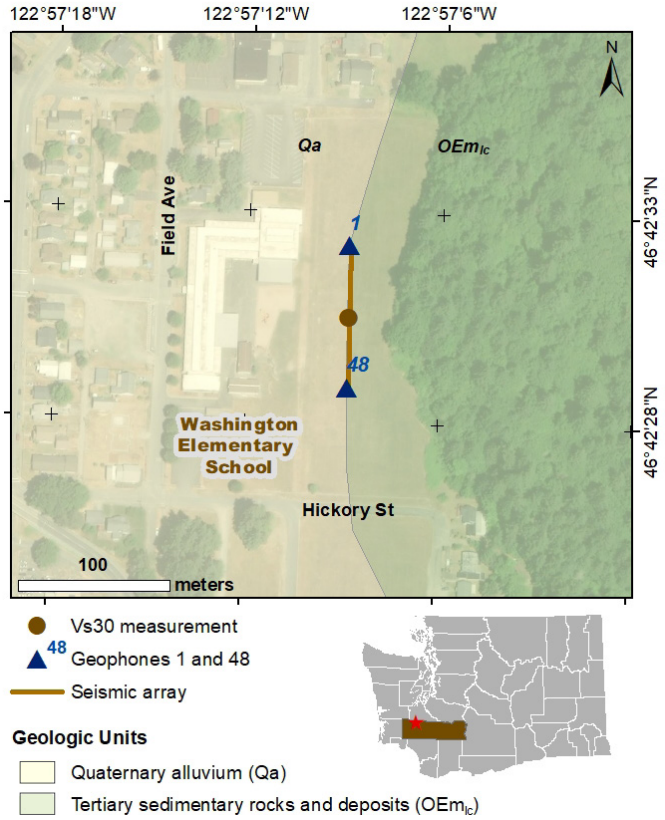
On September 30, 2020, a team from the Washington Geological Survey conducted a seismic survey at Washington Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on river sediments consisting mostly of boulder, cobble, and pebble gravel and sand (unit Qa).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

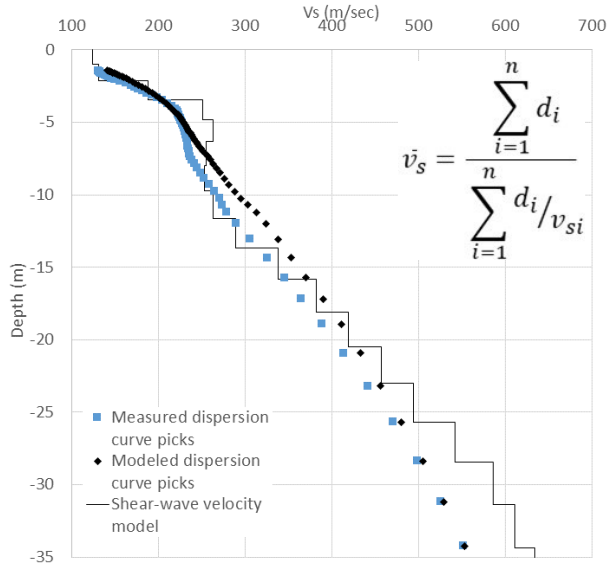
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also of decent quality, but the MAM disperion curves lack sampling in the top 5 m (16 ft). Forward and reverse MASW and MAM correlate well, depicting similar trends. Therefore the disperison curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 11.4 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.9 percent. The final model shows rapidly increasing velocity in the top 4 m (13 ft), then nearly constant velocity down to 12 m (39 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 305 m/sec, which places the site solidly in the D site class. All initial models also place this site in the D class, so the site can be confidently classified. This is within the predicted site class of D–E.

GEOLOGY

The 1:100,000-scale geologic map shows the school building sitting on Quaternary alluvium (unit Qa) with a predicted site class of D–E. Nearby boreholes south of the school, also on unit Qa, show silty sand in the top 21 m (70 ft), and either dense sand and gravel or sandstone below. The seismic array appears to be on a mapped boundary between unit Qa and Tertiary sedimentary rocks and deposits (unit Oem_{lc}) with a predicted site class of B. However, our velocity model does not show velocity indicative of bedrock until below 30 m (100 ft). As this is below 30 m (100 ft), it does not affect our measurement of Vs30. This indicates the geologic map contact boundary should be adjusted slightly east of this site, and the site class change is due to low-resolution mapping.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_S) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

WEST VALLEY JUNIOR HIGH

WEST VALLEY SCHOOL DISTRICT, YAKIMA COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

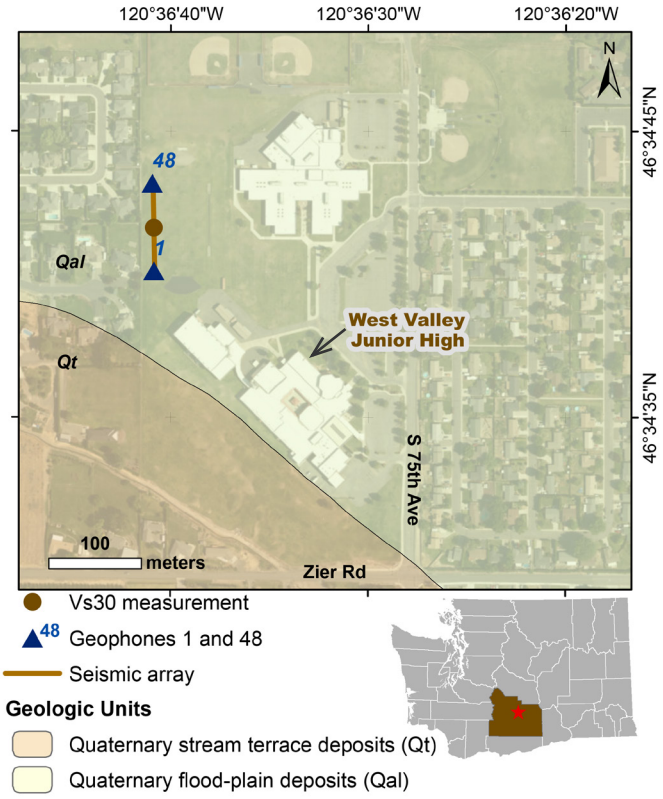
On September 24, 2020, a team from the Washington Geological Survey conducted a seismic survey at West Valley Junior High. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quaternary fluvial sand, silt, and gravel with minor lacustrine deposits (unit Qal). Mapped to the southwest is Quarternary alluvium terraced deposits consisting of silt, sand, and gravel (unit Qt).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Very strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

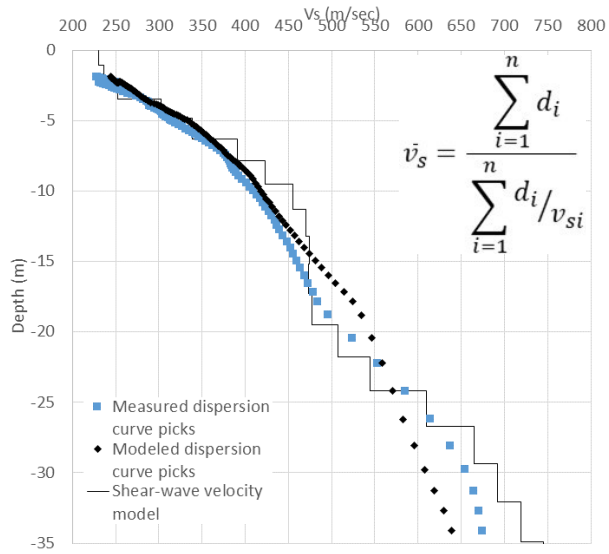
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality so that the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft), and there is noticeable interference from higher modes. The microtremor analysis method (MAM) dispersion image is decent quality but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves depict similar trends, therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 10.5 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 4.8 percent. The final model is unconstrained in the top 2 m (7 ft), and below this shows generally increasing velocity to 11 m (36 ft), then nearly constant velocity down to 19 m (62 ft), and then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 429 m/sec, which places the site solidly in the C site class. All initial and inverted models place this site in the C site class, so the site can be confidently classified. This is different from the predicted site class of D.

GEOLOGY

The 1:24,000-scale geologic map places the school buildings and seismic array on Quaternary fluvial deposits (unit Qal), with Quaternary alluvium (unit Qt) to the southwest. The 1:100,000-scale geologic map, which is used to predict site class, has slightly different unit contacts. This lower-resolution mapping places the north half of the campus on Quaternary alluvium (predicted site class D–E), and the school buildings of the junior high on both Quaternary eolian deposits (predicted site class D) and Pliocene sedimentary rocks (predicted site class B). Nearby boreholes on unit Qal show mostly layers of conglomerate above 15 m (50 ft) and claystone or sandstone below, occasionally with a layer of sand around 15 m. This matches our velocity model, which shows a layer of less compressible materials 11–19 m (36–62 ft). The velocity model does not reach rock velocity above 30 m, so it is unlikely that sedimentary rocks are present underneath the school at depths that affect Vs30, but there could be weathered or fractured sedimentary rocks at these depths. The higher-resolution mapping places the school on a unit that does not have a corresponding unit in the 1:100,000-scale geologic map that is used to predict site class, but the description of this unit matches with a site class of C. The change in site class is thus likely due to low-resolution mapping.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

WHATCOM MIDDLE SCHOOL

BELLINGHAM SCHOOL DISTRICT, WHATCOM COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

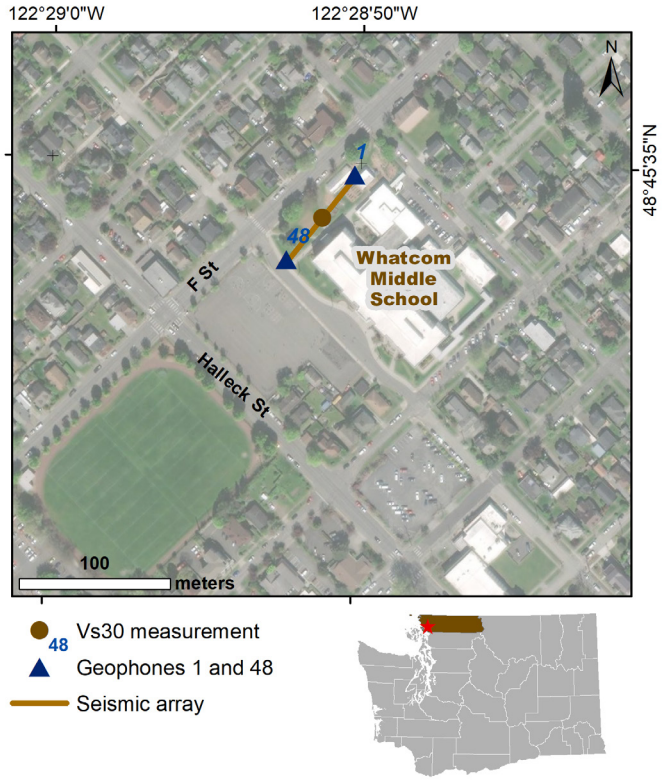
On September 20, 2019, a team from the Washington Geological Survey conducted a seismic survey at Whatcom Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 70.5 m (231 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift, consisting mostly of gravelly silt with dropstones and layers of gravel, sand, silt, and clay.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Low to moderate

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

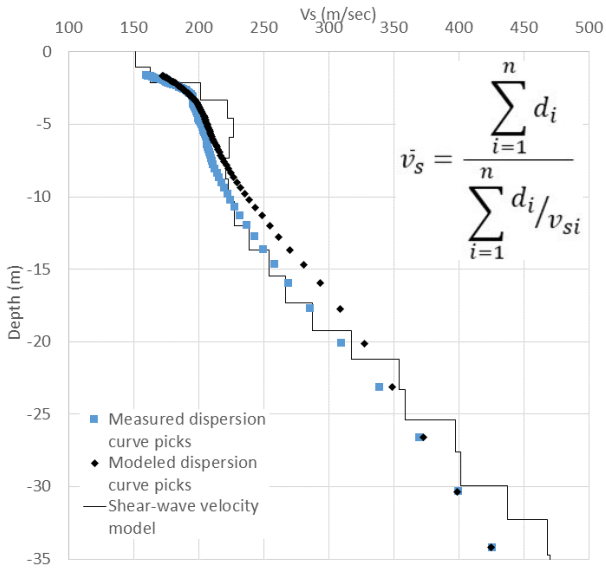
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is excellent and correlates well with both forward and reverse MAM. All three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 8.3 percent. The inversion was carried out for six iterations and resulted in a final model with an RMSE of 3.7 percent. The final model shows rapidly increasing velocity in the top 4 m (13 ft), then a slight velocity increase down to 10 m (33 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 262 m/sec, which places the site in the middle of the D site class. This is the same as the predicted site class of D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

WILDWOOD PARK ELEMENTARY SCHOOL

PUYALLUP SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

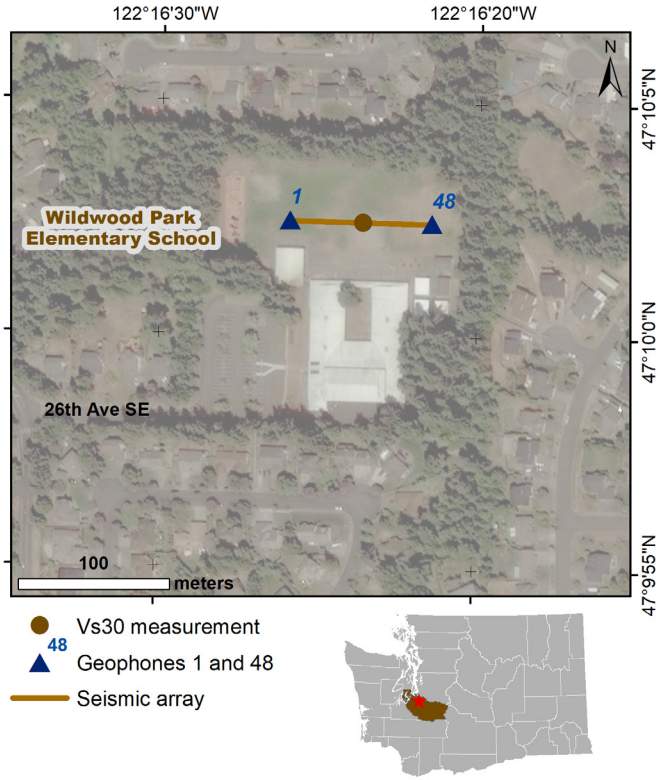
On July 21, 2020, a team from the Washington Geological Survey conducted a seismic survey at Wildwood Park Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of C–D.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift, consisting mostly of stratified sand and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

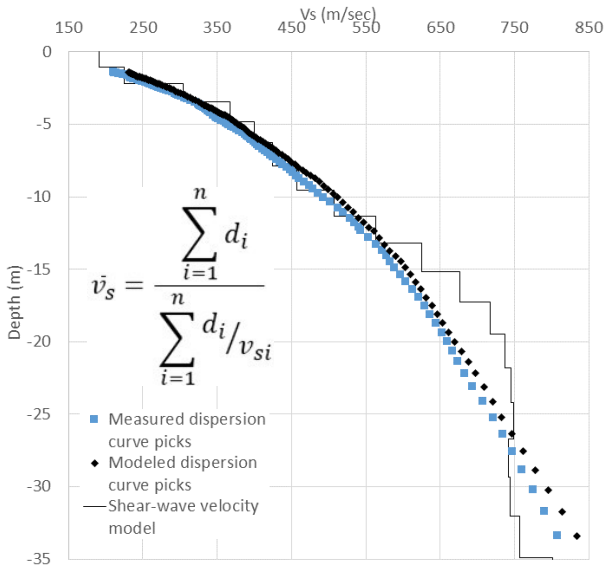
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is poor quality, but the fundamental mode can still be picked with some confidence. MAM and the forward and reverse MASW dispersion curves correlate well, depicting similar trends. The three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 11.2 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.2 percent. The final model shows generally increasing velocity down to 20 m (66 ft), and then nearly constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 504 m/sec, which places the site in the middle of the C site class. All initial models also place this site in the C class, so the site can be confidently classified. This is within the predicted site class of C–D.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

WILLAPA ELEMENTARY SCHOOL

WILLAPA VALLEY SCHOOL DISTRICT, PACIFIC COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

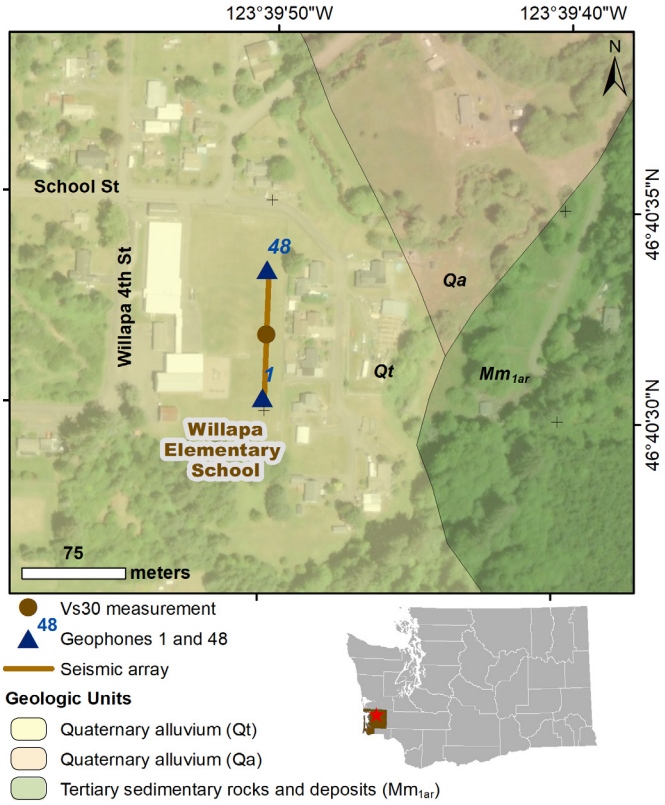
On August 22, 2019, a team from the Washington Geological Survey conducted a seismic survey at Willapa Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Quarternary alluvium terraced deposits consisting of silt, sand, and gravel (unit Qt). To the northeast is Quaternary alluvium, river sediments consisting mostly of boulder, cobble, and pebble gravel and sand (unit Qa). To the east is Tertiary sedimentary rocks and deposits, comprising volcanic sandstone and siltstone (unit Mm_{1ar}).

Liquefaction
Very low to low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

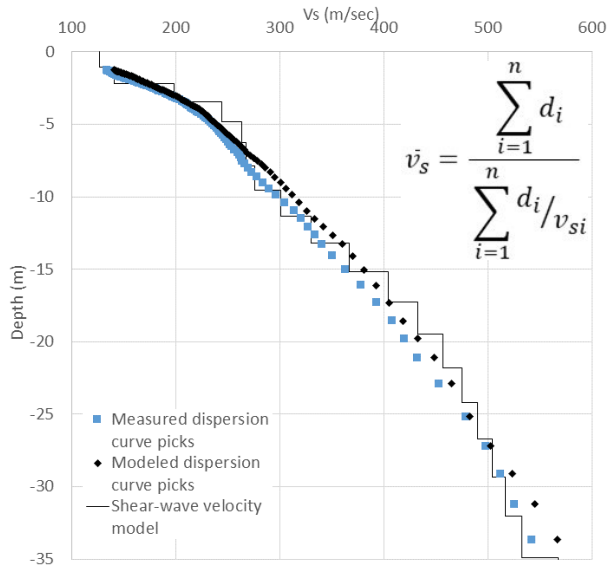
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is also decent quality, and the resulting dispersion curve depicts trends similar to the MASW dispersion curves. All MASW and MAM dispersion curves sample down to 30 m (100 ft), therefore the slightly higher quality forward direciton MASW is combined with the MAM into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 12.1 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.6 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows rapidly increasing velocity to 5 m (16 ft), then nearly constant velocity to 10 m (33 ft), then generally increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 318 m/sec, which places the site solidly in the D site class. This is different from the predicted site class of C.

GEOLOGY

The 1:100,000-scale geologic map places the school building and the seismic array on Quaternary alluvium terraced deposits (unit Qt). Mapped to the east is Tertiary sedimentary rocks (unit Mm_{1ar}) with a predicted site class of B, and to the northeast is Quaternary alluvium (unit Qa) with a predicted site class of D–E. There is only one nearby borehole, and this shows sand and silt to 12 m (38 ft), consistent with either unit Qa or Qt. The velocity model does show a change in velocity structure at this depth which may indicate a subsurface change, however this is likely Qa overlaying Qt. Therefore the site class change is likely due to mismapping, and higher-resolution mapping would place the the school on unit Qa.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

WILLIE STEWART ACADEMY

TACOMA SCHOOL DISTRICT, PIERCE COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

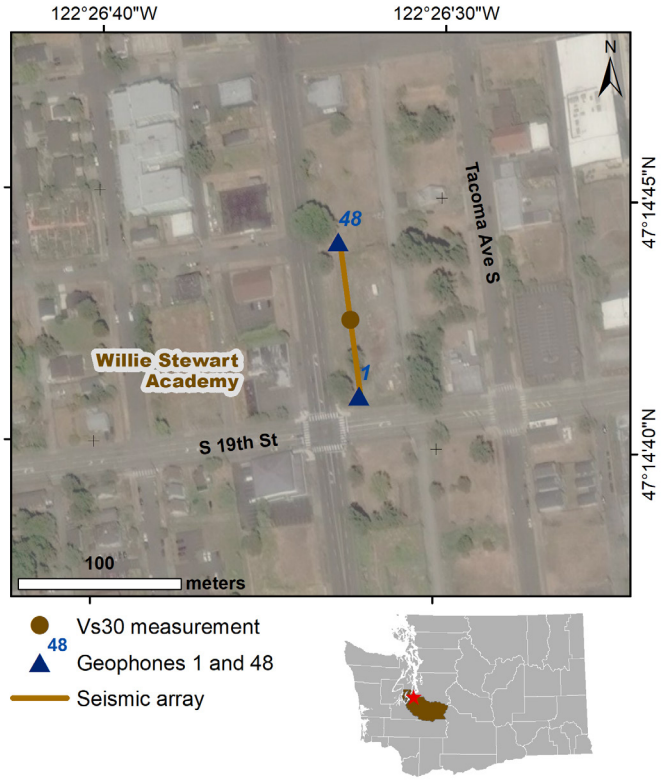
On August 8, 2020, a team from the Washington Geological Survey conducted a seismic survey at Willie Stewart Academy. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS C



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on continental glacial outwash.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

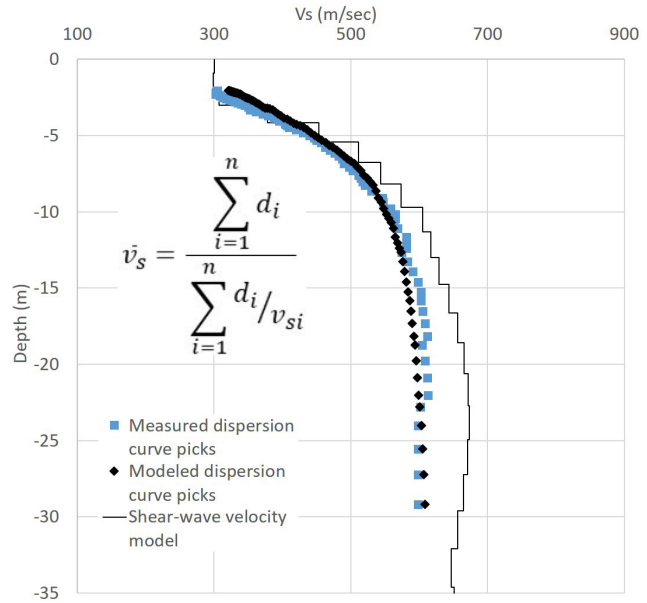
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image correlates well with the MASW, but is not needed because the forward direction MASW adequately samples to 30 m (100 ft).

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the dispersion curve from the MASW forward direction (located beyond the end of geophone 1). The initial model had an RMSE of 10.3 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 5.3 percent. The final model shows generally increasing velocity down to 10 m (30 ft), then slowly increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 549 m/sec, which places the site in the middle of the C site class. All initial models are in the middle of the C class as well, so the site can be confidently classified. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_s) for the upper 30 m is shown in the middle left corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

WILSON MIDDLE SCHOOL

YAKIMA SCHOOL DISTRICT, YAKIMA COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

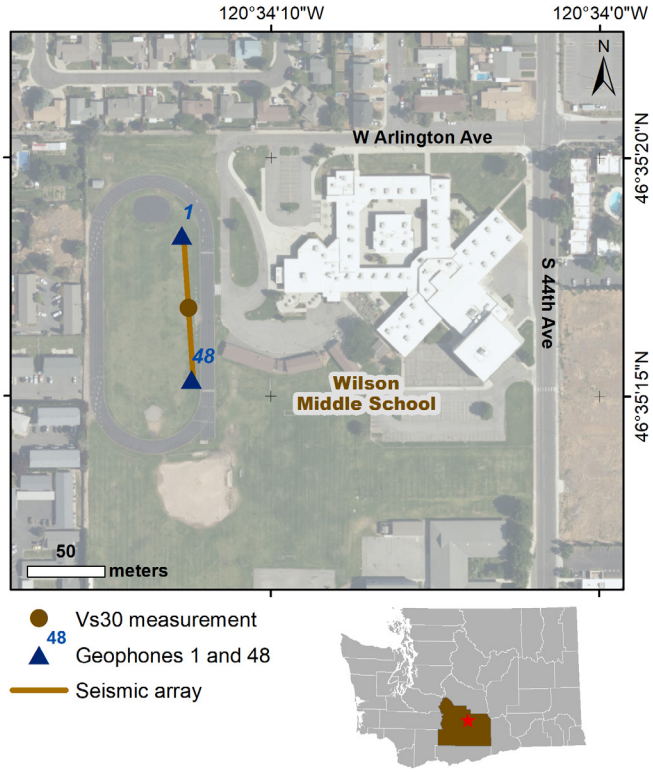
On October 7, 2020, a team from the Washington Geological Survey conducted a seismic survey at Wilson Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of B.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school and surrounding areas are sitting on Quaternary alluvium, comprised mostly of course gravel and sand (unit Qtu).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Unknown, not negligible

Ground Shaking
Very Strong

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

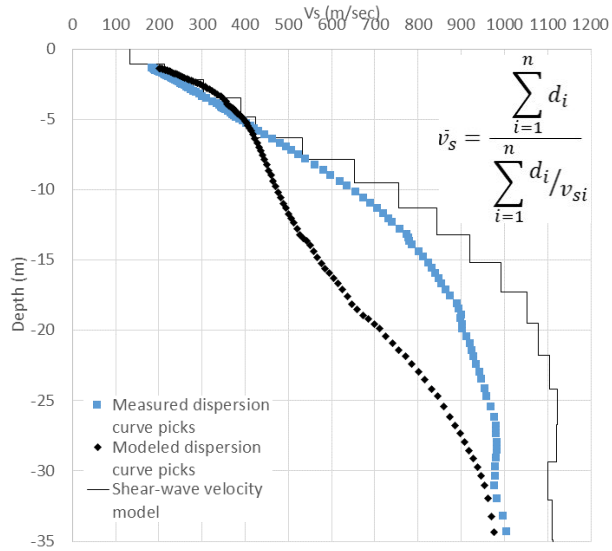
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. The microtremor analysis method (MAM) dispersion image is excellent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves depict similar trends, therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 15.3 percent. The inversion was carried out for eight iterations and resulted in a final model with an RMSE of 6.5 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows generally increasing velocity to 17 m (56 ft), then slowly increasing velocity to 24 m (79 ft), then nearly constant velocity down to 30 m (100 ft). Our best Vs30 measurement is 560 m/sec, which places the site in the middle of the C site class. With the clear coherence in the dispersion images and all inital and inverted models placing this site in the middle of the C site class, this site can be confidently classified. This is different from the predicted site class of B.

GEOLOGY

The 1:24,000-scale geologic map places the school, the array, and the surrounding area on Quaternary stream terrace deposits (unit Qtu). The closest contact with a different geologic unit is ~350 m to the north, and is Tertiary volcanic and sedimentary rocks (unit Teug). The 1:100,000-scale geologic map, which is used to predict site class, has slightly different unit contacts and places the school on the sedimentary rocks, with a predicted site class of B. To the north is Quaternary alluvium with a predicted site class of D. The stratigraphy of nearby boreholes varies somewhat, but generally reaches sandstone or hardpan by depths of 12 m (40 ft), with looser sediments above. This is consistent with our velocity model, which reaches rock velocity at ~10 m (33 ft). The higher resolution mapping, boreholes, and velocity structure indicate this site could be alluvium overlaying sedimentary rocks, which would explain the measured site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

WOODLAND MIDDLE SHOOL AND PRIMARY SCHOOL

WOODLAND SCHOOL DISTRICT, COWLITZ COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

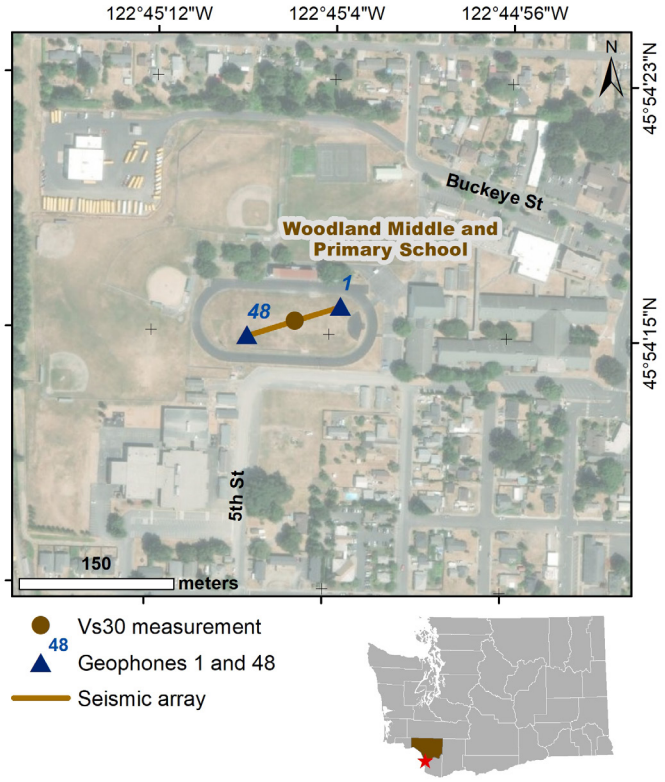
On March 9, 2020, a team from the Washington Geological Survey conducted a seismic survey at Woodland Middle School and Primary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The schools are on soft soil, which would amplify ground shaking relative to rock.
- Site class is within the predicted site class of D–E.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **E**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The schools are sitting on Quaternary alluvium composed predominantly of unconsolidated silt, sand, and gravel.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Moderate to high

Ground Shaking
Severe

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion curves contain strong higher modes but are generally decent quality so that the fundamental mode can be picked with confidence. However, the MASW dispersion curves do not adequately sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is of decent quality and the fundamental mode can be picked. Overall, the MASW and MAM dispersion curves agree well over a broad frequency band, so the MASW (forward and reverse direction) and MAM dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model has an RMSE of 8.26 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.4 percent. The final velocity model shows rapidly increasing velocity in the upper 5 m, then mostly constant velocity to 10 m, and steadily increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 158 m/sec, which places the site in the E class. This is within the predicted site class of D–E.

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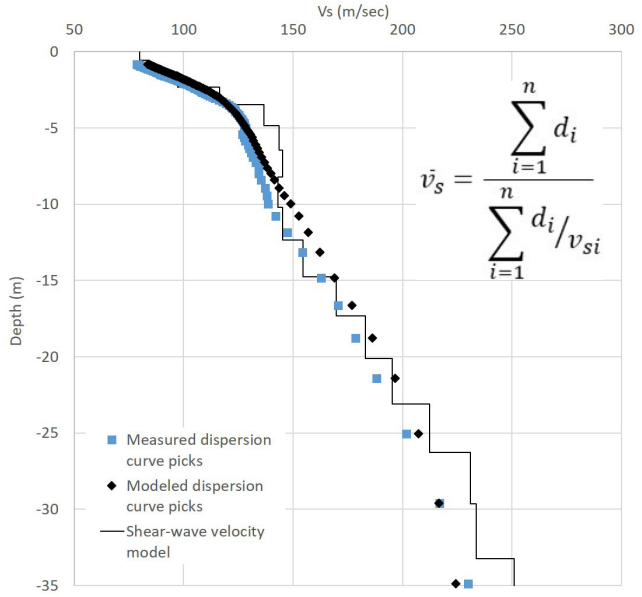


Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (V_S) for the upper 30 m is shown in the upper right corner. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

WOODLANDS ELEMENTARY SCHOOL

CENTRAL KITSAP SCHOOL DISTRICT, KITSAP COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

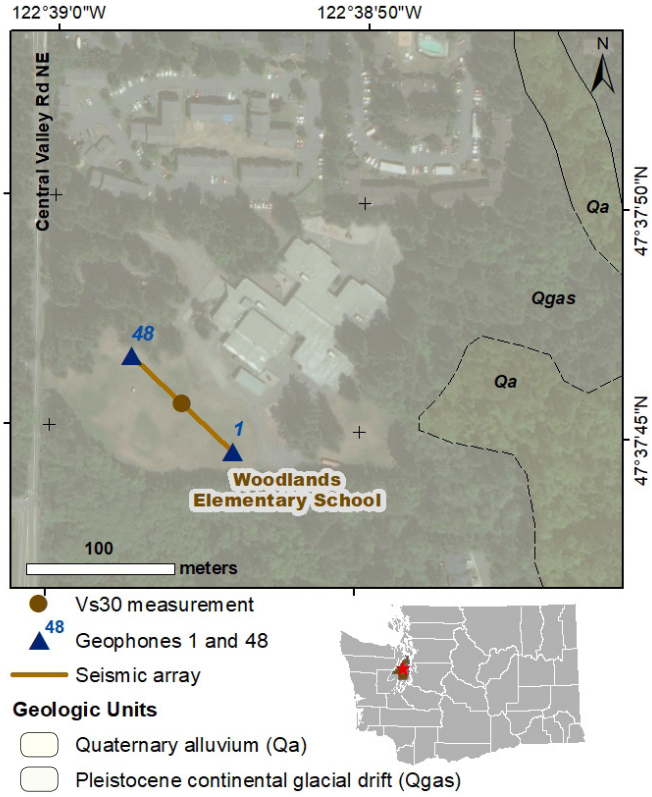
On April 16, 2021, a team from the Washington Geological Survey conducted a seismic survey at Woodlands Elementary School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on stiff soil, which would amplify ground shaking relative to rock.
- Site class is different from the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **D**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial drift (unit Qgas), consisting mostly of sand with some pebbles or silt. To the east is Quaternary alluvium (unit Qa).

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

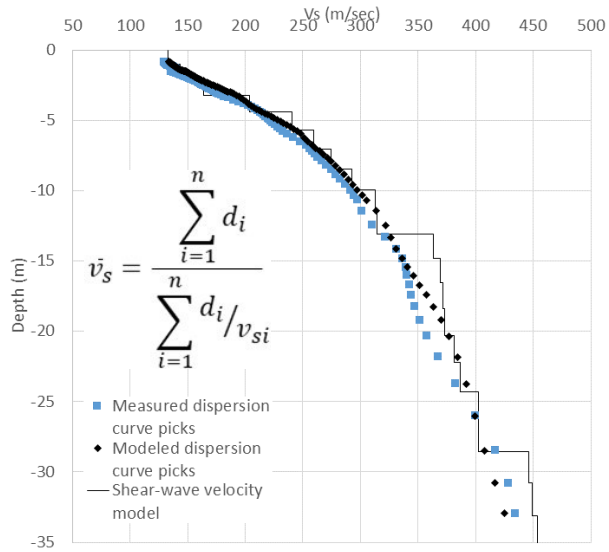
The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are poor quality so the fundamental mode can be picked with some confidence. However, the MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is decent quality, and the resulting dispersion curve depicts trends similar to the forward and reverse MASW dispersion curves, with some variance at higher frequencies. Therefore the three dispersion curves are combined into a single model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 12.0 percent. The inversion was carried out for seven iterations and resulted in a final model with an RMSE of 4.6 percent. The final model is unconstrained in the top 1 m (3 ft), and below this shows generally increasing velocity to 13 m (43 ft), then more slowly increasing velocity down to 30 m (100 ft). Our best Vs30 measurement is 295 m/sec, which places the site in the middle of the D site class. All initial and inverted models place this site within the D class, so the site can be confidently classified. This is different from the predicted site class of C.

GEOLOGY

The 1:24,000-scale geologic map places the school and array on continental glacial drift (unit Qgas), with Quaternary alluvium (unit Qa) closely to the east. The 1:100,000-scale geologic map, which is used to delineate site classes, has slightly different borders. This lower resolution map places the school and array on continental till with a predicted site class of C, and ~300 m to the east the map shows a sliver of Quaternary alluvium with a predicted site class of D–E. Nearby boreholes show clay, silt, sand, and gravel, often with hardpan layers generally ~12 m (40 ft) thick in the upper 30 m (100 ft). The 1D velocity structure does not indicate this hardpan layer is present under the school, so the change in site class could be due to lateral heterogeneity within the unit, or mismapping of the Qa unit borders.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.

WOODWARD MIDDLE SCHOOL

BAINBRIDGE ISLAND SCHOOL DISTRICT, KITSAP COUNTY, WA

WASHINGTON 2019–2021 SCHOOL SEISMIC SAFETY PROJECT SITE CLASS ASSESSMENT

WHAT IS SITE CLASS?

Site class estimates how local soils amplify earthquake-induced ground shaking, and is based on how fast seismic (shear) waves travel through the upper 30 m (100 ft) of the soil (Vs30). Site class has been approximated for the entire State of Washington, but these predictions aren't always accurate where geology is complex. The site class measured for this project accounts for geologic complexity and is therefore more accurate.

HOW DID WE MEASURE SITE CLASS?

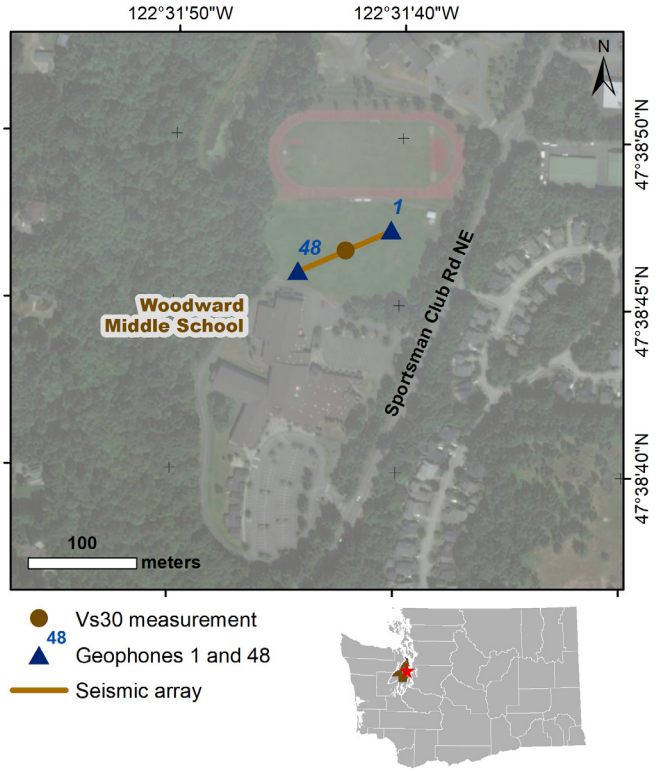
On October 7, 2020, a team from the Washington Geological Survey conducted a seismic survey at Woodward Middle School. We measured Vs30 by laying out 48 geophones (ground motion sensors) in a 94 m (308 ft) array. Then we conducted (1) an active survey in which a sledgehammer was struck against the ground to generate seismic waves; and (2) a passive survey where we measured ambient seismic noise. These surveys let us calculate Vs30 at the center of the array, which is then correlated to site class using the table below. It is generally accurate to assume the site class is the same under the array and the school.

WHAT DID WE LEARN?

- The school is built on soft rock or very dense soil, which would amplify ground shaking relative to rock.
- Site class is the same as the predicted site class of C.

Site class	Description	Vs30 (m/sec)	Ground shaking amplification
A	Hard rock	>1,500	Low
B	Rock	760–1,500	↓
C	Soft rock or very dense soil	360–760	↓
D	Stiff soil	180–360	↓
E	Soft soil	<180	High

MEASURED SITE CLASS **C**



Location of seismic array at the school campus.

WHAT SOILS ARE UNDER THE SCHOOL?

The school is sitting on Pleistocene continental glacial till, mostly a compact silt or sand-rich matrix containing sub- to well-rounded clasts.

GEOLOGIC HAZARDS AT THE SCHOOL

Liquefaction
Very low

Ground Shaking
Violent

Active Fault Proximity
Within 5 miles of an active mapped fault

See Washington Geological Survey Open File Report 2019-01 for more information.

TECHNICAL OVERVIEW OF RESULTS

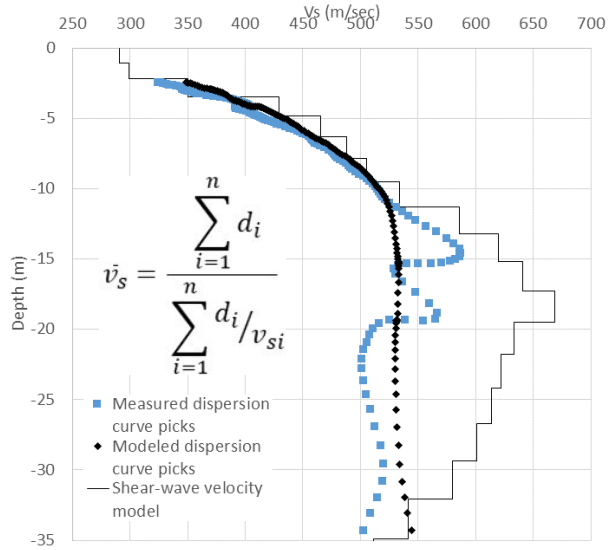
This section provides a technical overview of the geophysical methods and results of the seismic site characterization.

DISPERSION CURVE

The term dispersion image refers to the image of phase velocity versus frequency of a record. Dispersion curve refers to the manually picked fundamental mode in a dispersion image. The multi-channel analysis of surface wave (MASW) dispersion images from the forward and reverse directions are decent quality so that the fundamental mode can be picked with confidence. However, most MASW dispersion curves do not sample down to 30 m (100 ft). The microtremor analysis method (MAM) dispersion image is also decent quality, but does not sample the shallow layers. MAM and the forward and reverse MASW dispersion curves depict similar trends, therefore the three dispersion curves are combined into a single final model.

VELOCITY MODEL

An initial model was generated using the 1/3 wavelength approximation and the combined dispersion curves. The initial model had an RMSE of 7.5 percent. The inversion was carried out for five iterations and resulted in a final model with an RMSE of 4.4 percent. The final model is unconstrained in the top 2 m (7 ft), and below this shows generally increasing velocity to 18 m (59 ft), then a significant velocity reversal down to 30 m (100 ft). Our best Vs30 measurement is 524 m/sec, which places the site in the middle of the C site class. This is the same as the predicted site class of C.



Final inverted velocity model with measured dispersion curve and modeled dispersion curve. The equation used to calculate the average shear wave velocity (Vs) for the upper 30 m is shown in the middle left of the figure. d_i = thickness of any layer between 0 and 30 m. V_{si} = shear wave velocity in m/sec of the layer.