Coastal Erosion Management Strategy

Engineering and Geotechnical Techniques for Shoreline Erosion Management in Puget Sound

Coastal Erosion Management Studies, Volume 4

WASHINGTON STATE DEPARTMENT OF ECOLOGY

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Report 94-77

Shorelands and Environmental Assistance Program
WASHINGTON DEPARTMENT OF ECOLOGY
Olympia, Washington 98504-7600

Coastal Erosion Management Strategy

This report is one in a series or reports commissioned or completed by the Shorelands and Environmental Assistance Program of the Washington Department of Ecology in fulfillment of the Coastal Erosion Management Strategy project. The project is dedicated to seeking answers to questions on appropriate technical standards for coastal erosion management, the environmental impact of shoreline stabilization techniques, and the assessment and development of policy alternatives. The reports in the series are listed on page iii. Inquiries about the Coastal Erosion Management Strategy project should be directed to the project manager and series editor:

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Coastal Erosion Management Studies

Volumes in the Coastal Erosion Management Studies series will be published over a period of time. At the time of publication of this volume, the printing schedule was as follows.

Volume	Title	Status
Volume 1	Coastal Erosion Management Studies Executive Summary	Published January 1995
Volume 2	Coastal Erosion Management: Annotated Bibliographies on Shoreline Hardening Effects, Vegetative Erosion Control, and Beach Nourishment	Published June 1994
Volume 3	Inventory and Characterization of Shoreline Armoring, Thurston County, Washington, 1977 - 1993	Not published
Volume 4	Engineering and Geotechnical Techniques for Coastal Erosion Management in Puget Sound	Published June 1994
Volume 5	Shoreline Armoring Effects on Physical Coastal Processes in Puget Sound, Washington	Published August 1994
Volume 6	Policy Alternatives for Coastal Erosion Management	Published June 1994
Volume 7	Shoreline Armoring Effects on Living Resources and Coastal Ecology in Puget Sound, Washington	Published August 1994
Volume 8	Geotechnical and Land Use Techniques for Coastal Bluff Management in Puget Sound	Published August 1994
Volume 9	Regional Approaches to Address Coastal Erosion Issues	Published June 1994
Volume 10	Coastal Erosion Management in Puget Sound: Final Environmental Impact Statement	Not published
Volume 11	Coastal Erosion Management in Puget Sound: Technical and Policy Guidance for Local Government	Not published

Preface

The shores of Washington's inland coast—greater Puget Sound—undergo both shoreline erosion and landsliding. The overall rates of shoreline retreat are usually minor, maybe an inch or two a year, but in some areas may average as much as half a foot per year. This is usually due to a combination of bluff undercutting and steep slope failure, resulting in landslides. At any particular location, landslides occur infrequently, often decades apart. Simple shoreline wave erosion *by itself* is not often the problem in Puget Sound.

Marine shoreline erosion is a concern to both coastal property owners and the users and managers of coastal public resources. Coastal property owners are naturally concerned with protecting their investments in land and buildings. Unfortunately, houses and other buildings are often built dangerously close to the shoreline. Most property owners react to incidents of erosion by erecting erosion control structures such as concrete or rock bulkheads. If properly constructed, these shoreline armoring structures can slow most forms of wave induced shoreline erosion for a period of time, but will probably do little to prevent continuing landsliding. Many shoreline property owners consider shoreline armoring critical to the protection of their real estate.

Resource managers are, of course, concerned about any adverse effects on the habitats which support biological resources such as fish and shellfish and are charged with protecting the public property right in those resources. The scientific literature seems to indicate that shoreline armoring (and the associated vegetation clearing) typically results in the following adverse effects:

- Sediment supply to nearby beaches is cut off, thus leading to "starvation" of the beaches for the sand and other fine grained materials that typically make up a beach.
- The hard face of shoreline armoring, particularly concrete bulkheads, reflects energy back onto the beach, thus exacerbating beach erosion.
- In time, a sandy beach is transformed into gravel or cobbles, and may even be scoured down to bedrock, or more commonly in the Puget Sound basin, a hard clay. The footings of bulkheads are exposed, leading to undermining and failure.
- Vegetation which shades the upper beach is eliminated, thus degrading the value of the beach for spawning habitat.
- Any transformation of the character of the beach affects the kind of life the beach can support.

Request for Investigation and Assessment

The Thurston and Mason County Commissioners, and the Pierce County Executive, in 1991, requested that the Department of Ecology (Ecology) investigate the effects of wide spread shoreline armoring and prepare a programmatic environmental impact statement on the cumulative effects of bulkheading and other forms of armoring. These elected officials were reacting to the large numbers of bulkhead permit applications in recent years, and were voicing concern over their uncertainty about the wisdom of permitting large scale unmitigated shoreline armoring.

Legislative Action

In an action unrelated to the local government requests, the Washington State Legislature in 1992 passed *Engrossed Senate Bill 6128* which amended the Shoreline Management Act to provide for the following:

- Local governments must have erosion management standards in their Shoreline Master Programs. While most local governments have erosion sections in their SMP, these existing regulations may not be as comprehensive as ESB 6128 requires.
- These standards must address both structural and non-structural methods of erosion management. Structural methods are typically bulkheads or rip rap. Non-structural methods include building setbacks and other land use management approaches.
- The standards must give a preference for permitting of erosion protection measures for residences occupied prior to January 1, 1992 where the erosion protection measure "is designed to minimize harm to the shoreline natural environment." This implies no preference for protection measures first occupied after January 1, 1992.
- ESB 6128 expands erosion protection from just a residence to "single family residences and appurtenant structures."
- Permit application processing by local government must be carried out in a timely manner. Shoreline property owners testifying for the bill cited local government delays in permit approval as onerous. Local governments report that most permit delays are caused by incomplete or inaccurate information on the permit application.

The Coastal Erosion Management Strategy

The legislature was unable to provide local governments or Ecology with the funds necessary to carry out the intents of ESB 6128 because of reduced tax revenues. Fortunately, Ecology was successful in obtaining a grant under the federal Coastal Zone Management Act to carry out a comprehensive Coastal Erosion Management Strategy.

CEMS—the Coastal Erosion Management Strategy—is a three year, multi-task program aimed at (1) satisfying local elected officials' requests for assessment of the cumulative effects of shoreline armoring, (2) developing the standards for shoreline erosion management mandated by ESB 6128, and (3) assessing regulatory alternatives for erosion management. Tasks 1 - 4 were completed in 1992-93. Tasks 5 - 7 were completed in 1993-94, and tasks 8 and 9 in 1994-95.

Task 1. Inventory and Characterization of Shoreline Armoring, Thurston County, Washington, 1977 - 1993. Thurston County was selected as the study area for a pilot project because of the availability of large amounts of relevant information already in data management and GIS (geographic information system) computer file formats. This study provides quantitative estimates of the rate and character of shoreline armoring which are not readily available for most of Puget Sound.

Task 2. Engineering and Geotechnical Techniques for Shoreline Protection in Puget Sound. The generally accepted engineering and geotechnical techniques for selected erosion management alternatives (bulkheading, revetments, wave attenuation, beach nourishment, etc.) appropriate to the tidal range, wave energy, and geologic conditions characteristic of Puget Sound are assessed. This report provides the basis (in part) for development of State guidance recommendations to local government for adoption of standards for appropriate erosion management measures.

Task 3. Shoreline Armoring Effects on Physical Coastal Processes in Puget Sound. The key assumptions and questions about the effects of shoreline armoring on coastal processes are evaluated based on the technical literature, and sensitized to Puget Sound conditions. Selected local case examples are provided.

Task 4. Coastal Erosion Management Regulation: Case Examples and Critical Evaluation. Regulatory approaches to coastal erosion management in Puget Sound and other states are evaluated, and policy alternatives for Washington are assessed. This report will provide the basis (in part) for development of State guidance recommendations to local government for adoption of coastal erosion management procedures.

Task 5. Shoreline Armoring Effects on Biological Resources and Coastal Ecology in Puget Sound. Following on from Task 3, the direct effects of shoreline armoring and the secondary effects of changes to coastal processes and conditions upon biological resources are assessed. Selected local case examples are provided.

Task 6. Coastal Bluff Management Alternatives for Puget Sound. A large measure of bulkheading is in reaction to slope failures, not shoreline erosion *per se*. Slope instability is caused by a combination of inherent geologic weaknesses, ground water loading, and toe erosion. Following on from tasks 2 and 4, this task addresses coastal bluff management alternatives.

Task 7. Regional Approaches to Coastal Erosion Management. Traditionally, shoreline management and erosion control permitting has been on a case-by-case basis. Many "soft" approaches to erosion management (e.g. beach nourishment) or mitigation for adverse effects must be carried out on a regional basis to be effective. Both the technical and political feasibility of regional erosion management is assessed.

Task 8. Coastal Erosion Management Environmental Impact Statement. This task will integrate the special study reports and other information into a programmatic environmental impact assessment.

Task 9. Coastal Erosion Management Recommendations for Puget Sound. Based largely on the foregoing studies, this task will formulate specific model elements which can be recommended as amendments to local Shoreline Master Programs. The guidance will be published as a chapter in Ecology's *Shoreline Management Guidebook*.

Task 1, Inventory and Characterization, was completed by Thurston Regional Planning Council. Tasks 2 through 7 were completed CH2M Hill and Battelle Memorial Laboratories under contract to Ecology. Tasks 8 and 9 will be completed by Ecology.

Tasks 1 through 7 are each designed to answer a relatively narrow set of questions, therefore each task completion report presents only a very limited portion the study. Until the entire project has been completed, the analytical studies have been integrated (Task 8), and Ecology has developed its guidance to local government (Task 9), no conclusions should be drawn from the individual study reports.

This volume, *Engineering and Geotechnical Techniques for Shoreline Erosion Management in Puget Sound*, reports on various techniques which are *technically* appropriate for application to coastal erosion management in Puget Sound, but not necessarily under all environmental, regulatory, or economic circumstances. The Department of Ecology is not endorsing these techniques as universally useful. The purpose of this task in the CEMS project was to provide Ecology with some of the information necessary to make recommendations to local government for amending their Shoreline Master Programs in accordance with the mandates of ESB 6128. That guidance will be issued by Ecology in a later volume in this report series.

The CEMS project is a balancing of concerns and mandates. The Shoreline Management Act (SMA) has goals of both "planning for and fostering all reasonable and appropriate uses" while at the same time "protecting against adverse effects to the public health, the land and its vegetation and wildlife, and the waters of the state and their aquatic life." ESB 6128, in amending the SMA, gave a preference for permitting of erosion protection measures for residences occupied prior to January 1, 1992 where the erosion protection measure "is designed to minimize harm to the shoreline natural environment."

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The principal author of this report is Jack Cox, M.S. Engineering (Purdue University), P.E., a Senior Coastal Engineer with CH2M HILL in Seattle. Additional editorial contributions were made by Keith Macdonald, Ph.D., Oceanography (Scripps Institution of Oceanography), and Tom Rigert, M.S. Physics (Renssalaer Polytechnic Institute). Dr. Macdonald is also the Project Manager for the Coastal Erosion Management Strategy contract.

We owe special thanks to the following individuals, each of whom reviewed our draft report and offered constructive suggestions for improvements: Douglas Canning and Hugh Shipman, both with the Washington Department of Ecology's Shorelands and Coastal Zone Management Program; Ken Bates, P.E., and Neil Rickard, both with the Washington Department of Fisheries; and Professor Richard Sternberg, a specialist in nearshore processes and sediment dynamics at the University of Washington School of Oceanography.

Additional valuable insights were provided by coastal geomorphologist, David Simpson, M.S., P.E.; and environmental policy specialist, Gretchen McCabe, M.S., and marine ecologist, Ronald Thom, Ph.D., both with Battelle.

Materials used to prepare the technical "cutsheets" in Appendix A are drawn from a wide variety of sources that are acknowledged directly in the text and graphics. Report graphics were prepared by Dennis Kirby and Chris Sutton; text word processing was accomplished under the direction of Mary Morris.

We particularly acknowledge our thanks to Douglas Canning and Hugh Shipman, Ecology's Project Mangers, who provided leadership and encouragement to bring this study to a fruitful conclusion.

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1. Introduction

A wide variety of different techniques has been used to control shoreline erosion throughout the world. Most often these have been in the form of "hard" structures consisting of building an erosion-resistant barrier along the shoreline to keep the land from retreating. More recently, the beach itself has been recognized as an effective wave attenuator or breakwater, and efforts have focused increasingly on trying to retain the beach in a sufficiently competent form so that it protects adjacent lands from loss or damage.

No erosion control technique is, by definition, good or bad; rather, each has its limits of performance. The technical feasibility and effectiveness of a particular technique are determined by the setting for the application; what might work in one setting might not work in another. Simply copying a method used successfully elsewhere does not necessarily assure a satisfactory result.

The principal factors that determine a technically appropriate shore protection technique for a specific location include the local shoreline geology, the wave energy regime, and the ultimate goals of the landowner in altering the shoreline. Often only the first and second factors are used in defining an appropriate solution, without regard for the third. Selection of a shoreline protection technique, however, must also consider the intended function. Other factors such as resources and regulatory agency acceptability, desired period of performance, and acceptable economic risk also must be considered by the property owner but are specifically excluded from this evaluation.

Scope of Study

This report presents a range of shoreline protection techniques that are technically feasible for shorelines around Puget Sound. For reasons outlined in the Preface, this review emphasizes residential applications. The methods include construction of traditional hard structures as well as "soft" solutions that use natural site features or materials. The two solutions most often found today in Puget Sound-poured in place vertical concrete bulkheads and near-vertical placed rock walls-represent only a small portion of the options available. Soft alternatives include creation of new beaches as barriers, introduction of erosion-resistant vegetation, dewatering of the beach face, and many others. Also presented are feasible composite systems that combine individual hard or soft techniques, as well as quite different nonconstruction-related activities such as building setbacks and drain field removal.

The shoreline protection techniques presented in this report were selected from a compilation of new and traditional techniques that have been applied throughout North America and abroad. Special attention was given to parts of the United States that have shoreline conditions similar to those in Puget Sound, particularly the Great Lakes and the bays of the East Coast (O'Neill, 1985, 1986; Shorelines, Inc., 1992). Particular emphasis is placed on the current best management practices for shoreline protection already in use in Washington State (Canning, 1991). Additional information regarding local construction practices and materials was obtained from the literature as well as from Puget Sound area construction contractors.

Besides identifying the range of feasible shore protection techniques, this report presents a ***site-specific decision model*** to assist regulatory staff and property owners in the selection of methods that are technically suitable for a particular site. This model enables an interested party to start with a definition of need (purpose and goals) and a characterization of the site's natural features and to develop a list of suitable methods for arresting shoreline erosion at that particular site.

The physical and biological impacts that might result from use of the alternative shoreline protection techniques are not addressed in this report. These impacts are described in the technical reports produced for Tasks 3 and 5 of this same contract. Once identified, the physical and biological impacts can be added to the results of this technical suitability analysis to help select the most appropriate shoreline protection techniques for specific locations.

The primary purpose of this report is to provide the Washington State Department of Ecology (Ecology) with information on the engineering and geotechnical approaches to shoreline protection that are ***technically feasible*** for use in Puget Sound. This broad array of technically feasible approaches to regional shoreline protection must next be assessed for compatibility with existing regulatory authorities such as the Shoreline Management Act, the Hydraulics Code, and local Shoreline Master Programs. Such an assessment might indicate that, due to environmental or other regulatory requirements, some approaches may not be appropriate at particular sites.

Study Approach

Technically feasible shore protection techniques for Puget Sound were selected in a process that began by compiling a comprehensive list of potential techniques. These methods included approaches used successfully in the past as well as the most recent improvements. Major literature sources that were reviewed are listed in Section 6, References.

All the techniques identified were then screened for their technical effectiveness in meeting the intended shore protection function under the range of shoreline geological conditions and wave energies that occur in Puget Sound. A separate screening was performed for each of the three factors (function, geology, and wave energy) to ensure thorough consideration of engineering performance under the various conditions that occur in Puget Sound. During the screening process, techniques not suited for Puget Sound were eliminated.

The techniques were rated for their ***technical feasibility*** and ***effectiveness*** on the basis of evaluations published in the literature, modified by the direct engineering experience and judgment of the team's senior coastal engineers. The point of view taken during this rating process was that of an individual waterfront land parcel owner who desires shore protection (i.e., erosion control) without consideration of potential impacts to adjacent properties. (These potential impacts are discussed in the Task 3 technical report.)

Following selection of the feasible alternatives, ***general design guidelines*** were developed for each shore protection technique. These guidelines provide enough information to aid in selecting specific methods for a particular site but cannot be used by themselves to design a site-specific application. Additional professional engineering evaluation and design will still be necessary for the construction of a suitable shore protection system for a specific site.

Organization of Report

Following this introduction, Section 2 provides a brief description of the basic physical processes involved in coastal erosion. This discussion focuses on the forces involved and the spatial and temporal characteristics of shoreline change.

Section 3 presents information for use by shoreland regulators and landowners in determining site characteristics that affect selection of an appropriate shoreline protection technique. This information includes the types of functions that shoreline protection could provide for an individual property owner. Also given is a list of questions to help a landowner determine the goals of shore protection for a specific site. The section then describes typical Puget Sound settings in terms of landforms and wave energies.

Section 4 provides a list of 20 technically feasible shore protection techniques for Puget Sound. The acceptable methods are grouped into categories of hard, soft, composite, and nonstructural activity solutions. They are rated for their applicability to the landowner's desired function, the site landform, and the site wave energy. Significant advantages and disadvantages of particular techniques are compared. The literature consulted in developing the list of feasible methods is listed in Section 7, Works Cited.

A site-specific decision model is given in Section 5 for use by shoreland regulators and landowners who desire to select a technically feasible shore protection method for a specific property on Puget Sound. This model provides a sequence of steps for generally categorizing a site, then using the information in Section 4 to choose the most technically suitable technique. To facilitate the decision process, general design guidelines for each technique are provided in Appendix A.

2. Erosion Processes

Erosion in Perspective

The shore zone-where land meets sea-is one of the most active, dynamic, and constantly changing environments on the earth's surface. This holds true for the protected waters of Puget Sound as well as along the open ocean coast, although the magnitude and rates of shore processes are generally lower in Puget Sound.

As the energy contained in ocean waves is dissipated on the shoreline, sediments are in a continual state of flux as erosional and depositional processes strive to reach a dynamic equilibrium. Wave erosion, smoothing out shoreline irregularities, contributes sediment to the adjacent beach. These beach sediments are continually reworked and transported by wave-driven alongshore currents until they are eventually lost to some depositional sink. This "river of sand," continually moving along the shoreline, provides a critical natural defense of the land against the waves. Structural intervention along the shore often disrupts this natural line of defense resulting in increased, rather than decreased, erosional problems.

Bascom (1980) provides an excellent, reader friendly, general account of these shoreline processes; Downing (1983) focuses on how such processes impact Puget Sound; and Silvester and Hsu (1993) present more recent innovative concepts for dealing with coastal stabilization.

The purpose of this introduction is to stress that erosion along the shore is not inherently "bad"—indeed the feeding and nourishment of the shoreline with an adequate supply of sedimentary material provides the best natural defense against excessive erosion. Further, awareness of the inevitability of coastal erosion, and its generally episodic nature, provides a more rational framework for long-term management of both coastal resources and coastal development.

Erosion in Puget Sound

This section provides a general description of the physical processes that influence shoreline erosion with emphasis given to the causes and effects of erosion typical of the landforms and wave characteristics of Puget Sound. Knowledge of these local erosion characteristics is essential for identifying feasible shore protection techniques.

The shoreline of Puget Sound consists primarily of steep bluffs fronted by narrow beaches. The bluffs and beaches are interconnected, and a change in one affects the other. As shown in Figure 2.1, loss of beach material exposes the base or toe of the bluff to wave attack and scouring of material from the toe. When sufficient material is removed, toe support for the bluff face is lost, and the bluff face becomes oversteepened. A slide or collapse of all or a portion of the face occurs and progresses until a new stable angle of repose is established on the bluff face. Material that has slumped onto the beach is gradually eroded away, reexposing the toe of the bluff and initiating the erosion cycle again.

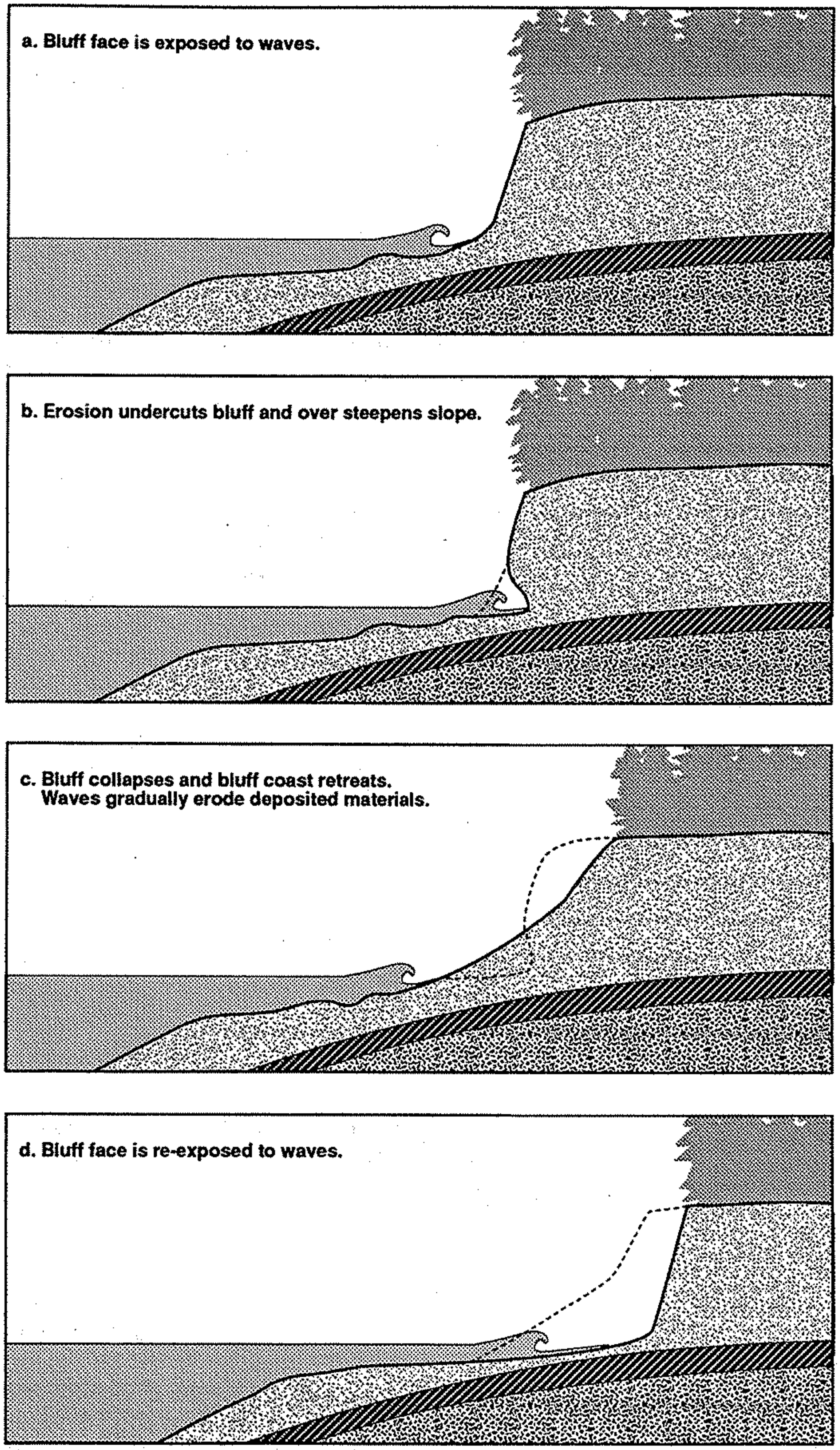


Figure 2.1 Typical bluff failure sequence resulting from toe erosion

Figure 2.2 shows that this pattern of toe erosion, slumping, deposition, and erosion causes episodic shoreline changes that are fundamentally different from the long-term trends. Over time intervals of at least 10 years, but more often 20 to 30 years, the rates of retreat of a bluff crest and bluff toe have been found to be generally equal. However, during time intervals of 5 years or less, the rate of retreat of either toe or crest could be as much as four times as large as the other, depending on which stage of instability (toe loss or crest loss) is occurring (Sunamura, 1982a). Therefore, short-term assessments of erosion rates are not good indicators of the average, long-term erosion rate at a site.

Similar phenomena occur when a bluff failure is caused by surface water runoff or excessive groundwater discharge through the bluff face. This can be due to natural seeps and springs or to excess water caused by building and roadway runoff, landscape sprinkling, or septic field discharge. Increased water content lowers the friction between soil particles, allowing the bluff face to slide more easily. The primary difference between toe-related slope collapse and ground or surface water-induced failures is that toe failures tend to originate at the bottom of the slope and propagate up the face while ground and surface slumping usually starts higher on the slope.

The landowner's observations of the loss rate of property commonly reflect the maximum short-term loss rate rather than the average long-term rate of loss. Solutions that treat bluff collapse must be able to accommodate the episodic failure, but the need for and scale of the solution should be based on the average rate, which represents the actual risk to the property. If a bluff face has already been brought to equilibrium, the strategy for future defense need be based on only an average loss rate and not the higher episodic loss rate.

The offshore to onshore slope of a beach (called the beach profile), is dictated by the immediate wave environment. During times of little storm activity, waves tend to be long and flat so that waves running up on a beach will percolate down through the substrate rather than running back on the surface. In this process, sediment is carried up onto the beach and becomes deposited there. This condition is often referred to as a summer beach profile because, in the typical summer wave environment, beaches are rebuilt (Figure 2.3, top).

When winter storms occur, the waves tend to be steeper, and run-up on the beach is more vigorous. The upper beach face quickly saturates so that percolation of the run-up is inhibited. The saturated beach sand is easier to displace, and much of the sand is carried back offshore in the return cycle of the wave where it is deposited in a less energetic environment. The dry beach area then has the appearance of narrowing. This condition is referred to as a winter profile (Figure 2.3, bottom) and is associated most often with severe winter storms.

This seasonal variation in beach profiles shows that the "total beach" is not simply the visible dry portion but is also the underwater area that includes the transported sand. As the storm waves diminish, and the waves flatten, the upper beach begins to rebuild again. Without other influences to add or remove sand, a long-term balance will develop with the sand that is lost and recovered. The beach will then be in equilibrium although the dry beach width can vary with time.

Beach and bluff processes, however, are not limited to the cross-shore direction alone. The material taken from the bluff face and placed on the beach is also spread along the beach in downdrift areas. Downdrift areas are the pathways of sand movement driven by waves that impinge on the shoreline at an angle. This alongshore (parallel to the shore) sand movement behavior is depicted in Figure 2.4.

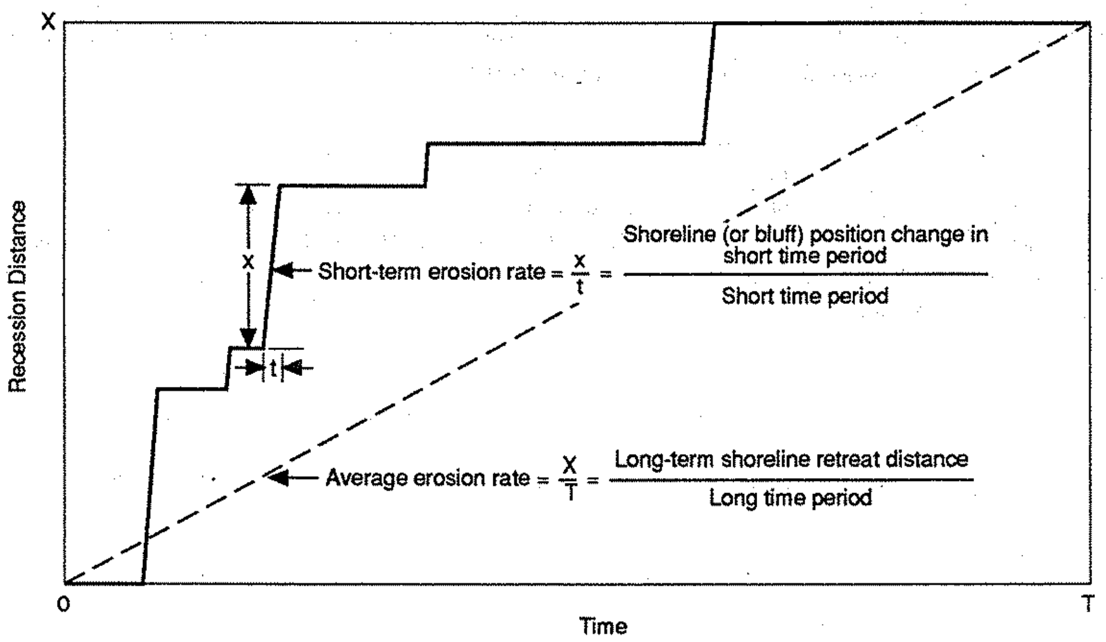


Figure 2.2 Short-term vs. average bluff erosion rates

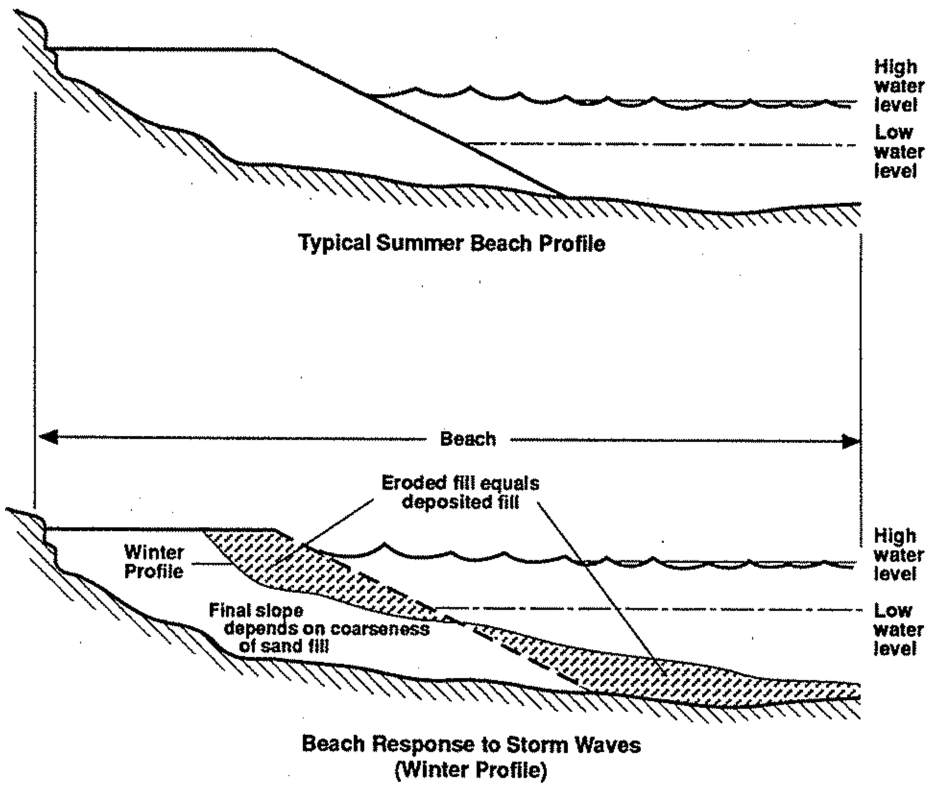


Figure 2.3 Summer and winter beach profiles

Because there is a continuous alongshore transport applied to the beach, a continual supply of sand must be maintained, or the beach will narrow and bluff toe erosion will begin. The angle at which the wave strikes the beach determines how much power exists to push the sand along. The rate and direction of sediment movement vary with the changing wind directions and waves are also a function of the size of the material being moved.

Changing wind and wave directions interacting along an irregular shoreline create areas of faster and slower sediment transport. Beaches with faster moving sediment tend to be erosive, and those with slower movement tend to be depositional. Between the two extremes are equilibrium beaches where new sand entering the site is in balance with old sand leaving. Depositional areas are defined as sediment sinks, and eroding areas, as sources. Sources also include slumping bluffs and river mouths, which deliver a new supply of sediment to the alongshore sand transport system. The coastline can be divided into a series of sediment source-to-sink units, called drift sectors (drift cells; Figure 2.5), each of which is self-contained.

If a supply of sediment is lost, either by damming a stream discharge or preventing erosion in a particular area, the deficit must be recovered elsewhere because the driving force of wave action is spatially continuous. When particular reaches of shoreline have been starved of a sediment supply, the potential of the waves to move the sediment can far exceed the available material to be moved. In such cases, reintroducing sediment might not restore the shoreline, nor will hardening the shorelines necessarily change it further.

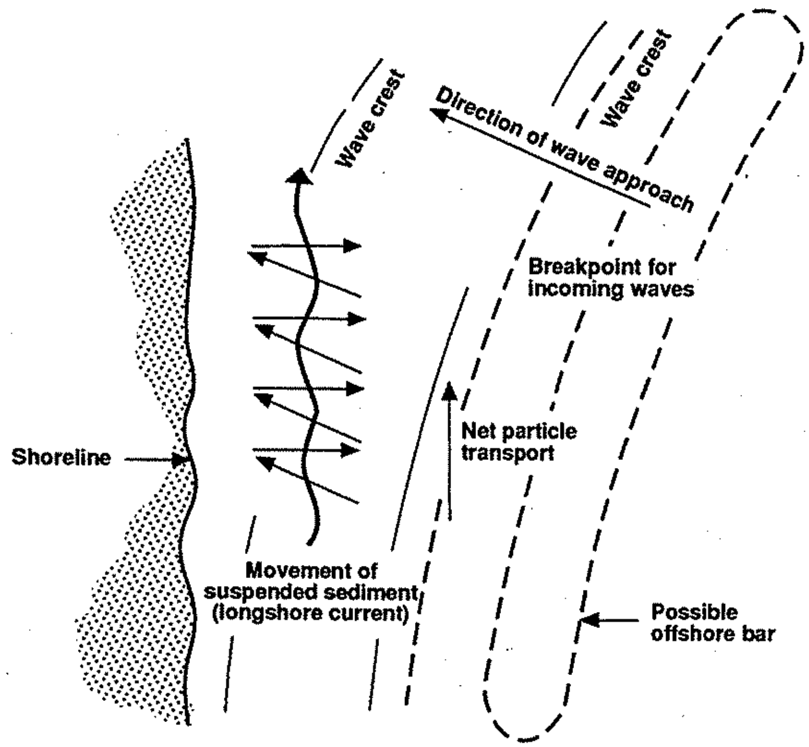
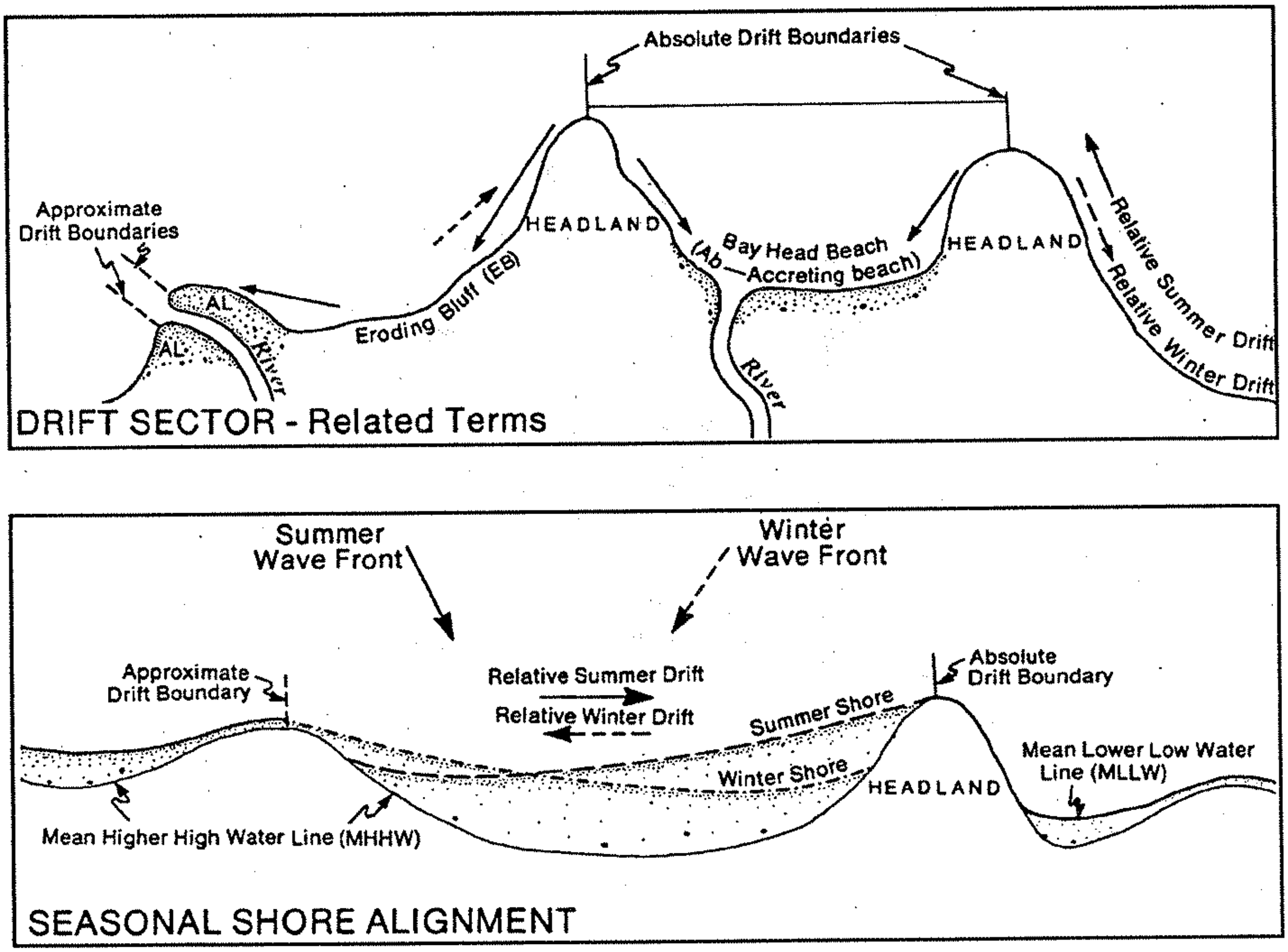


Figure 2.4 Alongshore sedimant transport



Source: Coastal Zone Atlas of Washington, 1977-1980.

Figure 2.5 Typical drift sectors

3. Identification of Erosion Problem

This section presents information that will enable property owners and regulators to identify the site characteristics that will determine the best solution for a specific shoreline erosion problem.

The shore protection goals of the property owner play a significant role in determining the technical feasibility of a specific shore protection method. Some shore protection applications are industrial in nature, with intended uses that are not for erosion control alone but also provide other uses such as docks and vessel terminals. Other methods are intended to work as part of a large-scale master plan and might not be suited for individual property sites with only limited shoreline frontage. This discussion focuses on the shoreline alteration needs of a residential property owner with limited shoreline frontage and financial resources. The following goals are considered to address residential erosion management needs:

- Slow shoreline retreat. Prevent the present position or shape of the shoreline from changing.
- Prevent toe erosion. Block wave action from reaching the toe of steep bluffs and causing erosion and eventual collapse of the slope.
- Prevent bluff collapse from nonwave causes. Provide additional buttressing to a slope to prevent collapse from forces or influences that occur on top or inside the bluff.

To aid in identifying the appropriate shore protection solution for a particular site, Table 3.1 lists questions that can be used to link a site's observable natural characteristics to the goals listed above. A positive response to these questions could indicate the applicability of the goal to that site. Positive responses in more than one category would suggest that the solution might need to serve several goals.

Geology or Landform

The relatively protected shores of Puget Sound are not exposed to the continuous pounding of surf experienced along the open ocean coastline. The large tidal range that characterizes the Sound also generates beach forms that differ from those of East Coast estuaries, and the biologically highly productive and sensitive nearshore makes Puget Sound distinct from bluffed shorelines of the freshwater Great Lakes.

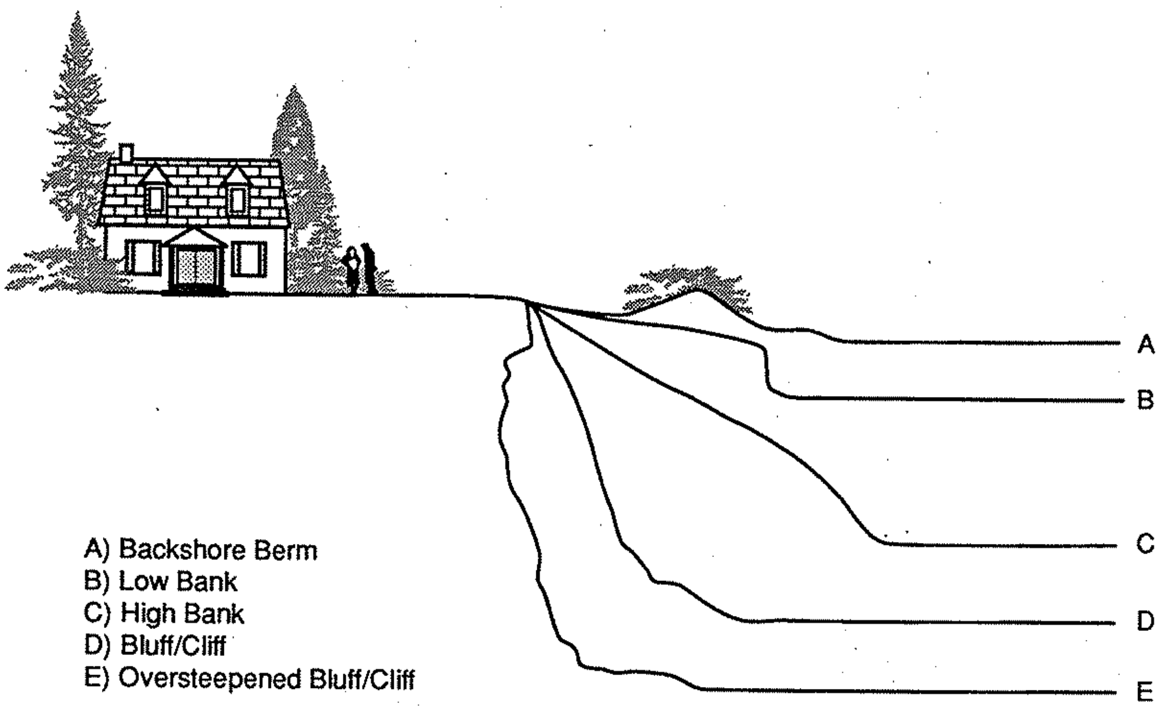
Excellent, well-illustrated accounts of the geology and landforms of Puget Sound shorelines are provided in several popular texts such as *The Coast of Puget Sound, Its Processes and Development* by John Downing (1983), *The Shape and Form of Puget Sound* by Robert Burns (1985), and *Living with the Shore of Puget Sound and the Georgia Strait* by Thomas Terich (1987).

Table 3.1 Questions for Establishing Shore Erosion Causes	
Shoreline Retreat	
1.	Has the summer dry beach lowered or the beach position shifted landward over a period of 2 or more years?
2.	Is the beach composed of a thick layer (i.e., greater than 2 feet) of sand or silt?
Toe Erosion	
1.	Does the bluff or bank toe lack mature vegetation (i.e., with bushes or trees)?
2.	Has the bluff or bank toe position retreated noticeably?
Bluff Instability from Nonwave Causes	
1.	Is the bluff or bank slope largely unvegetated and scored with erosion channels?
2.	Are there signs of drainage, water seeps, mudflows, or slumps on the face of the bluff or bank?

Puget Sound is generally characterized as being rimmed by bluffs, frequently fronted with tidal flats exposed at low tide. In most areas, the bluffs reach to the water's edge and are steep and unstable. In some areas, low flat deltas exist, usually at the mouth of rivers and streams; for example, the Nisqually and Nooksack Deltas. In a few areas, such as the San Juan Islands, the shoreline is rocky. Because a large preponderance of the shoreline is bluffed, a common erosion-related change in the shoreline is a bluff failure, which causes large masses of material to collapse episodically (Tubbs, 1975). In these individual events, the local erosion rate appears large; however, the occurrence of these failures is so infrequent that the average erosion rate of the same shoreline might be only 10 percent, or less, of the localized episodic rates.

The Puget Sound shoreline (Figure 3-1) can be generally characterized as including four distinctive landforms:

- Marshes
- Beaches
- Banks
- Bluffs



Source: Myers Biodynamics, 1993.

Figure 3.1 Typical Puget Sound coastal slope profiles

Marsh areas (not illustrated) tend to be located in relatively quieter water (low-energy) settings at the distributaries of rivers, streams, and creeks. They are low and flat, are often inundated at high tide, and have vigorous growth of vegetation. They are classified as sensitive coastal wetland habitats critical to fish life and are subject to very rigorous regulatory controls.

Beaches along Puget Sound are flooded to varying degrees by the tides. Typically, "dry beaches" are narrow but are fronted by broader intertidal flats. Beaches may include berms and backshore areas that can be repositories of significant woody debris and are characterized by distinctive vegetation. Beach sediments range in texture from fine sand and mud to coarse gravel and cobbles; the coarser the material, the steeper the beach. Depending on the energetics of the site, beaches can front a marsh area.

Banks are typically 5 to 10 feet tall. A beach might or might not be present in front of the bank. Banked shorelines are the most common area for recreational or residential development because of the presence of dry land close to the water.

Bluffs are higher than banks and around Puget Sound are usually formed from various layers of glacial till, sands, and clays. The different layers in the bluff affect groundwater seepage and influence the stability of the slope. Banks and bluffs can be eroded by material being washed away from the base or toe, causing a slumping of the slope, or by slippage upslope as a result of ground or surface water runoff (Tubbs, 1975).

A fifth shoreline type, exposed bedrock, also appears in some areas of Puget Sound, such as the San Juan Islands. Because bedrock is erosion-resistant, erosion remedies are rarely necessary.

Wave Energy

Shoreline landforms and protection structures are resistant to damage from wave action up to certain threshold levels. For "soft" unprotected shorelines, the apparent rates of change are gradual but tend to increase substantially as certain wave heights are experienced. In "hardened" artificially armored shoreline situations, the threshold is more distinct, with damage appearing more abruptly once a certain wave state is reached.

The U.S. Army Corps of Engineers (Galveston District, 1975) determined that a 2-foot wave can break a nailed wall away from its footing. Similarly, the majority of substantial changes in beach forms first seem to appear when waves approach 2 feet in height. Sunamura (1982b) found that virtually all wave-induced erosion of bluffs could be attributed to waves in excess of 2 feet. The rate of erosion was directly related to the fraction of the year when wave heights exceeded 2 feet and the proportion of time that tides allowed the waves to reach the base of the bluffs.

The Federal Emergency Management Agency (FEMA), which publishes maps for flood-risk insurance purposes, has adopted similar standards also using waves in excess of 2 feet as a delineation between a low-risk erosion environment (AH-Zone) and a higher risk environment (AO-Zone). In the highest risk environment (V-Zone), where waves are 4 feet or larger, the erosive power changes dramatically because the doubling of the wave height increases its damage potential by a factor of four.

The shoreline wave environment of Puget Sound can be subdivided into these same three levels of exposure. These categories are presented as wave roses at various locations in the *Washington State*

Department of Ecology Coastal Zone Atlas (1977-80). For simplicity, the three levels of wave exposure may be considered low energy, moderate energy, and high energy, respectively. The fetch length (i.e., distance the wind blows over the water to generate waves), wave height, and FEMA classes representative of each of these three exposure levels are listed in Table 3.2.

Low-energy environments are typified by waves that do not exceed 2 feet in the worst events. The shoreline would have a FEMA classification of AH or would be unclassified. The sites might experience small boat wakes, have short fetches (less than 1 mile), or have wide, shallow, flat foreshores. Many south Puget Sound shore areas are in the low-energy classification. Bluffs in these areas are not likely to suffer significant wave-induced erosion although south-facing beaches can be affected by major storm events that sometimes move in from the south north-facing beaches also can be eroded by storms with a much smaller recurrence frequency.

Table 3.2 Site Wave Exposure Classification

Wave Energy	Fetch Length (miles)	Nearshore Wave Height (ft)[a]	FEMA Class[b]
Low	0 - 1	0 - 2	AH
Medium	1 - 5	2 - 4	AO
High	>5	>4	V

[a]Wave height calculated for 30-mph wind speed, 30-foot water depth, and adequate time for full wave development.
[b]AH-Zone, floods areas with ponding of 1 to 3 feet.
AO-Zone, floods areas with 1 to 3 feet sheet flow.
V-Zone, floods areas with wave heights of 4 feet or greater.

Moderate-energy environments are those with waves no more than 2 to 4 feet in height. These shore areas would appear as AO-Zones, or have a V-Zone abruptly change to an A-Zone at the "hard structure line" on a FEMA flood insurance map. These environments are characterized by frequent large boat wakes, longer fetches (1 to 5 miles), and steeper shorelines. The majority of central Puget Sound shorelines fit into this moderate-energy classification.

High-energy environments are characterized by waves reaching the shore that are greater than 4 feet in the worst event. The V-Zone boundary on a FEMA flood insurance map would appear well landward of the water's edge. These sites typically have a long fetch (greater than 5 miles), with waves generated over deeper water. This high-energy environment in Puget Sound is typified by the western shores of Whidbey Island, which face directly into the Strait of Juan de Fuca. Other locations receiving 4-foot waves include portions of Whatcom County, the south San Juan Islands, and north Jefferson County. Local shores can also be affected by major storm events characterized usually by strong southerly winds.

The above classifications are based on a wave climatology, or long-term characterization of the wave conditions. It is always possible for a specific site classified in one energy level to occasionally experience conditions typical of a higher energy level. Therefore, an energy designation should not be viewed as a "maximum engineering design condition" but, rather, as the typical environmental condition of a particular site.

4. Feasible Shore Protection Techniques

This section describes the shore protection techniques considered technically feasible for Puget Sound sites. The applicable approaches are first described as a full range of possible techniques, organized as hard, soft, composite, and activity-type solutions. The individual shore protection techniques are then rated for applicability to specific goals, landforms, and wave energy regimes.

Feasibility Criteria

Identification of technically acceptable shoreline erosion defense strategies was based on three criteria: the real operational need for protection, the geologic or landform setting of a particular site, and the degree of exposure of the site to erosion. The operational need incorporates the owner's intended use of the waterfront and considerations of how the erosion is occurring—i.e., Is a bluff being undercut? Is there danger of waves running up onto a property? Is a fronting beach disappearing? The geologic or landform setting provides a practical limit to the types of solutions that might be employed, in terms of both how prone to erosion the site might be and how compatible the site is with certain construction types. The degree of exposure of the site determines how aggressive or robust a solution must be both to survive and to perform as intended.

The three criteria also provide a basis for focusing shore alteration techniques specifically appropriate to Puget Sound. The combinations of landform, site exposure, and operational needs create unique combinations for possible solutions. For example, Puget Sound shorelines tend to have less active recreational use than elsewhere in the country. Hence, the need for broad expanses of beach for public use is reduced, allowing for the possibility of leaving the shoreline less accessible. At the same time, the relatively protected waters of the Sound, in comparison to other shorelines, afford opportunities to apply large-scale, natural-appearing solutions that are inherently native in appearance but can tolerate only limited wave attack. This introduces an opportunity to promote the clear preference stated in the Washington Shoreline Management Act to "preserve the natural character of the shoreline." The unusually rich and widely recognized biological resources of Puget Sound further reinforce the potential importance of protecting natural shoreline characteristics.

Range of Appropriate Techniques

Protecting the shoreline from erosion can take the form of "hard" construction and armoring methods, "soft" methods such as beach nourishment, composite methods combining both hard and soft components, and nonstructural activities (see Task 4 report [Volume 6]) that involve local zoning or land use regulations. Soft solutions do not necessarily imply unaltered natural protection; rather, they refer to a compliant method that can naturally deform and adjust over time in response to changing shore conditions. Composite methods are an incorporation of both hard and soft methods and possibly activities. Within each of these primary groupings, several of the techniques can be further subdivided into in-water and out-of-water concepts.

The shoreline protection methods presented here are a synthesis of numerous methods applied in both Puget Sound and in other geographic areas with similar geologic and climatic conditions. Because

Puget Sound shorelines consist primarily of bluffs, and the waters are reasonably protected, typical open-ocean coast methods are not generally applicable. The bodies of water that offer the best models for physical comparison of erosion control methods are the bluffed bays of the East Coast, specifically the Delaware and the Chesapeake (Shorelines, Inc. 1992), and the shorelines of several of the Great Lakes (O'Neill, 1986; Keillar and Miller, 1987; SEWRPC, 1988). None of these methods represents exactly the same environments, however, because of the much greater tidal range experienced in Puget Sound and because of different regional emphases on shoreline uses versus nearshore biological productivity. However, most of the elements of these model shorelines do offer reasonable parallel conditions that allow extrapolation to Puget Sound conditions.

This review of shore protection methods also incorporates guidance offered by states that have enacted the strongest regulation of shoreline use and alteration. These include Virginia, North and South Carolina, Maryland, Delaware, Massachusetts, Michigan, and Wisconsin. The final list of methods includes those that are currently common practice in Puget Sound, along with practices allowed on other model shorelines that are also physically applicable to Puget Sound. In some cases existing regulations or policies might at present preclude the use of a particular approach in Puget Sound. For example, the Hydraulic Code for the State of Washington regulates placing fill or constructing systems below the ordinary high water (OHW) line. However, many protection methods, including those that use beach nourishment and revegetation, are designed to be used below OHW.

The following shoreline protection methods are applicable to Puget Sound. These techniques are listed in the categories of hard, soft, and composite activities. Details about each of the techniques are presented in Appendix A. The information given in Appendix A includes basic forms of construction, representative dimensions, major advantages and disadvantages, and suitability for each of the four basic landform types.

- Hard Structures
    - Bulkhead
    - Zero-clearance bulkhead
    - Seawall
    - Revetment
    - Riprap
    - Gabions
    - Grout-filled bags
    - Floating attenuator
    - Breakwater
- Soft Structures
    - Sand fill

- Gravel fill
- Beachface dewatering
- Beach strand
- Shoreline vegetation
- Bluff vegetation
- Groundwater drainage
- Slope regrading

• Composite Systems
  - Headland/pocket beaches
  - Perched beach
  - Groin systems

Hard structures entail constructing a rigid installation whose purpose is to deflect or attenuate wave energy or retain a failing area of shore. Bulkheads, seawalls, revetments, grout bags, and gabions are all structures built at or behind the water's edge and functioning in essentially the same manner, differing only in the style of construction and ability to survive in the environment. A new and promising application of revetments is to bury them with native-size sediment to maximize aesthetics and shoreline access while providing the protection of a hard structure during a catastrophic storm event. Breakwaters and floating attenuators are barrier structures constructed in the water and are intended to reduce the wave action before it reaches the shoreline.

Soft structures are also intended to reduce the erosive action of the water, but are intended either to emulate a natural shoreline or to be nonintrusive in the environment. Artificial shoreline simulation using sand or gravel fill, including creating long beach strands, is intended to absorb wave energy reaching the shore by allowing the shoreline to "deform," flexibly and naturally, in response to wave action. A new shoreline is created in front of the old; this technique occupies more physical space than a hard structure would require. It is therefore more intrusive than a hard method but could have a more natural appearance. Because the shoreline deforms in response to varying intensities of wave action, the beach geometry might change both spatially and temporally, disappearing and reappearing. The line of defense is not constant for a deformable shoreline as it is with hard structures; therefore, continuous protection of a specific location is less easy to guarantee. However, total shoreline protection, including adjacent properties, is increased as the beach is spread alongshore. Less intrusive soft solutions entail planting vegetation to hold sediment in place, burying drains in a beachface, or incorporating a drain in the bluff surface or substrata. The drain reduces and controls the flow of water, keeping the sediments drier and, thus, more resistant to erosion.

Composite solutions incorporate the positive aspects of both hard and soft methods. This approach employs limited use of structural elements to reduce, but not eliminate, wave attack, and effectively confines the deformation of a soft solution so that its performance is more controlled and predictable.

Examples are the creation of artificial headlands, projecting out in the water to create pocket beaches trapped between, and creation of perched beaches by installation of underwater sills that allow artificial beaches to be built landward of the sill. Composite structures are physically intrusive, but still give a natural, though perhaps non-native, setting to the shoreline.

Off-the-shelf "manufactured systems" are also available to implement both hard and soft approaches to erosion control. These include a wide variety of interlocking concrete blocks and modules that can be used to build retaining walls, revetments, and offshore breakwaters, as well as offshore artificial "vegetation"—plastic kelp—that can moderate wave action. These systems represent specialized approaches to some of the generic techniques addressed in this report, and their applicability is not substantially different from that of the generic techniques.

Nonstructural activities provide techniques for addressing the source of the problem. Bluffs can be restabilized by removing any bluff weakening factors. Such actions include relocating an existing septic drain field or irrigation system well back from a bluff edge so that drainage into and onto the bluff is reduced. Similarly, the overburden pressure on the top of a bluff that could induce slumping could be eliminated by relocating any structures sufficiently far from the edge.

Several methods of shoreline protection that are used successfully elsewhere have been specifically discarded for use in Puget Sound. An example is the use of submerged reef breakwaters. This innovation in coastal design, highly regarded as being environmentally desirable because it is not visible from land and also creates fish habitat, reduces the energy of waves before they reach the shore. This method is particularly sensitive to changes in water depth, because the depth of the water determines whether a wave will break or not. Widely fluctuating water (tide) levels, as occur in Puget Sound, would make its potential performance marginal here. Other inappropriate shoreline protection methods were examined and treated similarly. Only techniques that appear similar to those identified in Appendix A should be considered appropriate for use in Puget Sound.

Application to Specific Sites

The feasible shore protection techniques presented in Appendix A were evaluated independently to determine how well each method meets the three selection factors: the property owner's goals, the site geology and landform, and the site wave exposure. The applicability of each shore protection technique to the various categories within each of the three selection factors is described in the following subsections.

Landowner Concerns and Goals

Table 4.1 shows the applicability of various shore protection methods to meet the landowner's goals for addressing specific causes of erosion. The applicability is based on professional engineering judgment and observations of field applications as to how well a particular approach meets the goal. For example, if the major threat is toe erosion and bluff collapse, placing a beach fill in front of the bluff will do little to buttress the toe-although it may reduce the frequency with which waves strike the toe and thus slow erosion. Similarly, planting vegetation on a slope will be effective only in controlling surface water runoff and will do nothing to halt deep-seated soil slumping.

A retreating shoreline is the most common reason for loss of property. Upland structures are not usually in danger of damage from direct wave attack or flooding, but rather must be protected from undercutting and collapse. The goal of shore protection in these cases is to limit the amount of shoreline retreat or to reduce damage and increase safety in the event of land loss, at least in the area of immediate concern.

Placing a wall-style hard structure (bulkhead) or rock matrix system (revetment, gabions, stacked blocks, or grout-filled bags) at the foot of a bluff or behind a beach can reduce land loss at a particular site and provide damage protection to upland areas. Such approaches, however, do not actually stabilize the beach or reduce its tendency to be eroded away. (Indeed, as indicated in the Task 3 physical impacts report [Volume 5], installing these hard structures may actually increase local beach erosion and loss rates.) In contrast, barrier forms of protection, such as floating attenuators, offshore breakwaters, or beach sills, will actually hold or perhaps even increase the width of a beach area. Soft solutions can be applied to address several of the goals in instances where substantial structural strength is not needed to accomplish a goal. Composite-style solutions-armored headlands/ pocket beaches, for example—can usually be applied to meet all of the goals by incorporating the best features of both hard and soft methods.

When beaches are narrow, waves can attack the toe of the slope directly. When sufficient material is lost from the toe, all or a portion of the slope fails and slides down onto the beach. This loss can compromise upland structures. Slope collapse tends to be progressive from the waterline upward. In this case, the toe area of the slope must be defended in some way so that material cannot be removed. Groundwater and surface runoff of a bluff can also lead to a sliding collapse of a slope. In such a case, wave impingement is unrelated to the real problem. These slope failures tend to originate near the crest of the slope and propagate downward. To prevent these upslope failures, the goal is to introduce techniques that will increase the resistance of the slope to sliding, either by buttressing the toe against movement or by removing the source of the problem-e.g., poor drainage, excessive groundwater, or soil solution. (Bluff stabilization techniques and development near unstable bluffs will be addressed more fully in Phase 2, Task 6, of this study. [Volume 8])

Table 4.1 Technique Applicability to Cause of Erosion[a]			
Shore Protection Technique	**Slow Retreat**	**Prevent Undercutting**	**Stabilize Bluff**
Hard Structures			
Bulkhead	**	*****	*****
Zero-clearance bulkhead	*	**	**
Seawall	**	*****	*****
Revetment	**	*****	*****
Riprap	N/A	****	***
Gabions	**	****	N/A
Grout-filled bags	**	****	N/A
Floating attenuator	***	**	N/A
Breakwater	*****	***	N/A
Soft Structures			
Sand fill	****	***	N/A
Gravel fill	****	****	N/A
Beachface dewatering	****	***	N/A
Beach strand	*****	****	N/A
Shoreline vegetation	**	**	N/A
Groundwater drainage	N/A	N/A	*****
Surface runoff control	N/A	N/A	***
Slope regrading	N/A	N/A	*****
Bluff vegetation	N/A	N/A	N/A
Composite Systems			
Headland/pocket beach	*****	****	N/A
Perched beach	****	***	N/A
Groin systems	****	N/A	N/A

[a]See Section 3.

Applicability Rating: * ** *** **** *****
Least >>> to >>> Most

Landforms

Table 4.2 shows the applicability of the shore protection techniques to the four regional landform types. The applicability is presented as a range, again based on professional engineering experience and judgment.

Landforms influence the applicable techniques in two ways: constructibility and adaptability (or compatibility). Certain soils might provide insufficient foundation to support certain types of construction. Topography might simply preclude the use of certain methods that depend entirely on the amount of change in relief.

Marshy areas—quite apart from their sensitivity as regulated, protected, habitats—are generally not well suited to hard wall-type structures because the landform does not permit easy construction. Soft structures such as sand fills at a marsh edge can be equally inappropriate because the hydraulics of the marsh can be disrupted. Beaches, in order to maintain their integrity, require solutions that emulate the natural shoreline or at least allow the shoreline to be sustained without being intrusive. Solutions for banked and bluffed shorelines usually include a need to provide support for some upslope activity. Therefore, compatible solutions for sloped areas either involve hard structural elements or incorporate adjustments to the slope to accommodate the upslope activities.

Certain types of protection techniques are inherently similar to a native landform although their appearance might be different. Artificial headlands with pocket beaches are similar to naturally formed embayments. Nearshore breakwaters simulate naturally occurring rocky reefs. Floating attenuators do not interfere with natural shoreline processes, but simply reduce their intensity. The applicability of a method does not imply camouflaging the approach, but rather introducing an approach or process that could naturally exist at that site.

Wave Energy

Table 4.3 summarizes the maximum wave energy to which any particular shore protection technique should be exposed. The wave energy limits set for each method were determined for use on individual residential property sites (i.e., rather than several adjacent properties considered together). Also considered were the practical limits on how large an installation would be required to resist the wave action. Application of a particular approach in the next higher energy regime is sometimes possible if appropriate detailed professional engineering analysis is performed; however, significant maintenance problems and poor performance can be expected if the applicability range is stretched too far.

Hard solutions most often are used in moderate- to high-energy wave environments, where greater resistance to the natural forces is required. Soft solutions tend to be more compliant and can often adjust to a variable range of wave conditions. The limits on soft solutions generally are controlled by the amount of room and the amount of material available to "deform" in a severe storm event. Composite structures increase the applicability range by incorporating the traits of both hard and soft techniques. For example, a sand beach can effectively resist most storms, provided the beach is wide enough and long enough. However, for limited sand volumes or beach widths, hard structures must be added to help hold the sand against higher storm waves.

Table 4.2 Technique Applicability to Geologic Settings				
Shore Protection Technique	**Marsh**	**Beach**	**Banks**	**Bluffs**
Hard Structures				
Bulkhead	*	*	*****	*****
Zero-clearance bulkhead	*	*	***	***
Seawall	*	*	*****	*****
Revetment	*	*	*****	*****
Riprap	*	*	*****	***
Gabions	*	*	*****	***
Grout-filled bags	*	*	****	**
Floating attenuator	***	***	***	***
Breakwater	****	*****	*****	***
Soft Structures				
Sand fill	**	*****	***	**
Gravel fill	**	***	***	**
Beachface dewatering	**	****	*	*
Beach strand	**	*****	****	***
Shoreline vegetation	*****	****	***	*
Groundwater drainage	*	*	**	****
Surface Runoff Control	*	*	**	****
Slope regrading	*	*	*****	****
Bluff vegetation	*	*	***	***
Composite Systems				
Headland/pocket beach	****	*****	*****	***
Perched beach	****	*****	***	***
Groin systems	*	*****	***	**

Applicability Rating: * ** *** **** *****
Least >>> to >>> Most

Table 4.3 Maximum Wave Exposures for Applicable Techniques				
Shore Protection Technique	**Fetch Length (miles)**	**Nearshore Wave Height (ft)[a]**	**Maximum FEMA Class[b]**	**Maximum Energy Regime[c]**
Hard Structures				
Bulkhead	<5	<4	AO	M
Zero-clearance bulkhead	<1	<2	AH	L
Seawall	>5	>4	V	H
Revetment	>5	>4	V	H
Riprap	<5	<4	AO	M
Gabions	<5	<4	AO	M
Grout-filled bags	<5	<4	AO	M
Floating attenuator	<5	<4	AO	M
Breakwater	>5	>4	V	H
Soft Structures				
Sand fill	<1	<2	AH	L
Gravel fill	<5	<4	AO	M
Beachface dewatering	<5	<4	AO	M
Beach strand	>5	>4	V	H
Shoreline vegetation	<1	<2	AH	L
Groundwater drainage	N/A	N/A	N/A	N/A
Surface runoff control	N/A	N/A	N/A	N/A
Slope regrading	N/A	N/A	N/A	N/A
Bluff vegetation	N/A	N/A	N/A	N/A
Composite Systems				
Headland/pocket beach	>5	>4	V	H
Perched beach	<5	<4	AO	M
Groin systems	>5	>4	V	H

[a]Wave height calculated for 30-mph wind speed, 30-foot water depth, and adequate time for full wave development.
[b]See Section 3 and Table 3-2 for definitions.
[c]L = low, M = moderate, H = high wave energy regime (Table 3-2).

Significant differences in resistance to wave exposure can be seen in Table 4.3 even for seemingly small differences in shore protection design approaches. The most notable example is the difference in applicability between standard bulkheads and zero-clearance bulkheads. Depending on specific design details, zero-clearance bulkheads (which are built into a bluff face rather than being built in front of a slope and then backfilled) are considered less resistant to wave exposure because of the greater chance for wave overtopping and subsequent direct scour of the bluff face. Conversely, zero-clearance bulkheads project less onto the beach than standard bulkheads, possibly lessening the likelihood of wave overtopping. They may also be vulnerable because of an inability to create protection at the bulkhead ends by providing flanking walls. For these reasons, zero-clearance bulkheads against bluff slopes are best used in low-energy environments. Other differences in the table consider durability of different construction materials and techniques, and whether failure of the method would have catastrophic or noncatastrophic results.

5. Site-Specific Decision Model

This section presents a proposed decision model to help shoreland regulators and property owners determine which methods meet the desired protection goals for a particular site's geologic setting and observable wave exposure. Since the user of the model might be unfamiliar with many site details, it is presented in a form that permits protection technique selection on the basis of a minimum of critical information about the specific site. The decision model being proposed will require field testing before it can be adopted for widespread use.

Figure 5.1 is a logic flow chart for selecting one or more feasible shore protection techniques when only basic information is known about the site. Once it has been determined that a specific site does have an erosion problem that requires an engineering or geotechnical solution, the flow chart is entered first by examining what is happening near the water. If the beach has narrowed, or the toe of a bank or bluff has retreated, erosion of the property is probably wave induced and, thus, requires a wave-related solution. If both loss of upslope area *and* toe retreat are observed, both wave erosion and upland sources of erosion might be contributing. If the erosion rates are less than these thresholds, the problem might be more of a *perception problem* than a real erosion problem. Answering the questions posed in Table 3.1 will help identify both the nature of the problem and resulting appropriate protection goal.

After the problem is identified, it is placed in its proper setting by defining the landform and the wave exposure of the site. The landforms are marsh, beach, bank, or bluff, as discussed in Section 3. The wave exposure is low, moderate, or high; the appropriate category for the site can be determined from Table 3.2.

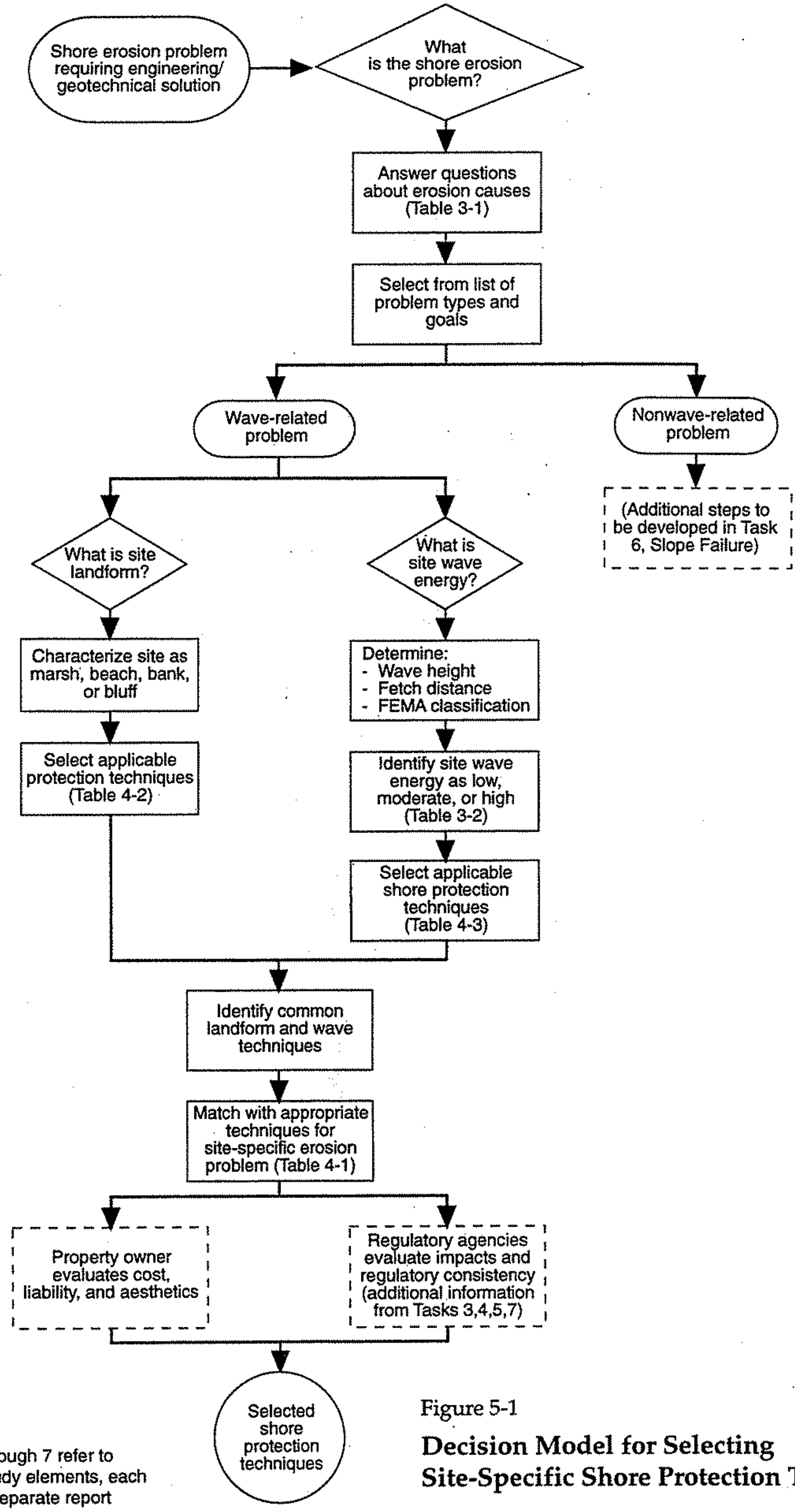
Once the erosion problem and site setting have been categorized, the most appropriate shore protection techniques can be selected from the tables in Section 4. Table 4.2 can be used to select appropriate solutions for the site's landform. Table 4.3 gives a parallel list of what erosion control methods perform best in varying wave exposure regimes. Methods selected in common between these two tables are the options available. This options list is then further refined through Table 4.1 to determine which technique(s) would work best to achieve the intended goal.

The implementation of shore protection need not be limited to one technique alone, but may incorporate various elements of different shore protection techniques. The environmentally preferred least disruptive approach, generally supported by a cost minimization goal, is to use the lowest energy level option that is applicable. This can often be accomplished by incorporating higher-energy-resistant elements with a lower energy approach.

Armored headlands and pocket beaches are one example of making a lower energy beach solution work at a higher energy site (Figure 5.2). Another example is depicted in Figure 5.3, which demonstrates the composite use of a low revetment to minimize view barriers, a regraded vegetated slope to gently absorb wave energy that overtops the revetment, and a drain to capture runoff and aid in stabilizing the slope. A third technique can be to embed one solution within another; such an example is where a revetment is buried inside a beach fill. Under normal wave conditions, the revetment remains buried and the beach remains intact. However, during severe storm events the beach could be sacrificially lost, but further erosion would be halted by the now exposed rock revetment.

The refinement of design options by the goals and functions that need to be satisfied will usually produce two or three final candidate designs. The selection of the best from that list will need to be made by the property owner, partially based on cost, but also based on resources and regulatory agency requirements and the potential environmental impacts associated with that choice. Analyses of potential environmental and resource impacts are presented in the Task 3 [Volume 5] and Task 5 [Volume 7] reports prepared for this study. Financial considerations related to the selection process will also strongly influence the final selection of an approach. Other issues include the level of risk the owner is willing to accept in case of failure, the intended life of the structure, how easily the chosen solution can be constructed and repaired, and the aesthetics of what is to be installed.

The issue of "risk" has a significant impact on the final selection of an appropriate shore protection technique. Risk of failure, or concern about a contractor liability if a solution does fail, often drives the owner, the designer, and the contractor to propose solutions that are substantially more robust than would normally be needed. Currently, solutions are designed to "never" fail, rather than allowing for some anticipated failure under severe conditions, followed by repairs. In fact, most solutions eventually do fail, if only due to old age and the corrosive effect of the marine environment on building materials. This never fail philosophy has tended to discourage use of methods that have a strong need for maintenance, such as the soft solutions (e.g., beach fills and revegetation). Promoting less rigid, more natural alterations to the shoreline will require careful consideration and allowance for this risk of failure.



Note: Tasks 3 through 7 refer to other contract study elements, each the subject of a separate report

Figure 5-1

Decision Model for Selecting Site-Specific Shore Protection Techniques

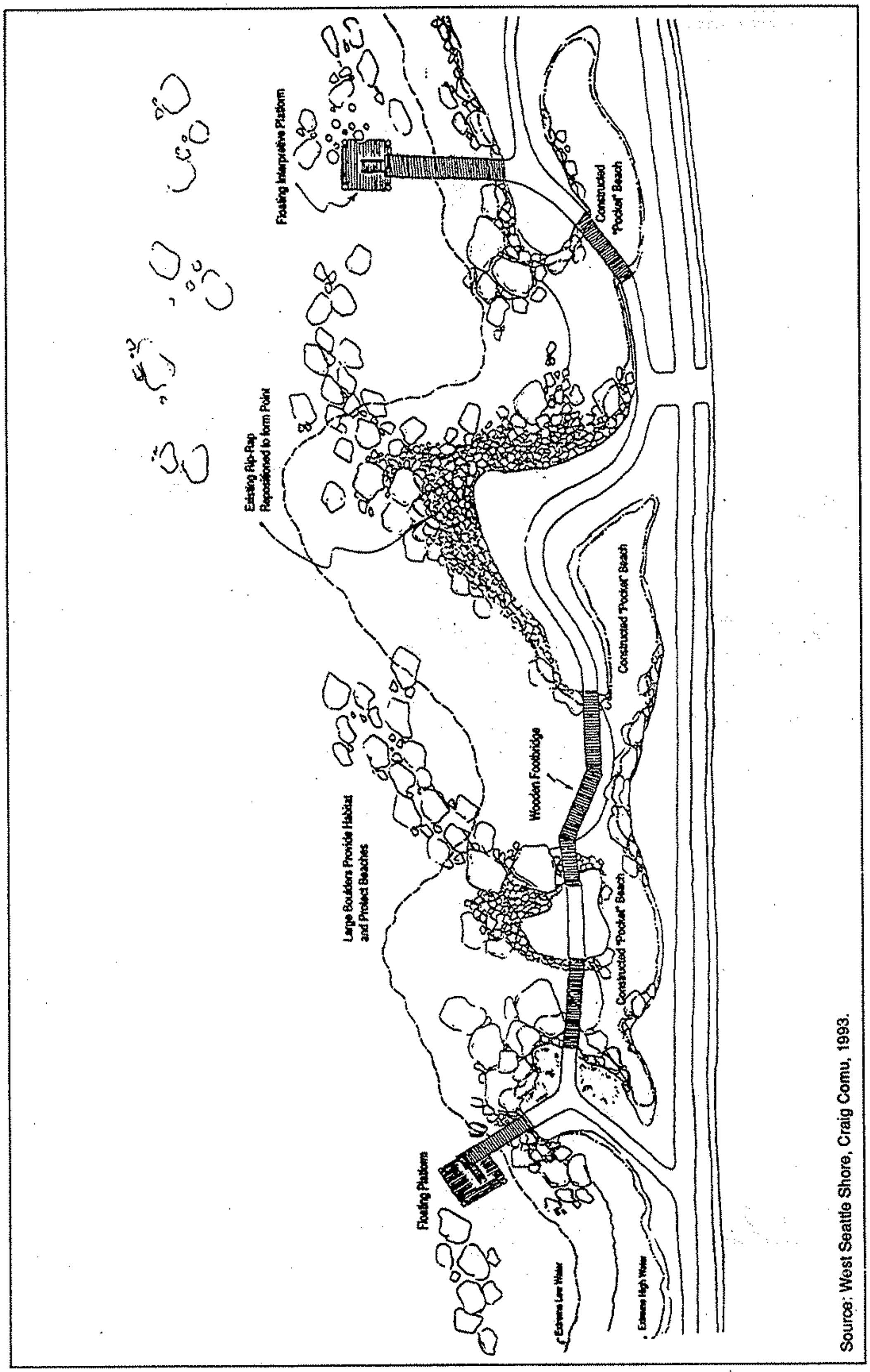
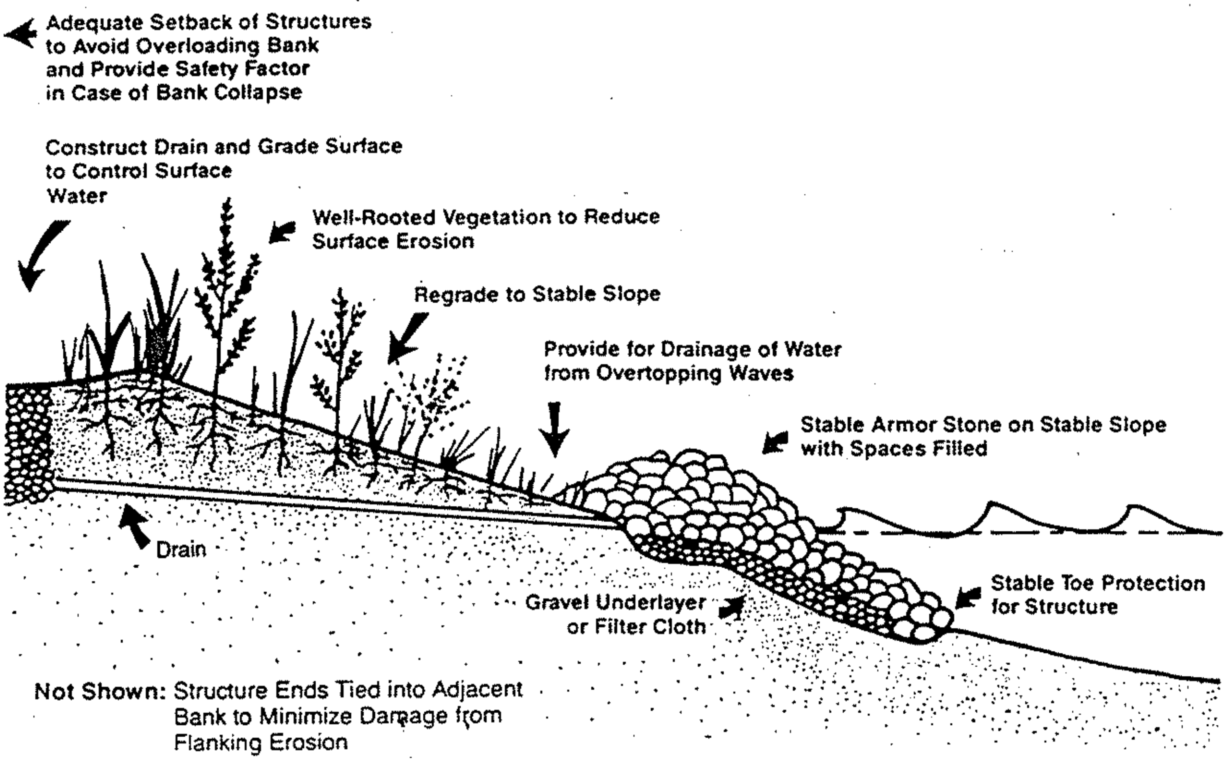


Figure 5.2 Creative use of headlands and pocket beaches to replace standard rip-rap



Source: Keillor and Miller, 1987.

Figure 5.3 Conceptual example of composite erosion control system

6. Glossary

Accretion. May be either natural or artificial. Natural accretion is the buildup of land, solely by the action of the forces of nature, on a beach by deposition of water- or airborne material. Artificial accretion is a similar buildup of land by reason of an act of man, such as the accretion formed by a groin, breakwater, or beach fill deposited by mechanical means.

Alongshore. Parallel to and near the shoreline; **Longshore**.

Artificial Nourishment. The process of replenishing a beach with material (usually sand) obtained from another location.

Backrush. The seaward return of the water following the uprush of the waves.

Backshore. That zone of the shore or beach lying between the foreshore and the coastline comprising the **berm** or **berms** and acted upon by waves only during severe storms, especially when combined with exceptionally high water.

Bar. A submerged or emerged embankment of sand, gravel, or other unconsolidated material built on the sea floor in shallow water by waves and currents.

Beach. The zone of unconsolidated material that extends landward from the low water line to the place where there is marked change in material or physiographic form, or to the line of permanent vegetation (usually the effective limit of storm waves). The seaward limit of a beach-unless otherwise specified-is the mean low water line. A beach includes **Foreshore** and **Backshore**. See also **Shore**.

Beach Berm. A nearly horizontal part of the beach or backshore formed by the deposit of material by wave action. Some beaches have no berms, others have one or several.

Beach Strand. Beach strands are long, uninterrupted stretches of natural or artificially created beach. They act as dynamic wave energy absorbers, deforming in both plan and section to accommodate the wave conditions. Beach strands typically have wide, dry beaches.

Bluff Toe. The face of a bluff where it meets the beach.

Breakwater. A structure protecting a shore area, harbor, anchorage, or basin from waves.

Bulkhead. A structure or partition to retain or prevent sliding of the land. A secondary purpose is to protect the upland against damage from wave action.

Diffraction. Bending of the direction of propagation of a wave when it meets an obstacle.

Downdrift. The direction of predominant movement of littoral materials.

Drift Sector (also known as a Drift Cell or Littoral Cell). A segment of shoreline along which littoral, or longshore, sediment movement occurs at noticeable rates. It allows for an uninterrupted movement, or drift, of beach materials. Each drift sector includes: a feed source that supplied the sediment, a driftway along which the sediment can move, an accretion terminal where the drift material is deposited, and boundaries that delineate the ends of the drift sector.

Feeder Bluff. An eroding shoreline bluff that supplies sedimentary material to downdrift shorelines.

Fetch. The horizontal distance (area) in which waves (seas) are generated by a wind having a fairly constant direction and speed. Sometimes used synonymously with **Fetch Length**.

Foreshore. The part of the shore that (1) lies between the crest of the seaward berm (or upper limit of wave wash at high tide) and the ordinary low-water mark, and (2) is ordinarily traversed by the uprush and backrush of the waves as the tides rise and fall.

Gabion. A wire mesh box filled with smaller sized stones but constrained by the mesh to act as a monolithic unit.

Groin. A shore protection structure built (usually perpendicular to the shoreline) to trap littoral drift or retard erosion of the shore. **Groin field**. A series of groins acting together to protect a section of beach.

High Water Line. The intersection of the plane of mean high water with the shore. The shoreline delineated on the nautical charts of the National Ocean Service is an approximation of the high water line. For specific occurrences, the highest elevation on the shore reached during a storm or rising tide, including meteorological effects.

Higher High Water (HHW). The higher of the two high waters of any tidal day. The single high water occurring daily during periods when the tide is diurnal is considered to be a higher high water.

Higher Low Water (HLW). The higher of two low waters of any tidal day.

Hindcasting, Wave. The use of historic synoptic wind charts to calculate characteristics of waves that probably occurred at some past time.

Jetty. A structure extending into a body of water designed to prevent shoaling of a channel by littoral materials and to direct and confine the stream or tidal flow. Jetties are built at the mouths of rivers or tidal inlets to help deepen and stabilize a channel.

Leeward. The direction *toward* which the wind is blowing; the direction toward which the waves are traveling.

Littoral. Of or pertaining to a shore, especially of the sea.

Littoral Cell. See Drift Sector.

Littoral Current. Any current in the littoral zone caused primarily by wave action, e.g., **Longshore Current, Rip Current**.

Littoral Drift. The sedimentary *material* moved in the littoral zone under the influence of waves and currents.

Littoral Transport. The *movement* of littoral drift in the littoral zone by waves and currents. Includes movement parallel (longshore transport) and perpendicular (on-offshore transport) to the shore.

Load. The quantity of sediment transported by a current. It includes the suspended load of small particles and the bedload of large particles that move along the bottom.

Longshore. Parallel to and near the shoreline; **Alongshore**.

Longshore Current. The littoral current in the breaker zone moving essentially parallel to the shore, usually generated by waves breaking at an angle to the shoreline.

Lower High Water (LHW). The lower of the two high waters of any tidal day.

Lower Low Water (LLW). The lower of the two low waters of any tidal day. The single low water occurring daily during periods when the tide is diurnal is considered to be a lower low water.

Mean Sea Level. The average height of the surface of the sea for all stages of the tide over an 18.6-year period, usually determined from hourly height readings.

Nearshore Current System. The current system caused primarily by wave action in and near the breaker zone, and which consists of four parts: the shoreward mass transport of water; longshore currents; seaward return flow, including rip currents; and the longshore movement of the expanding heads of rip currents.

Nourishment. The process of replenishing a beach. It might be brought about naturally by longshore transport, or artificially by the deposition of dredged materials.

Ordinary High Water Line (OHWL). A legal term from Washington Department of Fisheries Hydraulic Code Rules (WAC 220-110-020):

> ...the mark on the shores of all waters that will be found by examining the bed and banks and ascertaining where the presence and action of waters are so common and usual and so long continued in ordinary years, as to mark upon the soil a character distinct from that of the abutting upland, in respect to vegetation: *Provided*, That in any area where the ordinary high water line cannot be found the ordinary high water line adjoining saltwater shall be the line of mean higher high water and the ordinary high water line adjoining freshwater shall be the line of mean high water.

Perched Beach. A beach or fillet of sand retained above the otherwise normal profile level by a submerged dike.

Percolation. The process by which water flows through the interstices of a sediment. Specifically, in wave phenomena, the process by which wave action forces water through the interstices of the bottom sediment and which tends to reduce wave heights.

Pile. A long, heavy timber or section of concrete or metal to be driven or jetted into the earth or seabed to serve as a support or protection.

Profile Deflation. Lowering of the beach profile (elevation) due to erosion.

Quarrystone. Any stone processed from a quarry.

Reflected Wave. That part of an incident wave that is returned seaward when a wave impinges on a steep beach, barrier, or other reflecting surface.

Reflection Coefficient. Percentage of wave energy (expressed in terms of wave height) that is reflected back to sea.

Refraction (of water waves). (1) The process by which the direction of a wave moving in shallow water at an angle to the contours is changed: the part of the wave advancing in shallower water moves more slowly than that part still advancing in deeper water, causing the wave crest to bend toward alignment with the underwater contours. (2) The bending of wave crests by currents..

Return Walls. Walls built at the terminal ends of bulkheads, perpendicular to the bulkhead face, that securely anchor the bulkhead to the native shoreline and prevent end erosion.

Revetment. A facing of stone, concrete, or other material built to protect a scarp, embankment, or shore structure against erosion by wave action or currents.

Riprap. A protective layer or facing of quarrystone, usually well graded within wide size limit, randomly placed to prevent erosion, scour, or sloughing of an embankment or bluff; also the stone so used.

Rubble-Mound Structure. A mound of random-shaped and random-placed stones protected with a cover layer of selected stones or specially shaped concrete armor units. (Armor units in a primary cover layer may be placed in an orderly manner or dumped at random.)

Run-up. The rush of water up a structure or beach on the breaking of a wave. Also **Uprush, Swash**. The amount of run-up is the vertical height above still-water level to which the rush of water reaches.

Scarp, Beach. An almost vertical slope along the beach caused by erosion by wave action. It may vary in height from a few centimeters to a meter or so, depending on wave action and the nature and composition of the beach.

Scour. Removal of underwater material by waves and currents, especially at the base or toe of a shore structure.

Seawall. A structure separating land and water areas, primarily designed to prevent erosion and other damage as a result of major wave action, and usually incorporating special geometric shapes for redirecting wave energy. See also **Bulkhead**.

Sheet Pile. A pile with a generally slender flat cross section to be driven into the ground or seabed and meshed or interlocked with like members to form a diaphragm, wall, or bulkhead.

Shingle. (1) Any beach material coarser than ordinary gravel, especially any having flat or flattish pebbles. (2) Beach material of smooth, well-rounded pebbles that are roughly the same size. The spaces between pebbles are not filled with finer materials. Shingle often gives out a musical sound when stepped on.

Shoreface. The narrow zone seaward from the low tide **shoreline**, covered by water, over which the beach sands and gravels actively oscillate with changing wave conditions.

Shoreline. The intersection of a specified plane of water with the shore or beach (e.g., the high water shoreline would be the intersection of the plane of mean high water with the shore or beach). The line delineating the shoreline on National Ocean Service nautical charts and surveys approximates the mean high water line.

Storm Surge. A rise above normal water level on the open coast due to the action of wind stress on the water surface.

Tidal Flats. Marshy or muddy land areas that are covered and uncovered by the rise and fall of the tide.

Toe. Lowest part of bluff, bank, or shoreline structure, where a steeply sloping surface meets the beach.

Training Wall. A wall or jetty to direct current flow.

Undercutting. The removal of material at the base of a steep slope or cliff by erosive action of waves or running water.

Updrift. The direction opposite that of the predominant movement of littoral materials.

Wave Energy Flux. Transfer of energy from wave motion to sediment movement.

Wave Period. The time for a wave crest to traverse a distance equal to one wavelength. The time for two successive wave crests to pass a fixed point.

Wetlands (Biological). Lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water.

Wetlands (Jurisdictional). Land forms that support, under normal conditions, a predominance of hydrophytic (wetland) vegetation, hydric (wetland) soil types, and wetland hydrology. Typically, they are jurisdictionally defined as: "Those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions (Federal Interagency for Wetland Delineation, 1989)."

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Appendix A
Shore Protection Design Guidelines

APPENDIX A

This appendix contains technical "cutsheets" that describe the various shoreline protection approaches discussed in the report text. The cutsheets outline general construction details and important parameters and elements in the design. Inclusion of a particular approach does not signify approval of that approach by Ecology, nor by any other local, state, or federal regulatory agency, nor does it constitute an endorsement or recommendation for use of that approach. The following additional caveats also apply:

- The cutsheets are intended to suggest representative sizes and scales for the installations or methods but should not be considered as specific design guidance.
- Implementation of any shore protection concept requires a thorough site study and preparation-by an appropriately qualified design/engineering professional-of a design and installation approach appropriate to the specific site conditions.
- Engineering specifications from other geographical areas may not be applicable in Puget Sound because of unique local considerations.
- Specific local, state, and/or federal regulatory and permit requirements-including careful consideration and avoidance of physical and ecological impacts-may also need to be satisfied before a particular project can be implemented.

In addition to diagrammatic information on the shore protection methods, and text which describes applicability, fundamentals of operation, advantages and disadvantages, photographs are included of typical installations. Each concept is also indexed to ***suitability of application*** for a given landform type—i.e., bluff, bank, beach, or marsh. The rankings range from one star to five stars, with the latter representing the best, or most appropriate, application. In general, a three-star ranking could be viewed as being marginally suitable or beneficial. Any approach with a rating less than three stars should be considered very carefully before application since it may even have detrimental characteristics in certain settings. No single approach will be suitable for all situations, and some approaches that may be highly detrimental in some instances may be highly beneficial, and appropriate, in others.

The shoreline protection approaches discussed in this appendix are as follows:

Hard Structures

- Bulkheads
- Zero-clearance bulkheads
- Seawalls
- Riprap and revetments
- Gabions
- Grout-filled bags
- Floating attenuators
- Breakwaters

Soft Structures

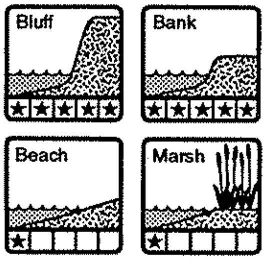
- Sand fills
- Gravel fills
- Beachface dewatering
- Beach strands
- Shoreline vegetation
- Groundwater drainage
- Surface runoff control
- Slope regrading
- Bluff vegetation

Composite Systems

- Headland/pocket beaches
- Perched beaches
- Groin systems

BULKHEADS

Suitability for landforms



Bulkheads are vertical barriers that act as deflectors of wave energy, or as soil retainers, or both. Historically, they are the most common form of erosion protection used in Puget Sound. Any type of bulkhead can give effective retention of soil and protection against erosion if properly sized for the local wave and soil/ sediment conditions.

Bulkheads generally appear in one of three forms: cast-in-place vertical concrete walls; large rock walls; or sheet style walls assembled from rows of planks, panels, or piles of timber, steel, or concrete. Timber walls have become less popular due to concerns over environmental effects of treated wood (see Ecology Focus Sheet, "Creosote-treated Wood in the Aquatic Environment," April 1993). Concrete or rock materials are now more frequently used. The ultimate selection of material to use in construction of a bulkhead is most often based on cost, availability of material, access to the site, and familiarity of the contractor with the construction methods.

It should be noted that bulkheads (as well as seawalls and revetments) are intended to resist erosion at the base of a slope, rather than hold or support the slope itself. Although a bulkhead will hold its own backfill, and possibly a small wedge of sedimentary material on a low bank, it cannot be expected to provide support for a higher bluff face.

One desirable feature of a bulkhead is that the structure can be built to a height of 10 to 15 feet above the existing beach and can be placed seaward of the existing bank or bluff toe. Fill can be placed behind the bulkhead, and the slope can be regraded from the top of the bulkhead rather than from the existing bluff toe. This effectively reduces the bank or bluff top regrading distance required to achieve a stable bluff slope. Thus, the necessary cutting back of the top of the bluff to form a stable slope can be reduced significantly if a bulkhead is constructed. From the landowner's perspective, another advantage of a bulkhead is that it provides a uniform (tidy) appearance and can be readily adapted to additional recreational facilities such as walkways, piers, and boat slips that might enhance the owner's use of the shoreline.

Terminal ends of bulkheads are points of wave focusing, which can cause localized erosion of adjacent unarmored shorelines and lead to loss of fill material from behind the bulkhead ends. Return walls (i.e., walls perpendicular to the bulkhead face) should be added and securely embedded into the native shoreline to prevent this end erosion. Curved or angled return walls are generally perceived to cause smaller impacts to adjacent property and make less abrupt transitions to the shoreline than perpendicular end walls. Squared bulkhead ends, although focusing greater wave energy on the adjacent shoreline, give the greatest amount of protection to upland areas being protected by the bulkhead.

Disadvantages of a bulkhead are that the structure is inflexible (i.e. cannot adjust and deform if overloaded by waves), and maintenance, when required, is difficult and costly. In addition, the presence of a bulkhead affects the adjacent shoreline areas by modifying and focusing wave energy. A bulkhead deflects the wave energy both upward, often leading to overtopping, and downward, resulting in severe scouring at the base of the structure. It is therefore likely that existing beach areas in front of the bulkhead would be modified by the wave action, becoming coarser grained, with a deeper profile.

Cast-in-Place Concrete Bulkhead

A cast-in-place, reinforced concrete bulkhead, as illustrated in Figure 1a, consists of a wide concrete base with a cantilevered wall. The wall is constructed with weep holes for drainage and is backfilled with coarse granular material to prevent hydrostatic pressure buildup and frost heave. Riprap toe protection should also be provided to counteract scour. The toe scour protection may be buried under the beach one or more feet to maintain the environmental aesthetics, yet still be effective provided undercutting of the wall is prevented. The footing of the concrete wall may also be extended deeper to protect against scour. The cast-in-place concrete bulkhead derives its total capacity for resistance to sliding or overturning from its weight distribution, so a substantial base is often required.

Many bulkheads are built in front of an existing slope and then backfilled. Alternatively, the slope can be carved back and the bulkhead built flush (recessed) into the slope or be built tight against an existing decaying wall (Figure 1b). The advantage of this technique is that the fronting beach width is maximized. The disadvantage of this "zero-clearance" approach is that no wave overtopping protection is afforded. To prevent erosion of the slope above the wall, the wall might need to be constructed higher than if the wall were built farther away from the slope. The taller wall, in turn, requires that the buried counterfort toe must extend further out into the beach to prevent the wall from failing. Zero-clearance bulkheads may therefore be less adaptable, or suitable to only some bank and bluff situations.

Sheet-Style Bulkheads

Sheet-style walls are constructed of pilings, planking, or panels that form a continuous wall. The wall may be composed entirely of vertical piles or interconnected sheeting driven in a linear alignment, or may be a mixture of vertical piles supporting panels or horizontal planking. The walls may be constructed of steel, concrete, or timber material. The wall develops its strength from cantilever action derived from deep embedment of the toe. To resist failure, the wall must typically be rooted so that the penetration depth of the wall is at least half as great as the height of the exposed portion of the wall. Alternatively, or in addition, the cantilevered wall section may be anchored into the slope with tie-backs and "deadmen."

A typical sheet style wall installation is depicted in Figure 2. Depending upon the depth of embedment of the wall, toe erosion protection might be required. Good drainage from the wall is required to relieve any added water pressure built up behind it. Special pile-driving equipment is required to install this type of structure. If treated wood is to be used in the wall construction, the owner should first review State of Washington Department of Ecology advisories on the environmental effects of wood treatment, noted above.

Vertical Rock Walls

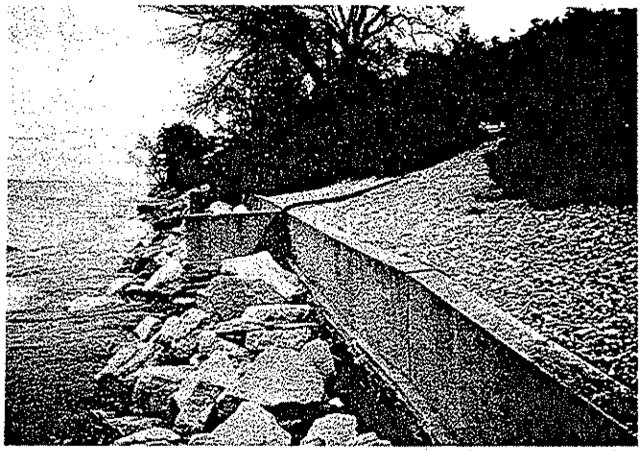
Vertically stacked rock walls constructed of oversized rock functionally retain the soil and are commonly used for upland slopes or banks. An example rock wall detail is shown in Figure 3. As a general rule, vertical rock walls should never be constructed taller than 8 feet or be intentionally placed in direct contact with water action–yet they are widely used in central Puget Sound. For direct water contact, sloped rock revetments should be employed.

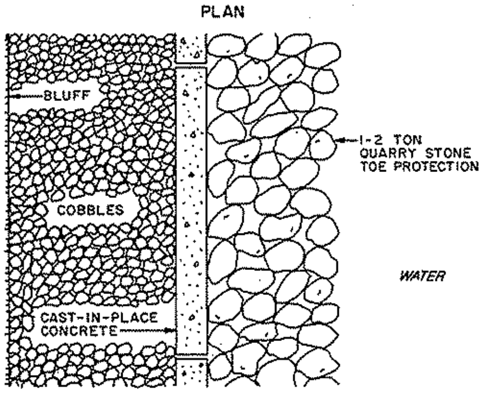
If the wall is to be built near but above OHWL, so that exposure to wave action will be very limited, the following guidelines should be employed. The embedment depth of the invert (lowest point of the rock) of the base tier of stones should be at least twice the expected water depth at the wall during a storm. Ideally, the crest of that same rock will be at least one-and-one-half water depths above the storm water level. Any rock placed vertically above the base tier should be considered sacrificial and likely to be dislodged during a major storm. For this reason, vertical rock walls constructed near the OHWL should be at most two stones high, and preferably constructed of only one course composed of extremely large stones. Any stones used in construction of vertical rock walls along the shoreline should be at least 4 feet in their smallest dimension. Large granular fill, which cannot be lost through the voids between the armor rocks, is required immediately behind the wall.

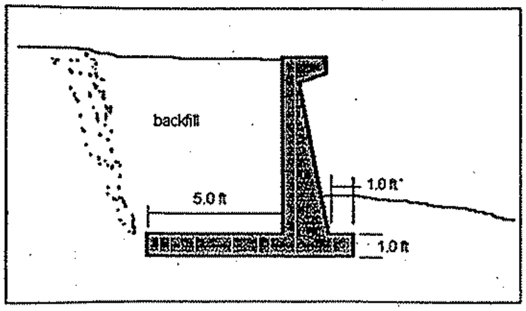
Unlike cast-in-place and sheet-style bulkheads, vertical rock walls can be built so that they undulate more naturally with the shoreline, thus helping to break up wave reflections. In addition, natural shoreline features such as trees, stumps, and large woody debris can be incorporated into the face of a rock wall to give a more natural appearance and promote habitat values. In some cases vegetation can also serve to reinforce the wall.

Figure 1

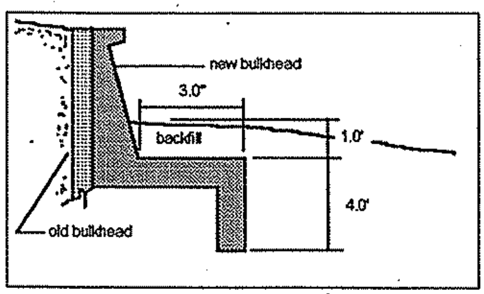
Typical Concrete Gravity Bulkhead







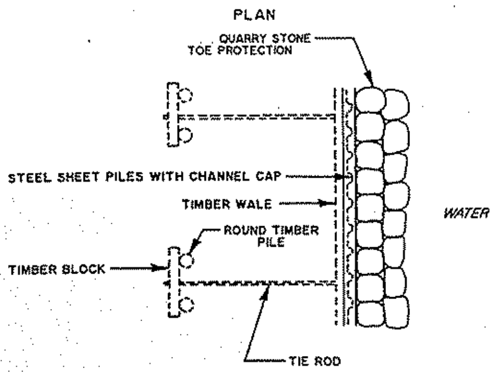
a) Conventional gravity bulkhead profile.

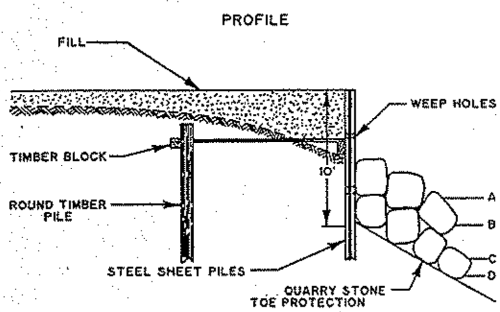


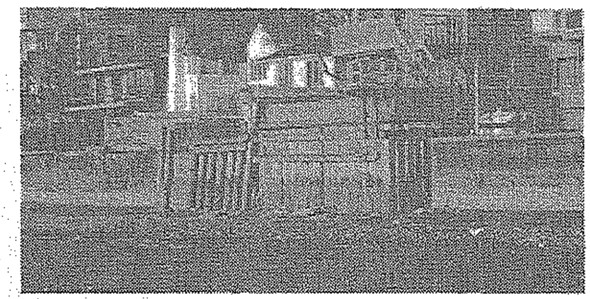
b) Zero-clearance bulkhead profile.

Figure 2

Typical Sheet Piling Bulkhead







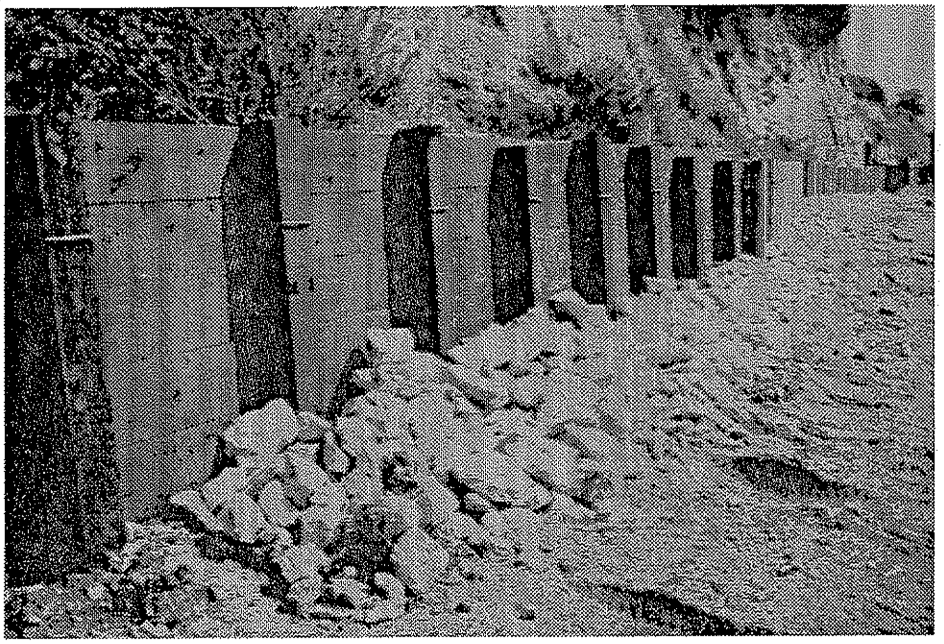
LEGEND

DESIGN WATER LEVELS
A. DESIGN HIGH STILL WATER LEVEL PLUS WIND SETUP
B. DESIGN HIGH STILL WATER LEVEL
C. ANNUAL MEAN WATER LEVEL
D. LOW WATER DATUM

NOTE: THE DESIGN SPECIFICATIONS SHOWN HEREIN ARE FOR A TYPICAL STRUCTURE. THE DETAILED DESIGN OF SHORE PROTECTION MEASURES MUST BE BASED ON A DETAILED ANALYSIS OF WAVE CLIMATE, COST AND AVAILABILITY OF CONSTRUCTION MATERIAL, SPECIFIC GRAVITY AND QUALITY OF THE STONE, TYPE OF FOUNDATION MATERIAL AND EXISTING SHORELINE GEOMETRY.

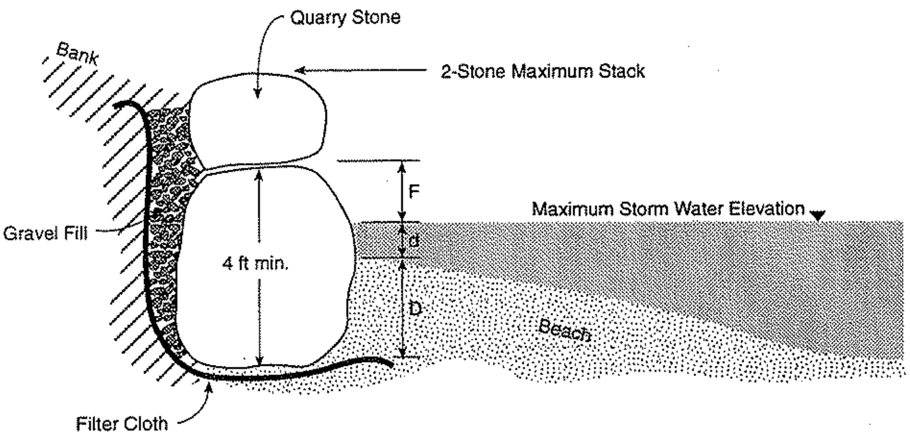
Source: Southeastern Wisconsin Regional Planning Commission (SEWRPC). *A Lake Michigan Shoreline Erosion Management Plan for Northern Milwaukee County Wisconsin.* Community Assistance Planning Report Number 155. Waukesha, Wisconsin. December 1988.

Figure 1
Typical Timber Bulkhead

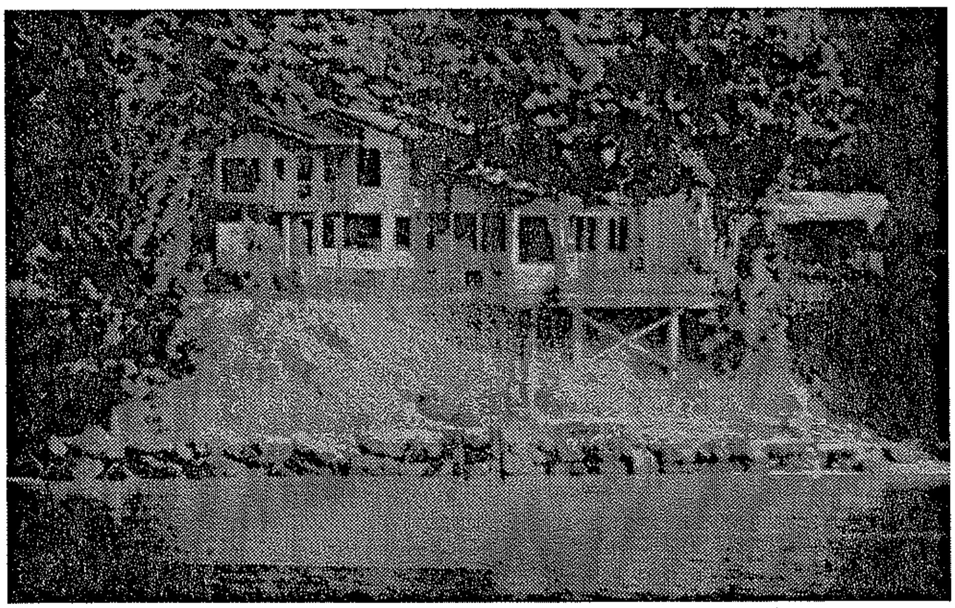


Timber bulkhead with rock toe protection
Oak Harbor, Island County
Source: U.S. Army Corps of Engineers, *Low-Cost Shore Protection*, August 1981.

Figure 2
Typical Vertical Rock Wall



Stormwater depth at wall = d
Embedment depth (D) = 2d (minimum)
Freeboard (F) = 1.5d (minimum)

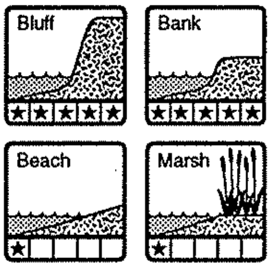


Rich Passage, Kitsap County
Source: Hugh Shipman

SEA35072.T2.2C / Bulkhead/RockWall / 8-2-93 / CJS / JH

SEAWALLS

Suitability for landforms



Seawalls are massive, gravity-held bulkheads intended to resist severe wave attacks and prevent significant wave overtopping and backland inundation. Seawalls typically have a substantially greater mass and three-dimensional form than does a simpler wave wall-like bulkhead. They differ from bulkheads in their larger size, the intensity of wave action they can resist, and the amount of protection they must provide. They usually include a splash apron along the crest to prevent erosion caused by wave action overtopping the structure. Seawall designs vary considerably in geometric form but generally incorporate features intended to redirect the wave action. Two typical seawall configurations are step faced to spread the wave loading time or are recurved to reduce overtopping with minimum structure height.

Stepped Seawall

A cast-in place concrete-stepped seawall is shown in Figure 1. (Note that, in the example shown, dense vegetation cover has been maintained to protect the slope behind the seawall.) As shown in the figure, the face of the seawall is stepped toward the water. The concrete-stepped seawall does not require deep embedment or piles beneath the beach because it has a very broad cross section; the steps provide access to the shore. The structure is clearly more suitable for shoreline access than are most rock revetments or other types of vertical bulkheads.

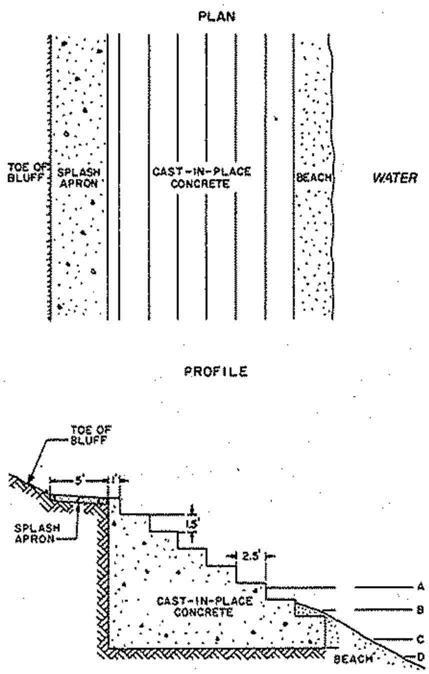
Recurved Seawall

The recurved concrete seawall is shaped to throw the up-rushing wave back seaward (Figure 2). The top elevation is usually less than with other walls, and backland areas remain drier. The disadvantage is that wave forces on recurved walls are high, requiring significantly greater structural reinforcement and anchoring.

Seawalls are more complicated to construct than are bulkheads or revetments and commonly entail a significant reworking of both the beach and adjacent upland to accommodate the structures. Construction costs are commensurately greater. Because the seawall is designed to redirect wave energy, such an installation frequently also includes supplemental armoring of the foreshore and adjacent beach areas.

Figure 1

Typical Concrete-Stepped Seawall



Source: Southeastern Wisconsin Regional Planning Commission (SEWRPC). *A Lake Michigan Shoreline Erosion Management Plan for Northern Milwaukee County Wisconsin*. Community Assistance Planning Report Number 155. Waukesha, Wisconsin. December 1988.

LEGEND

DESIGN WATER LEVELS

A. DESIGN HIGH STILL WATER LEVEL PLUS WIND SETUP
B. DESIGN HIGH STILL WATER LEVEL
C. GEODETIC VERTICAL DATUM
D. LOW WATER DATUM

NOTE: THE DESIGN SPECIFICATIONS SHOWN HEREIN ARE FOR A TYPICAL STRUCTURE. THE DETAILED DESIGN OF SHORE PROTECTION MEASURES MUST BE BASED ON A DETAILED ANALYSIS OF WAVE CLIMATE, COST AND AVAILABILITY OF CONSTRUCTION MATERIAL, SPECIFIC GRAVITY AND QUALITY OF THE STONE, TYPE OF FOUNDATION MATERIAL, AND EXISTING SHORELINE GEOMETRY.

Figure 2

Typical Recurved Seawall

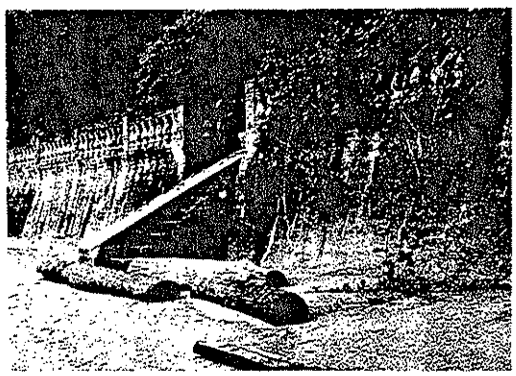
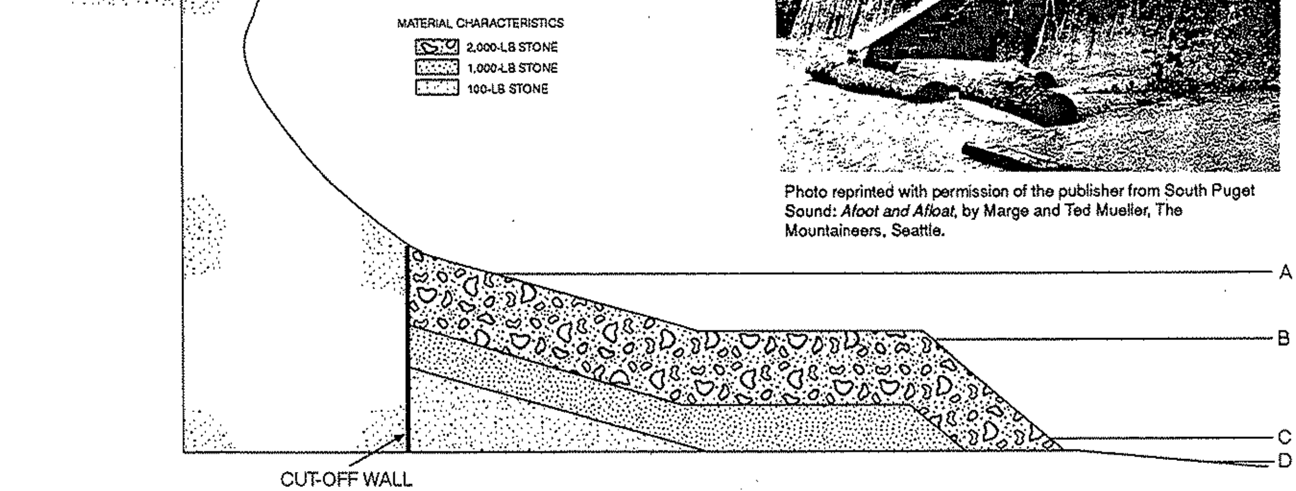


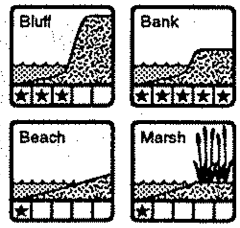
Photo reprinted with permission of the publisher from South Puget Sound: *Afoot and Afloat*, by Marge and Ted Mueller, The Mountaineers, Seattle.



RIPRAP AND REVETMENTS

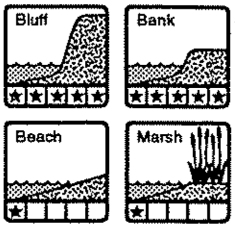
Riprap

Suitability for landforms



Revetments

Suitability for landforms



The terms "riprap" and "revetment" refer to an armored slope. Riprap generally is considered smaller sized material placed against an existing slope. A revetment is larger material that is built as an armor layer or as an embankment. Although both are intended to dissipate wave energy, a revetment section may also be configured to add passive resistance to lateral sliding of a slope face while riprap is typically simply laid against the slope.

Riprap and revetment designs providing three levels of protection are illustrated in Figure 1. A light revetment might require 2 to 3 tons of stone per lineal foot of shoreline; a medium revetment, 3 to 5 tons of stone per foot; and a heavy revetment, 5 to 10 tons of stone per foot. The size of the armor stones needed to provide adequate protection is dependent on the wave height (Figure 1), the specific gravity and quality of the stone, the slope of the structure, and the degree of interlocking between individual stones.

An alternative design, known as a berm revetment, uses a thick layer of variable-size armor stone with an average weight typically less than one-half the weight of the stone required by conventional design methods. Because individual stones are mobile, the revetment is complaint and deformable, depending on the wave environment. A berm revetment is essentially a very coarse material, steep beach. Wave action shapes the thick armor layer into a form that dissipates the wave energy.

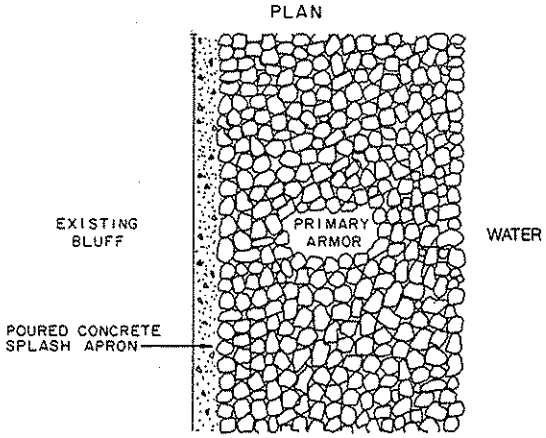
Another alternative, the buried revetment, improves shoreline access and aesthetics (Figure 2). The gravel face of the water-facing slope is the primary defense against wave erosion. Should the wave energy increase beyond the ability of the gravel slope to cope, erosion can continue until the buried revetment is exposed. The buried revetment is designed to arrest local shoreline erosion from storm-generated waves until a maintenance program is initiated to restore the shore or beach to its natural-looking, original, and low-energy equilibrium condition.

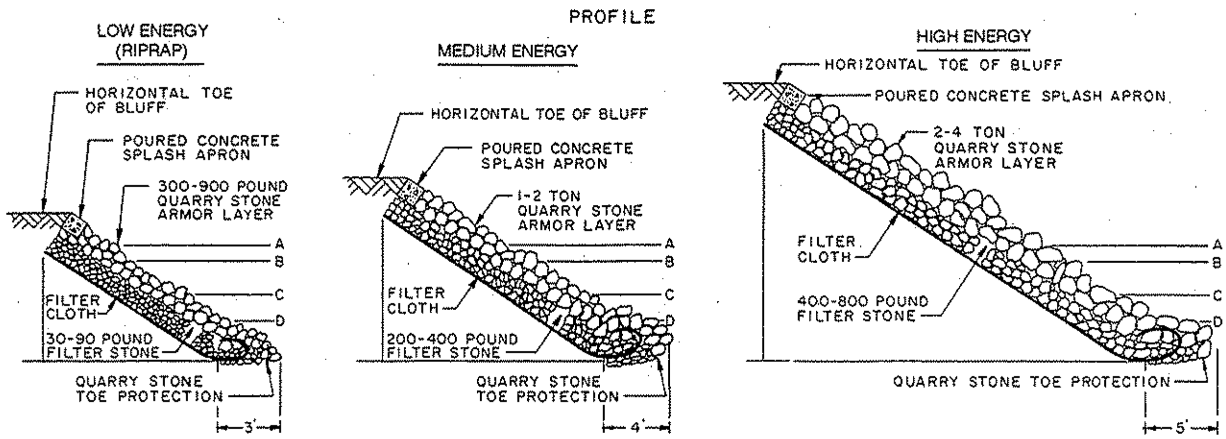
The advantages of riprap or a revetment are that they are relatively easy to construct and maintain, they are flexible and can therefore withstand some movement or displacement of materials without total failure, and they provide a relatively natural appearance to the shoreline.

The primary disadvantage is that the irregularly piled rocks generally interfere with use of the immediate shoreline area for recreational activities and might preclude access to the water (Figure 1). Riprap or a revetment is generally poorly suited for active recreational use although facilities such as walkways and piers may be incorporated into the design to promote passive uses and fishing access. Riprap and revetments, particularly steep structures, do reflect wave energy although less than would most bulkheads of equivalent size. This reflected energy can scour offshore material, especially immediately in front of the structure. The resulting steeper offshore slope would allow larger waves to reach the shoreline.

The life of riprap or a revetment depends on the durability of the rock used for construction and on the degree of maintenance performed. These structures can be affected by settling and displacement of the rock. If armor stones are moved by wave action, the entire structure could be weakened if not properly maintained. Riprap or revetments placed directly on sand beaches without proper filter material (Figure 1) and those using undersized armor stone are particularly prone to failure.

Figure 1
Typical Riprap and Revetment





LEGEND

DESIGN WATER LEVELS

A. DESIGN HIGH STILL WATER LEVEL PLUS WIND SETUP

B. DESIGN HIGH STILL WATER LEVEL

C. ANNUAL MEAN WATER LEVEL

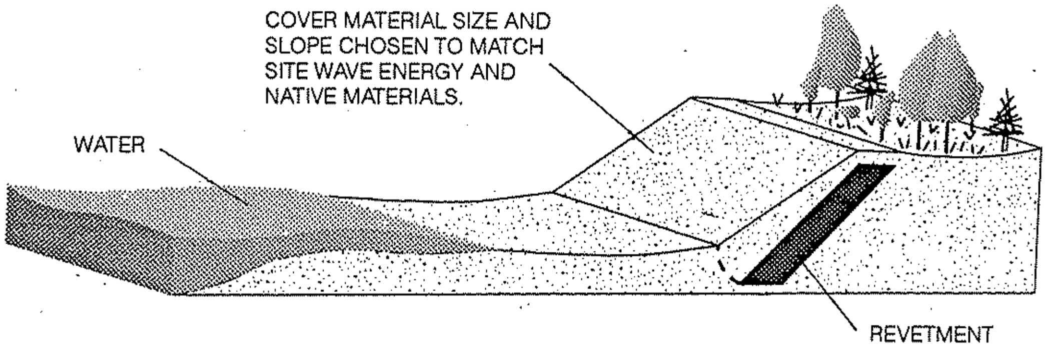
D. LOW WATER DATUM

SLOPES: 1V = 1.5H

NOTE: THE DESIGN SPECIFICATIONS SHOWN HEREIN ARE FOR A TYPICAL STRUCTURE. THE DETAILED DESIGN OF SHORE PROTECTION MEASURES MUST BE BASED ON A DETAILED ANALYSIS OF WAVE CLIMATE, COST AND AVAILABILITY OF CONSTRUCTION MATERIAL, SPECIFIC GRAVITY AND QUALITY OF THE STONE, TYPE OF FOUNDATION MATERIAL, AND EXISTING SHORELINE GEOMETRY.

Source: Southeastern Wisconsin Regional Planning Commission (SEWRPC). *A Lake Michigan Shoreline Erosion Management Plan for Northern Milwaukee County Wisconsin.* Community Assistance Planning Report Number 155. Waukesha, Wisconsin. December 1988.

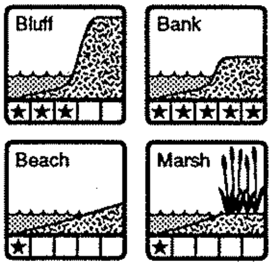
Figure 2
Typical Buried Revetment



Source: Keillor, J. Philip, and Allen H. Miller. *Coastal Processes Manual. A Training Manual for Evaluating Coastal Property.* University of Wisconsin Sea Grant Institute WIS-SG-87-430. 1987.

GABIONS

Suitability for landforms



Gabions are rectangular containers fabricated from a triple-twisted hexagonal mesh of heavily galvanized steel wire filled with rocks small enough for easy handling. Figure 1 depicts schematically typical one-tier and two-tier gabion wall installations. Photographs of typical gabion retaining wall installations are shown in Figures 2 and 3. Vegetation can be purposely introduced into gabion walls or allowed to grow and become established as volunteer vegetation over time.

For easy handling and shipping, gabions are supplied folded into a flat position and bundled together. Each gabion is readily assembled by unfolding and binding together all vertical edges with lengths of connecting wire stitched around the vertical edges. The empty gabions are placed in position and wired to adjoining gabions. They are then filled with cobblestone-size rock (10 to 30 cm in diameter) to one-third their depth. Two connecting wires are then placed in each direction, bracing opposing gabion walls together. The connecting wires prevent the gabion baskets from "bulging" as they are filled. This operation is repeated until the gabion is filled. After filling, the top is folded shut and wired to the ends, sides, and internal baffles. During the filling operation, live rooting plant species may be placed among the rock. If this is done, some soil should be placed in the gabions with the branches, and the basal ends of the plants should extend well into the backfill area behind the gabion wall.

The simplest gabion structure is a 3-foot-high wall using one tier of gabions. A second tier of gabions can be placed on top of the first tier and set back 18 inches (i.e., stepped back) without any significant design constraints. Gabion walls that are higher than two tiers (6 feet) usually require significant additional design constraints. As higher tiered walls are designed and used, the foundation of the gabion wall must be increased or additional bracing must be employed to hold the wall against overturning moments from the backfill.

Several different design configurations are possible with gabions. They may have either a sloped or a stepped-back front. The choice of type depends upon application although the stepped-back type is generally easier to build when the wall is more than 10 feet high. The number and arrangement of gabion units also depend on whether a level or an inclined backfill is used behind the wall. Walls higher than three tiers (9 feet) should be designed under the supervision of a registered civil engineer.

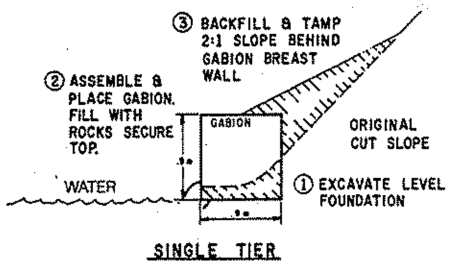
Some advantages of gabion walls are:

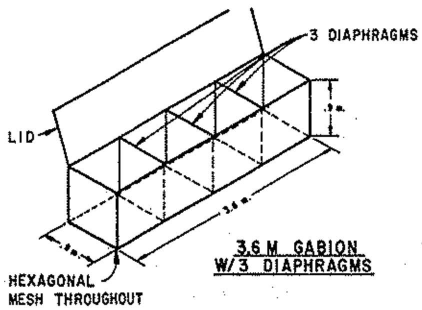
- Allow use of material of convenience
- Ease of handling and transportation
- Speed of installation
- Flexibility (tolerant to substantial differential movement and require minimal foundation preparation)
- Permeability to water (hence good groundwater drainage)

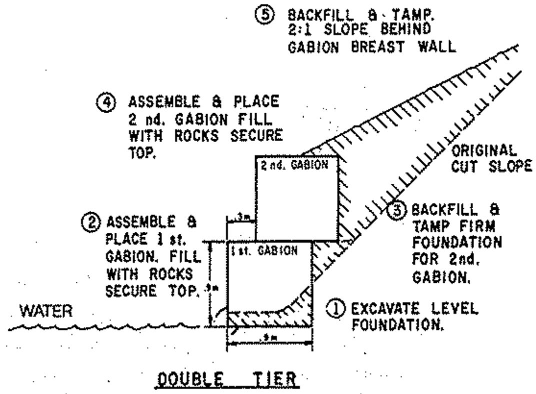
Disadvantages include corrosion and loss of strength of the wire cage due to both sand abrasion and the salt water environment and possible safety hazard to the public from exposed wire. Gabions are also vulnerable to damage by drift logs.

Figure 1

Gabion Wall Assembly and Placement







Source: Gray, Donald H., and Andrew T. Leiser. *Biotechnical Slope Protection and Erosion Control.* Malabar, Florida: Robert E. Krieger Publishing Co. 1989.

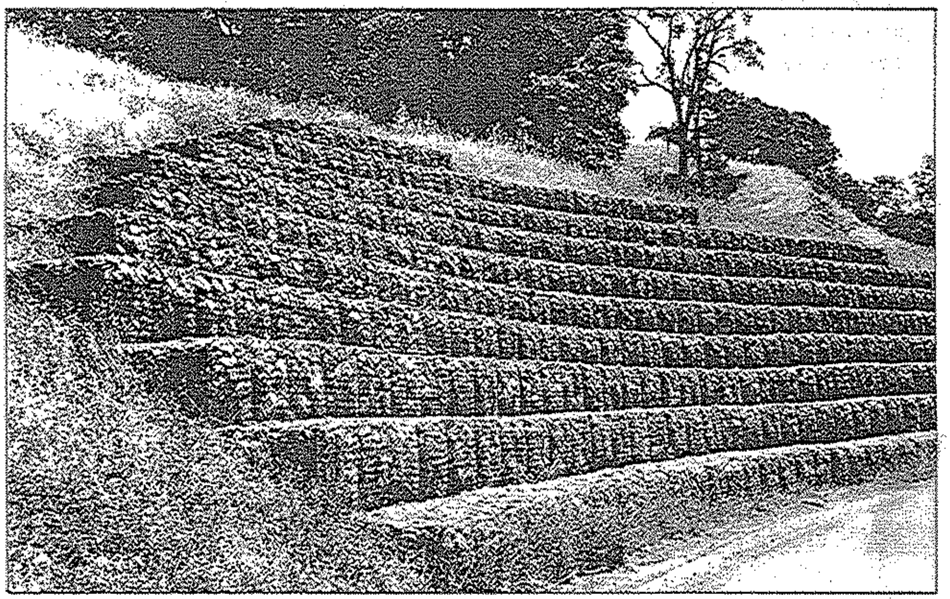


Figure 2

Stepped-Front Gabion Wall Following Construction

Source: Gray, Donald H., and Andrew T. Leiser. *Biotechnical Slope Protection and Erosion Control.* Malabar, Florida: Robert E. Krieger Publishing Co. 1989.

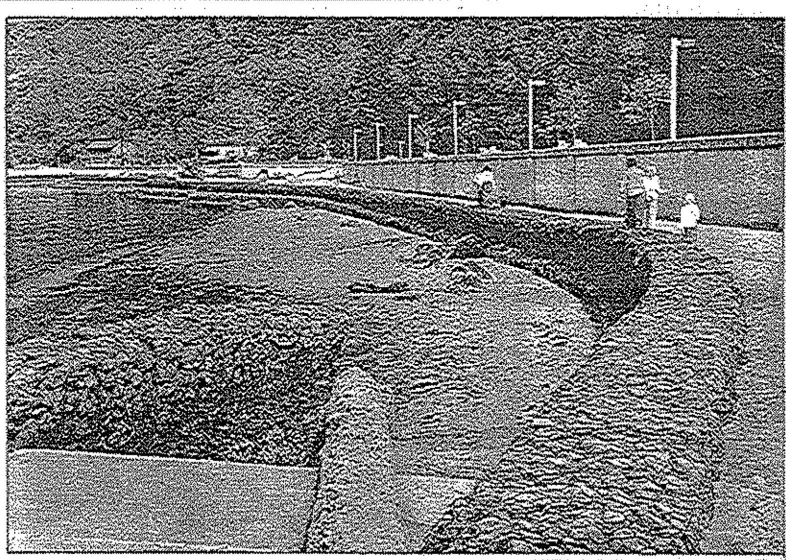


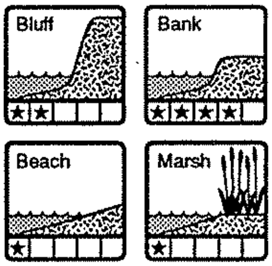
Figure 3

Gabion Bulkhead at Ed Munro Seahurst County Park

Photo reprinted with permission of the publisher from South Puget Sound: *Afoot and Float,* by Marge and Ted Meuller, The Mountaineers. 1991.

GROUT-FILLED BAGS

Suitability for landforms



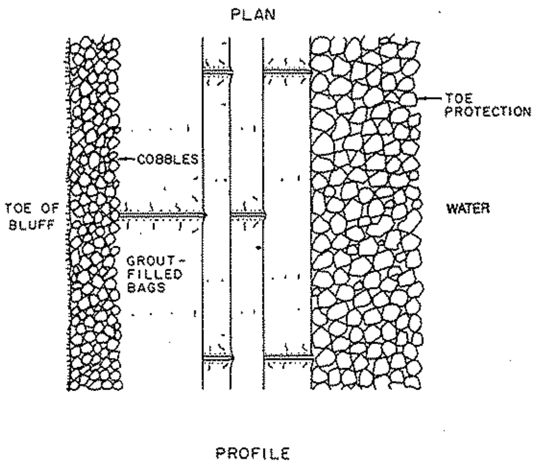
Large grout-filled bags can be placed at the toe of bluffs to form revetments. The primary advantage of a grout-filled bag over a standard revetment is that it can be constructed where access is limited. A grout pump that can be operated from the top of a bluff is used to fill the bags. In addition, the structure is readily adaptable to add-on construction if additional structure height is necessary. The bags are nested together before hardening, creating an initially tight wall. They are the most appropriate for low- to moderate-wave-energy environments, as are commonly found around Puget Sound.

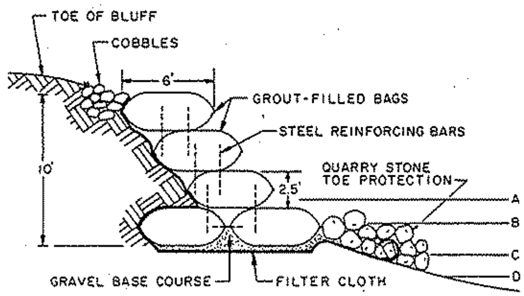
These bags are typically 6.0 feet deep by 2.5 feet high, and up to 20.0 feet long. When filled with grout, each 20-foot-long bag weighs about 14 tons. As shown in Figure 1, the bags should be placed parallel to the shore with reinforcing bars installed both vertically and horizontally to hold the bags together. A filter cloth and a gravel bed should be placed beneath the bags to provide drainage and prevent the underlying soil from being undercut by wave action or groundwater seepage.

The primary disadvantage of a grout-filled bag revetment is that it is inflexible and is therefore more vulnerable to damage by wave forces than is an equivalent riprap revetment. Because of this relative inflexibility, it is particularly important to provide a sound foundation for the bags. The bags might not be as durable as quarry stone in some applications and could be susceptible to failure because of scour-induced settlement. Because concrete is not as dense as natural rock, a larger volume of concrete is required to provide the same weight, and therefore protection, as natural rock.

Figure 1

Typical Grout-Filled Bag System





LEGEND

DESIGN WATER LEVELS

A. DESIGN HIGH STILL WATER LEVEL PLUS WIND SETUP

B. DESIGN HIGH STILL WATER LEVEL

C. ANNUAL MEAN WATER LEVEL

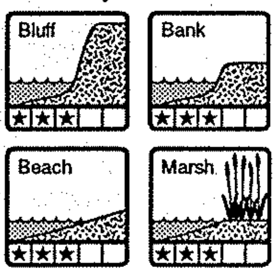
D. LOW WATER DATUM

NOTE: THE DESIGN SPECIFICATIONS SHOWN HEREIN ARE FOR A TYPICAL STRUCTURE. THE DETAILED DESIGN OF SHORE PROTECTION MEASURES MUST BE BASED ON A DETAILED ANALYSIS OF WAVE CLIMATE, COST AND AVAILABILITY OF CONSTRUCTION MATERIAL, SPECIFIC GRAVITY AND QUALITY OF THE STONE, TYPE OF FOUNDATION MATERIAL, AND EXISTING SHORELINE GEOMETRY.

Source: Southeastern Wisconsin Regional Planning Commission (SEWRPC). *A Lake Michigan Shoreline Erosion Management Plan for Northern Milwaukee County Wisconsin.* Community Assistance Planning Report Number 155. Waukesha, Wisconsin. December 1988.

FLOATING ATTENUATORS

Suitability for landforms



Floating wave attenuators are an alternative to bottom fixed structures as a means of reducing incident wave energy on a shoreline.

Floating attenuators, as shown in Figure 1, may be constructed of buoyant materials or shapes such as log bundles or rafts, hollow prisms, catamarans, buoyant panels, and flexible assemblies. The size of the attenuators is dictated bythe wave environment, but they are typically 10 to 20 feet in width with drafts up to 5 or more feet. They operate on the principle of reflecting, absorbing, or dissipating wave energy.

Figure 2 shows the wave transmission characteristics of representative attenuator types. The figure reveals that the wave transmission associated with log rafts or bundles is large in comparison to "engineered" attenuators such as prisms, catamarans, and buoyant panels. A typical 4-second wave in Puget Sound would have a length off 82 feet. Log rafts would need to be nearly 100 feet wide to achieve 40 percent transmission. Other systems need to be only 20 feet wide to achieve the same result. It is also important to note that no attenuator is able to achieve zero wave transmission.

Floating attenuators are advantageous where offshore slopes are steep and fixed breakwaters would be too expensive because of the deep water. They also are desirable at sites where water circulation or fish migration is an important consideration. In suitable applications they could be an inexpensive and possibly multipurpose solution serving, for example, as both a wave damper and a dock.

These structures have significant limitations. Floating attenuators are not able to reduce the propagation of long-period waves (with periods greater than about 4 seconds) effectively. In partially protected waters, such as behind rubblemound breakwaters or in areas with fetch limited to less than 3 miles, some designs of floating structures can reduce moderate-size waves of a few feet in height. Many sites in Puget Sound are appropriate for wave attenuator applications. Another disadvantage is that they require regular maintenance and can have a limited life. In addition, failure of a floating attenuator tends to be catastrophic because the sinking or loss of a module leaves the site totally exposed to wave action.

Figure 1
Floating Wave Attenuator Groups

Source: Bellingham Marine Industries, Bellingham, Washington.

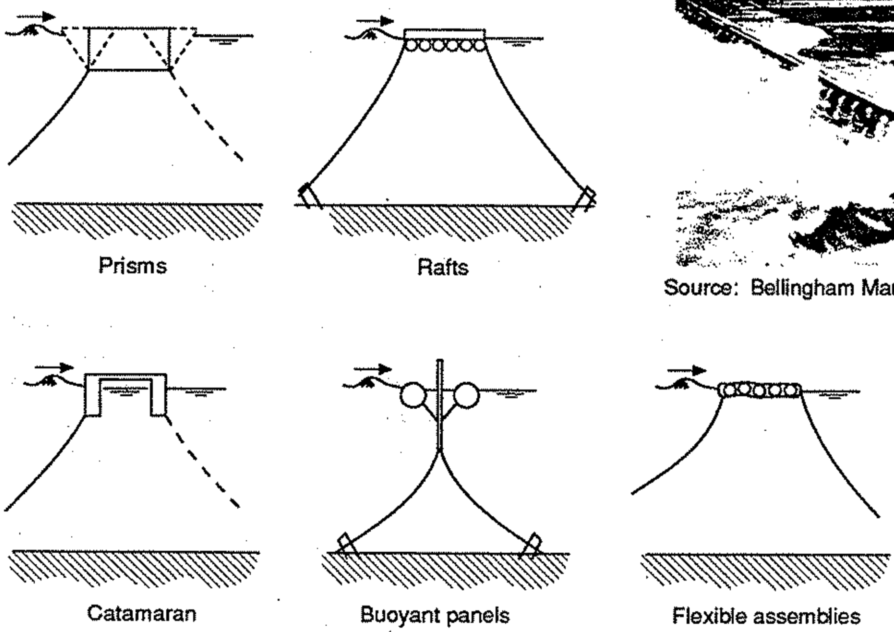
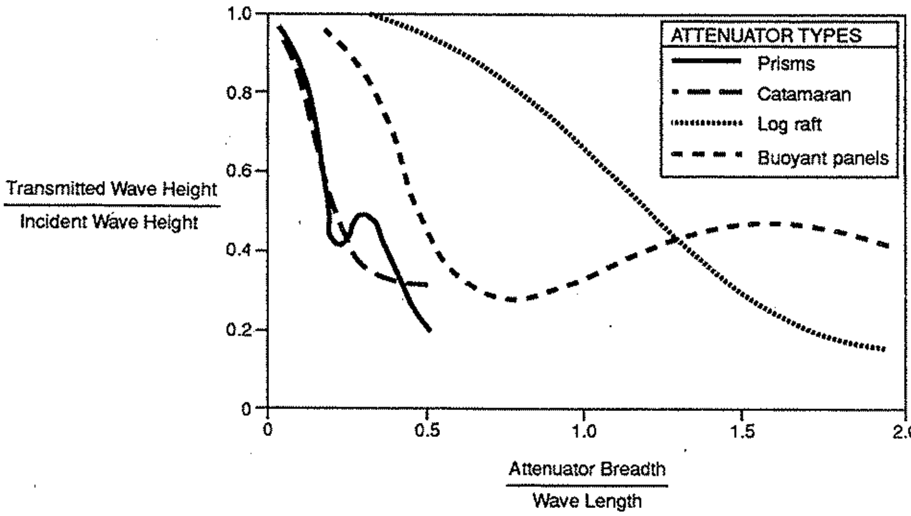


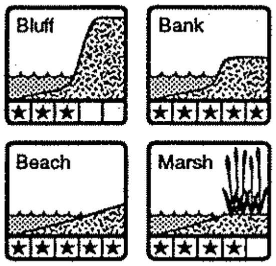
Figure 2
Wave Transmission Coefficients for Representative Floating Attenuators in Deep Water



Source: Kowalski, T. (ed.) *1974 Floating Breakwaters Conference Papers.* Marine Technical Report Series Number 24. Kingston: University of Phode Island. 1974.

BREAKWATERS

Suitability for landforms



Breakwaters are intended to prevent or reduce the transmission of wave energy behind it by absorbing or reflecting energy back to the main water body. Breakwaters generally fall into two forms, walls or mounds. Walls are tightly engineered structures and tend to be more reflective, whereas mounds are more compliant and conforming and absorb some of the energy.

Breakwaters used for shore protection are generally placed parallel to the shore in water depths less than 10 feet. If breakwaters are too porous, they allow a high percentage of longer period wave energy to pass through, causing excessive wave action behind the structure.

Wall Breakwater

Wall-type breakwaters can be constructed of parallel sheet piles (i.e., solid to the bottom) or pile-supported panels (i.e., which may be open below), as shown in Figure 1. Many variations are found in the design of wall breakwaters. Wall breakwaters are often used when available space is at a premium or when a small footprint on the bottom is important to protect the marine habitat.

If the breakwater extends to the bottom, riprap toe protection is required along the base to prevent scouring. Wall breakwater structures provide navigable water up to their edge. They are generally left open near the bottom to promote circulation and allow for fish migration.

A disadvantage of the wall breakwater is that the face of the structure does not absorb wave energy. If improperly located, these structures can cause severe reflected wave conditions that can create a safety problem for boaters and induce erosion elsewhere.

Mound Breakwater

Mound breakwaters are constructed of stone or pre-formed concrete shapes and have a trapezoidal section. Such breakwaters are generally located less than 100 feet from the shoreline. In some applications, the breakwater might tie back into the shoreline, or the system might be supplemented by groins. Usually, the breakwaters are constructed as a series of detached units, as depicted in Figure 2.

In a typical installation in Puget Sound, a filter cloth would be placed on the bottom, covered with 5- to 90-pound stone, and then by 300- to 900-pound stone. An armor layer, consisting of 1- to 3-ton stone, would then be placed. The breakwaters would extend to a height about 2 feet above the design maximum instantaneous water level. A beach nourished with coarse sand or gravel could be maintained behind the breakwaters. Periodic addition of beach fill likely would be required.

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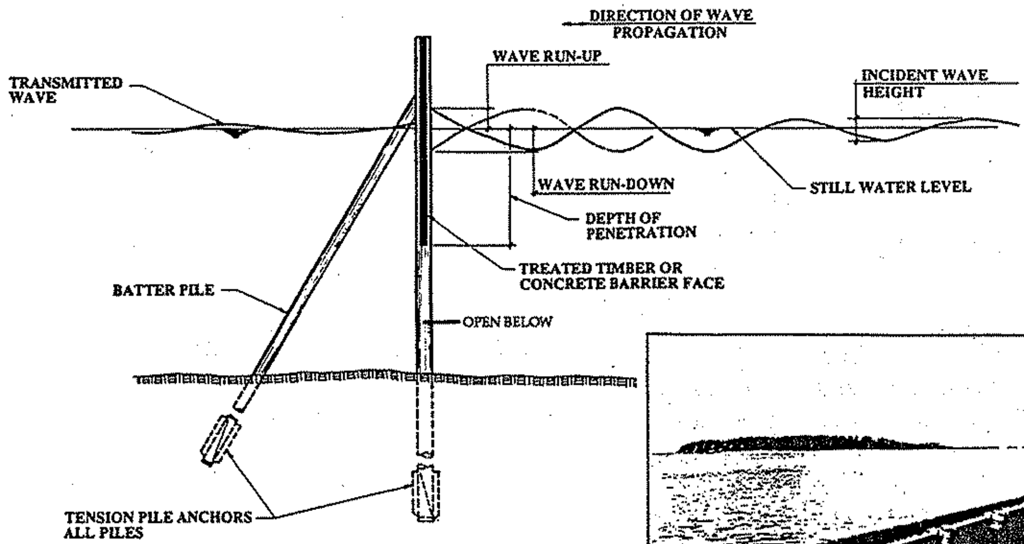
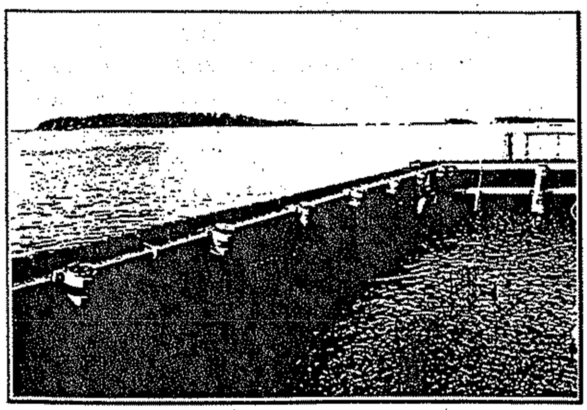
Figure 1

Typical Wall-Type Breakwater

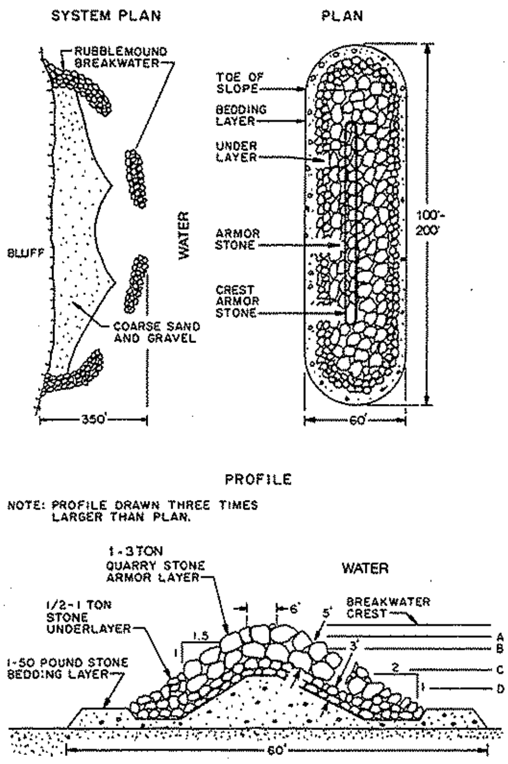


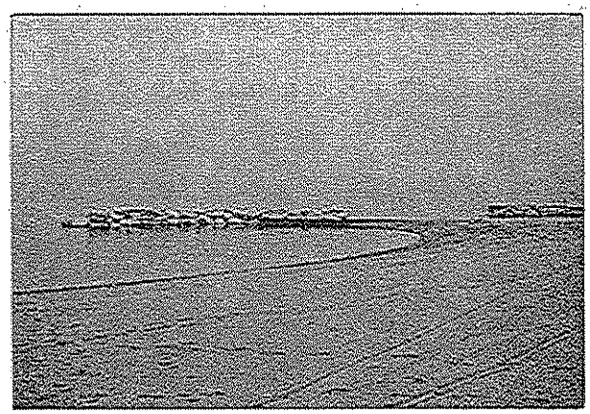


Source: Peratrovich, Nottingham & Drage, Seattle, Washington.

Figure 2

Typical Segmented Rubblemound Breakwater System





LEGEND

DESIGN WATER LEVELS

A. DESIGN HIGH STILL WATER LEVEL PLUS WIND SETUP

B. DESIGN HIGH STILL WATER LEVEL

C. ANNUAL MEAN WATER LEVEL

D. LOW WATER DATUM

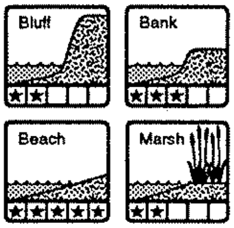
NOTE: THE DESIGN SPECIFICATIONS SHOWN HEREIN ARE FOR A TYPICAL STRUCTURE. THE DETAILED DESIGN OF SHORE PROTECTION MEASURES MUST BE BASED ON A DETAILED ANALYSIS OF WAVE CLIMATE, COST AND AVAILABILITY OF CONSTRUCTION MATERIAL, SPECIFIC GRAVITY AND QUALITY OF THE STONE, TYPE OF FOUNDATION MATERIAL AND EXISTING SHORELINE GEOMETRY.

Source: Southeastern Wisconsin Regional Planning Commission (SEWRPC). *A Lake Michigan Shoreline Erosion Management Plan for Northern Milwaukee County Wisconsin.* Community Assistance Planning Report Number 155. Waukesha, Wisconsin. December 1988.

SAND AND GRAVEL FILLS

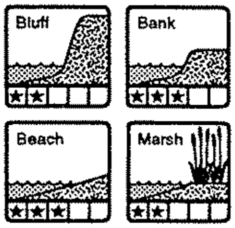
Sand fills

Suitability for landforms



Gravel fills

Suitability for landforms



In relatively quiescent waters (i.e., with infrequent waves less than 2 feet high), small beach fills can be used to combat minor erosion. Beach fills can be composed of varying size material, but normal practice is to place sand or gravel that is at least as coarse as the native beach material. Larger material maybe placed at a steeper slope and is more resistant to wave attack. Table 1 indicates the natural equilibrium beach slopes that will result from use of different sediment grain sizes.

Beach fills of limited width–a few hundred feet–generally have a useful life of 5 years or less. This is due to the rapid loss of material from the flanks of the fill caused by oblique wave attack and resulting longshore transport of material.

Because beach fills are typically of short length alongshore, they require placement in natural embayments or between retaining structures to help hold them in place. Terminal structures, such as groins, can be used to retain the fill laterally while sills placed offshore can help retain the toe. A beachface dewatering system can be installed with the fill to help hold the newly added beach material in place.

To be effective, the beach fill needs an adequate cross-shore width to permit natural shape deformation and absorption of wave energy. The designed cross-shore width can be estimated as a function of acceptable damage of upland areas for a given return period storm. This is shown in Figure 1 where the damage function D is the cost value of damage as a proportion of the upland land value.

Table 1
Estimated Beach Slopes That Would Form on Various Beach Fill Materials

Breaking Wave Height	Beach Slope (degrees) Fine Sand (0.125 mm)	Medium Sand (0.5 mm)	Very Coarse Sand (1.5 mm)	Very Fine Gravel (3 mm)	Fine Gravel (6 mm)	Medium Gravel (12 mm)	Coarse Gravel (24 mm)
3 feet	1	3	4	6	8	12	16
6 feet	<1	2	3	4	6	8	12
9 feet	<1	1	2	3	5	7	10
12 feet	<1	1	2	3	4	6	8

Note: Calculated by using the following formula from J. W. Kamphuis, M. H. Davies, R. B. Nairn, and O. J. Sayao, Calculation of littoral sand transport rates, *Coastal Engineering*, Vol. 10, pp. 1-21 (1986):

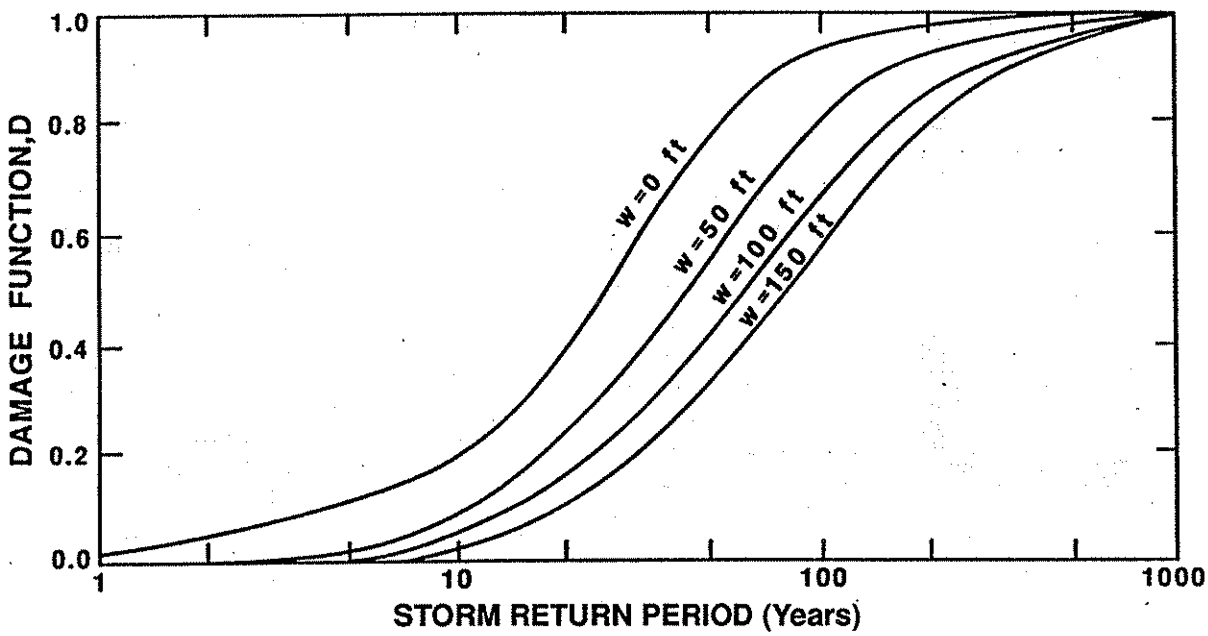
$$m=\tan^{-1}\left[1.8\left(\sqrt{\frac{H}{D}}\right)^{-1}\right]$$

where m = beach slope (degrees)
H = breaking wave height (m)
D = beach particle diameter (m)

Source: SEWRPC

Figure 1

Cost Value of Damage, as a Function of Upland Land Values, for Various Beach Widths, w, and Storm Return Periods

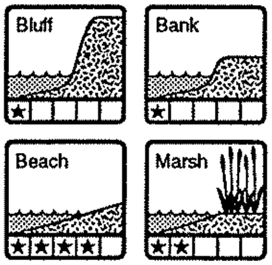


The decrease of upland value – i.e., structural damage, cost of repair, and replacement, or loss of acreage – can be balanced against the cost to maintain a beach fill of width (w), against the risk of occurrence of any return period storm event.

Source: Cambell, T.R. Dean, A. Mahta, and H. Wang. *Short Course on Principles and Applications of Beach Nourishment.* Florida Shore and Beach Preservation Association and University of Floida Coastal and Oceanographic Engineering Department. February 13, 1990.

BEACHFACE DEWATERING

Suitability for landforms



Beachface dewatering entails removing water from the beach sediment by pumping water out of perforated pipe buried in the beach. The principle of beachface dewatering is to emulate the natural summertime process of sand accretion and prevent the erosion that normally is caused in the winter by the action of storm waves.

Puget Sound summer winds generally are gentle, and the waves are long and shallow. The active beach face becomes only partially saturated; wave run-up easily percolates downward; transport of sand is toward the shore only; and the net result is an accumulation of sand.

In the winter, frequent storms and short and steep waves saturate the beach face, lowering the sediment's resistance to motion. The turbulent surf from large breaking waves keeps sand suspended, and the higher water table produces positive seepage out of the beach face, allowing the backwash to lift sand off the beach face and into suspension. The result is that the backwash of sand is equal to or greater than the uprush, and the net effect is erosion.

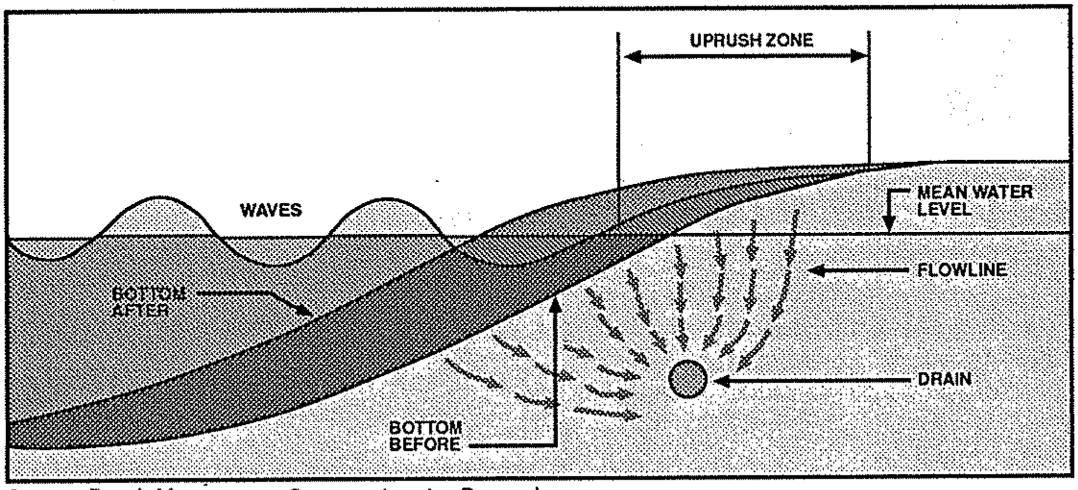
By lowering the water table adjacent to the drain tube, beachface dewatering reduces the hydraulic pressure and creates an unsaturated zone in the beach face. This zone makes downward percolation of wave run-up possible throughout the year and cuts off the subterranean flow of water to the ocean. As a result, the volume of the backwash is less; the erosion process is reduced; and a wider beach is maintained. Figures 1 and 2 show a typical dewatering layout and the effects on the beach profile and groundwater levels.

Pumping rates and pipe sizes are determined by the range of tidal fluctuations and the desired beach width. Under ideal conditions, up to 60 feet of beach width can be maintained by this method.

The primary advantage of beachface dewatering is that a constant shoreline (beach) can be maintained. Disadvantages include the extent of the drain field needed to accommodate large tidal fluctuations and the power consumption necessary to operate the well pump.

Figure 1

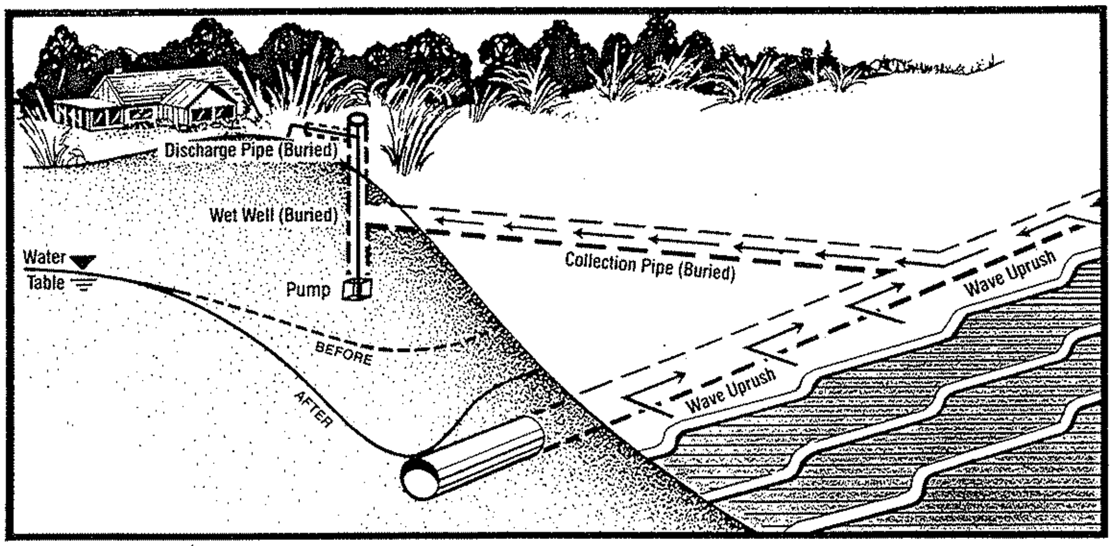
Beach Profile Change from Beachface Dewatering



Source: Beach Management Systems, Lyngby, Denmark.

Figure 2

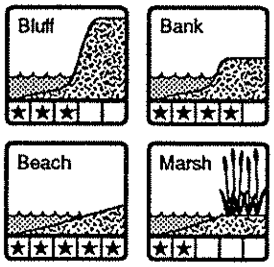
Effect of Typical System on Groundwater Table



Source: Coastal Stabilization, Inc., Rockaway, New Jersey.

BEACH STRANDS

Suitability for landforms



Beach strands are long, uninterrupted stretches of natural or artificially created beach. They act as dynamic wave energy absorbers, deforming in both plan and section to accommodate the wave conditions. Beach strands typically have wide dry beaches. On shorelines that have no existing beach, beach strands can be designed to be a fixed installation, providing wave protection to back beach and upland areas. Fixed installations typically require terminal structures, such as jetties, to prevent lateral loss of material. Depending on the variability of wave approach and intensity of wave activity, intermediate structures such as groins or nearshore breakwaters might be added to more evenly distribute and hold the beach to some minimum desired beach width. Fixed beach strands offer no benefit to downdrift areas and might even contribute to some erosion by causing trapping of whatever material is already in the littoral system.

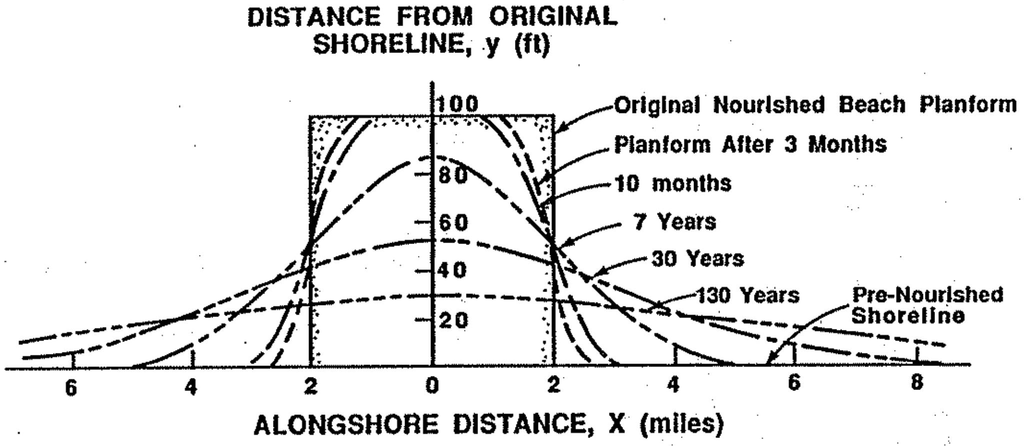
Beach strands also can be designed to act as feeder beaches to reintroduce sediment to an existing sediment-starved shoreline. In this case, no retaining structures are used, and the beach is allowed to narrow gradually as the material spreads downdrift. Typical changes in beach strand platform over time are shown in Figure 1. The fraction of material remaining on a created beach without terminal structures is shown in Figure 2 for various configurations and lengths of time.

Over the life of the project, feeder strand beaches appear to perform equally well either by placing all the sediment in one area and then allowing it to spread naturally or by spreading the material along the entire project length initially.

Advantages of beach strands include their natural appearance, frequent environmental compatibility with the native shoreline, and ability to accommodate a variety of wave conditions and water levels as well as being somewhat self-healing. Their principal disadvantage is that to be effective they generally need to be very large projects with regular maintenance and sand renourishment required. Their specific performance in attenuating waves at any given time is a function of the beach width at that time and cannot be predicted reliably.

Figure 1

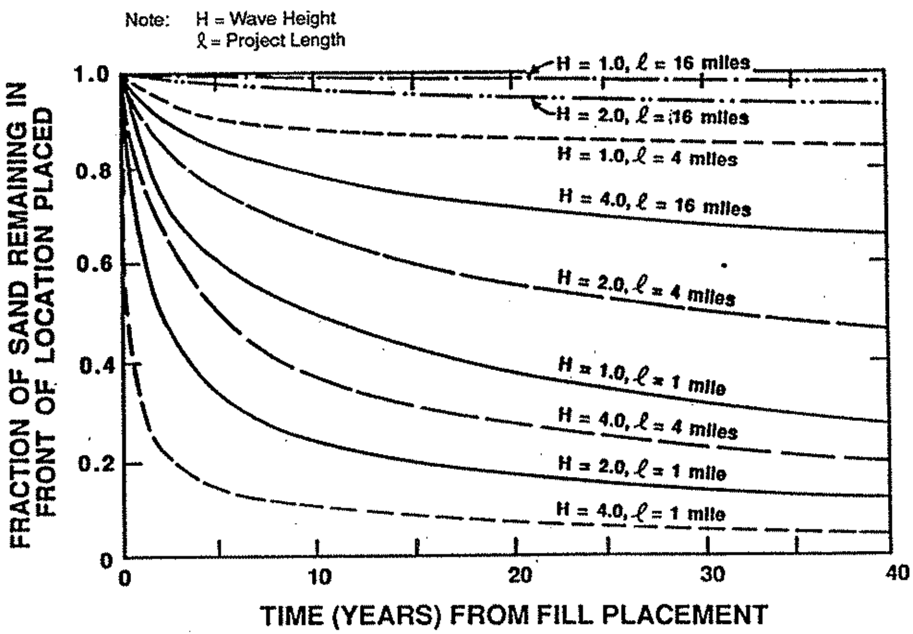
Example Evolution of Initially Rectangular Nourished Beach Planform



Note: Example for Project Length, ℓ, of 4 Miles, Effective Wave Height, H, of 2 Feet, and Initial Nourished Beach Width of 200 Feet.

Figure 2

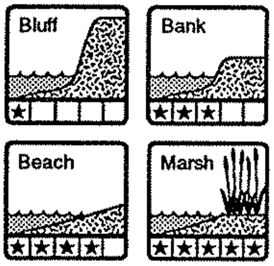
Effect of Longshore Transport



Source: Cambell, T.R. Dean, A. Mahta, and H. Wang. *Short Course on Principles and Applications of Beach Nourishment.* Florida Shore and Beach Preservation Association and University of Florida Coastal and Oceanographic Engineering Department. February 13, 1990.

SHORELINE VEGETATION

Suitability for landforms



Under favorable circumstances, a planting program to establish shoreline vegetation can be an effective approach to shoreline protection. Species of grasses, sedges, and rushes are suited to marshes along moderate- to low-energy shorelines that are flooded periodically by brackish water. Dune species, particularly grasses, are especially adapted to the low-nutrient, low-moisture environment of the higher beach elevations where they are subject to abrasion by windblown sand particles.

Even though shoreline vegetation provides significant help in stabilizing beaches and preventing erosion, vegetation alone cannot prevent erosion from heavy wave action, nor can it prevent movement of shoreline bluffs activated by groundwater action.

Marsh Plants

Coastal marshes are herbaceous plant communities that are normally inundated or saturated by surface or groundwater. They can be narrow fringes along steep shorelines or cover wide areas in shallow, gently sloping shore regions typically found in bays and estuaries. In saltwater marshes, salinity is generally equal to, or slightly less than, seawater (35 parts per thousand). Freshwater marshes experience water level fluctuations resulting from groundwater table and seasonal changes. Vegetation prevalent in saltwater marshes of Puget Sound is discussed below.

Pickleweed *(Salicornia virginica).* Pickleweed can be used from mean high water to extreme high tide. It will spread both by seeds and vegetatively (by rhizomes and tillers). Pickleweed can be established easily by seeding or by transplanted peat-pot seedlings and, in fact, often invades disturbed surfaces during the first growing season.

Sedge *(Carex lyngbyei).* Sedge marshes are usually found in areas such as river deltas where silty soils exist. They grow above the mean tide level and are not especially salt tolerant. The plant may respond to nitrogen and phosphorous under deficient conditions. *Carex* appears to be one of the best marsh plants available in the Pacific Northwest.

Tufted Hair Grass *(Deschampsia caespitosa).* This plant predominates in high marshes subject to flooding only by higher high tides. It is a good sediment accumulator and stabilizer once established. It is generally easy to transplant and quick to establish.

Arrowgrass *(Triglochlin maritima).* This plant will frequently invade and colonize disturbed marshes, trapping sediments and debris and helping to create a substrate for other plants. Planting should follow the method described for sedges.

Beach and Dune Plants

The protection of the upland portions of sandy shorelines can be accomplished through the creation of barrier dunes and the stabilization of present dunes. Vegetation used to initiate the building of barrier dunes is specially adapted to the severer environment of the beach area. Barrier dune formation can occur naturally, but it is usually slow. Utilization and proper management of the natural processes can accelerate the development.

The beach provides a generally harsh environment for plant growth. Plants must tolerate rapid sand accumulation, flooding, salt spray, sandblasts, wind and water erosion, wide temperature fluctuations, drought, and low nutrient levels. Plants capable of stabilizing coastal dunes, however, occur where there is sufficient rainfall to support plant growth.

European beachgrass and American dunegrass are the dominant sand-stabilizing plants of the

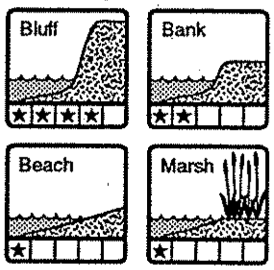
Puget Sound region. American beachgrass (*Ammophila brevilingulata*) can also be applicable in the area.

European Beachgrass *(Ammophila arenaria).* This plant is inexpensive and used widely. Although it effectively traps sand, it forms dense stands with little outward spread, causing the resulting dunes to have steep windward slopes. Another disadvantage is that it will often exclude native species, making it difficult to establish mixed plantings.

American Dunegrass *(Elymus mollis).* Although this grass is native to the Northwest, it is more difficult and expensive to propagate than either European or American beachgrass. The grass tends to produce low, gently sloping dunes, often preferable to those dunes built by European beachgrass.

GROUNDWATER DRAINAGE

Suitability for landforms



Reducing the water content of a bank or bluff can be expected to help stabilize a slope significantly. However, detailed, site-specific analyses of the groundwater conditions must be conducted at the preliminary engineering phase to affirm the feasibility of groundwater drainage systems. Groundwater drainage must also be considered during and following the construction of fill projects in order to prevent excess hydrostatic pressures caused by either the blockage of natural seepage paths or the compression of saturated soils by the weight of the fill material.

Drainage systems require relatively minor maintenance and should not limit the use of the shoreline. A groundwater drainage system need not disturb the vegetative cover on a bluff slope or require changing the slope geometry. A limitation of groundwater drainage as a slope stabilization control measure is that drainage is usually economically feasible only in granular layers. The removal of water within clay glacial till layers is usually too costly and difficult. Therefore, the drain system must be designed to intercept the water before it encounters the clay.

Three alternative groundwater drainage systems are described below: horizontal drains, vertical drains, and trench drains.

Horizontal Drains

A horizontal drain is a small-diameter boring drilled into the face of the bluff slope on a 5 to 10 percent grade and fitted with a perforated pipe. As shown in Figure 1, a system of collector conduits is provided to carry the collected water to the base of the bluff or to a suitable outlet. A horizontal drainage system is most effective in layers of granular material containing sand and gravel. Drains are usually spaced across the face of the bluff slope at suitable intervals based on the anticipated flow rates and soil permeability.

Advantages of a horizontal drain system are that the system drains by gravity and requires relatively little maintenance. The primary disadvantage of the system is that access to the base of the bank or bluff to install the drains is often difficult.

Vertical Drains

A vertical drain, or well, usually consists of a large-diameter boring drilled vertically from the top of the bluff into the water-bearing strata. Water can be either pumped from the well or tapped with a gravity outlet, as shown in Figure 2. Gravity-drained vertical wells can be connected to horizontal drains that carry the collected water out of the bluff to a safe point of disposal. Water pumped from a vertical well can be discharged to the base of the bluff or to a suitable surface water outlet. Unlike most horizontal drains, vertical drains can be designed to drain several water-bearing strata separated by impermeable layers.

Detailed geotechnical analyses are required in the preliminary engineering phase to determine the necessary location, spacing, depth, and pumping rate of the well points. Under favorable conditions, relatively large amounts of water can be pumped from the wells to lower the groundwater table. In addition, access to install the drains is generally not a problem because vertical drains are installed from the top of the bank or bluff.

Disadvantages of this system are that the wells must be pumped continuously to maintain the lower water table, and substantial maintenance of the wells and pumps might be required.

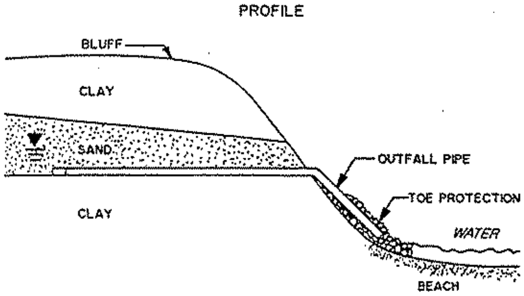
Trench Drains

The purpose of a trench drain is to intercept and divert shallow seepage. A typical design consists of a narrow trench–usually 18 to 24 inches wide and 2 to 6 feet deep–dug parallel to the edge of the bluff, in which a perforated collector pipe is installed. The pipe is connected to a discharge outlet and the trench backfilled with granular material, as shown in Figure 3.

A trench drain is relatively inexpensive, is easy to install, and drains by gravity. The disadvantage of this system is that it is limited to areas of shallow seepage although deeper water-bearing strata sometimes can be drained by constructing the trench on the face of the bluff. Trench drains need to be constructed with great care so as not to disturb existing beneficial vegetation or initiate slope failure.

Figure 1

Horizontal Drainage System



Source: Owen Ayres & Associates, Great Lakes Shore Erosion Protection, Structural Design Examples, 1978, and SEWRPC.

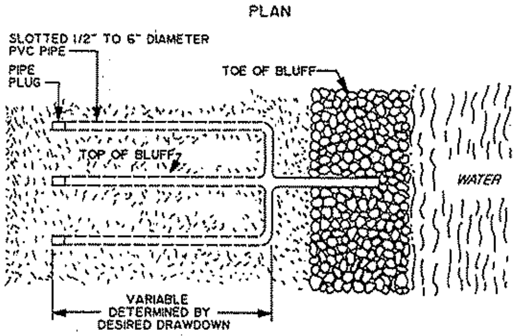
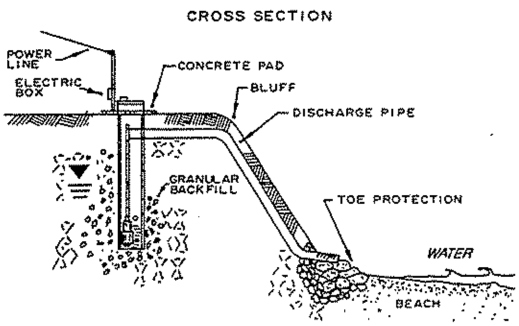
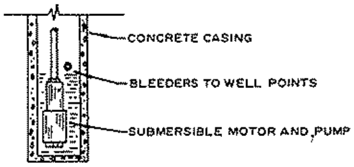


Figure 2

Vertical Drainage System





Source: SEWRPC.

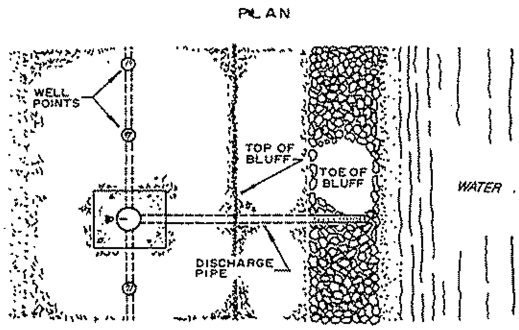
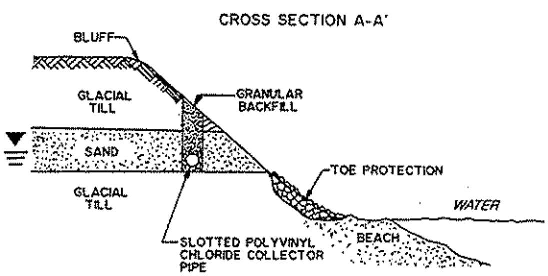
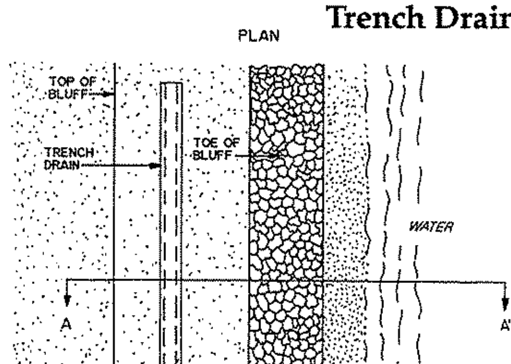


Figure 3

Trench Drains

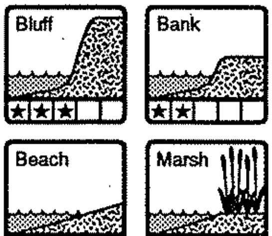




Source: Southeastern Wisconsin Regional Planning Commission (SEWRPC). *A Lake Michigan Shoreline Erosion Management Plan for Northern Milwaukee County Wisconsin.* Community Assistance Planning Report Number 155. Waukesha, Wisconsin. December 1988.

SURFACE RUNOFF CONTROL

Suitability for landforms



Techniques for preventing and reducing bluff erosion due to surface runoff include ground cover practices, diversions, and slope drains. These methods serve to stabilize the soil surface and reduce the erosive forces of runoff. They are applicable to newly constructed slopes or slopes with existing surface erosion problems. These methods can be employed either for temporary erosion control during construction or for permanent slope stabilization. They require relatively minor maintenance, but proper installation is essential for correct function.

Ground Cover Practices

Ground cover practices for prevention of surface runoff erosion include application of inert facings, organic mulches, and live materials (Gray, 1991). Live material cover practices include seeding and biogeotechnical vegetative stabilization, as discussed separately under the heading "Bluff Vegetation."

For steep bluffs (greater than 1V:2H), common seeding practices must be augmented with measures to stabilize the soil and promote plant growth. These measures include application of organic mulches (e.g., straw or wood chips) and installation of two-dimensional erosion control meshes or nets, three-dimensional mats, and cellular grids.

Erosion control meshes, which generally incorporate natural materials (e.g., straw, wood or coir fiber, or jute), are placed on the disturbed surface after seeding. The plant seedlings grow through the mesh, and the plant roots bind around the strands of the mesh to form a continuous mesh/soil/root system. These systems increase resistance to erosive forces, improve lateral continuity of plant cover, and assist plant roots in retaining soil. Meshes developed from natural materials degrade over time, thereby adding organic matter to soil. They are commonly used for steep slope applications, for temporary protection during construction, and for permanent slope stabilization and seeding operations.

Three-dimensional mats or honeycomb grids are used for permanent stabilization. Typically constructed of a geotextile material such as nylon or polyethylene, they are generally stronger than mesh and can withstand higher flow velocities. Mats are placed on a graded surface, filled with topsoil, and seeded. They are typically nondegradable, which might not be desirable for some slope applications.

It is critical that mesh and mat materials be anchored to the soil tightly and in accordance with manufacturers' specifications; otherwise, erosion can occur under the material. For steep slope applications (greater than 1:1), these materials should be oriented lengthwise down the slope, as shown in Figure 1.

Riprap and articulated concrete blocks are additional methods for permanent slope stabilization and erosion protection. Articulated concrete blocks are preformed locking blocks, providing a continuous flexible covering. Unlike riprap, these systems contain openings to the soil, allowing for vegetation establishment within the blocks.

These measures for protecting the soil surface and augmenting vegetative growth are expensive relative to simple seeding and mulching practices. However, they are effective on steep slopes and bluffs where seeding practices alone are not sufficient. For bluffs with erosion problems due to large volumes of surface runoff, diversions and slope drains should also be used.

Runoff Diversions

Runoff diversions include dikes (ridges of compacted soil) or ditches (excavated depressions) placed horizontally along a slope to intercept runoff and transport it at low velocities to a stabilized outlet (Washington Department of Ecology, 1992). Diversions reduce surface erosion and protect slope stability by reducing runoff volume and overland flow length and velocity. They can be used as temporary or permanent controls. A suitably sized outlet must be available to convey the concentrated flow down the slope to the beach.

Diversions used to prevent upslope runoff from running over the bluff are termed "interceptor dikes" or "ditches." For very tall slopes, diversions can be placed on benches constructed horizontally across the slope. Commonly constructed out of dirt, temporary dikes and ditches are inexpensive and can be stabilized permanently with vegetation. Diversions must be constructed at a proper grade to maintain drainage without creating erosive flow velocities, and they should be inspected regularly as failure could result in washout downslope.

Diversions placed at regular intervals along the slope are called "gradient terraces" (Figure 2). Terraces are constructed to drain across the slope at slight gradients (0.6 percent typical design slope), thereby lowering the runoff velocity and erosive force. They serve the additional benefit of trapping sediment. A disadvantage of terraces is the cost involved with construction and potential for sloughing if excessive water infiltrates into the bank. They are not suitable for steep, sandy, or rocky soils. A similar practice more suitable on slopes steeper than 2:1 is stair-stepping, or cutting of horizontal steps across the slope on which vegetation is then planted (Figure 3).

Slope Drains

Slope drains are surface pipes, paved chutes, or subsurface pipes used to transport runoff down steep slopes (Ecology, 1992). Interceptor ditches or berms usually are used at the top of the slope to direct the water to the drain inlet.

Surface pipes are used generally for temporary purposes, whereas chutes and subsurface pipes are permanent. These methods are very effective for transporting runoff from upslope areas to a stable discharge location at the bottom of the slope (i.e., on the beach) while protecting the slope from erosion. It is important to provide an energy dissipator such as riprap at the outlet of the drain to prevent erosion and undercutting at the outlet.

Figure 4 shows a typical surface pipe drain. Debris traps should be included at the entrance to the pipe to prevent clogging.

Subsurface slope drain methods include variations of the trench drain, which may also be used for groundwater drainage. These drains consist of perforated pipes placed in shallow trenches to pick up seepage and surface water and can be connected together with main and lateral lines to collect and convey runoff down the slope.

It is important that slope drains be properly sized because impacts due to ponding water and overflows would be significant. In addition, surface runoff generated on the slope itself can concentrate along the sides of the drain and undercut the structure. In order to reduce the potential for undercutting, care must be taken to compact the soil under the drain and entrance section and properly revegetate the disturbed drain corridor.

References

Gray, Donald H. *Influence of Ground Cover on Surficial Erosion.* Prepared for the 1991 Coir/ Geotextile Conference. September 1991.

Washington State Department of Ecology. *Stormwater Management Manual for the Puget Sound Basin.* The Technical Manual. February 1992.

Figure 1

Orientation of Erosion Control Mesh or Mat

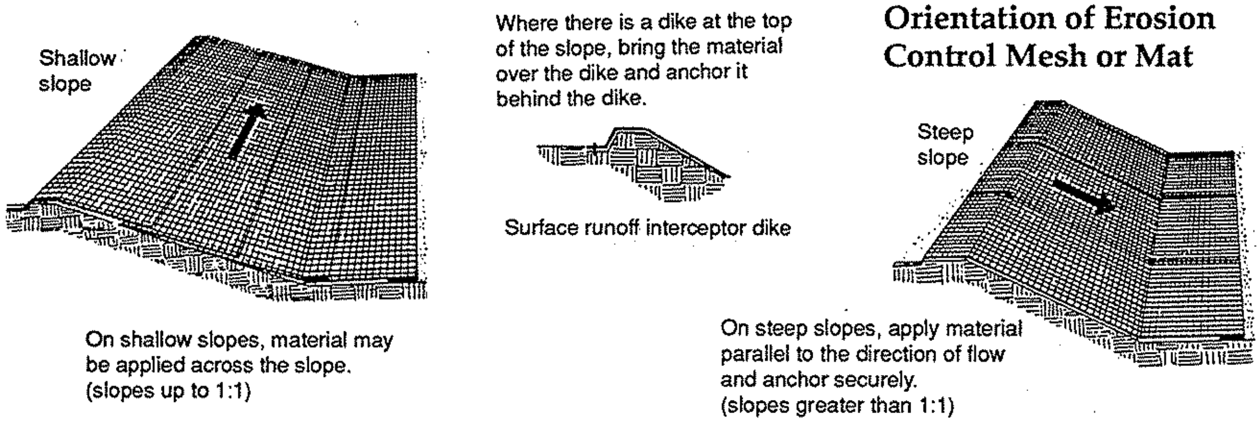


Figure 2

Gradient Terraces

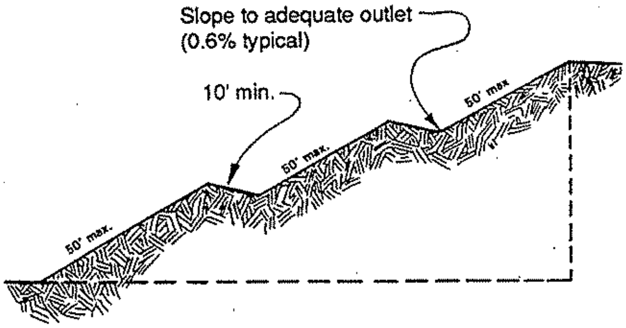


Figure 3

Stair-Stepping Cut Slopes

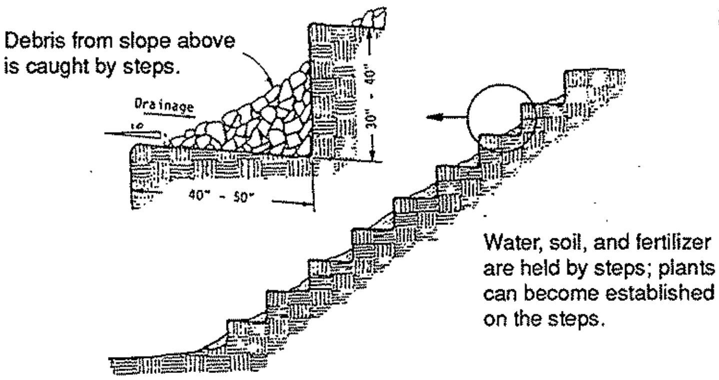
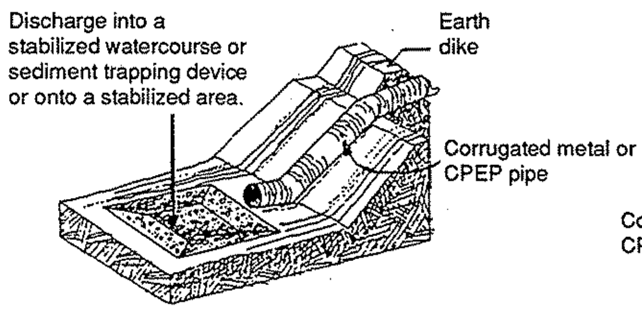
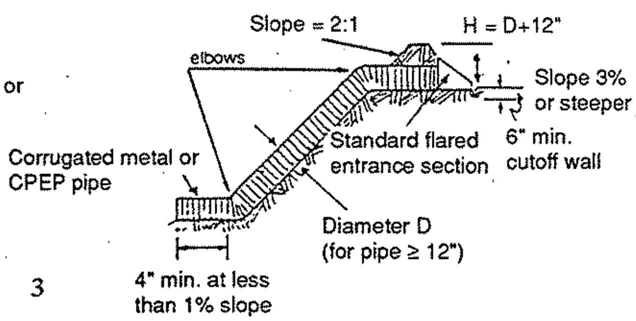


Figure 4

Surface Pipe Slope Drains

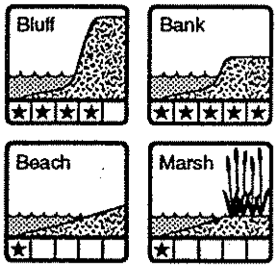




Source for all: Washington Department of Ecology, 1992.

SLOPE REGRADING

Suitability for landforms



Instability of shoreline bluffs and slopes can be controlled by flattening the slope angle, thus increasing the sliding friction in the soil. A slope can be flattened by adding material in front of the slope, cutting the slope to a flatter (lower) angle, or cutting the upper portion of the slope and placing the spoil at the toe. A steep slope can be stabilized by shaping terraces, which maintain a stable composite slope angle, into the face.

Bluff slope regrading can be accomplished by using earth-moving equipment to regrade the face of the slope to a flatter, more stable profile, as shown in Figure 1. A bluff slope of 1 horizontal (H) : 2 vertical (V) usually will provide a stable bluff slope.

Slope Cutback Method

The cutback method can be used only in areas where any permanent structures are located a sufficient distance from the edge of the bluff. Topsoil placement, seeding, and mulching would be required to develop a protective vegetative cover on the newly graded slope. Where needed, adequate toe protection, as well as drainage of surface water and groundwater, would have to be provided to maintain the regraded bluff slope.

The cutback method reduces or eliminates the need for the placement of fill on the bluff face. The disadvantage of the cutback method for bluff slope regrading is that land at the top of the bluff is lost.

Fill Method

Bluff slope regrading can also be accomplished by transporting soil, concrete rubble, and other clean fill from an outside source and placing it on the face of the bluff to provide a more gently sloping, stable profile. Filling will likely be required for bluffs where permanent structures are located close to the edge of the bluff. The fill materials, as shown in Figure 2, should be granular to enhance drainage. Fine-grained, clay-type materials are not suitable for fill material in areas susceptible to groundwater drainage problems.

Depending on the type of material used for filling, a slightly steeper angle–often approximating 35 degrees–may be used for portions of the regraded bluff slopes. Slopes constructed of fill material are normally terraced or contain compound slopes to intercept rainfall runoff. Filling should begin at the slope bottom, and some bluffs might need to be filled only along the lower portions of the slope because the upper slope is still at a stable angle of repose. Soil placement, seeding, and mulching would be required to develop a protective vegetative cover. Adequate toe protection would also be provided to maintain and protect the fill material.

The primary benefit of using the fill method is that land at the top of the bluff is not removed, which is particularly advantageous in areas where structures are located within 50 feet of the bluff edge. An adverse impact of using fill is the necessity to sometimes fill into the water in order to provide a stable slope. Other disadvantages include the trucking and aesthetic impacts associated with filling.

Cut-and-Fill Method

A combination of cutting the upper unstable portion of a bluff and placing that material–along with additional fill material, if necessary–at the base of the bluff can provide a stable bluff slope. The cut-and-fill method is shown in Figure 3. This method is limited to areas where structures are located at least 50 feet from the edge of the bluff slope. Soil placement, seeding, and mulching are required to develop a protective vegetative cover, and adequate toe protection should be provided to maintain the regraded bluff slope.

The advantage of using the cut-and-fill method over the cutback method is that less land is lost at the top of the bluff slope. The majority of the material needed for filling is already at the site, and compared to the total fill method, less fill material would extend out onto the beach or into the water.

Terracing Method

Slope stabilization can also be provided by placing a series of vertical retaining walls within the regraded bluff slope, as shown in Figure 4. The retaining walls may be constructed of stone, timber, interlocking concrete blocks, steel sheet pile, or gabions. The bluff slope between the retaining walls is regraded to a slope of 1H:3V or flatter and revegetated. The terracing method can provide improved access to the shoreline if a suitable walkway is provided. Depending on the design of the terrace system, less bluff material might need to be removed at the top of the bluff than with the cutback method or the cut-and-fill method.

The primary disadvantages of the terracing method are its relatively high cost and construction difficulty. Because of the high cost, it is most feasible to construct terraces on only the top one-third of the bluff slope where construction equipment can work from the bluff crest.

Figure 1

Cutback Stabilization Method

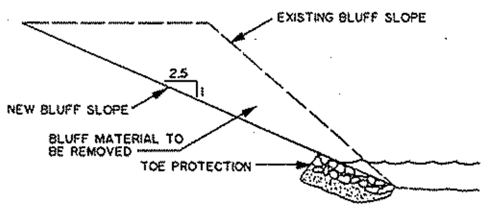


Figure 2

Fill Stabilization Method

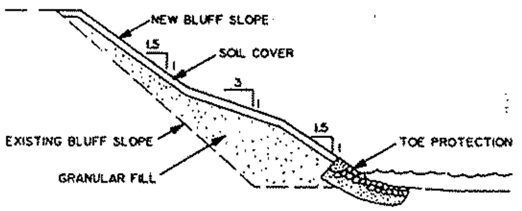


Figure 3

Cut and Fill Stabilization Method

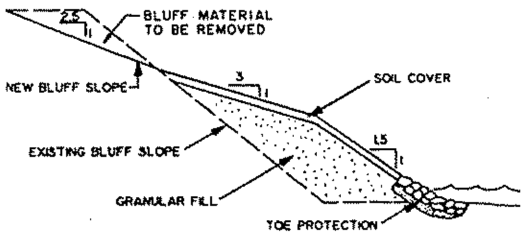
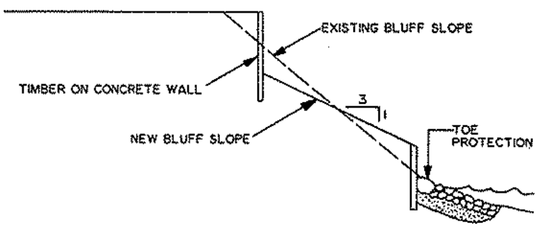


Figure 4

Terraced Stabilization Method



LEGEND

DESIGN WATER LEVELS

A. DESIGN HIGH STILL WATER LEVEL PLUS WIND SETUP

B. DESIGN HIGH STILL WATER LEVEL

C. ANNUAL MEAN WATER LEVEL

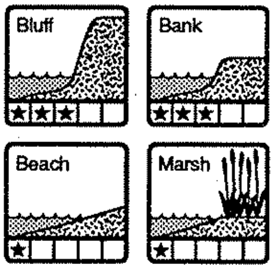
D. LOW WATER DATUM

NOTE: THE DESIGN SPECIFICATIONS SHOWN HEREIN ARE FOR A TYPICAL STRUCTURE. THE DETAILED DESIGN OF SHORE PROTECTION MEASURES MUST BE BASED ON A DETAILED ANALYSIS OF WAVE CLIMATE, COST AND AVAILABILITY OF CONSTRUCTION MATERIAL, SPECIFIC GRAVITY AND QUALITY OF THE STONE, TYPE OF FOUNDATION MATERIAL, AND EXISTING SHORELINE GEOMETRY.

Source: Southeastern Wisconsin Regional Planning Commission (SEWRPC). *A Lake Michigan Shoreline Erosion Management Plan for Northern Milwaukee County Wisconsin.* Community Assistance Planning Report Number 155. Waukesha, Wisconsin. December 1988.

BLUFF VEGETATION

Suitability for landforms



Maintenance of existing vegetation and revegetation of bare ground (denuded areas) can improve slope stability by preventing translational sliding, trapping sediment, and controlling surface runoff. In addition, a well-vegetated bluff slope is aesthetically pleasing and provides habitat for wildlife. The establishment of a vegetative cover has a modest cost and requires minimal maintenance. Alternative methods of revegetating bluff slopes include seeding, transplanting, and brush layering, as described below.

Further guidance on the selection and use of vegetation for slope stabilization is provided by two Washington Department of Ecology publications: *Vegetation Management: A Guide for Puget Sound Bluff Property Owners* (Elliot Menashe, 1993) and *Slope Stabilization and Erosion Control Using Vegetation: A Manual of Practice for Coastal Property Owners (Myers Biodynamics,* 1993).

Seeding

Grass and other herbaceous plant mixtures can be seeded by scattering the seed on the bluff face by hand; by hydroseeding, which distributes the seeding a mixture of water, fertilizer, and mulch; or by drilling, in which a seed and fertilizer are inserted into the soil and covered. Hydroseeding and drilling, which are best suited for large-scale planting and for planting steep slopes, are labor- and equipment-intensive and therefore more expensive methods of seeding. With hand broadcast seeding, fertilizer would be applied as needed, and mulch would be used to prevent erosion of the seed, to control weeds, and to reduce moisture loss. Straw and hay are the most suitable mulching materials; however, wood fiber mulches applied by hydroseeding have also given good results.

Spot seeding is an effective method of establishing many of the woody plants. This method enhances the successful germination of the seeds although it does require more intensive preparation and care of each seeding spot. Seeds are typically placed in holes approximately 4 inches deep with controlled-release fertilizers.

Mulching would again be used, but special care would be needed to prevent the mulch from interfering with seedling emergence or growth.

Transplanting

Transplanting might be necessary to revegetate difficult sites and can be used for establishing grasses, shrubs, and trees. Typically conducted by hand, transplanting would require careful attention for excavation of the holes, placement of the plants, fertilization, and watering. Transplanting provides the benefits of an immediate vegetative cover and allows the individual plants to be arranged as desired. It is, however, highly labor-intensive.

On particularly steep or erosive slopes, planting might need to be configured in small terraces or "contours" to further stabilize the bluff face.

Brush Layering

Contour brush layering consists of embedding green branches of shrub or tree species, preferably those that will root, on successive horizontal rows or contours in the face of a slope (Figure 1). Rooted cuttings have also been used in lieu of branches. The method is schematically illustrated in Figures 2 and 3. Brush layering could be incorporated for slope protection purposes during construction of a fill or embankment or alternatively used as a rehabilitation measure for seriously eroded and barren slopes.

Contour brush layering is similar in principle to a sloping reinforced earth revetment (Bartos, 1979). In both cases the reinforcement (metal strips and branches) is placed essentially horizontally in successive layers up the face of a slope. In a reinforced earth revetment, it is common practice to make the strip length (or width of reinforced volume) about one-third the slope height. This is an important difference because in contour brush layering the branches normally would not exceed 6 to 8 feet in length. Hence, to behave in a truly "reinforced earth" mode, the slope height should not exceed 18 to 24 feet. On the other hand, metal strips do not sprout and develop root laterals as will branches of species that will root. Thus, rooting provides an additional coherence and reinforcement to the face of the slope that tend to offset the limitations of branch length.

Favored Species

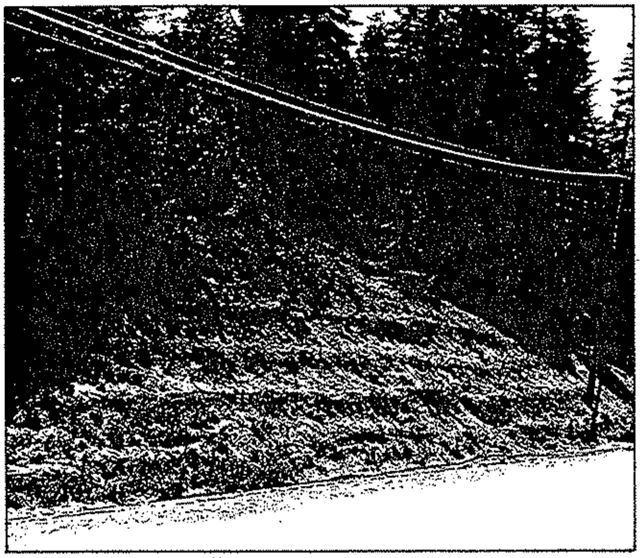
Grasses and ground covers can be used effectively where protection of the soil surface from wind and rain erosion is needed. Grass will often establish quickly and achieve good erosion controlling properties in just one growing season. Grasses, however, will form a thick mat ground cover that makes it especially difficult to get more desirable permanent vegetation established. While grasses provide a high degree of surface erosion protection, trees and shrubs are necessary to provide deep reinforcing roots that help prevent slope failure. In addition, grass may not provide the most desirable ground cover for wildlife uses.

Various shrub and tree species are known for their ability to stabilize banks and erosion-prone areas. Root structures provide soil reinforcement, which gains strength as the plants develop and the vegetation pumps moisture from the soils–a factor especially important along Puget Sound where water percolation through soil layers of steep slopes contributes to instability.

The favored species to use are willows. Hooker's willow (*Salix hookeriana*) grows commonly in coastal areas and has moderate sensitivity to salinity. Other willows that occur commonly in the Puget Sound but have less tolerance to salinity include Sitka willow (*Salix sitchensis*), *S. rigida*, and *S. lasiandra*. Another species known for its ability to stabilize soils is red osier dogwood, *Cronus stolonifera*. Some quick-sprouting trees such as Red Alder, *Alnus rubra*, can also be used effectively as long as their relatively short life span is taken into account.

Figure 1

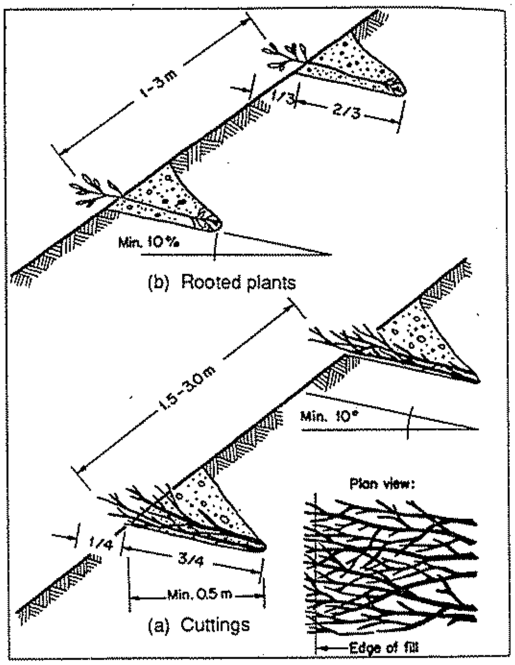
Bank Stabilization with Contour Brush Layers



Source: Gray, Donald H., and Andrew T. Leiser. *Biotechnical Slope Protection and Erosion Control.* Malabar, Florida: Robert E. Krieger Publishing Co. 1989.

Figure 2

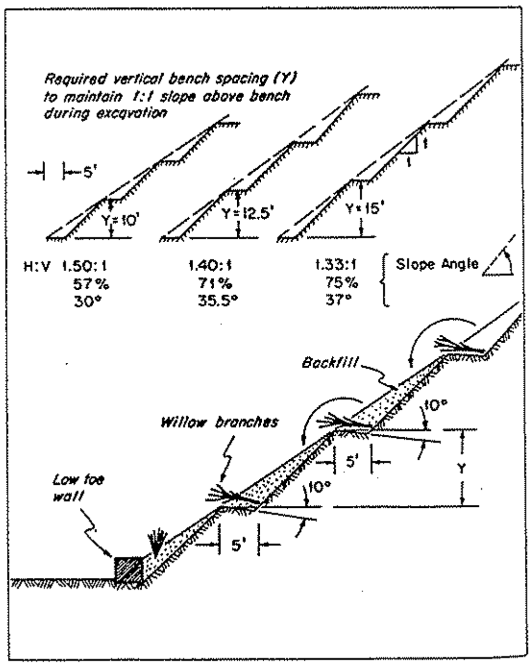
Brush-Layering Planting Depths



Source: Gray, Donald H., and Andrew T. Leiser. *Biotechnical Slope Protection and Erosion Control.* Malabar, Florida: Robert E. Krieger Publishing Co. 1989.

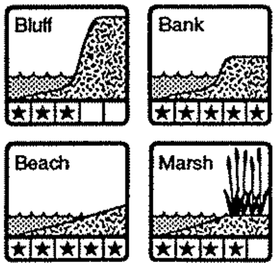
Figure 3

Contour Brush-Layering Sequence and Spacing



HEADLAND AND POCKET BEACH SYSTEM

Suitability for landforms



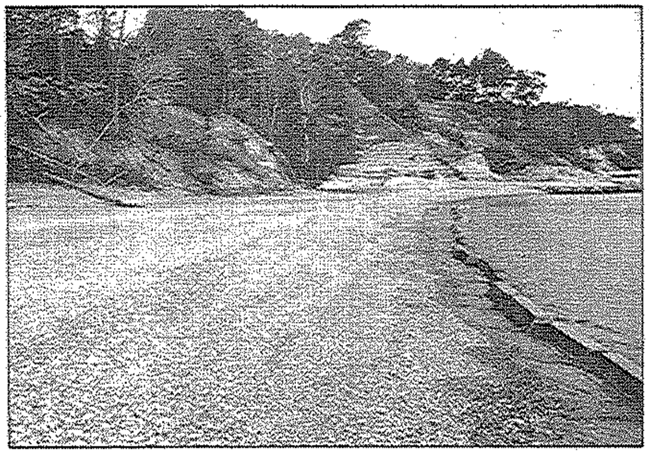
An armored headland and pocket beach system (Figure 1) acts like a groin system in that the headland is connected to and extends out from the shoreline. Coarse beach material is trapped or held within the protected pocket areas between adjacent armored headlands.

The armored headlands provide an intermittent barrier parallel to the shoreline to deflect wave action. The spacing between headlands is specified to allow wave energy to spread radially and be gently spent on the trapped beach material. Headlands typically delineate adjacent littoral drift sectors (cells) and, when created artificially, create "mini-drift sectors" that capture and conserve beach material.

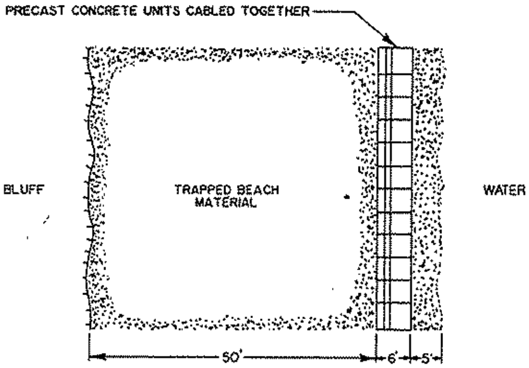
An installed armored headland and pocket beach system can create a relatively large amount of shoreland for recreational use. Design considerations for typical armored headlands are shown in Figure 1 and are similar to those for a revetment.

Figure 1

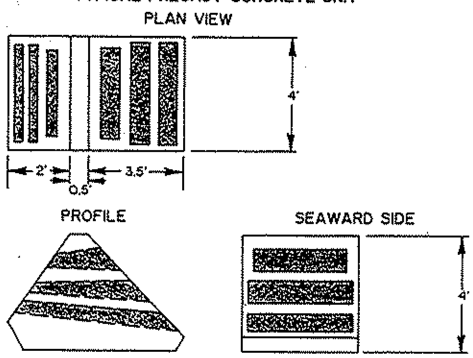
Typical Perched Beach and Concrete Fill System



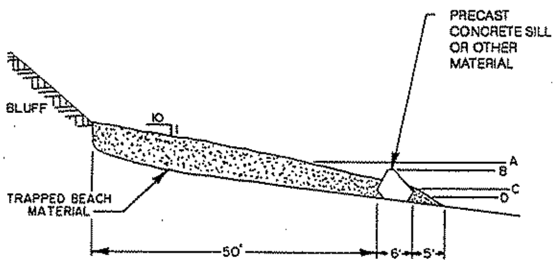
PLAN



TYPICAL PRECAST CONCRETE UNIT



PROFILE



LEGEND

DESIGN WATER LEVELS

A. DESIGN HIGH STILL WATER LEVEL PLUS WIND SETUP

B. DESIGN HIGH STILL WATER LEVEL

C. ANNUAL MEAN WATER LEVEL

D. LOW WATER DATUM

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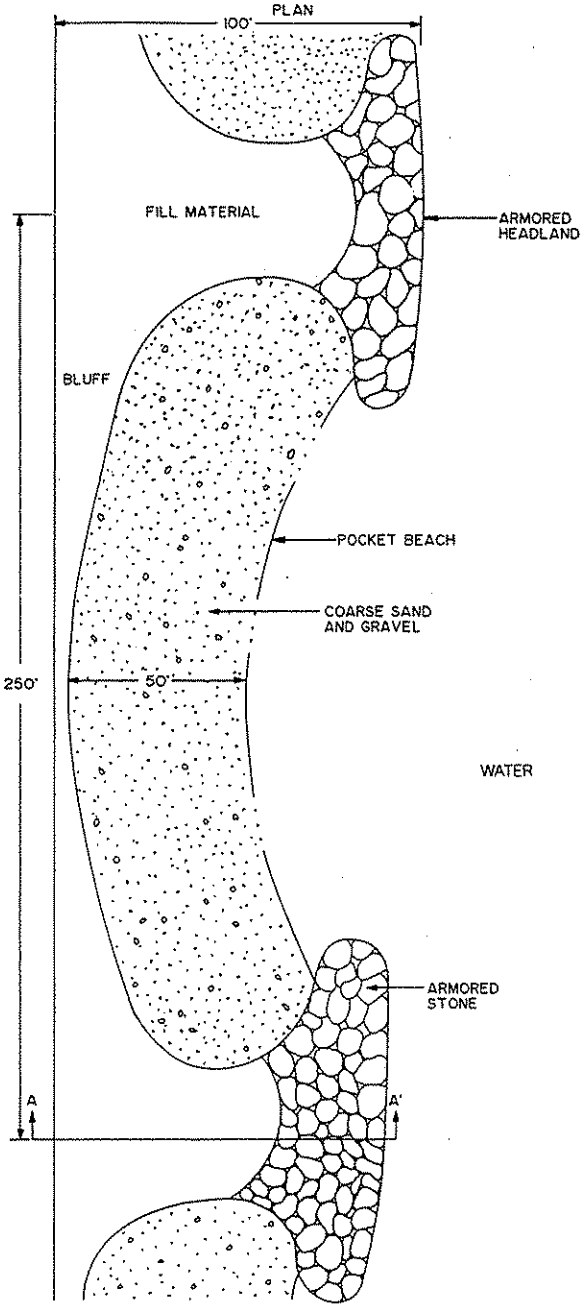
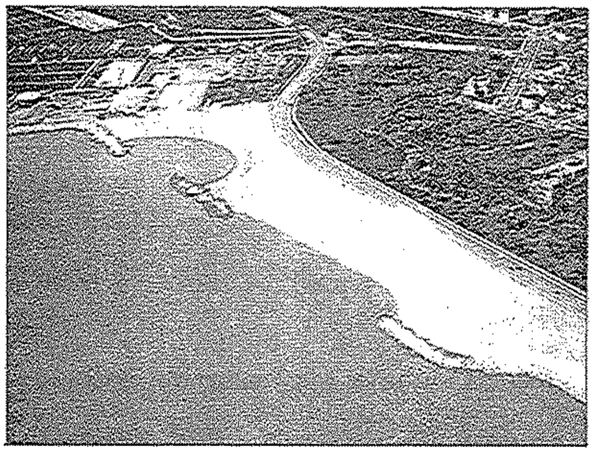
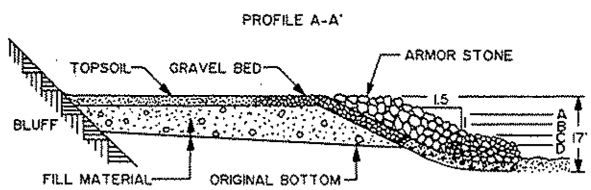
Source: Southeastern Wisconsin Regional Planning Commission (SEWRPC). *A Lake Michigan Shoreline Erosion Management Plan for Northern Milwaukee County Wisconsin.* Community Assistance Planning Report Number 155. Waukesha, Wisconsin. December 1988.

Figure 1

Typical Armored Headland and Pocket Beach System







LEGEND

DESIGN WATER LEVELS

A. DESIGN HIGH STILL WATER LEVEL PLUS WIND SETUP

B. DESIGN HIGH STILL WATER LEVEL

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D. LOW WATER DATUM

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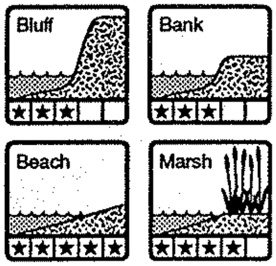
Source: Southeastern Wisconsin Regional Planning Commission (SEWRPC). *A Lake Michigan Shoreline Erosion Management Plan for Northern Milwaukee County Wisconsin.* Community Assistance Planning Report Number 155. Waukesha, Wisconsin. December 1988.

PERCHED BEACH

Suitability for landforms



A perched beach is a fill of sand, cobble, or larger material that is built or naturally accumulates behind a low sill. The beach elevation is permanently raised by the fill, as indicated by the term "perched." A typical perched beach is shown in Figure 1.

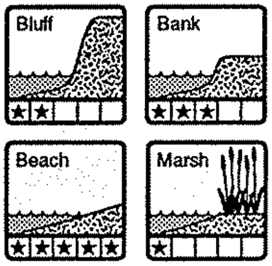
Perched beaches constructed of cobbles serve as wave-absorbing structures and are particularly suitable where the nearshore water is deep. A beach constructed of cobblestones ranging from 3 to 12 inches in diameter is able to absorb considerable wave energy while staying intact better than do beaches composed of sand and gravel. Reduced wave reflection from the cobbles would help prevent scouring by wave energy normally reflected by bulkheads or riprap revetments. The cobbles are typically swept by storm surge to form raised ridges on the backshore, adding protection to bluffs. Lateral migration of the cobbles can be controlled by constructing barriers similar to groins on the downdrift sides.

To increase the effectiveness of the perched beach and prevent the migration of the cobbles, a sill of quarry stone, sheet pile, or precast concrete units is placed seaward from the original shoreline. Wave attack on the shore is reduced by the sill's attenuating effect on the waves when they are still offshore. The sill trips and slows the waves. In addition to tempering storm surge and backwash, the sill system enhances the deposition of sediment from littoral drift along shore. Accretion of sediment can occur both landward and seaward of the sill. The sill is most effective in a shallow, low-wave-energy environment that contains a substantial amount of littoral drift material.

The disadvantage of a perched beach system is that the use of the shoreline and access to the water might be severely limited, depending on the size and shape of the cobbles. The usability of cobble beaches installed primarily for erosion control can be enhanced by placing a 1- to 2-foot layer of gravel on top of the cobbles. Although the gravel layer would need nourishment, the stability of the cobble base and the perched beach design would reduce the need for replacement material.

GROIN SYSTEMS

Suitability for landforms



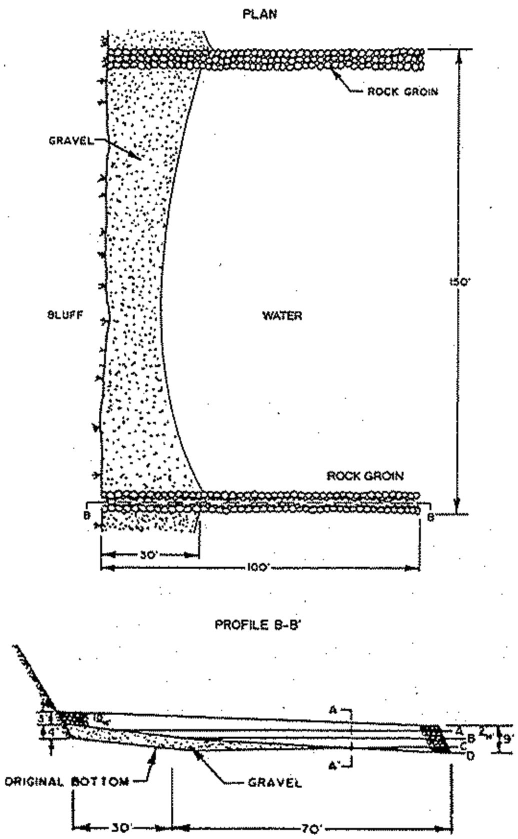
Groins are the most common type of structure used to maintain or create beaches. Groins can be constructed of rock, concrete, steel sheet pile, or timber. Groins extend out into the water perpendicular to the shoreline. They are intended to hold beach material and partially obstruct the littoral drift, thereby trapping sand upcurrent from the structure. If sufficient littoral drift is available, a series of properly designed groins can trap enough sand and gravel to build a beach that absorbs wave energy and protects the bluff toe. Capture of the sand creates a deficit elsewhere in the cell. Therefore, without supplemental sediment renourishment, retreat of a downdrift shoreline should be expected.

Groins can be employed constructively in conjunction with artificial beach nourishment. By prefilling the cells between groins, natural bypassing of existing sediments may continue.

Groin fields displace the waterline outward into deeper depths. Sediment moving along shore is forced into deeper water to move around the structure ends. Thus, groins can displace nearshore sandbar systems seaward.

Figures 1 and 2 show examples of rock and sheet pile groin systems designed to maintain a beach composed of gravel. The onshore portion of the groins would be constructed with a top elevation about 7 feet above the existing beach level to retain the beach fill. If sheet pile is used, the piles will typically penetrate into the bottom a distance equal to twice their exposed height. The orientation and spacing of a groin system are highly dependent on the site-specific details of the project location, but spacing generally should be equal to about one and one-half to twice the groin length. Groin length is generally kept shorter than the distance out to wave breaking so that some littoral material is assured of bypassing the groin. The groins should be of sufficient height to prevent excessive overtopping. Periodic replenishment of the beach material will be required.

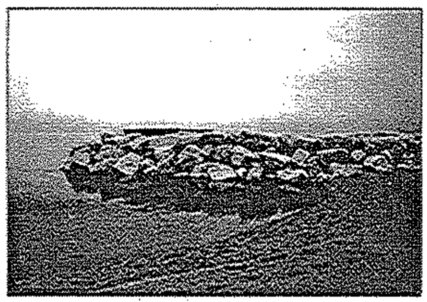
The height, orientation, and shape of groins may be modified, depending on the site characteristics, to either maximize beach containment or minimize trapping of the littoral drift. For example, the offshore end of groins may be sloped downward to reduce downdrift impacts.

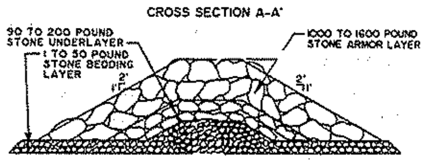


Source: U. S. Army Corps of Engineers and SEWRPC.

Figure 1

Typical Rock Groin System with Artificially Nourished Beach





LEGEND

DESIGN WATER LEVELS

A. DESIGN HIGH STILL WATER LEVEL PLUS WIND SETUP
B. DESIGN HIGH STILL WATER LEVEL
C. GEODETIC VERTICAL DATUM
D. LOW WATER DATUM

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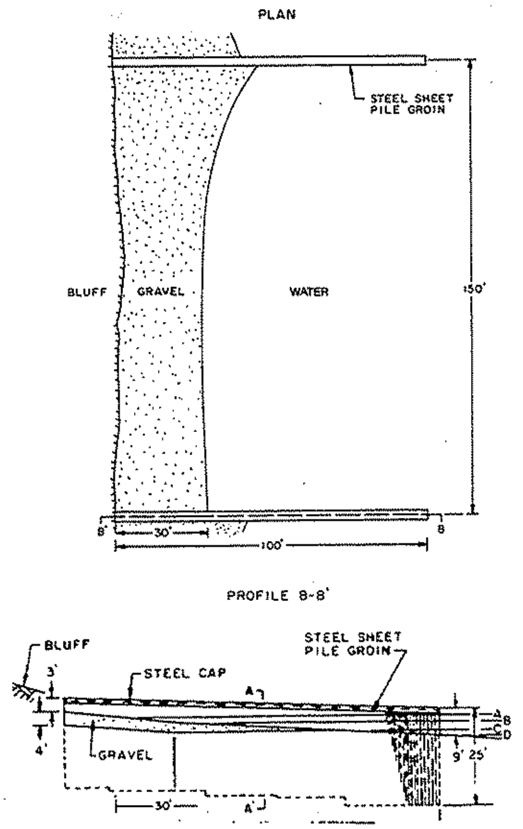
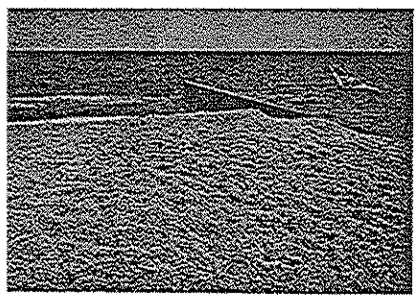
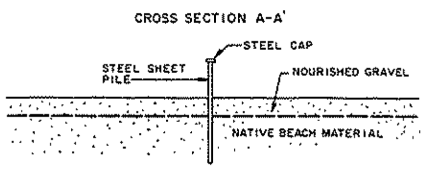


Figure 2

Typical Steel Sheet Pile Groin System with Artificially Nourished Beach





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