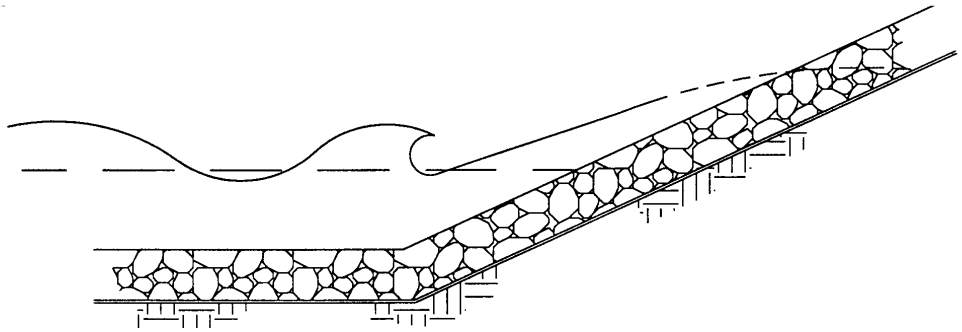
USDA NRCS
Natural Resources Conservation Service
St. Paul, MN

Slope Protection for Dams and Lakeshores

Minnesota Technical Release 2

October 1997



The United States Department of Agriculture (USDA) prohibits discrimination in all its programs and activities on the basis of race, color, national origin, gender, religion, age, disability, political beliefs, sexual orientation, and marital or family status. (Not all prohibited bases apply to all programs). Persons with disabilities who require alternative means for communication of program information (Braille, large print, audiotape, etc.) should contact the USDA's TARGET Center at 202 720-2600 (voice and TDD).

To file a complaint of discrimination, write USDA, Director, Office of Civil Rights, Room 326W, Whitten Building, 14th and Independence Avenue, SW, Washington, DC 20250-9410 or call 202-720-5964 (voice or TDD). USDA is an equal employment provider and employer.

CHAPTER 1: WIND AND WATER **2**

INTRODUCTION 2
IDENTIFYING THE EROSION 4
SHORELINE PROCESSES 4
Overland Runoff and Erosion *4*
Vegetation Removal *4*
Watercraft Waves *5*
Wind-Generated Wave Action *5*
Sediment Transport *5*
Shoreforms *6*
DESIGN CONSIDERATIONS 10
Revetments *10*
Wind Setup and Runup *11*
Vegetative Protection *11*
Ice Action *11*
Causes of Revetment Failure *16*

CHAPTER 2: REVETMENT DESIGN **17**

WAVE FREQUENCY 17
Definitions *17*
WIND DATA 18
DESIGN PROCEDURE 18
RIPRAP DESIGN 19
Overtopping Protection *26*
End Protection *26*
Toe Protection *26*
Filter and Bedding Materials *30*
CONCRETE PAVING BLOCK DESIGN 32
GABIONS 33
SOIL BIOENGINEERING 33

CHAPTER 3: SAMPLE PROBLEMS **35**

SAMPLE PROBLEM #1 35
SAMPLE PROBLEM #2 41

CHAPTER 4: MAINTENANCE **46**

CHAPTER 5: STATE REQUIREMENTS **51**

PERMITS 51
POLLUTION CONTROL 51
SEEDING AND MULCHING DISTURBED AREAS 51

CHAPTER 6: WATERCRAFT CONCERNS **52**

Chapter 1: Wind and Water

Introduction

This technical release has been developed to specifically address lakeshore protection in Minnesota. It replaces the Soil Conservation Service's Minnesota Technical Release No. 2, *Slope Protection for Dams and Lakeshores*, dated April 1988, which itself replaced a 1976 document with a similar name.

A demonstration project in Itasca and Aitkin Counties in northern Minnesota installed protection on lakeshore sites beginning in 1988. The subsequent monitoring of these installed sites has provided new information on what is effective under various circumstances. The lessons learned from this monitoring and other experiences are being incorporated into this document.

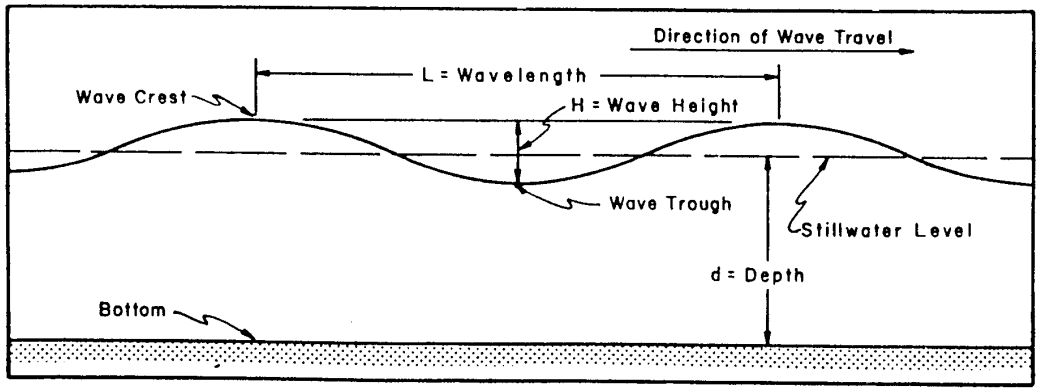
The basic design method in this document is based on the information in the *Shore Protection Manual*, prepared by the U.S. Army Corps of Engineers in 1984. Policy information for these designs is described in the Natural Resources Conservation Service (NRCS, formerly SCS) National Engineering Manual, part 501.50. The guiding standard is #580, entitled "Streambank and Shoreline Protection".

The procedure in this document is limited to locations where 1) the effective fetch is less than 10 miles and 2) the wave height is less than five feet. The design charts and information are for sites where the waves are fetch-limited as this condition is typical on Minnesota's inland lakes. For conditions outside these limits, special studies and design will be required. Documents listed in the bibliography may be of help.

NRCS appreciates the assistance of many in preparing and reviewing this document. Special thanks go to

Sonia M. M. Jacobsen, Hydraulic Engineer, St. Paul, MN
James G. Dusek, Area Engineer, NRCS, Duluth, MN
Michael Oja, District Conservationist, NRCS, Grand Rapids, MN
Steven Gorecky, District Conservationist, NRCS, Aitkin, MN
Ferris Chamberlain, U.S. Army Corps of Engineers, St. Paul, MN
Allan Kean, Chief Engineer, Minnesota Board of Water & Soil Resources
Gene Clark, Lakeshore Engineer, Minnesota Board of Water & Soil Resources
Morris Lobrecht, Design Engineer, NRCS, Des Moines, Iowa
James Axell, CADD Operator, St. Paul, MN

Figure 1-1. Wave Characteristics



Identifying the Erosion

The most basic prerequisite to managing shoreline erosion is to identify the forces that are causing it. This is often difficult because the processes responsible are not directly observable and only the aftermath of the erosion is evident. (reference 42)

Any change which occurs on the shoreline can affect the erosion and sediment balance of the entire lake. It may be necessary to examine conditions up and down the shoreline in addition to those at the site. Noting events which occurred in the past and anticipating likely future events will help guide the planning process.

The best way to monitor and assess erosion problems is to check the shoreline regularly and be observant for warning signs of accelerated erosion. Signs of serious problem situations include:

- A large area of bare soil along the shore, especially on a steep, high shoreline bank;
- Slumped material from landslides;
- Large or small gullies caused by overland runoff along the shoreline;
- A noticeable recession of the shoreline over a period of time;
- Leaning or downed trees with exposed roots on the shoreline;
- Large patches of unusually clouded (turbid) water near the lakeshore.

Most erosion is likely to occur during periods of high water, extreme wetness and/or high winds. Watching what happens on a shoreline during these times and comparing it to normal conditions or water levels can provide some insight into the causes of shoreline instability.

Identifying the erosion rate (number of feet that the shoreline recedes per year) is helpful to identify the severity of the problem. The erosion rate is probably not constant, but occurs in small and large increments, corresponding to storm events and wet periods. The highest priority for erosion control may be sites with rapid recession rates (more than 1 foot per year) (reference 42). The priority of sites may also be governed by the affects of erosion - economic and environmental. Over a period of time, measure the distance to the shore from a prominent, immovable object. Old photographs (aerial photos or snapshots) can help determine where the shoreline was in the past.

Shoreline processes

The first step in addressing a shoreline erosion problem is understanding the processes and forces at work. The following sections present basic information about shoreline processes as a foundation for considering alternatives.

Overland Runoff and Erosion

In shoreline areas where excessive runoff or bare soils are found, overland erosion may result. The toe of the bank may be stable with rills or gullies present on the upper bank. Both natural conditions (slope, soil type, drainage pattern) or human activities (impervious surfaces, vegetation removal, construction in progress) may increase the volume or velocity of overland runoff. Runoff may originate quite a distance away from a shoreline erosion site.

Vegetation Removal

The root systems of woody shoreline vegetation, and some herbaceous plants as well, augment the strength of all types of soil. Many shoreline erosion problems occur simply because too much natural woody vegetation has been removed, decreasing the strength of the shoreline soils. The above-ground portions of plants can dampen wave energy and hence their loss may also expose the shore to more erosive energy.

The conversion of shoreline vegetation from forest to lawn has occurred in many areas of development. Bank trampling and soil compaction by cattle, humans, and vehicles are

also important causes of vegetation loss and shoreline erosion.

Watercraft Waves

Power boats and other watercraft generate waves which can cause shoreline erosion, especially on smaller water bodies where the waves' energy is not dissipated before the waves reach shore. Some lakes have "no wake" ordinances in an attempt to reduce wave erosion and noise pollution.

The size of waves created by boats are determined by the volume of water displaced by the boat and the speed at which the boat is traveling. The wave size does not always increase with boat speed because at high speeds many boats "skim" across the surface (called planing) and therefore displace less water. Wave heights of up to three feet have been reported from boats operating on inland lakes. Boat waves are of a different physical nature than wind-generated waves, and contain more energy than a wind-generated wave of equal size. The operation of large, high speed boats on small water bodies can create waves greatly exceeding the size and erosive energy of any naturally occurring from wind. See Chapter 6.

Wind-Generated Wave Action

While waves are often present on the open coast, they are not continuous in sheltered waters. Nonetheless, they are often the major cause of erosion in these areas. The basic configuration of a wave is shown in Figure 1-1 to explain basic terminology. Wave height is the vertical distance between the wave crest and wave trough. Wave period is the time (in seconds) it takes two successive wave crests to pass a stationary point. Wavelength is the distance between successive crests.

On inland lakes, the size of waves created by wind depends primarily on two factors: wind speed and fetch (the over-water distance across which the wind blows). Wind duration and water depth also influence wave size but are major factors only on the oceans and Great Lakes. Wave energy is roughly proportional to the size of the wave (specifically to the square of the wave height). At any given time and location on a lake, waves of many different sizes are present. This is because not all waves start at the same point, but are being created continuously across the water surface. In addition, different waves move at different speeds.

As a wave moves through deep water, its basic characteristics do not diminish. However, when the water depth becomes shallower than 1/2 the wave length, the wave motion begins to encounter friction from the bottom. The wave speed slows, with a corresponding decrease in wavelength and an increase in height (steepening). The range of depths at which this usually occurs may be observed on the lake bottom as the area where ripple marks form. When the water depth is less than 1.3 times the wave height, the wave can steepen no further, and it collapses (breaks) in a cascade of foam and trubulence. Although much energy is lost in this nearshore "surf zone," diminished waves continue to move shoreward.

Example water depths and wave heights where breaking occurs:

Wave Height, Feet	Water Depth, Feet
1.0	1.3
2.0	2.6
3.0	3.9
5.0	6.5

When waves break either on a beach or against a structure, the uprush of water after breaking is called runup. It expends the wave's remaining energy. The runup height depends on the roughness and steepness of the structure or beach and the characteristics of the wave. Increased roughness and flatter shore slopes reduce the height of runup.

Sediment Transport

Shoreline material can include anything from bedrock to clay. Sand is the most common shoreline material. Slumping or erosion of a bluff causes material to be deposited at the base. Waves sort this material and carry fine-grained silts and clays far offshore where they settle to the bottom. The original deposit is eventually

reduced to sand, gravel and/or cobble fractions which form a beach. Eventually, if no other littoral material is carried to the site by waves, even the sand and fine gravel will disappear down the coast or offshore, leaving only cobbles or coarse gravel behind. However, a new supply of material may be deposited on the beach by a fresh failure of the bluff and the process begins again. In many cases, therefore, littoral materials comprising beaches are often derived from erosion of the adjacent shoreline.

Littoral (shoreline) materials are transported along the shore by waves (Figure 1-2). This alongshore sediment is also known as littoral drift. As waves approach the shore, they move to progressively shallower water where they bend or refract until finally breaking at an angle to the beach. The broken wave creates considerable turbulence, lifting bottom materials into suspension and carrying them up the beach slope in the general direction of the wave approach. Some distance up the beach, the motion reverses direction back down the beach slope. In this case, the downrush does not follow the path of the advancing wave but instead, moves down the slope in response to gravity. The next wave again carries material upslope, repeating the process, so that each advancing wave and the resulting downrush move material along the beach in the downdrift direction. As long as waves approach from the same direction, the alongshore transport direction remains the same.

Littoral materials are also moved alongshore by another process. The waves generate a somewhat weak, downdrift-moving current in the breaker zone, but the turbulence places material temporarily in suspension and permits the alongshore current to carry it downdrift. The material generally settles out again within a short distance, but the next wave provides the necessary turbulence for additional movement. The downdrift movement of material is thus caused by zigzag motion up and down the beach, and the turbulence and action of the wave-generated alongshore current.

Shoreforms

Shoreforms are those distinct shapes or configurations which mark the transition between land and sea. *Cliff* shorelines consist primarily of relatively resistant rock. On the other hand, *bluff* shorelines are composed of such sediments as clays, sands, and gravels, or erodible rock. Cliffs rarely suffer severe or sudden erosion but undergo slow steady retreat under wave action over a long period. Such shorelines often cannot be protected at a low cost because available alternatives may not be as durable as the rock forming the cliff.

Erosion problems are common along bluff shorelines where a variety of forces and processes act together (Figure 1-3). The most prevalent causes of bluff erosion and recession are scour at the toe (base) by waves and instability of the bluff materials themselves. As Figure 1-3 illustrates, a typical bluff often consists of layers of different soils, which do not stand permanently at a vertical face. Failure of the slope depends on the nature of the material. A cohesive material (clay) will move as large blocks either by toppling due to undercutting or by sliding out in a curved arc. Granular material (sand or gravel) will erode easily by flowing water and wave action. Vertical sided blocks will drop due to an undercutting of the slope or the soil will suddenly flow down an inclined plane. Height is a factor because high bluffs (over 20 feet) impose greater stresses and are likely to have more severe stability problems than low bluffs.

The internal strength of soils can decrease when it becomes saturated by groundwater and seepage flows within the bluff. The added weight of buildings and other structures can increase stresses on the soil and contribute to slope failure.

The other major cause of bluff shoreline problems is wave action at the toe. Figure 1-3 shows a beach formed of fallen materials. As described earlier, waves sort this material, moving clays and silts offshore while leaving sands and gravels for the beach. During storms, the waves can reach the bluff itself and erode or undercut the toe. The slope of the offshore bottom is important to wave action on a bluff. If the offshore slopes are steep, deep water is closer to shore, more severe wave activity is possible and maintaining a protective beach is

more difficult. Flat offshore slopes result in shallower water near the shoreline, which inhibits the heavy wave action from reaching the bluff.

Figure 1-2. Alongshore Sediment Transport

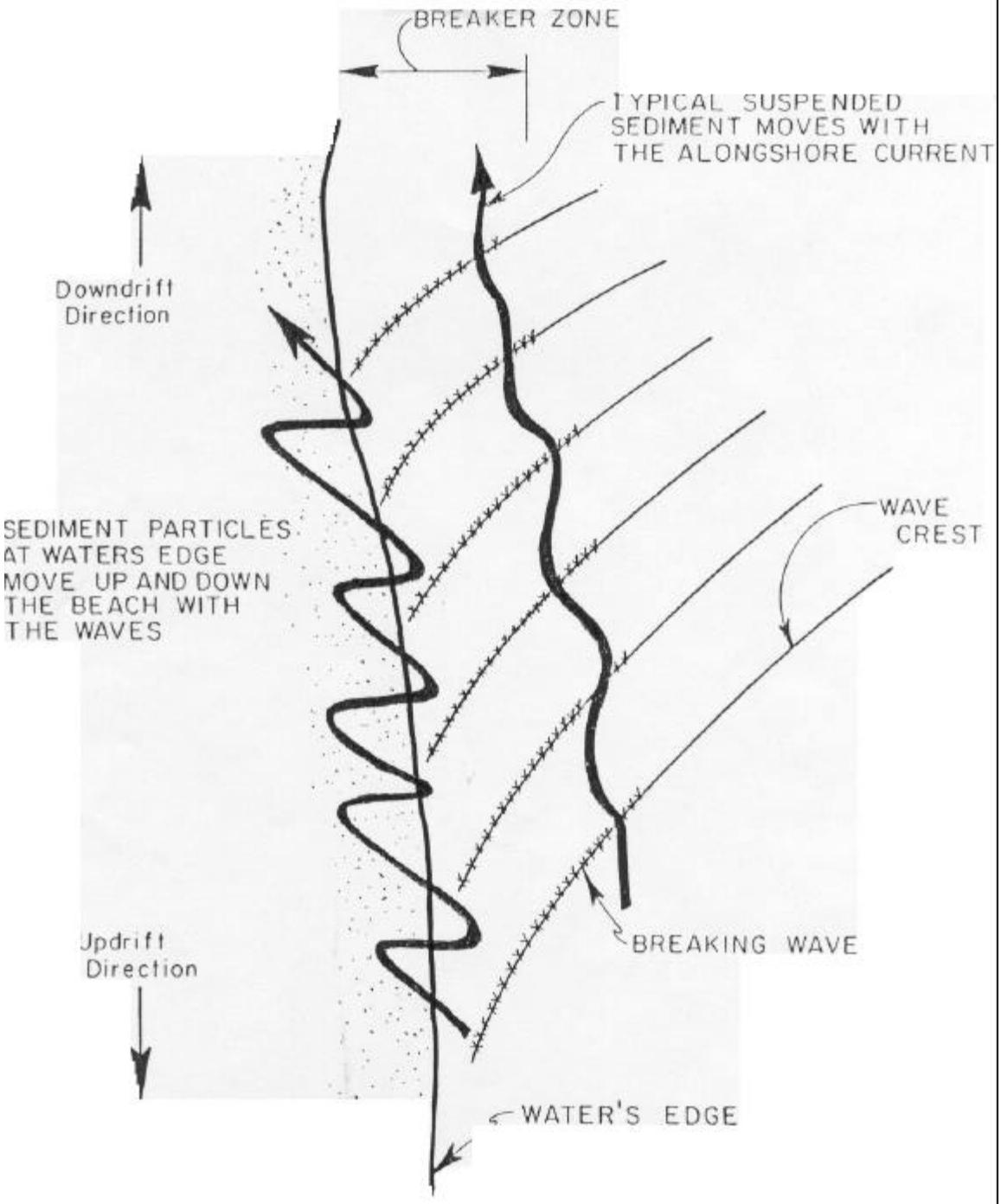


Figure 1-3 Causes of Bluff Erosion and Retreat

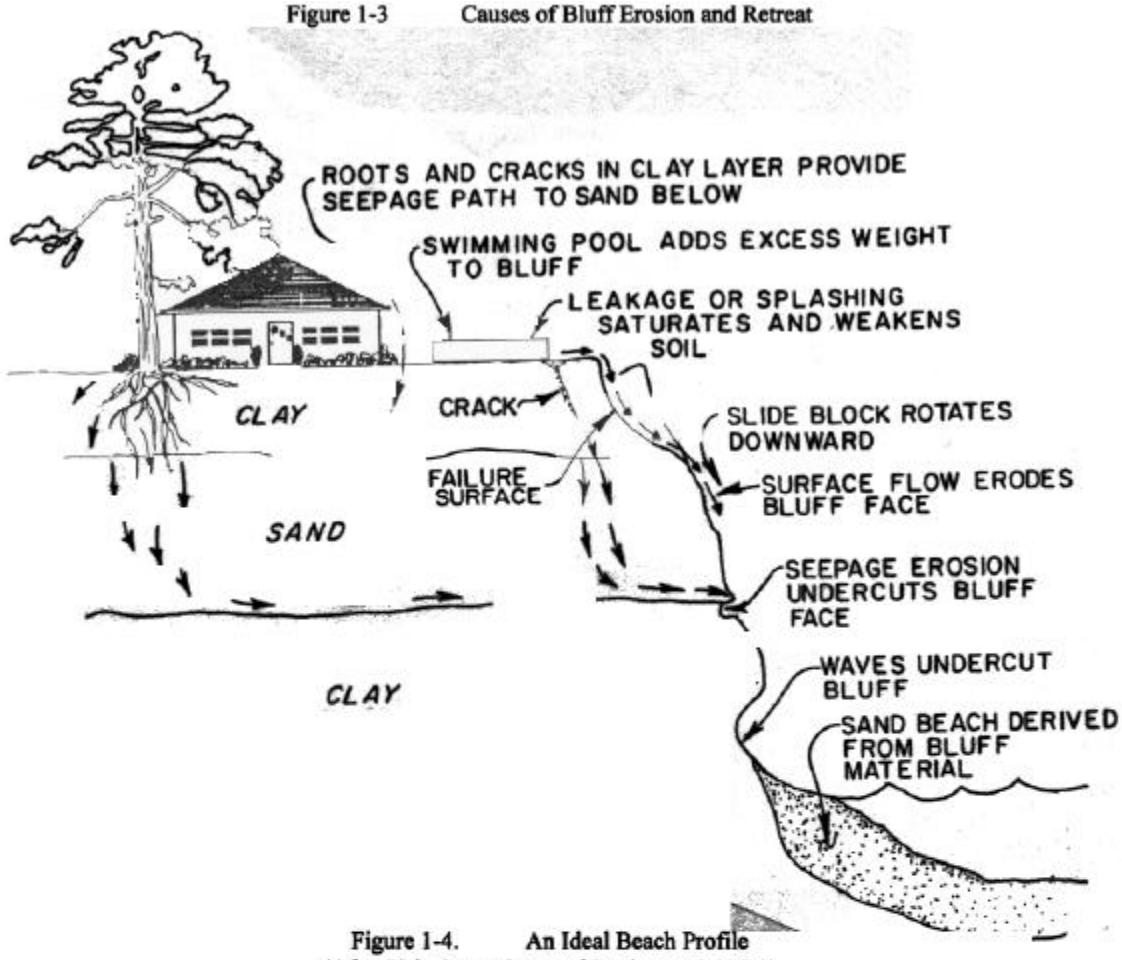
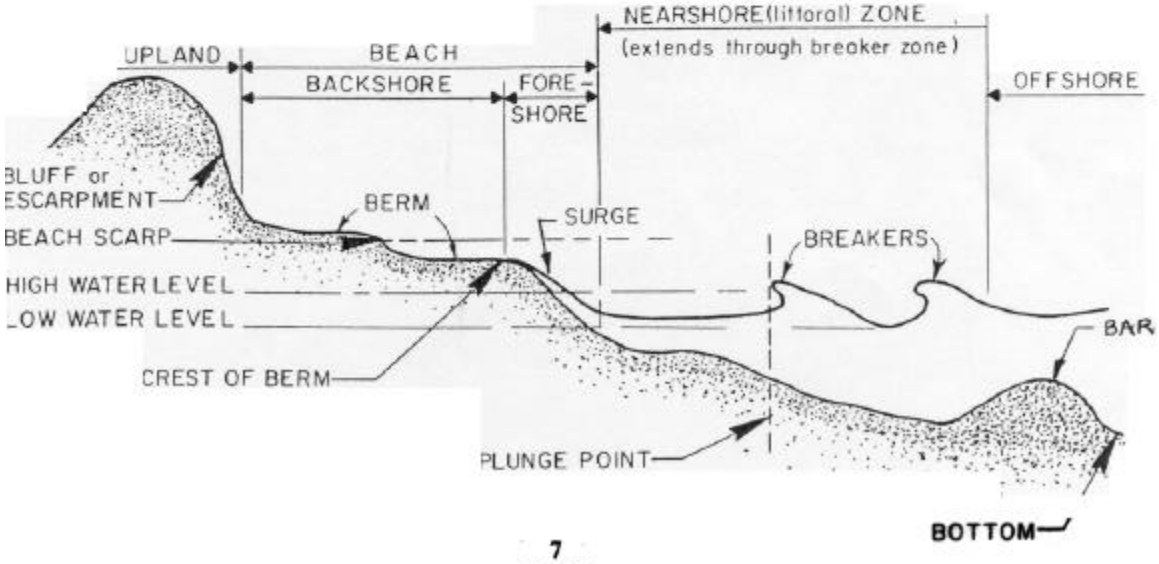


Figure 1-4. An Ideal Beach Profile
(After U.S. Army Corps of Engineers (1977a))



The most common shoreforms are beaches and erodible plains which are composed of those sediments ranging from silts to gravels that slope gently up and away from the water's edge. Because they seldom reach more than 5 to 10 feet above the still water level of a lake, such shorelines are susceptible to flooding as well as erosion.

Figure 1-4 depicts an idealized beach profile. Waves approach from offshore, finally breaking and surging up the foreshore. At the crest, the profile flattens considerably, forming a broad berm inaccessible to normal wave activity. The beach berm is often backed by a low scarp formed by storm waves, a second berm and eventually a bluff or dune. During periods of either increased water levels or wave heights, the sand above the low water level is eroded, carried offshore and deposited in a bar. Eventually, enough sand collects to effectively decrease the depths and cause the storm waves to break farther offshore. This reduces the wave action on the beach and helps re-establish equilibrium.

Design Considerations

In response to an erosion problem, three basic alternatives are usually pursued: (1) do nothing, (2) relocate endangered structure, and (3) take positive action to halt the erosion. This third alternative is the subject of the rest of this Technical Release.

Bulkheads and seawalls typically require significant structural design, difficult construction, and are quite costly. Additionally, they can relfect waves rather than dissipate them and many consider such walls unattractive. Breakwaters and groins restrict shoreline access, may be detrimental to wildlife habitat, and can cause other downshore problems. Due to these drawbacks, these practices are not viewed favorably by the NRCS or Minnesota Department of Natural Resources (DNR) for Minnesota's inland lakes. Publications 6 and 15 in the bibliography are helpful for information on these measures. The primary type of protection available is revetment to protect the lakeshore from further erosion. Some success has been noted with soil bioengineering techniques alone or in combination with revetment. The reader is referred, however, to other documents for detailed information on the design of soil bioengineering protection.

The Natural Resources Conservation Service in Minnesota does not provide technical assistance for protection measures which use materials such as old tires and car bodies for revetment protection. These materials are not wise choices for ecological and aesthetic reasons.

Revetments

A revetment is a heavy facing (armor) on a slope to protect it and the adjacent upland against wave scour (Figure 1-5). Revetments depend on the soil beneath them for support and should, therefore, only be built on stable foundations. Slopes steeper than 3:1 (3 feet horizontal for every 1 foot vertical distance) are less desirable for revetments. Fill material, when required to achieve a uniform slope, must be properly compacted. Revetments only protect the land immediately behind them and not adjacent areas. Also a downdrift shore may experience increased erosion if formerly supplied with material eroded from the now-protected area.

Revetments are comprised of three components: the armor layer, the filter layer, and toe protection. The primary component, the armor layer, must be stable against movement by waves. Typical armor components include rough, angular rock and variously shaped concrete blocks. The second layer, the filter, supports the armor against settlement, allows groundwater drainage through the structure, and prevents the soil beneath from being washed through the armor layer by waves or groundwater seepage. This may be commercial filter fabric or a gradation of sand and gravel. The third component, toe protection, prevents undermining, settlement or removal of the revetment's waterward edge.

Overtopping (not including spray) which may erode the top of the revetment can be limited by a structure height greater than the expected runup height or by protecting the land at the top of the revetment with an overtopping apron.

Flanking, a potential problem with revetments, can be prevented by tying each end into adjacent shore protection structures or the existing bank. If the bank later retreats, the ends must periodically be extended to maintain contact. Flanking is the erosion of the shoreline on either side of a protective measure. (See Figure 1-5) The armor layer maintains its position under wave action either through the weight of, or interlocking between, the individual units. Revetments are either flexible, semi-rigid or rigid. *Flexible* armor retains its protective qualities even with severe distortion, such as when the underlying soil settles or scour causes the toe of the revetment to sink. Riprap (quarrystone, field stone or concrete "man-made" stone) and gabions are considered to be flexible shore protection measures. A *semi-rigid* armor, such as interlocking concrete blocks, can tolerate minor distortion, but the blocks may be displaced if moved too far to remain locked to surrounding units. Once one unit is completely displaced, such revetments have little reserve strength and generally continue to lose units (unravel) until complete failure occurs. The principal drawback to the use of precast paving blocks is that they are only one layer, and when their strength is undermined, there is no reserve protection. Concrete blocks can be cabled together or linked by plastic rods. This enables the mat to withstand significant distortion without failure. *Rigid* structures may be damaged and fail completely if subjected to differential settlement or loss of support by underlying soil. Grout-filled mattresses of synthetic fabric and reinforced concrete slabs are examples of rigid structures.

Revetments are sometimes effective in bluff situations. Low bluffs that can be regraded to a stable slope may be effectively protected by revetments. The toe of a high bluff can be protected by revetment, either alone or in conjunction with other measures such as a buttress to stabilize a landslide. Drainage controls are mandatory if groundwater and seepage adversely affect slope stability. The stability of a slope and its suitability for protection will need to be determined on an individual basis. The slope must be reasonably stable to justify revetment on the toe or the entire slope.

Revetments are suited for protecting features directly behind the beach in a low-plain situation, since they absorb wave energy and are flexible if settlement occurs. However, they can have an adverse aesthetic effect on the beach, and can limit use or access to the shore.

The full-page diagram labeled Figure 1-6 depicts the importance of a rough, slanted face for minimizing wave runup. Note that these values are *relative* to each other and NOT absolute numbers to be used in design. This chart was included to clarify the theory that has been used in developing the design charts. The designer is encouraged to use flatter slopes, and angular materials wherever possible.

Wind Setup and Runup

The sketch in Figure 1-7 illustrates wind setup and wave runup. The setup is an increase in the still water level (SWL) of the lake due to "piling up" of the water caused by the force of the wind. If the water returns to a calm condition, the wave setup disappears. The wave runup is caused by the dissipation of the energy of the wave against the shore. It is the highest point in elevation reached by a wave as its energy is dissipated.

Vegetative Protection

In some situations, vegetation may be part of a lakeshore protection package. Some success has been noted in planting bulrushes and other vegetation in shallow water offshore. These plants dissipate the wave energy before it reaches the shore. Information on the design of vegetative protection is contained in reference 43. Vegetation has been planted in shallow water on berms to reduce the impact of waves. Also, vegetation has been planted above revetments to extend the area of protection in the wave runup zone.

Ice Action

The freeze and thaw cycles caused by changing weather can exert tremendous ice pressure on the shoreline. The probable maximum pressure

that can be produced by water freezing in an enclosed space is 30,000 pounds per square inch.

Figure 1-5. Flank Protection

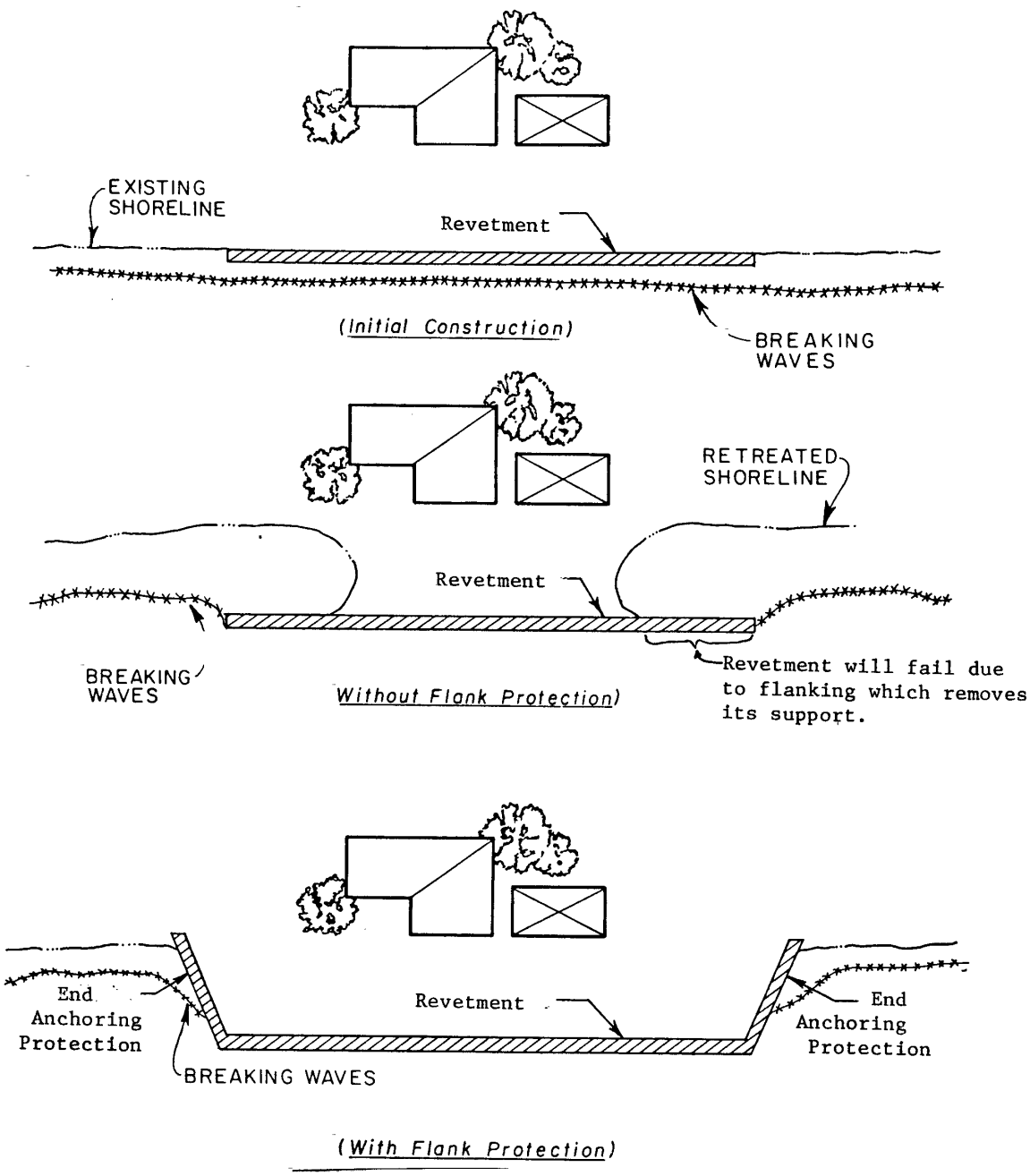


Figure 1.6 Wave Runup Heights

W: P: Lp ight

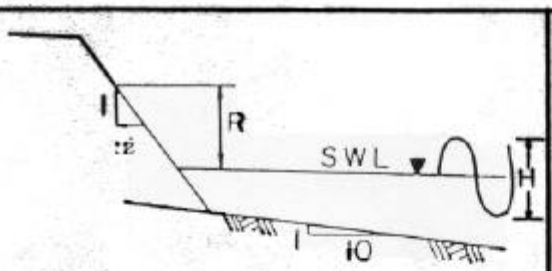
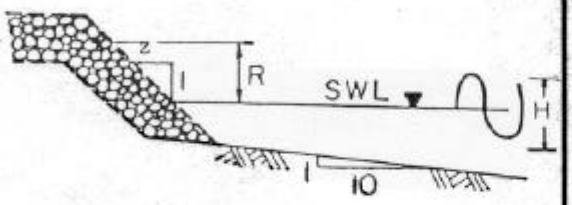
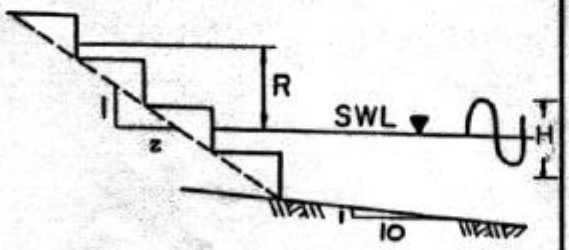
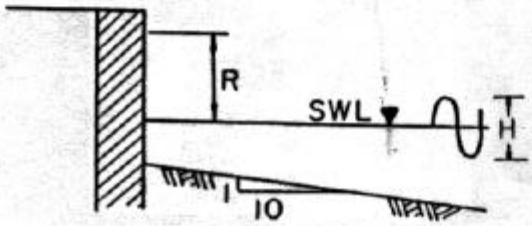
	z	R
 SMOOTH FACE	1.5 2.5 4.0	2.25 1.75 1.50
 ROUGH FACE	z 1.5 2.5 4.0	R 1.25 1.00 0.75
 STEPPED FACE	z 1.5	R 2.00
 VERTICAL FACE	z —	R 2.00

Figure 1-7. Definition Sketch of setup (S) and runup (R).

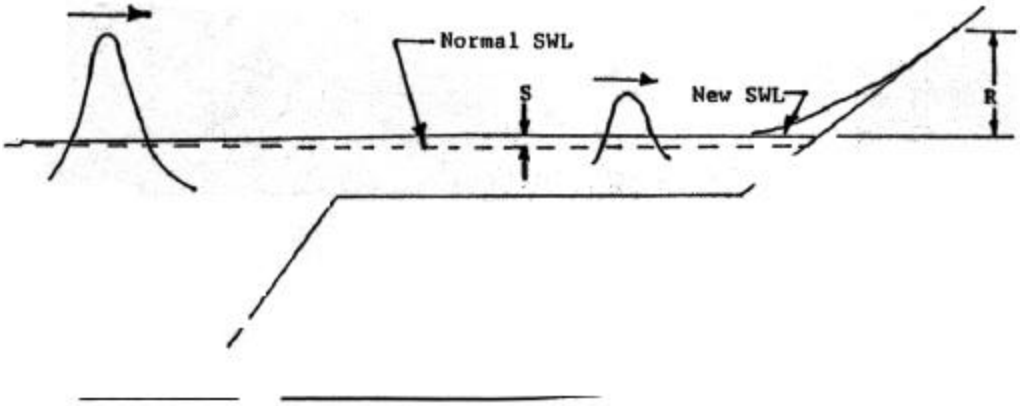


Figure 1-8. Inadequate or No Filtering

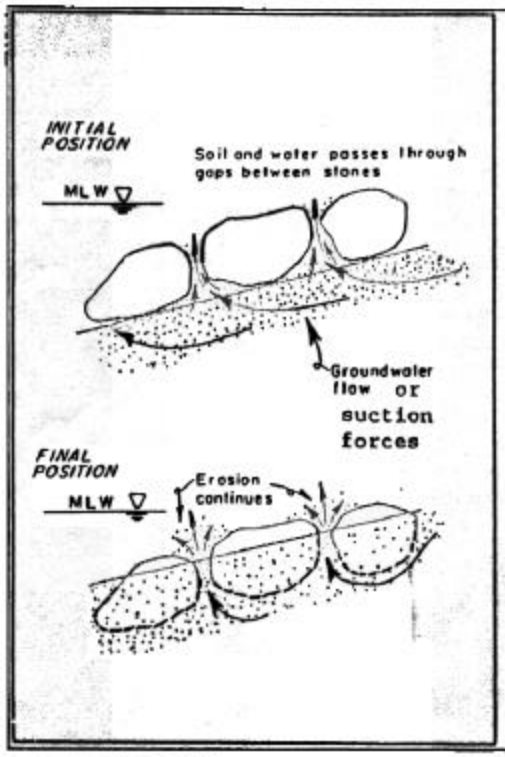
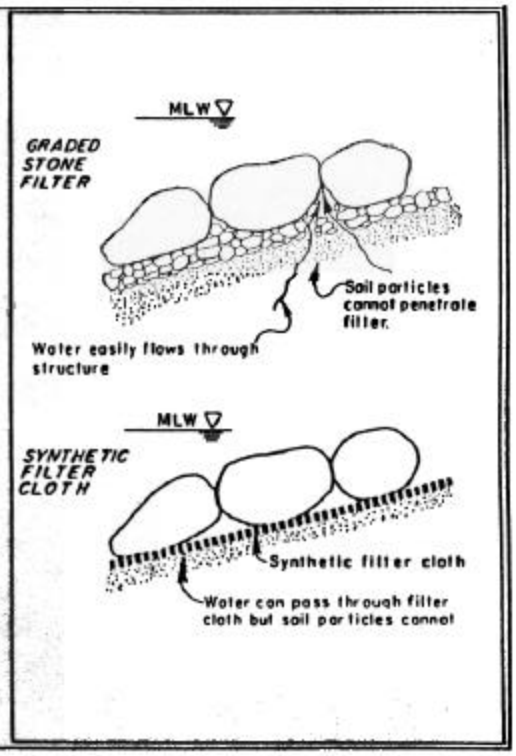


Figure 1-9. Proper Filter Design



As ice changes from a temperature of -20° F. to 32° F, the total expansion of an ice sheet that is one mile long is 3.75 feet (reference #15, page 7-254). Any protection installed on a shoreline will be tested by these forces. Observations indicate that protection must have enough mass to resist large movements and enough slope to cause the ice to deflect upwards. Normal ice thickness in Minnesota lakes may be 24 to 30 inches. In shallow water, the shore bottom may freeze and move with the ice. Open water beneath the ice provides a flexure point to allow buckling. Water beneath the ice can exert a hydrostatic pressure to assist in lifting the ice up the face of the shore protection. Some success has been noted with aeration systems which keep the ice open for a distance. This area gives the ice a place within which to expand, or a weak spot where the buckling can occur without damaging valuable property. Figure 1-10 shows three possible interactions between ice and shore that are experienced on Minnesota lakes.

Ice damage may occur in a number of different ways: 1) breakdown of rocks due to freeze-thaw action, 2) plucking of rocks by rising and falling ice sheets due to water level changes, 3) shoving action by moving ice sheets (moving by expansion during the freeze-thaw process, or moving by wind forcing ice sheets against a shore).

A study by the U.S. Army Corps of Engineers (Corps or COE) (reference #36) indicated that little or no damage occurred to riprap when ice rode up the riprapped slope (3:1 or flatter). Most of the damage occurred when ice was piled up on the riprap and the incoming ice sheet was forced to go between the riprap and the piled-up ice. Some of the rock was removed from the bed and brought to the surface of the ice pile. The most severe damage occurred at or below the waterline. It has been suggested that riprap should have a D_{50} in excess of the maximum winter ice thickness to avoid plucking of rock by rising ice sheets. The study concluded that the D_{100} of the rock should be 2-3 times the thickness of ice to avoid damage by ice shoving for slopes flatter than 3:1 and D_{100} should be three times the ice thickness for a slope that is 1.5:1 (H:V). Rock of this size is not practical to use on Minnesota's inland lakes, since ice is 24 to 30 inches thick in a typical year. The study did note that a literature review revealed practically no guidance for design of riprap in regions subject to ice that considered ice in the design.

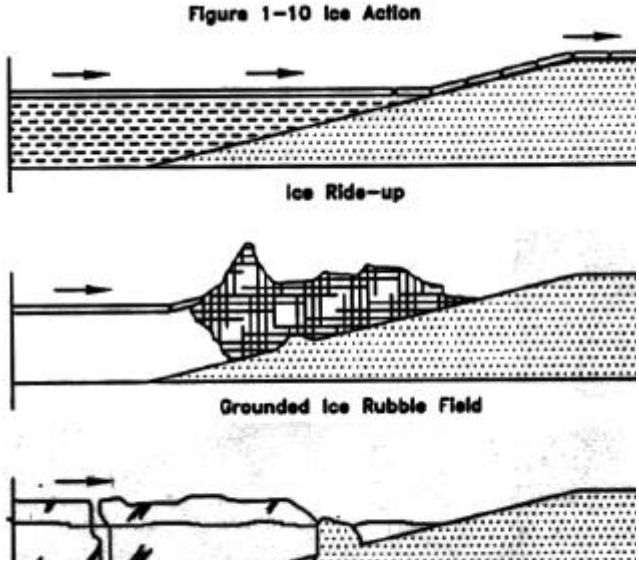
Two schools of thought continue to pervade discussions of protection against ice action. 1) Make the riprap large and heavy to resist the forces of ice. The sizing recommendations mentioned above from reference #36 follow this theory. 2) Make the rock size as small as possible that will still withstand the forces of wave erosion. Then the ice may move the rock, but the landowner(s) can easily put it back in place without a lot of expense that often results when a contractor is hired. The second school of thought has been followed more often in Minnesota and is believed to be working well here as a balance between installation and maintenance costs, and saitsfactory for long-term erosion protection.

Causes of Revetment Failure

Many reasons for failure of lakeshore protection measures have been identified. They are listed here to caution the designer and those overseeing installation of possible problems. Some of these causes can be controlled, or designed for, but others, such as icejacking, may be unpredictable or produce forces too great to be reasonably handled by revetments.

1. Riprap was not graded as specified. This includes skip grading.
2. The riprap segregated during placement. This produced pockets of finer material and groupings of large rock.
3. The bedding or filter layers were eroded downslope by backwash. (See Figures 1-8 and 1-9.) This may occur during construction before the rock is installed or the material may be leached out (sucked) through the rocks due to incompatible bedding/rock design.
4. Poor placement of rock on filter cloth caused holes and rips in the cloth which allowed bank material to erode.
5. The toe of the riprap was not properly keyed into the lakebed or designed to allow ice rideup.
6. A poorly designed filter or bedding caused pore pressure to build up in materials beneath the filter or bedding layers. The permeability of the filter was then less than the permeability of the base material. This lifted or moved the slope protection. This action occurs primarily at the still water level or at a break in the slope.
7. If the riprap is too small and light-weight, it can be moved by the direct force of the wave. This is especially a problem on steeper slopes.
8. The riprap may deteriorate by weathering.
9. Ice sheets may expand and contract as weather changes cause growth in the ice sheet. This may push up the shore material into ridges and move revetment. This can be a maintenance problem only, or it can destroy an installation.
10. The wind may push large ice chunks into the shoreline.
11. The stability of the bank on which the revetment is placed was not adequately evaluated and considered.

Figure 1–10 Ice Action



Chapter 2: Revetment Design

These design procedures and criteria are recommended for revetment used as protection against wind-generated wave action. They are intended for use on small inland lakes and with dams and reservoirs receiving assistance from the Natural Resources Conservation Service (NRCS). Generally, these have an effective fetch of less than 10 miles and a significant wave height of less than five feet.

Research has indicated that it is important that the protection be an inclined plane. If the surface is vertical or nearly so, it increases the wave runup and overtopping. Vertical shore protection also causes wave reflection downward as well as upward, which increases the scour. The inclined plane absorbs some of the energy of the wave, especially if it is rough. Research has also indicated that the wave's remaining energy may be safely dissipated by having a berm at the top of the protection.

Wave Frequency

Significant wave height (Hs) is the average of the highest 1/3 of waves in the spectrum experienced at a given point. Real waves are not all the same size at a given point in time and location; hence real waves cover a range or spectrum of sizes.

The Corps of Engineers (reference #15) and the American Railway Engineering Association (reference #1) vary the significant wave height (Hs) by the frequency of the wave. In this way, the value of the property being protected can be a factor in the design. Table 2-1 shows the factors used to increase significant wave height in the Corps' design procedure (reference #15, page 7-2).

Table 2-1. Design Frequency Factors for Waves

Definition	Notation	Factor
Highest 1/3 *	Hs	1.0
Highest 10%*	H10	1.27
Highest 5% *	H5	1.37
Highest 1% *	H1	1.67

* Average of _____ of all waves

Table 2-2 relates the design wave frequencies in Table 2-1 to practical situations by assigning them to a hazard class. Imminent danger to property of value is the primary consideration when selecting a safety factor for the design.

Table 2-2. Design Factor Selection

Hazard	Riprap	Riprap	Gabions & C. Block ♠
	Runup & WPH ∗	Rock Size	
Low	1.27	1.0	1.27
Moderate	1.37	1.27	1.37
High	1.67	1.27	1.67

♠ C. Block is precast concrete block, any style
∗ WPH is wave protection height

Definitions

Low Hazard: Failure of the protective measure does not endanger anything of value; distance from shore to anything of value exceeds 40 feet. The raw bank height is less than 5 feet.

Moderate Hazard: Failure of the measure increases the threat to something valuable; distance form shore to anything of value exceeds 20 feet. The raw bank height is less than 10 feet.

High Hazard: Failure of the measure would threaten existence of a valuable structure or property; distance from shore to anything of value is less than 20 feet.

Note: When Hs is used, some damage may result to the shoreline in extreme events. Where this is unacceptable, or maintenance may be poor, it is advised to increase the design wave frequency. Raw bank height may be only the lower portion of the total bank height. Use the two terms with caution.

Wind Data

The principal factor affecting the design for slope protection is wind generated wave action. The mechanics of wave generation are extremely complex. The forces causing erosion during wave attack on an earthen slope are both varied and complex. To evaluate wave height, the following factors that create waves in open water must be analyzed: (1) design wind direction, (2) effective fetch, and (3) wind velocity and duration. Each revetment material has different design considerations so each is addressed separately in this chapter.

Appendix A contains information on wind for the first-order weather stations in and around Minnesota. The map at the beginning of the appendix identifies the counties in Minnesota which are to use each first-order station for design. The fastest mile wind can be a sudden, short-lived gust (as short as two minutes) while the prevailing wind tends to blow for long periods. Research has indicated that the fastest mile wind lasts for too short of a time to be used for design.

Although the 1983 edition of the SCS National Technical Release No. 69 uses fastest mile wind data to determine critical wave height, the state-of-the-art methods use a wind speed with a longer duration. The wind records for Minnesota indicate the fastest wind speed that has ever been recorded for a given point on the compass, and the probability of a given wind speed for any point on the compass. This information has been evaluated in Appendix A with definitive values given for the wind stress factor for each compass direction. Wind stress factors were determined using the steps in the Corps' *Shore Protection Manual* (reference #15). Wind data from the National Climatic Center in Asheville, NC was examined for the thirteen stations in and around Minnesota. The wind speed that was calculated for use in determining the wind stress factor was the speed which equals or exceeds 95% of the observed, recorded wind speeds for the years of record. See Appendix A for more information on these calculations.

Design Procedure

The procedure followed here is adapted from the 1984 edition of the *Shore Protection Manual* published by the U.S. Army Corps of Engineers (reference #15). The Corps is the leader in research and application of shore protection measures. The 1984 *Shore Protection Manual's* design procedure supersedes the design method published in the 1977 version of the Corps' *Shore Protection Manual*, upon which the 1983 version of the SCS's TR69 is based.

The inland lakes in Minnesota in general are not extremely deep lakes. Experience has shown that designs in Minnesota fit the criteria for using deep water wave design procedures. Hence, the reader is referred to the Corps' *Shore Protection Manual's* design procedure for the shallow waves if it is needed, since the situation is rare.

Computation sheets are given in appendix B for the design procedure which follows. Sample problems are in Chapter 3.

Step 1. From knowledge of the site conditions, determine whether the site hazard is high, medium or low.

Step 2. Using an aerial photograph, USGS quad map or other planimetric view of the lake, locate the site needing protection. Draw a line across the open water of the lake from the design point, in a nearly perpendicular manner. This line's location may be varied within reasonable judgment to reflect long expanses of water which may be key in the production of wind-generated waves. The dominant wind direction during open water months should be considered. Measure the length of any possible radials to determine the fetch length, F, of each. Choose a critical fetch length for the design and use it as the effective fetch, Fe.

Step 3. Describe the fluctuation of the lake level and determine reasonable still water elevation(s) to use. DNR has information on lake levels on many Minnesota lakes. If the bounce in the lake level is small, it may be satisfactory to use only one elevation as the still water level. Otherwise, it may be wise to use different numbers for the low and high still water elevations so that the

designed protection covers the range of lake levels typically experienced. These water levels should be not extremes but "typical" high and low points for the lake level.

Step 4. Note the direction of the wind that would affect the site if it blew directly toward the site along the radial chosen in Step 2 for the effective fetch. Find the compass point (1 of 16) that most nearly falls on this radial.

Step 5. The wind data available for Minnesota has been summarized in Appendix A. Using the map in Appendix A, note which weather station provides information for the design site. Find the wind stress factor in Appendix A for the compass point chosen in Step 4.

Step 6. Use the chart in Figure 2-1 or equation 2-1 with the effective fetch (Fe) and the wind stress factor (Ua) to determine the period of the wave (T). Equation 2-2 below relates the wave period (T) to the wave length (L).

$$T = 0.559 \{UaFe\}^{1/3} \qquad \text{(Eq'n 2-1)}$$

$$L = 5.12\ T^2 \qquad \text{(Eq'n 2-2)}$$

Step 7. Use equation 2-3 below or the chart in Figure 2-1 to determine the significant wave height (Hs) for the effective fetch (Fe) and use the wind stress factor (Ua) determined in step 4. If the effective fetch is less than 0.5 mile, use Fe as 0.5 mile.

$$Hs = 0.0301\ Ua\ (Fe)^{0.5} \qquad \text{(Eq'n 2-3)}$$

Step 8. Choose a design frequency for the site from Table 2-2 and note the appropriate design factor (DF) from Table 2-2. Note that these are minimum design factors that may need to be increased for local circumstances. Multiply the Hs calculated in Step 7 by the design factor, DF, to obtain the design wave height (Ho). Note that the design factor is different for determining runup and wave protection height compared to what is used to determine rock size.

Also, if waves generated by watercraft are believed to be larger and more critical than those generated by wind, at this point substitute the larger Ho value as appropriate. See Chapter 6 for information on watercraft waves.

Step 9. Record the slope ratio chosen for the site, based on site characteristics. Use Figure 2-2 with Ho/L to determine the runup (R) of the waves. For revetment other than angular riprap, multiply R by 1.2. This accounts for the smoother surface and the lower unit weight and therefore less energy dissipation. The setup (S) is 0.1 times the design wave height (Ho), but no more than 0.5 feet.

Step 10. The lower limit for the riprap is 1.5 times the design wave height (Ho). The minimum upper limit for the riprap is the sum of the wave runup (R) and the wind setup (S). Add these two values (R and S). This sum is the wave protection height (WPH). If the elevation of the lower limit extends below the existing lake bottom, the designer may elect to use a type a or type c toe protection as illustrated in Figures 2-5 and 2-6. The upper limit may be increased to account for the Ordinary High Water elevation (OHW). See Chapter 5 for information on state requirements.

Step 11. Fluctuations in the lake level are important to consider. The upper limit amount should be added to the highest "typical" water level determined in Step 3 to find the maximum elevation of the protection. The lower limit value should be subtracted from the lowest "typical" water level determined in Step 3 to find the lowest elevation where protection is needed.

The procedure below guides the selection of a revetment such as riprap by choosing rock size and gradation.

Riprap Design

The principal influence on the resistance to displacement provided by durable riprap is the size of rock. For successful performance, the riprap must be placed so that individual rock particles will not be displaced by the forces of waves or by the erosion of underlying bedding, filter, or embankment materials.

Figure 2-1 Nomograms of deepwater significant wave prediction curves as functions of wind speed, fetch length, and wind duration. (Adapted from Reference #15)

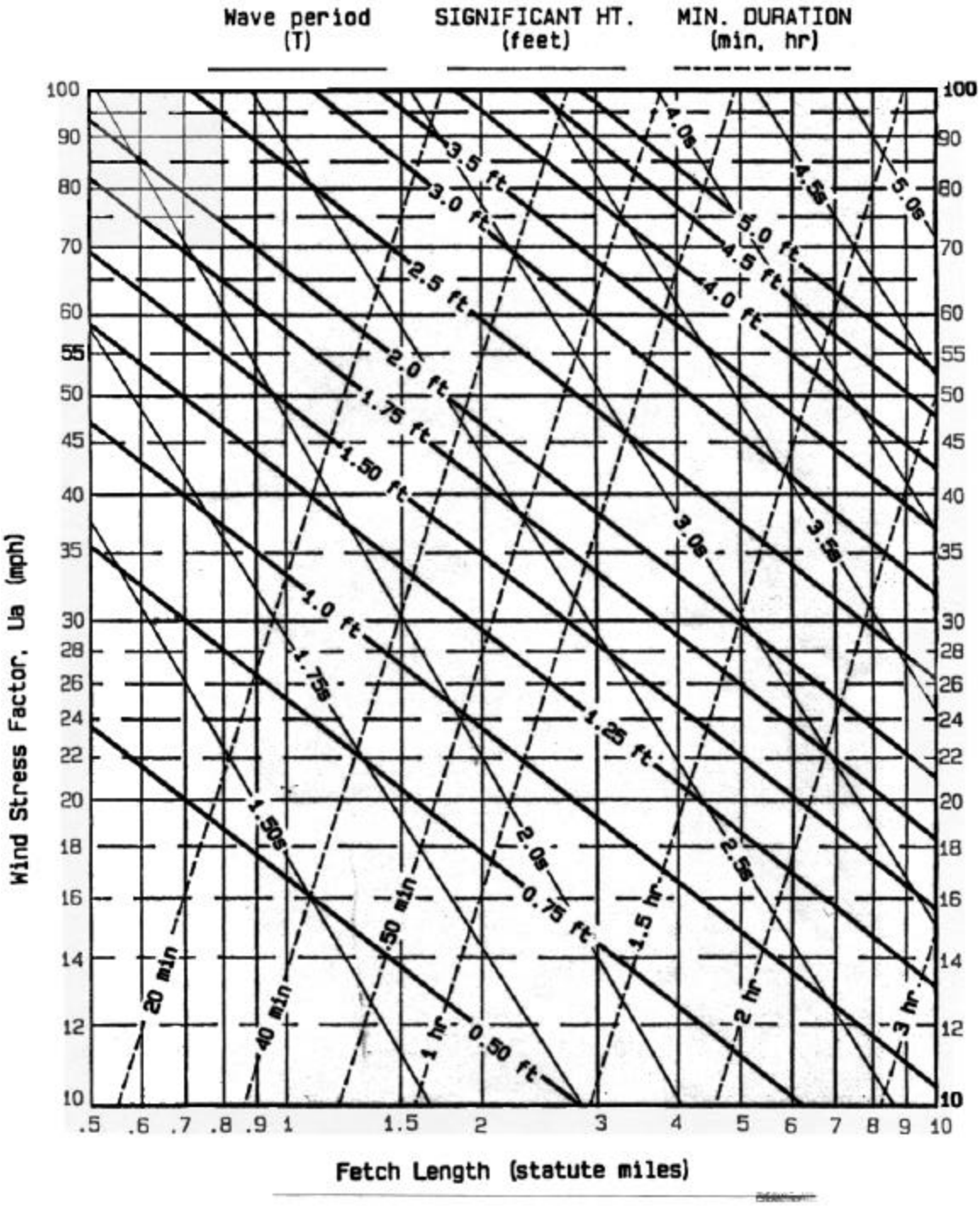
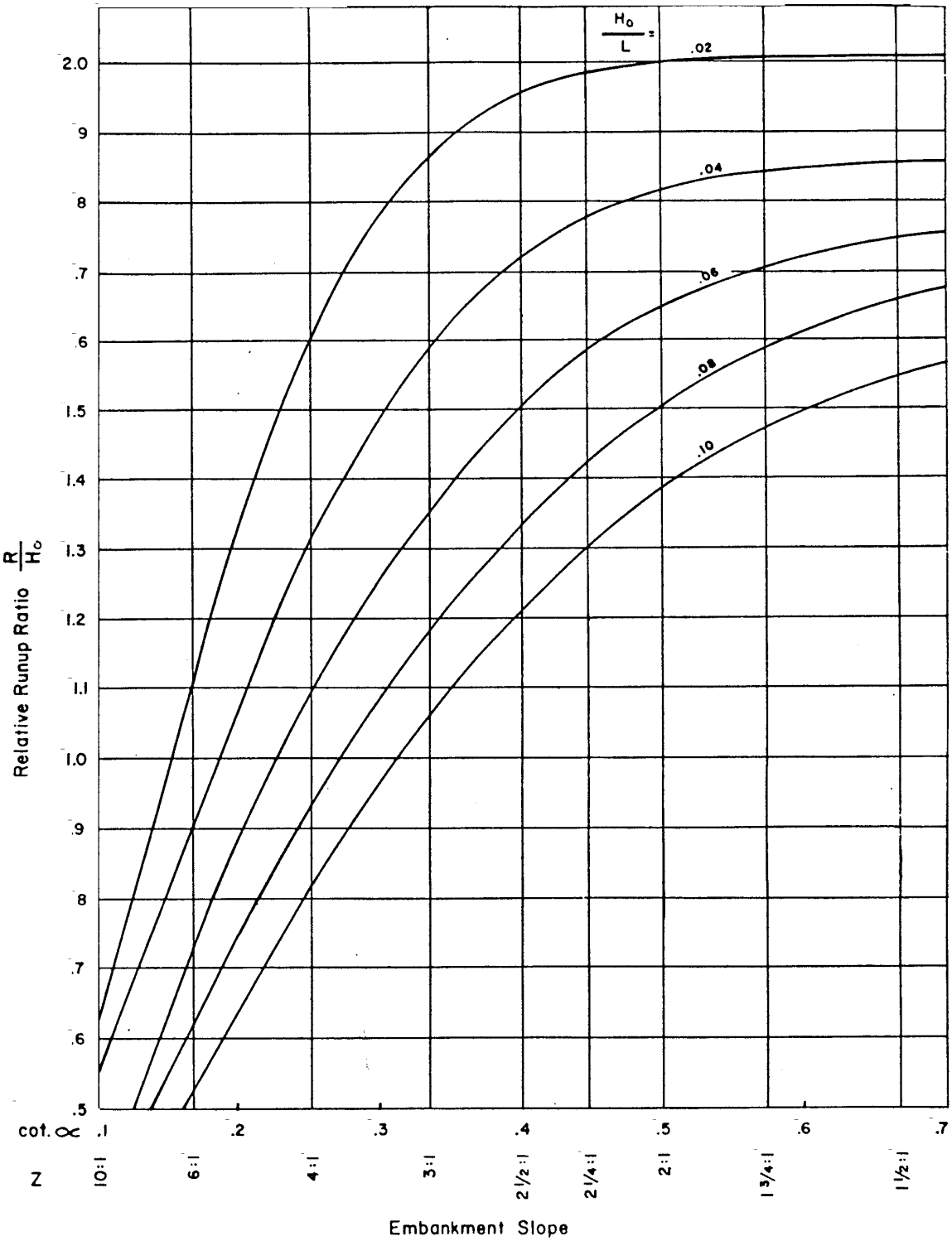


Figure 2-2. Wave Runup Ratio (from Reference #17)



The factors involved in selecting the optimal rock size for a satisfactory installation are :

- Weight of the rock
- Gradation of the riprap
- Thickness of the riprap layer
- Roughness of the riprap surface
- Slope of the embankment face
- Conditions of filter, bedding or both
- Rock shape (angular or rounded)

Step. 12. Note the slope ratio selected in Step 9 and record it again here. Using Table 2-2, select the design factor (DF) that is appropriate for the revetment to be used. Find the significant wave height (Hs) determined in step 7 and multiply this by the design factor (DF) for revetment.

Step 13. Determine the needed rock weight. The size of rock needed is determined from relationships of wave heights, wave velocities, and drag on the rock relative to the stable size of rock needed to resist these forces for a given location. This is principally determined using what is known as "Hudson's equation," given here as equation 2-4. This is used for the weight of an armor unit of nearly uniform size. For a graded angular riprap armor stone, equation 2-5 is used. The values commonly used for the "K" factors are shown in Table 2-4, which is from Chapter 7 of reference #15. The tables in Appendix C identify possible families of equations that can be computed using a given specific gravity, slope angle, and assumptions about the angularity and roundedness of the rock. The weight and size may be determined using equations 2-4 through 2-7 or the tables in Appendix C. Note that the wave height (Ho) value used here may have been determined using a design factor from Table 2-2 that was different from that used for determining wave runup.

$$W = \frac{w_r \; Ho^3}{K_D \, (S_r - 1)^3 \cot \theta} \qquad \text{(Eq'n 2-4)}$$

where,

W = the weight in newtons or pounds of an individual armor unit in the primary cover layer. (When the cover layer is two quarrystones in thickness, the stones comprising the primary cover layer can range from about 0.75W to 1.25W, with about 50% of the individual stones weighing more than W. The gradation should be uniform across the face of the structure, with no pockets of smaller stone. The maximum weight of individual stones depends on the size or shape of the unit. The unit should not be of such a size as to extend an appreciable distance above the average level of the slope.

w_r = unit weight (saturated surface dry) of an armor unit in N/m^3 or lb/ft^3. Note: the substitution of ρ_r, the mass density of the armor material in kg/m^3 or $slugs/ft^3$, will yield W in units of mass (kilograms or slugs). A unit weight of 165 lbs/ft^3 corresponds to a specific gravity of 2.65 and a unit weight of 156 lbs/ft^3 has a specific gravity of 2.50.

Ho = design wave height at the structure site in meters or feet

S_r = specific gravity of the armor unit, relative to the water at the structure ($S_r = w_r/w_w$)

w_w = unit weight of water; for fresh water this is 62.4 lbs/ft^3

θ = angle of structure slope measured from horizontal in degrees

K_D = stability coefficient that varies primarily with the shape of the armor units, roughness of the armor unit surface, sharpness of edges and the degree of interlocking obtained in placement (see Table 2-4).

K_{rr} = stability coefficient for angular, graded riprap, similar to K_D. (See Table 2-4)

$$W_{50} = \frac{w_r \; Ho^3}{K_{rr} \, (S_r - 1)^3 \cot \theta} \qquad \text{(Eq'n 2-5)}$$

For rock that is partially angular and partially rounded, a combination of K factors may be used. For example, with 2 layers of rock under breaking wave conditions, rock that is considered to be 30% angular and 70% rounded has a K of $0.3(K_{rr}) + 0.7(K_D) = 0.3(2.2)+0.7(1.2) = 1.5$.
The tables in Appendix C or equation 2-6 should be used to convert W_{50} to d_{50}, being certain to use the correct specific gravity for the rock that will be installed. Over much of Minnesota, a specific gravity of 2.50 is reasonable; in northeastern Minnesota, often rock is used with a specific gravity of 2.65.

$$d = 1.15\ (W/w_r)^{1/3} \qquad \text{(Eq'n 2-6)}$$

where, d = equivalent stone dimension in feet and the other parameters are the same as defined for equations 2-4 and 2-5. If the terms of equation 2-6 are rearranged, it can also be expressed as

$$W = d^3(w_r)/1.52 \qquad \text{(Eq'n 2-7)}$$

Step 14. After a W_{50} has been determined for the riprap gradation, the entire gradation will need to be specified. The entire gradation is determined using Table 2-5. The gradation may be expressed as weight or size in the specifications.

A gradation envelope should be specified in the construction specifications or on the drawings. A rule of thumb for size difference between envelope sides is 20-30% on a particle size for the major part of the envelope. Figure 2-3 illustrates the concept.

Table 2-4. Suggested K_D or K_{rr} Values for Use in Determining Armor Unit Weight
Non-Damage Criteria and Minor Overtopping

Armor Units	**Number of Units in Layer**	**Placement**	**K_D or K_{rr} Value Breaking Wave**	**K_D or K_{rr} Value Nonbreaking Wave**
Quarrystone (K_D)				
Smooth, rounded	2	Random	1.2	2.4
Smooth, rounded	>3	Random	1.6	3.2
Rough angular	1	Random	not recommended	2.9
Quarrystone (K_{rr})				
Rough Angular	any	Random	2.2	2.5
(graded)				
Minimal toe**	any	Random	3.5	4.0

Note: The K_D values for smooth, rounded quarrystone for breaking waves are unsupported by test results but were estimated by the authors of the Corps' *Shore Protection Manual*, 1984.
** Meant to be used when a minimal riprap toe is installed in combination with bioengineering techniques.

Table 2-5. Riprap Gradation

Size of Stone	**Percent of total weight smaller than the given size**
2.0 to 2.5 x d_{50}	100
1.6 to 2.1 x d_{50}	85
1.0 to 1.5 x d_{50}	50
0.3 to 0.5 x d_{50}	15

Practical tips on sizing and installing riprap are contained in Minnesota Technical Release No. 3, "Loose Riprap Protection." It is advisable to place the bedding or filter material just ahead of the riprap. The installer should check that the bedding is in the proper location, and hasn't moved, just before the riprap is placed. The materials should be deposited as close to their final location as possible.

Step 15. The thickness of the riprap should be 1.25 x the maximum d_{100} size, but not less than 12 inches. This is to ensure that the rock thickness will be larger than the maximum rock

size, expecting to have more than one layer of rock over most of the revetment. The Corps' *Shore Protection Manual* (reference #15, page 7-207) recommends limiting use of graded riprap to design wave heights less than or equal to five feet. One exception is noted here. When using a type d toe protection with a d_{50} of 4" or less, a thickness of 9 inches is adequate.

Figure 2-3. Gradation Curve Example

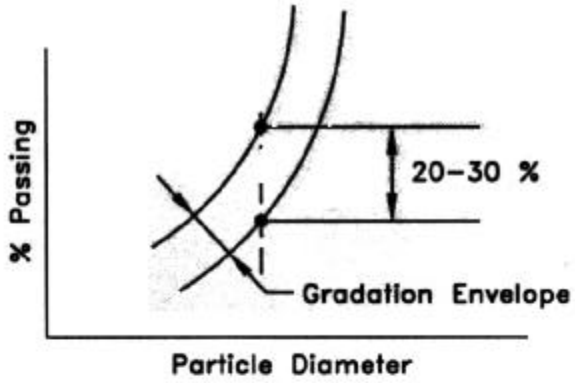
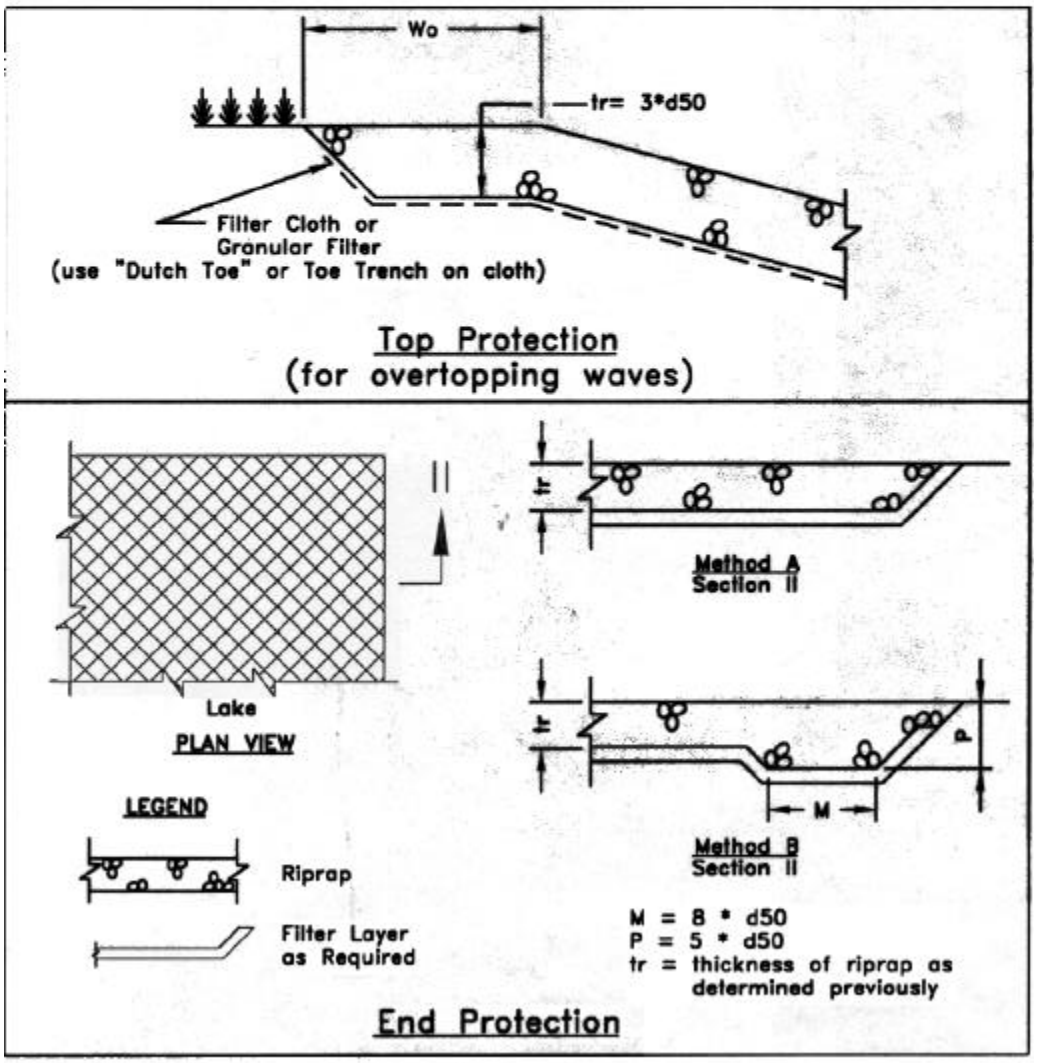


Figure 2-4. Top and End Protection



Overtopping Protection

Step 16. Check whether overtopping protection is required. Figure 2-4 shows possible configurations to protect the top and ends. When the wave runup height reaches an elevation higher than the top of the bank, protection of the top must include an overflow apron. The width of the overtopping apron (Wo) should be three feet horizontally for every foot of runup not protected by embankment but not less than 1.5 feet in any case. See Figure 2-4 for an illustration of this. The overflow apron prevents soil particles from moving lakeward as the wave recedes back to the lake.

The overtopping apron may be adjusted based on Ordinary High Water (OHW) information for the lake. See Step 10 of the design procedure and
Chapter 5 of this document for state requirements.

End Protection

Step 17. The ends are subject to attack by outside forces and must be reinforced against possible failure. End protection is needed if the rock is terminated at a point that is not known to be stable. Figure 2-4 shows the two types of end protection. If the rock is terminated at a stable point such as a controlling structure, natural rock outcropping, etc., Method A in Figure 2-4 may be used. In some cases, some questions will exist as to the stability of the end section. Method B should then be used as shown in Figure 2-4. In cases where the lake bottom slope is flatter than 5:1, Method A end protection may be used in the water and Method B on the bank at the designer's discretion. Method B has a deepened and expanded toe to hold against scour forces. Figure 2-4 illustrates the sizing of this section.

Toe Protection

Step 18. A critical part of the design of shoreline revetment is protection of the toe. The breaking waves will "scrape along the bottom" causing a scour that will try to undermine the revetment. Four alternate toe protection designs are offered in Figures 2-5, 2-6 and 2-7, using either a granular bedding/filter or a geotextile cloth. It is important to anchor the edge of the geotextile, if used, by burying the end in a 6" trench, or curling the geotextile into the riprap in a "Dutch Toe". When the geotextile is installed under water, the best alternative for anchoring the lower edge may be covering it well with larger rock.

A type a toe (with either a geotextile or a granular bedding/filter) is meant for lakeshores with shallow water and a flatter lakebed slope. A trench is cut in the bottom to install the toe. The type a toe is preferred for sites where ice action is known to have taken place. It encourages ice to ride up and over the riprap, especially if the slope of the riprap is flatter than 5:1. The ice does not have a protruding riprap toe to push as illustrated in Figure 1-10.

Based on experience, the critical length, La, for this type of toe should be between 3 and 6 feet. The length needed is based on a comparison between what is needed for the rock size vs. the anticipated scour. For rock size, the toe length is estimated by 15 x d50. For scour protection, the length is calculated by subtracting the lower limit elevation calculated in step 10 from the lake bottom elevation near shore, and multiplying that result by 3. Figures 2-5 and 2-6 illustrate the toe layout.

A type b toe (with either a geotextile or a granular bedding/filter) is meant for lakes with deep water at the shore. This type of toe protection stabilizes the bank through a region where scour is likely to occur. The thickened section of riprap is to extend to the elevation calculated for the lower limit of the riprap. This type of toe should be used where a drop-off occurs within 50 feet of the shore, or where a steep bank is encountered. This may mean that the toe is beneath the lake bottom a short distance to limit potential scour.

In the type b toe, the thickness is increased to 5 x d50 to provide a source of rock. The site will armor itself if the wave scour does infringe on the toe if sufficient rock is available in the toe.

Figures 2-5 and 2-6 illustrate the critical length

Figure 2-5. Three toe types with geotextile

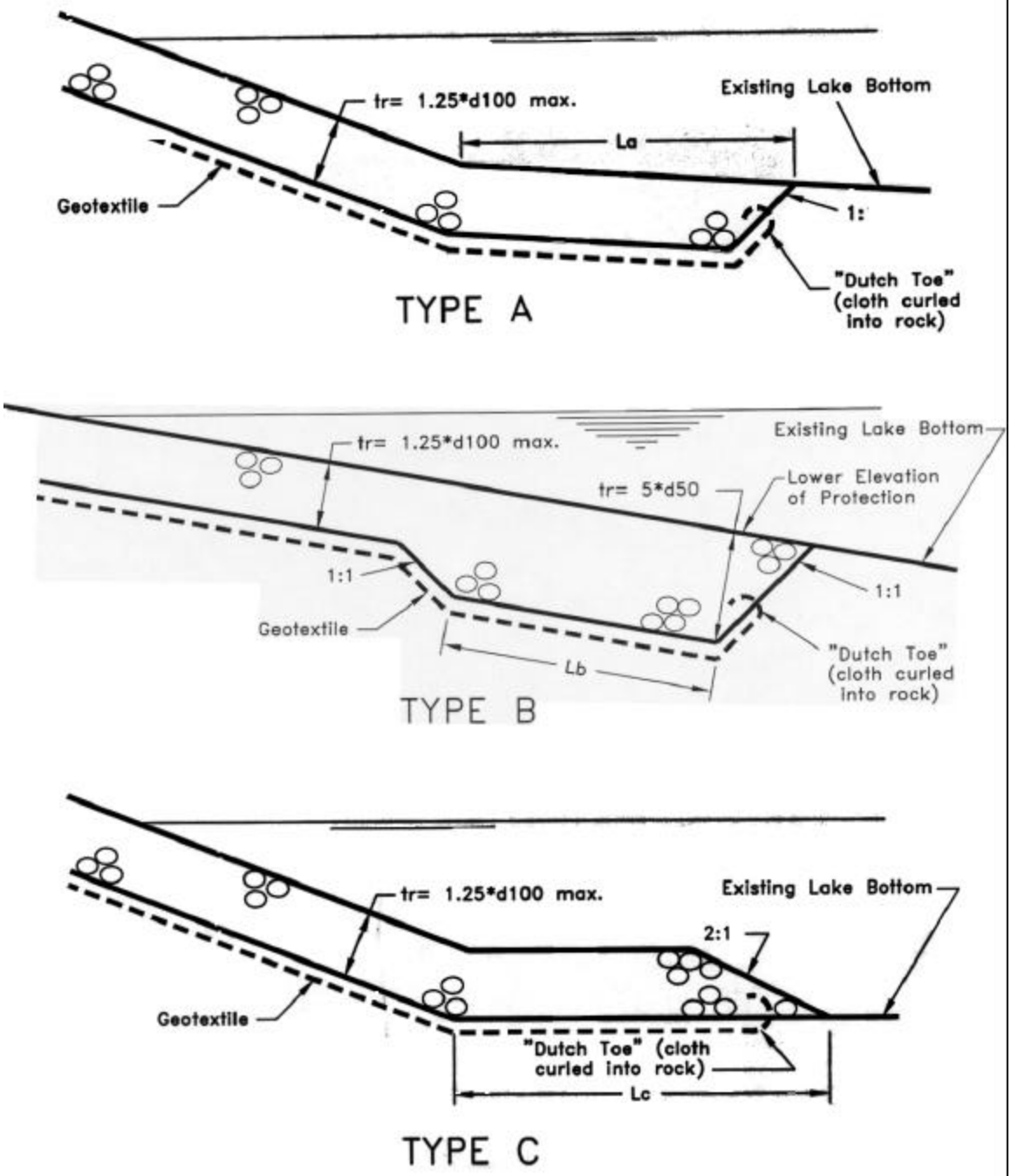
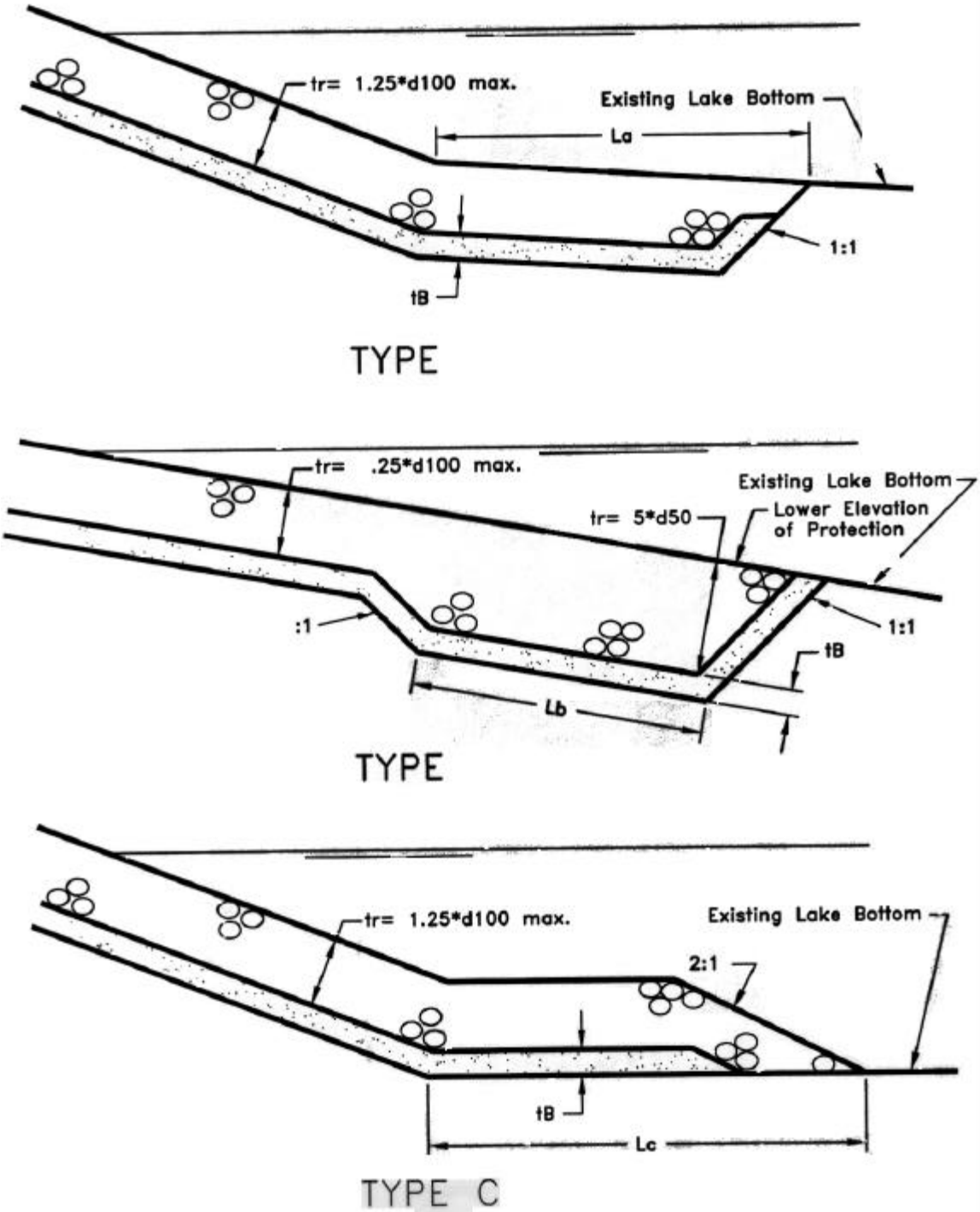


Figure 2-6. Three toe types with granular filter



of the toe protection, Lb. This is used as 8 x d50 based on practical experience.

A type c toe (with either a geotextile or a granular bedding/filter) is intended for sites that have experienced little or no ice action. The rock is placed on top of the existing lake bottom. When the riprap is placed on the lake bottom, it may protrude above the water, be at or near the still water level, or be significantly below the water level, or vary among these three depending on fluctuations in lake level. This should be discussed with the landowner, as liability issues may arise with water craft traveling close to shore. This toe may be needed where a site has limited access for large equipment, and hence means to dig a toe trench are not available.

Based on experience, the critical length, Lc, for this type of toe should be between 3 and 6 feet. The length needed is based on a comparison between what is needed for the rock size vs. the anticipated scour. For rock size, the toe length is estimated by 15 x d50. For scour protection, the length is calculated by subtracting the lower limit elevation calculated in step 10 from the lake bottom elevation near shore, and multiplying that result by 3. Figures 2-5 and 2-6 illustrate the toe layout.

A type d toe (with either a geotextile or a granular bedding/filter) is intended for sites where it is difficult to distinguish a slope change from the shore to the lake, and it is desired to place the riprap on top of the existing lakebed. Such a toe is susceptible to ice damage as the rock is on top of the lakebottom and may be pushed when the ice freezes to the lake bottom or to the riprap.

The toe should be extended to the calculated lower limit, or at least 4 feet waterward of the normal low lake level elevation, whichever is shorter. This is illustrated in Figure 2-7 for both geotextile and granular bedding. Note that the geotextile is to be anchored at the bottom with larger rock. If underwater installation allows for it, a “Dutch Toe” or 6” toe trench may be used.

Filter and Bedding Materials

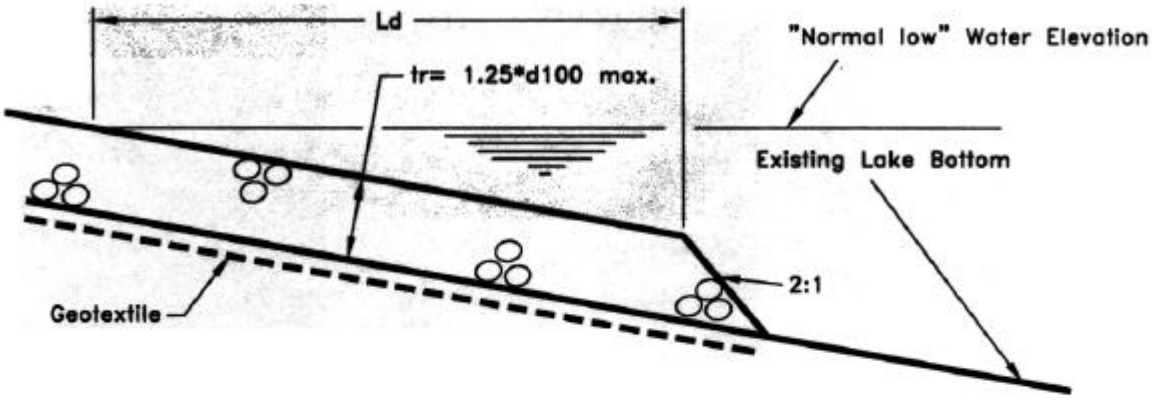
Step 19. Determine what filter or bedding will be used. A filter may be a graded granular material or a geotextile or a combination of these. Filter or bedding may be described as a layer or combination of layers of pervious materials graded in such a manner as to provide drainage, yet prevent the movement of soil particles through the layer due to flowing water. Figures 1-8 and 1-9 show the purpose of a filter or bedding layer. In order for the filter material to function as intended, it must restrict movement of the base material and must not be leached out through the riprap by wave action.

Bedding is a layer of material which primarily distributes the load of the overlying material, such as riprap. It may not act as a filter for underlying material but must be graded such that it will not be washed or leached out through the overlying material. A bedding is normally a graded granular material but may be a geotextile designed to be load-bearing.

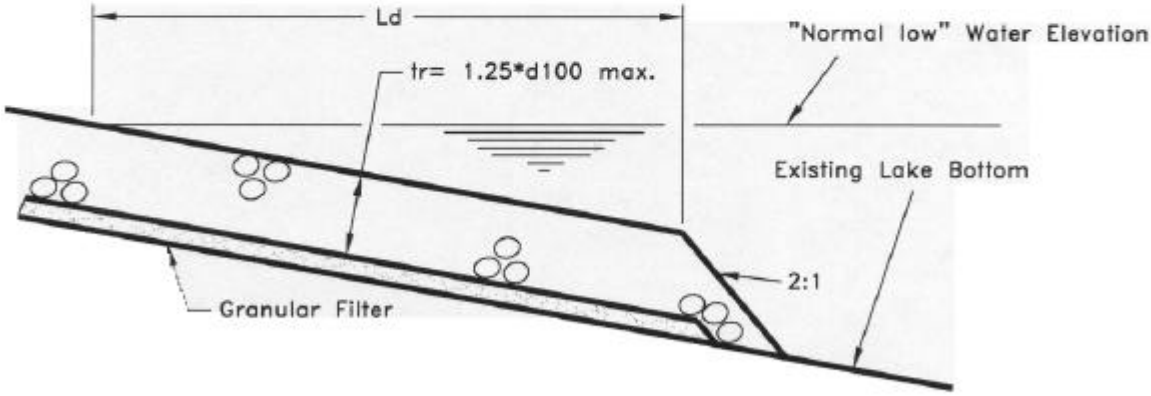
Commercially made filter fabric or geotextile is acceptable, and even preferred, in place of a granular filter in many instances. The physical durability of a geotextile fabric is evaluated by its tear resistance, puncture and impact resistance, resistance to ultraviolet damage, flexibility and tensile strength. Filter fabric is normally used over sandy soils and can only safely protect soils having not more than 50% passing the 0.1 mm sieve. When filter cloth is used, the ends should be buried - at least 6 inches and preferably 12 inches. The Corps of Engineers recommends use of a Dutch toe (wrapping the end of the filter fabric into the protection) as illustrated in Figure 2-5. Many prefer use of a 6” trench at the top and sides of a slope to bury the ends of the geotextile so it can’t pull back out of the rock.

A 4 to 6 inch layer of sand may be desirable between the filter cloth and the riprap as a cushion to prevent tearing of the cloth during installation of the rock. Limiting the drop height for the rock placement also helps minimize the damage to the geotextile. Some designers require bedding material on top of a geotextile to anchor the geotextile against the soil as the

Figure 2-7. Type d toe with either geotextile or granular filter.



TYPE D WITH GEOTEXTILE



TYPE D WITH GRANULAR

contact between layers is critical for the total filter system to function as intended.

The filter or bedding layer thickness shall be the greater of 1) 1.33 times the maximum grain size of the bedding, 2) six inches, or 3) 1/3 the thickness of the riprap, whichever is greater, but shall not be more than 12 inches. The gradation of the filter and bedding material should be designed in accordance with SCS Soil Mechanics Note 1 and the information contained here.

In general, nonwoven geotextiles are recommended for lakeshore installations as they are not as slippery, can stretch more before tearing, and they help build the underlying natural filter better than woven geotextiles. Refer to Minnesota Material Specification MN-592 - Geotextile for detailed information. Geotextile products may be subject to deterioration when exposed to ultraviolet rays, as in sunlight. To avoid shortening the life of the geotextile, follow the manufacturer's recommendations for handling and storing geotextile. Exposed geotextile can be a fire hazard as well, so covering it entirely is important for this reason also.

A filter is required beneath rock riprap when 1) the base soil is non-plastic or has a plasticity index (PI) less than 15 <u>and</u> is <u>not</u> coarse enough to meet the gradation required to prevent leaching through the riprap; or 2) a phreatic line will outlet seepage from the shore above the lake level. The granular filter material must meet the requirements in the Minnesota Material Specification No. 521. Bedding material is required for materials having a PI greater than 15 except for materials classified as CL or CH with a liquid limit (LL) greater than 40. Bedding is not required for CL soil or CH soils with a LL greater than 40, unless the engineer determines it is needed to distribute the load on the foundation soils.

The following equations shall be used to make the filter compatible with the riprap gradation. The filter gradation curve should approximately parallel the rock riprap curve or have a flatter slope.

d_{15} (bedding- minimum) > d_{15}(riprap-maximum)/40 > 0.42 mm (No. 40 sieve)	(Eq'n 2-8)
d_{15}(bedding-maximum) < d_{15} (riprap-minimum)/4	(Eq'n 2-9)
d_{85} (bedding-minimum) > d_{15}(riprap-maximum)/4	(Eq'n 2-10)
d_{50} (bedding - minimum) > d_{50} (riprap-maximum)/40	(Eq'n 2-11)

Concrete Paving Block Design

When formed using a dense concrete, precast concrete paving blocks can provide excellent shore protection. The Corps of Engineers has done research on the use of many kinds of precast concrete paving block, such as those illustrated in Figure 2-8. The designer should consider the fact that the resultant surface will be smooth, and therefore less effective at dissipating wave energy than a rougher surface. This situation may be desired by landowners to make the lakeshore more attractive for recreational uses. The blocks will be laid in a single layer and provide only one layer of protection. When this layer is disturbed, little protects the bank underneath. The armor layer can rapidly unravel during a storm event. The weight of the blocks alone cannot provide the same resistance to movement as riprap, so interlocking, cabled, or rod-tied blocks are preferred over those that merely lay side-by-side.

The individual types of precast concrete block vary in effectiveness for lakeshore protection. Manufacturer's literature should be read

carefully. References 4, 6 and 15 in the bibliography may be helpful for designing a protection measure which uses precast concrete paving blocks.

When designing lakeshore protection using precast concrete paving block, follow the steps in the design procedure. The runup must be increased by a factor of 1.2 to account for the smooth surface as noted in step 9 of the design procedure. Criteria for bedding and filter design should be followed as for riprap.

Gabions

Gabions also can provide acceptable shoreline protection. However, note that wave action will move the rocks around within the exposed gabion baskets, wearing through the wire over time, possibly shortening the life of the shore protection. Filling the gabions as compactly as possible helps reduce this concern. Use of the gabions above the lake level, where wave action is less frequent, is also a useful design strategy.

The designer is encouraged to follow the steps in the design procedure for determining the extent of the gabion protection. Design of the gabions themselves should follow manufacturer's recommendations. The wave runup should be increased by a factor of 1.2 as noted in step 8 of the design procedure. NRCS construction specification No. 64, "Wire Mesh Gabions," found in National Engineering Handbook Section 20 (NEH 20), should be followed for design and placement. The filter and bedding requirements are the same as stated for riprap above.

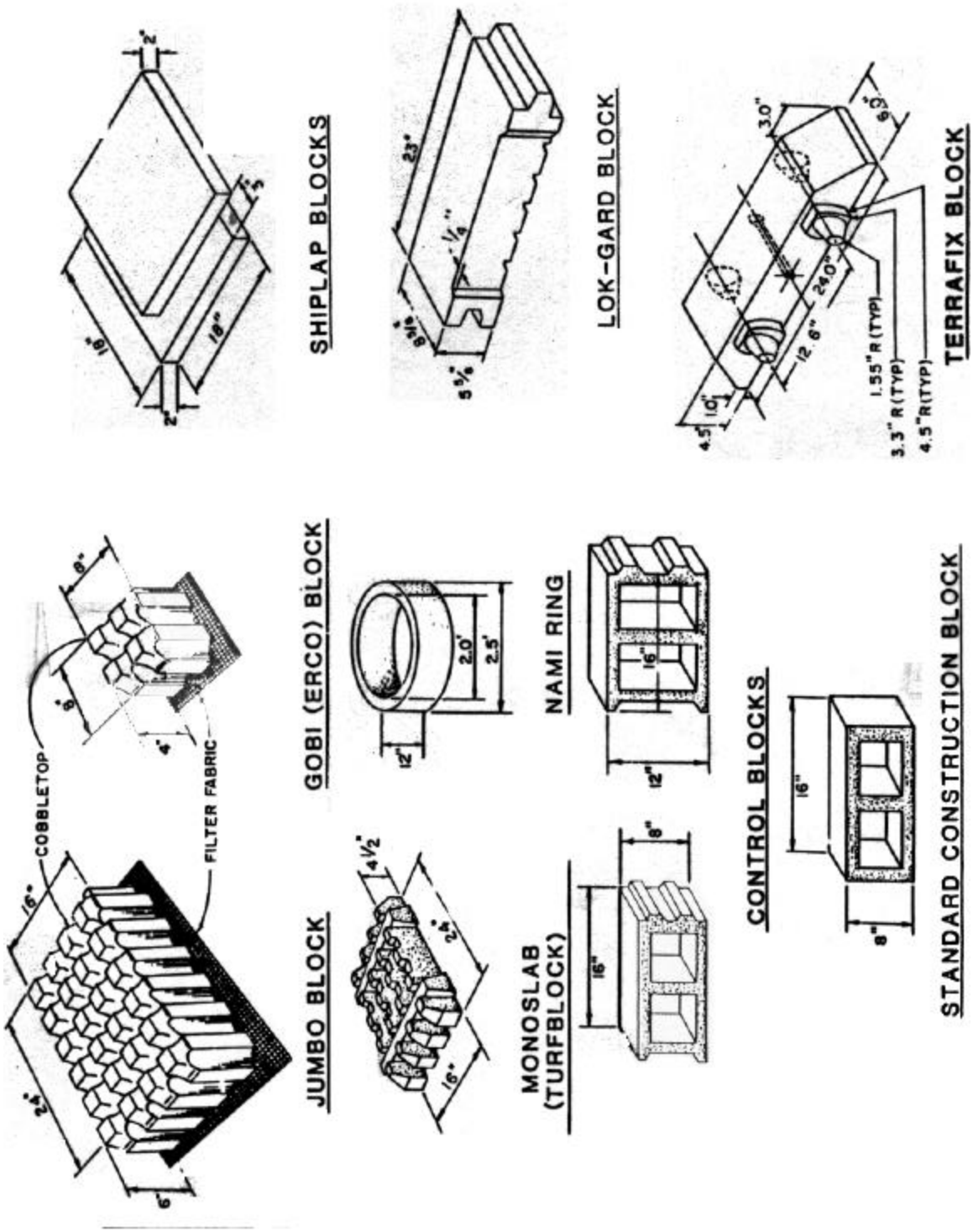
When designing lakeshore protection using gabions, follow the steps in the design procedure. The runup must be increased by a factor of 1.2 to account for the smoother surface as noted in step 9 of the design procedure. It is recommended to follow the criteria for bedding and filter design asis used for riprap.

Soil Bioengineering

NRCS encourages the use of soil bioengineering practices where appropriate and reasonable. These techniques have been used on Minnesota lakeshores. However, at this time, insufficient data exists to prepare specific design guidelines on bioengineering techniques for lakeshores. References 38-41 in Appendix E describe soil bioengineering techniques and guide choices for sites needing protection.

Steps 1-11 of the design procedure in this chapter are to be used for determining protection for sites which will use soil bioengineering techniques. Consideration must be given to overtopping protection, end protection and toe protection as well.

Figure 2-8. Revetment Blocks (U.S. Army Corps of Engineers)



Chapter 3: Sample Problems

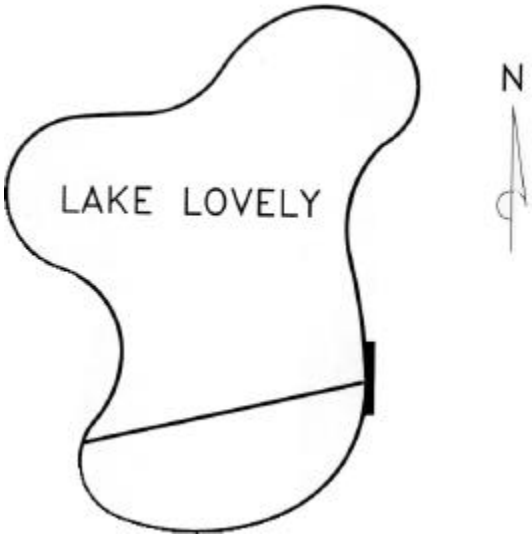
This chapter contains two sample problems to clarify the use of this technical release. The design forms from Appendix C are used to record the design information. The figures and tables contained in this document are used to calculate the design parameters.

Sample Problem #1

Given: A cabin located on Lake Lovely in the southern part of Otter Tail County, Minnesota is experiencing erosion. The cabin and garage are about 70 feet from the shoreline. The rock available in the area weighs about 156 lbs/ft^3 and is very angular.

With a little grading, the site seems to lend itself well to a 4:1 (horizontal to vertical) finished slope. The still water elevation is typically around 946.8 with little fluctuation. The elevation at the top of the bank is 947.2. The lake bottom just off shore is at an elevation of 946.0. The property on both sides of this cabin is covered with trees and shrubs which appear to have stabilized both sides. The landowner is interested in using a granular filter if needed as he owns a quarry in the area. He is open to using geotextile if it is more cost-effective. The critical open water distance was measured to be 1380 feet on an aerial photo of the site, as shown in the illustration below.

Find. The site needs a design for lakeshore erosion protection that uses rock.



APPENDIX B
DESIGN OF LAKESHORE PROTECTION

Page 1

Project Name SAMPLE PROBLEM #1 **County** Otter Tail **Lake** Lovely

By JMG **Date** 9/23/97 **Ckd By** JB **Date** 9/24/97 **Job Class** I

Step 1. Hazard: High Moderate (Low)

Step 2. Effective Fetch Computations:

From a map or aerial photograph, and information gathered, determine the critical open water distance for wave generation (fetch). Consider the dominant wind direction in open water months.

Fe = 1380 feet = 0.26 mile(s)

Note: If Effective Fetch (Fe) < 0.5 mile, use Fe = 0.5 mile Use Fe = 0.5 mile(s)

Step 3. Describe fluctuation of lake level:

minimal

Still Water Elevation(s) 946.8

Step 4. Wind direction along critical fetch WSW (compass point)

Step 5. First Order Weather Station Alexandria (Appendix A)

Wind Stress Factor (Ua) 27 miles/hour (Appendix A)

Step 6. Wave Period (T) (Eq'n 2-1 or Figure B-1) $T = 0.559[Ua \times Fe]^{1/3} =$ 1.33 seconds

Wave Length (L) (Eq'n 2-2) $L = 5.12\ T^2 =$ 9.1 feet

Step 7. Significant Wave Height (Hs) (Eq'n 2-3 or Fig. B-1) $Hs = 0.0301\ Ua\ (Fe)^{0.5} =$ 0.57 feet

Step 8. Design Factor (DF) (Table 2-2) 1.27

Design Wave Height (Ho) = Hs x DF = 0.57 x 1.27 = 0.72 feet

Step 9. Slope Ratio 4:1 (such as 3:1, 4:1) **Ho/L** = 0.72 / 9.1 = 0.08

R/Ho (Figure 2-2) 0.93 If material is not riprap, multiply: R/ Ho x 1.2 = N/A (new R/Ho)

Runup (R) = Ho x R/Ho = 0.72 x 0.93 = 0.67' use 0.7 ft

Setup (S) = 0.1 x Ho = 0.1 x 0.72 = 0.07 (not more than 0.5 feet)

use 0.1 ft

APPENDIX B
DESIGN OF LAKESHORE PROTECTION

Step 10. Lower Limit = 1.5 x Ho = 1.5 x 0.72 = 1.1 feet

Upper Limit (WPH) = R + S = 0.7 + 0.1 = 0.8 feet

Step 11. Upper elevation of protection: (upper) SWL + upper limit = 946.8 + 0.8 = 947.6

Lower elevation of protection: (lower) SWL - lower limit = 946.8 - 1.1 = 945.7

RIPRAP DESIGN

Step 12. Slope Ratio 4:1 **Design Factor (DF)** (rock size only) (Table 2-2) 1.0

Ho = Hs x DF = 0.57 x 1.0 = 0.6 feet
(Hs is the same as determined in Step 7)

Step 13. Determine W50 (Use Eq'n 2-4 and/or Eq'n 2-5 or select from the chart in Appendix C)
Determine or estimate the density, w_r 156 lbs/ft^3 or specific gravity Gs 2.50 of the rock

Describe rock expected: 50 % rounded and 50 % angular

$$W_{50} = \frac{w_r \, Ho^3}{(K_D \text{ or } K_{rr})(S_r-1)^3 \cot\theta} = \frac{156 \frac{lbs}{ft^3} (0.6')^3}{\left(\frac{1.2+2.2}{2}\right)(2.9-1)^3 4} = 6.797 (0.6')^3 = 1.47 \text{ lbs.}$$

W50 = 1.5 lbs. = **D50** 2.9 inches
(Use Table C-4 or C-5 to convert weight to equivalent size, or Eq'n 2-6 below)

d = 15 $(W/w_r)^{1/3}$ = 0.24 feet (Eq'n 2-6) **Use D50** 3 inches

Step 14.

Gradation calculated for this location:		
D_{100}	2.0 x D_{50} = 6"	2.5 x D_{50} = 7.5"
D_{85}	1.6 x D_{50} = 4.8"	2.1 x D_{50} = 6.3"
D_{50}	1.0 x D_{50} = 3"	1.5 x D_{50} = 4.5"
D_{15}	0.3 x D_{50} = 0.9"-use 1"	0.5 x D_{50} = 1.5"

Step 15. Thickness of Riprap = 1.25 x maximum D_{100} = 1.25 x 7.5 = 9.4"
use 2" minimum

APPENDIX B
DESIGN OF LAKESHORE PROTECTION

Step 16. Overtopping Protection

Step a) Elevation of top of bank (determined in field) 947.2
Step b) Upper elevation of protection (calculated on page 2, step 11)= 947.6

Step c) If step b is higher than step a, an overtoppping apron is required. {(step b)-(step a)} x 3 = width of apron shoreward (must be ≥1.5 feet)

Width of overtopping apron (Wo) = (947.6 - 947.2) x 3 = 1.2 feet (not less than 5 feet)
Use Wo = 1.5 feet

Ordinary High Water Elevation (OHW) from DNR if available N/A

Special considerations related to the OHW elevation: none

Step 17. End Protection: Method A X Method B (Choose one - see Figure 2-4)
Rationale for this choice:
secure end points

Step 18. Toe Protection: (Figures 2-5 and 2-6)
Follow steps a through f for an La or Lc toe; use step g for an Lb toe. Use step h for a type d toe.

Step a. 1.25 x D_{50} (riprap) = 3.75 inches

Step b. Elevation of existing lake bottom near shore = 946.0

Step c. Lower elevation of protection (computed in Step 11) = 945.7

Step d. {(step b) - (step c)} x 3 = 0.9 feet

Step e. Determine whether step a or step d results in a larger value. Write it here. 0.9 ft

Step. f. The value in step e must not be less than 3 feet (if it is, use 3.0 feet) nor larger than 6 feet (if it is, use 6 feet). This value is the length La or Lc as depicted in Figures 2-5 and 2-6.

La or **Lc** = 3.0 feet Go to Step 19

Step g. **Lb** = 8 x d50 = _____; use Lb = feet

Step h. **Ld** = the shorter value of 1) 6' (more at engineer's discretion) or 2) the lower elevation of protection calculated in step 11 on page 2. _____ See Figure 2-7.

APPENDIX B
DESIGN OF LAKESHORE PROTECTION

Page 4

Step 19. Filter or Bedding Requirements:

Use Geotextile or Use granular filter or bedding X (select one)

Granular Filter Design: 1 inch = 25.4 mm

d15 (bedding) > d15 (riprap)/40 > 0.42 mm (No. 40 sieve)
(min.) (max.) $\frac{1.5''}{40} = .0375'' = .95\ mm > 0.42mm$ OK

d15 (bedding) < d15 (riprap)/4
(max.) (min.) $\frac{1''}{4} = .25'' = 6.35mm$

d85 (bedding) > d15 (riprap)/4
(min.) (max.) $\frac{1.5''}{4} = .375'' = 9.5mm$

d50 (bedding) > d50 (riprap)/40
(min.) (max.) $\frac{4.5''}{40} = .11'' = 2.9\ mm$

	Minimum	Maximum
d100	.625" *	1.5" *
d85	.375"/9.5mm	1.1" *
d50	.11"/2.9mm	0.5" *
d15	0.04"/.95mm	.25"/6.35mm

* estimated after calculated points were plotted on MN-ENG-80 form - see page 36

Geotextile:
Woven_____ Non-woven _____
Description:

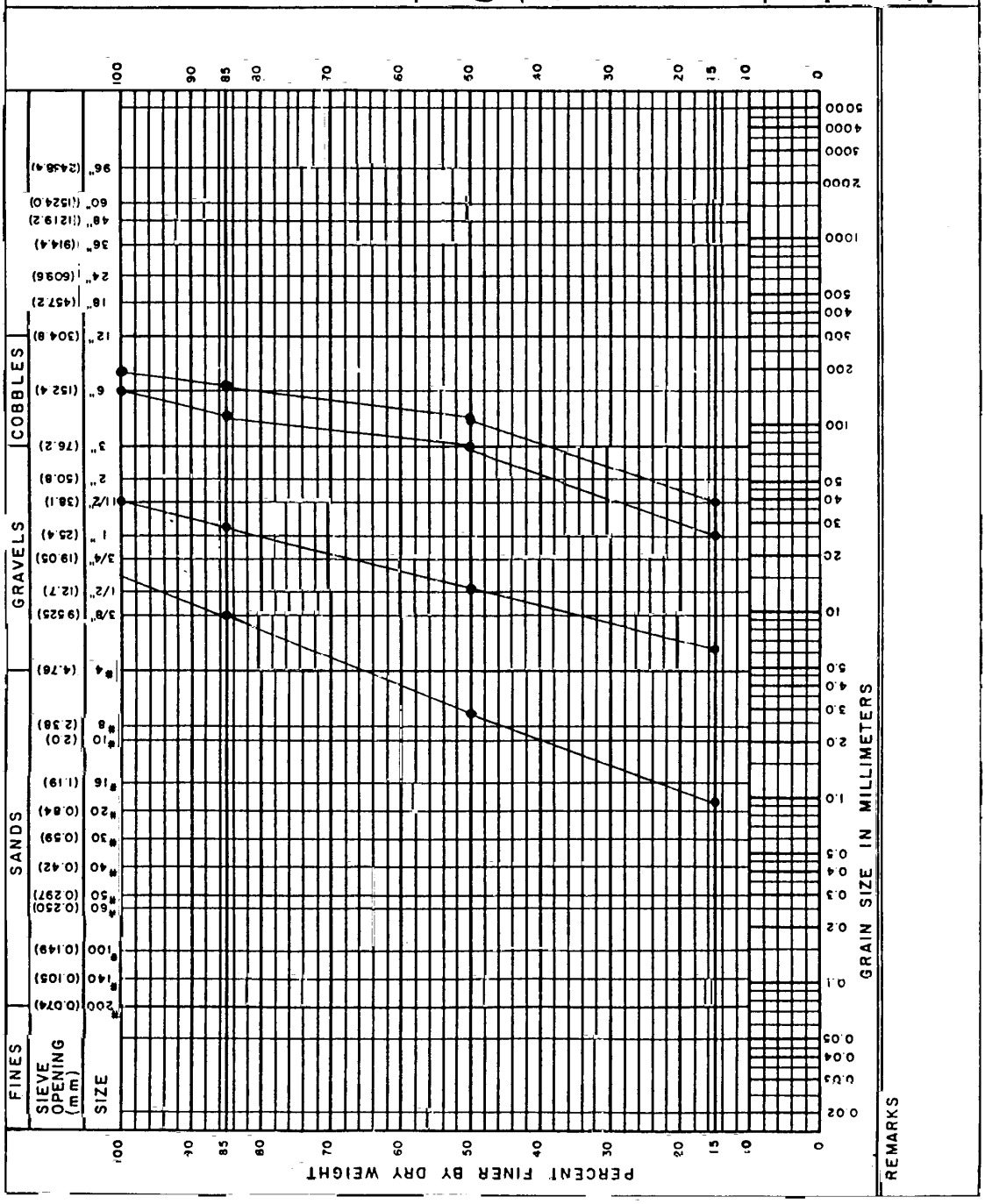
MN-ENG-80
12-76
(FILE CODE ENG-13)

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

RIPRAP, FILTER OR BEDDING MATERIALS

PROJECT and STATE: Minnesota- Sample Problem #1

DESIGNED AT: St. Paul | BY: SM²J | DATE: 9-23-97



☆U.S. GOVERNMENT PRINTING OFFICE 1978 – 666-303

Sample Problem #2

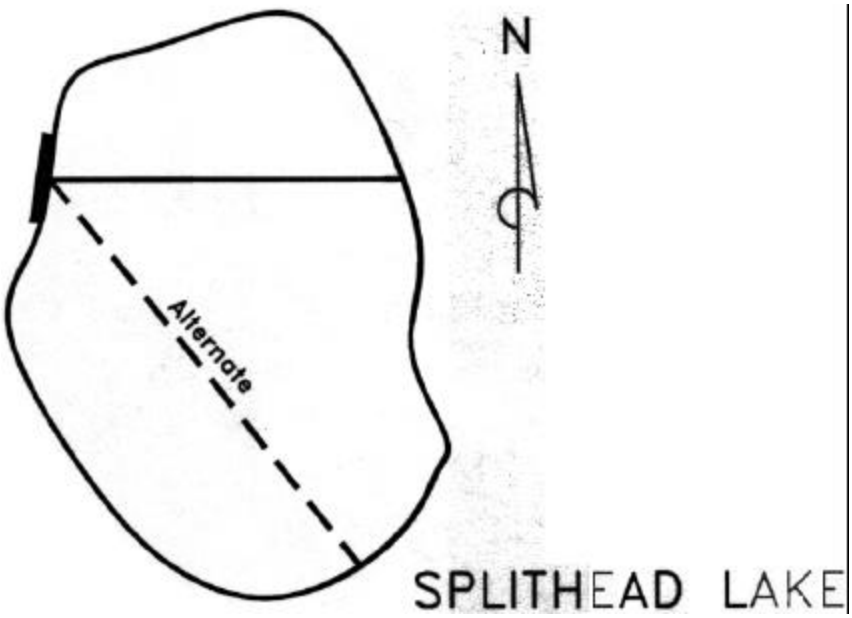
Given. A homeowner on Splithead Lake in Itasca County, Minnesota, desires lakeshore protection. The Minnesota Department of Natural Resources (DNR) keeps records of the lake levels on Splithead Lake and has indicated that the lake level fluctuates between 822.7 and 823.5. The rock available in Itasca County has both rounded corners and angular corners, in a ratio of about 50% of each. Its specific gravity is 2.50.

The top of the bank was surveyed to be at elevation 827.0 The bottom of the lake just off shore is 817.0. The distance from the home to the shoreline is about 35 feet. From a site visit, and the survey notes, it was determined that a 4:1 slope will fit the site well after a small amount of grading.

The landowners on either side of this property are also experiencing erosion; thus no secure end points for the protection measure are available. The two fetch lengths to be considered are 3770 feet to the east and 8080 feet to the southeast.

Find. Determine an appropriate design for rock riprap to protect this site.

Discussion. Two primary directions could be considered as the critical fetch direction for this site. The line that is drawn to the east is significantly shorter than the line to the southeast. If the wind stress factors for Bemidji are examined in Appendix A, it appears to make little difference because the two values are 34 and 35 miles per hour, respectively. A judgment, therefore, needs to be made for the design. One possibility is to average the two lengths. Another is to use the "worst case", that being the longest distance and the highest wind stress factor for maximum protection; this may be recommended where something of significant value is being protected. A third possibility is to use the shortest distance and lowest wind stress factor; this should only be considered when the damage potential is low, should the design be exceeded and the revetment is to be coupled with soil bioengineering techniques above the minimal rock toe, to provide a second level of protection. For the example, the "worst case" scenario was chosen. A still water elevation which is the average of the range of fluctuation is chosen.



APPENDIX B
DESIGN OF LAKESHORE PROTECTION

Page 1

Project Name SAMPLE PROBLEM #2 County Itasca Lake Splithead

By SM²J Date 9/23/97 Ckd By BMT Date 9/24/97 Job Class III

Step 1. Hazard: High (Moderate) Low

Step 2. Effective Fetch Computations:

From a map or aerial photograph, and information gathered, determine the critical open water distance for wave generation (fetch). Consider the dominant wind direction in open water months.

Fe = 8080 feet = 1.53 mile(s)

Note: If Effective Fetch (Fe) < 0.5 mile, use Fe = 0.5 mile Use Fe = 1.53 mile(s)

Step 3. Describe fluctuation of lake level:
822.7 to 823.5 is typical range per DNR lake leve records (1947-1996)

Still Water Elevation(s) 823.

Step 4. Wind direction along critical fetch SE (compass point)

Step 5. First Order Weather Station Bemidji (Appendix A)

Wind Stress Factor (Ua) 35 miles/hour (Appendix A)

Step 6. Wave Period (T) (Eq'n 2-1 or Figure B-1) $= 0.559[Ua \times Fe]^{1/3}$ 2.1 seconds

Wave Length (L) (Eq'n 2-2) $= 5.12\ T^2 =$ 22.7 feet

Step 7. Significant Wave Height (Hs) (Eq'n 2-3 or Fig. B-1) $Hs = 0.0301\ Ua\ (Fe)^{0.5}$ 1.3 feet

Step 8. Design Factor (DF) (Table 2-2) 1.37

Design Wave Height (Ho) = Hs x DF = 1.3 x 1.37 .78 feet

Step 9. Slope Ratio 4:1 (such as 3:1, 4:1) **Ho/L =** 1.78 22.7 = 0.078

R/Ho (Figure 2-2) 0.95 If material is not riprap, multiply: R/ Ho x 1.2 = N/A (new R/Ho)

Runup (R) = Ho x R/Ho = 1.78 x 0.95 = 1.7 feet

Setup (S) = 0. x Ho = 0.1 x 1.78 = 0.2 (not more than 0.5 feet)

APPENDIX B
DESIGN OF LAKESHORE PROTECTION

Page 2

Step 10. Lower Limit = 1.5 x Ho = 1.5 x 1.78' = 2.7 feet

Upper Limit (WPH) = R + S = 1.7 + 0.2 = 1.9 feet

Step 11. Upper elevation of protection: (upper) SWL + upper limit = 823.5 + 1.9 = 825.4

Lower elevation of protection: (lower) SWL - lower limit = 822.7 - 2.7 = 820.0

RIPRAP DESIGN

Step 12. Slope Ratio 4:1 **Design Factor (DF)** (rock size only) (Table 2-2) 1.27

Ho = Hs x DF = 1.3 x 1.27 = 1.65 feet
(Hs is the same as determined in Step 7)

Step 13. Determine W50 (Use Eq'n 2-4 and/or Eq'n 2-5 or select from the chart in Appendix C)
Determine or estimate the density, w_r 156 lbs/ft^3 or specific gravity Gs 2.50 of the rock

Describe rock expected: 50 % rounded and 50 % angular

use Eqn from Appendix C

$$W_{50} = \frac{w_r \; Ho^3}{(K_D \text{ or } K_{rr})\,(S_r-1)^3 \cot\theta}$$

$= 6.797\, H_o^3 = 6.797(1.65')^3$
$= 30.5$ lbs.

W50 = 30.5 lbs. = **D50** 8 inches
(Use Table C-4 or C-5 to convert weight to equivalent size, or Eq'n 2-6 below)

$d = 15\,(W/w_r)^{1/3}$ 0.67 feet (Eq'n 2-6) **Use D50** 8 inches

Step 14.

Gradation calculated for this location:			
D_{100}	2.0 x D_{50} = 16"	2.5 x D_{50} = 20"	
D_{85}	1.6 x D_{50} = 12.8"	2.1 x D_{50} = 16.8"	
D_{50}	1.0 x D_{50} = 8"	1.5 x D_{50} = 12"	
D_{15}	0.3 x D_{50} = 2.4"	0.5 x D_{50} = 4"	

Step 15. Thickness of Riprap = 1.25 x maximum D_{100} = 1.25 x 20" 25"

APPENDIX B
DESIGN OF LAKESHORE PROTECTION

Step 16. Overtopping Protection

Step a) Elevation of top of bank (determined in field) 827.0
Step b) Upper elevation of protection (calculated on page 2, step 11)= 825.0

Step c) If step b is higher than step a, an overtoppping apron is required. {(step b)-(step a)} x 3 = width of apron shoreward (must be ≥1.5 feet) not needed

Width of overtopping apron (Wo) = _____ _____) x 3 = feet (not less than 5 feet)
Use Wo = _____ feet

Ordinary High Water Elevation (OHW) from DNR if available 825.1

Special considerations related to the OHW elevation:
Protection is nearly to OHW; vegetate to top of bank

Step 17. End Protection: Method A _____ Method B X (Choose one - see Figure 2-4)
Rationale for this choice:

Step 18. Toe Protection: (Figures 2-5 and 2-6)
Follow steps a through f for an La or Lc toe; use step g for an Lb toe. Use step h for a type d toe.

Step a. 25 x D_{50} (riprap) = 10 inches

Step b. Elevation of existing lake bottom near shore = 817.0

Step c. Lower elevation of protection (computed in Step 11) = 820.0

Step d. {(step b) - (step c)} x 3 = -9 feet not appropriate

Step e. Determine whether step a or step d results in a larger value. Write it here. _____

Step. f. The value in step e must not be less than 3 feet (if it is, use 3.0 feet) nor larger than 6 feet (if it is, use 6 feet). This value is the length La or Lc as depicted in Figures 2-5 and 2-6.

La or **Lc** = _____ feet Go to Step 19

Step g. **Lb** = 8 x d50 = 64" = 5.3'; use Lb = 5.5 feet

Step h. **Ld** = the shorter value of 1) 6' (more at engineer's discretion) or 2) the lower elevation of protection calculated in step 11 on page 2. _____ See Figure 2-7.

APPENDIX B
DESIGN OF LAKESHORE PROTECTION

Step 19. Filter or Bedding Requirements:

Use Geotextile ___X___ or Use granular filter or bedding _____ (select one)

Granular Filter Design: 1 inch = 25.4 mm

d15 (bedding) > d15 (riprap)/40 > 0.42 mm (No. 40 sieve)
(min.) (max.)

	Minimum	Maximum
d100		
d85		
d50		
d15		

d15 (bedding) < d15 (riprap)/4
(max.) (min.)

d85 (bedding) > d15 (riprap)/4
(min.) (max.)

d50 (bedding) > d50 (riprap)/40
(min.) (max.)

Geotextile:
Woven_____ Non-woven ___X___
Description: Class 1 non-woven per MN materia specification 592- Geotextiles

Chapter 4: Maintenance

The Natural Resources Conservation Service (NRCS) policy in Minnesota requires that all maintenance is the responsibility of the landowner(s). Before any assistance is provided, the landowner(s) must sign an agreement stating that they are responsible for the maintenance of the installed practice. NRCS may assist with recommendations for maintenance only. Lakeshore protection may be disturbed by ice action or by waves larger than those used in design. These conditions can be addressed by designing flexible protection and protection that is easy to repair or replace with a moderate maintenance effort. The design and installation will be done to the best of the designers' ability and knowledge, and maintenance is totally the responsiblity of the landowner(s).

An unpredictable source of problems for lakeshore protection measures is ice jacking. When the ice expands in freezing, it pushes up and outward against the shores of the lake with very large pressure which can move almost any type of protection measure. Flexible measures such as riprap can be pushed up and out of place leaving holes in the protective layer. These holes can allow undermining of the protective layer and loss of its effectiveness. Semi-rigid measures, such as a concrete wall, can be cracked beyond repair. This technical release does not try to design specifically for this unpredictable force, although consideration is given to the phenomenon. The landowner should be told of the possiblity of ice action, and instructed on maintenance of their measure should this occur.

Geotextile products may be subject to deterioration when exposed to ultraviolet rays, as in sunlight. To avoid shortening the life of the geotextile, cover any geotextile which becomes exposed. Exposed geotextile can be a fire hazard as well.

The NRCS policy in Minnesota does not allow installation of high-maintenance protection, such as artificial nourishment, for a single landowner without a proven means to maintain the installation. This is fully described in the National Engineering Manual.

The technician, conservationist, or engineer involved in the project should discuss maintenance with the landowner(s) prior to the design of the measure. A maintenance plan should be prepared by the designer for the specific job. It should be discussed with the landowner(s). The landowner(s) must be aware of their responsibility in this area, and sign a maintenance agreement prior to installation of the measure. The plan must be attached to the maintenance agreement signed by the landowner.

The following pages are sample maintenance agreements that have been used for lakeshore sites.

Operation and Maintenance Plan

Rock Riprap Lakeshore Protection

Cooperator:_____Date:_____

By: _____Title:_____

Project Location:_____

The owner or sponsor of this project is responsible for the rock riprap lakeshore protection. Although these projects are designed with the best available technical knowledge, it must be recognized that any project needs to be properly operated and maintained including periodic inspection. Properly maintained lakeshore protection should last a minimum of ten (10) years. The following guidelines have been prepared for the operation and maintenance of this protection measure.

1. Immediately after completion of the project, all disturbed areas, such as wheel ruts and patches of bare soil, should be filled with clean topsoil, fertilized, seeded and mulched. Refer to the seeding specification in the design packet for this site. Nuture the vegetation so that it forms a dense stand to prevent erosion.

2. Inspect the project regularly, especially following strong winds and spring break-up of the ice. Repair damage immediately by replacing any dislodged rock. Be especially careful to cover all exposed filter material (granular or geotextile).

3. Equipment used on the lakeshore (for dock removal, boat launching, yard maintenance, etc.) must be kept away from the project to avoid damage to the project and the shore it is protecting

4. All trees and woody growth should be kept off the project site, whether it is alive and growing, or loose, dead material, unless the site is specifically designed to incorporate soil bioengineering techniques using woody materials.

5. This design considers potential damage by ice, but it was primarily designed for wind erosion protection. Repairs need to be made to rock moved about by ice if any areas become exposed such that waves may reach the natural soil and erode it. Contact the local NRCS office for assistance.

6. The rock has been designed to withstand forces of wave action for many circumstances. Extreme events may still occur which may alter the layout of the rock. It is important to restore the integrity of the revetment following such events. Contact your local NRCS office for assistance.

I have read the guidelines for the maintenance of the lakeshore stabilization project and agree to follow the guidelines.

Cooperator's signature:_____Date:_____

I have discussed the maintenance guidelines with the above cooperator.

Conservationist's signature:_____Date:_____

Operation and Maintenance Agreement

This agreement, made on _____ is between the _____Soil and Water Conservation District, hereafter referred to as the SWCD; the Natural Resources Conservation Service of the United States Department of Agriculture, hereafter referred to as NRCS; and _____, hereafter referred to as the Sponsor.

The Sponsor, SWCD, and NRCS agree to carry out the terms of this agreement for the operation and maintenance of the practice in the State of Minnesota. The practices covered by this agreement are identified as follows : (name of project)_____.

I. General:

A. The ***Sponsor*** will:

1. Be responsible for operating and performing or having performed all needed maintenance of practices, as determined by either NRCS or the Sponsor, without cost to the SWCD or NRCS.

2. Obtain prior NRCS approval of all plans, designs, and specifications for the maintenance work deviating from the O&M plan, and of plans and specifications for any alteration to the structural practice.

3. Be responsible for the replacement of parts or portions of the practice (s) which have a physical life of less duration than the design life of the practice(s).

4. Prohibit the installation of any structure or facility that will interfere with the operation or maintenance of the practice(s).

5. Comply with all applicable Federal, State and local laws.

6. Provide SWCD and NRCS personnel the right of free access to the project practice at any reasonable time for the purpose of carrying out terms of the agreement.

B. ***NRCS*** will:

1. Upon request of the Sponsor and SWCD and to the extent that its resources permit, provide consultative assistance in the operation, maintenance and replacement of practices.

II. Operation and Maintenance Plan (O&M Plan)

An O&M plan for each practice included in this agreement is attached to and becomes part of this agreement.

III. Inspection and Reports

A. The Sponsor will inspect the practices as specified in the O&M Plan.

B. The SWCD and NRCS may inspect the practice(s) at any reasonable time during the period covered by this agreement. At the discretion of the appropriate administrative person, NRCS personnel may assist the Sponsor with the inspections.

C. A written report will be made of each inspection and provided to the SWCD, NRCS, and (others if needed)_____.

IV. Time and Responsibility

The Sponsor's responsibility for operation and maintenance begins when a practice is partially done or complete and accepted or is determined complete by NRCS. This responsibility shall continue until expiration of the design life of the installed practice(s). The Sponsor's duties and liabilities for the practice(s) under other Federal and State laws are not affected by the expiration of this O&M agreement. Failure of the Sponsor to meet the requirements of this agreement shall require finanacial reimbursement to the _____.

V. Records

The sponsor will maintain in a centralized location a record of all inspections and significant actions taken, cost of the work, and completion date, with respect to operation and maintenance. SWCD or NRCS may inspect these records at any reasonable time during the term of this agreement.

Name of Sponsor_____

Authorized Signature:_____Date:_____

This action was authorized at an official meeting of the Sponsor named immediately above on _____ at _____.

Attested to:_____Title:_____

_____Soil and Water Conservation District

Authorized Signature:_____Title:_____

U.S.D.A. Natural Resources Conservation Service

Authorized Signature:_____Title:_____

Rock Riprap Shoreline Protection Measure

Site:_____

The following is a list of maintenance items that may be needed:

1. Remove any obstructions from the lake which may direct unnatural flow against the riprap lining.

2. Repair any areas of damaged riprap or filter material promptly. Failure to do this promptly could result in serious damage to the lakeshore.

3. Remove any trees or brush within the riprapped area.

4. Maintain vegetation by controlling weeds, fertilizing, etc. as needed.

Inspection will be made after the spring ice break-up for each year in the anticipated life of the measure (10 years).

Chapter 5: State Requirements

Permits

In Minnesota, the Department of Natural Resources (DNR) requires a permit for modifications to lakeshores that exceed certain minimum requirements. The Natural Resources Conservation Service (NRCS) encourages landowners to comply with this requirement. NRCS is willing to provide technical assistance to a landowner within the scope allowed in the NRCS National Engineering Manual (NEM). DNR publishes informational sheets on work that may be done without a permit. A copy may be obtained from a local DNR office, or through the state headquarters:

Department of Natural Resources
500 Lafayette Road
St. Paul, MN 55146

Many lakes in Minnesota have been investigated by DNR to determine the ordinary high water (OHW) level. This is used for controlling development on and around lakes. The landowner should check with DNR before beginning design to determine whether the lake has a defined OHW elevation. DNR has determined that water has been to this elevation for a period of time that is long enough to have damage potential. Therefore, it is well to consider the OHW in a design.

On many streams and lakes, a permit from the Corps of Engineers is required. A local permit may also be needed, such as from a lake conservancy district, watershed district, or county.

Pollution Control

During construction of a lakeshore protection measure, it is not uncommon that the soil in the lakebed and on the bank are disturbed. In many cases this causes a sediment plume which moves into the lake and may disturb and/or damage aquatic plant and animal species. The designer is strongly encouraged to require use of a floating silt curtain or other device to restrict the disturbed sediment to as small an area of the lake as is practical. The items of work and construction details in the specifications may reference the Minnesota Department of Transportation (MnDOT) specification 3887, Flotation Silt Curtain.

Seeding and Mulching Disturbed Areas

NRCS requires wise planning of construction operations to disturb the minimum amount of land possible during construction. This minimizes erosion which may cause movement of soil particles and attached nutrients into the lake. One important technique to minimize the impact of construction operations on the lake is to seed and mulch disturbed areas as soon as possible in the construction sequence. Also, the vegetative cover on land is not to be disturbed until it is needed for construction operations.

An NPDES permit may be required if the area disturbed meets the requirements for such a permit. It is the landowner's responsibility to obtain all permits.

Chapter 6: Watercraft Concerns

In sheltered harbors or bays, or along rivers and streams with a narrow width, the waves generated by watercraft may be more critical than those generated by the wind. Some research has been done on wave generation by boats. References 19 and 20 in the bibliography were used to provide the numerical data for this section.

A factor that must be considered is the distance that a wave must travel to reach the shore. In areas where boat speed is greatly reduced as they approach shore, the erosion of shorelines due to boats will be minimal. The author of reference 21 indicates the following rules of thumb are used for navigation channels:

- If the center of the navigation channel is less than 2000 feet from the bank, 50% or more of the bank erosion is due to navigation.

- If the center of the navigation channel is between 2000 feet and 3000 feet from shore, less than 50% of the bank erosion is due to navigation.

- If the centerline of the navigation channel is more than 3000 feet from the bank, the erosion is principally due to natural causes, not navigation.

The highest ship-generated waves are generally from smaller vessels that operate at high speeds rather than from the larger and slower tanker and cargo ships. Table 6-1 is a summary of the numerical research done in references 19 and 20 in the bibliography. These values may be used to estimate a wave height for design, if the designer feels that the wind-generated wave is not the critical condition for the site.

Boating activity has increased on many water bodies in recent years. Power boats and personal watercraft generate waves which can cause shoreline erosion, especially on smaller water bodies where the waves' energy is not dissipated before the waves reach shore. Some lakes have "no wake" ordinances in an attempt to reduce wave erosion and noise pollution.

The size of waves created by boats are determined by the volume of water displaced by the boat and the speed at which the boat is traveling. The wave size does not always increase with boat speed because at high speeds many boats "skim" across the surface (called planing) and therefore displace less water. Wave heights of up to three feet have been reported from boats operating on inland lakes. Boat waves are of a different physical nature than wind-generated waves, and contain more energy than a wind-generated wave of equal size. The operation of large, high speed boats on small water bodies can create waves greatly exceeding the size and erosive energy of any naturally occurring from wind.

Table 6-1. Wave Heights Generated by Vessels (Ref. 19 and 20)

Vessel Description	Distance to Shore, feet	Speed, miles/hour	Wave Height, feet
Cabin Cruiser	100	7.0-19.0	0.7-1.2
	300	19.0	0.8
	500	6.9-11.5	0.4-0.8
Tugboat	100	6.9	0.6
	100	11.5	0.3
	500	6.9	1.5
	500	11.5	0.9
Barge	100	11.5	1.4
	300	11.5	0.7
	500	11.5	0.3
Commercial Fishing Boat	100	6.2-18.4	0.2-2.2
	300	6.2-18.7	0.2-1.8
	500	6.3-19.0	0.2-1.2
High Speed Pleasure Boat	100	6-20	0.5-2.0
	500	6-20	0.5-1.5

A cabin cruiser is described to be 23’ long with a beam of 8.3’ and a draft of 1.7 feet. Its displacement is 3 tons. A tugboat has a length of 45 feet, with a 13’ beam and 6’ draft. Its displacement is 29 tons. A barge is 263 feet long with a 55’ beam and 14’ draft. Its displacement is 5420 tons. A commercial fishing boat has a length of 64 feet with a 12.83’ beam and draft of 3 feet. Its displacement is 35 tons. No further description was given for high speed pleasure boats.

APPENDIX A: WIND DATA **51**

METHOD USED: 51

Converting Wind Speeds to Wind Stress Factors: *51*

DESCRIPTION OF THE RECORDS USED: 54

APPENDIX B: BLANK DESIGN FORMS **57**

APPENDIX C: ROCK WEIGHT AND SIZE AND EQUATIONS **62**

APPENDIX D: GLOSSARY **67**

APPENDIX E: NOMENCLATURE AND SYMBOLS **71**

APPENDIX F: REFERENCES **72**

Appendix A: Wind Data

The National Climatic Center in Asheville, North Carolina is the central repository for information on wind for the weather stations in the United States. Thirteen stations in and near Minnesota have wind data.

Station	Record Length
Alexandria, Minnesota	6 years
Bemidji, Minnesota	5 years
Brainerd, Minnesota	5 years
Duluth, Minnesota	10 years
Fargo, North Dakota	3 years
Hibbing, Minnesota	3 years
International Falls, Minnesota	16 years
Minneapolis/St. Paul, Minnesota	10 years
Redwood Falls, Minnesota	5 years
Rochester, Minnesota	18 years
St. Cloud, Minnesota	7 years
Sioux Falls, South Dakota	4 years
Thief River Falls, Minnesota	6 years

A study by Donald Baker (reference #18) concluded that 10 years of record is ample when looking at wind patterns. Many of the records above are partial records which were put together for the sake of wind energy studies and wind frequency analysis. The lengths of record given above were deemed reasonable for the purpose here.

Figure A-1 is a map of Minnesota showing the thirteen recording stations. Lines have been drawn to denote recommended boundaries for use of the data for any given weather station. For sites close to one of these boundaries, the designer may wish to consider wind stress factors for more than one station.

Method used:

For each of the thirteen stations, the wind frequency data was examined. For each of the 16 compass points, a speed was calculated which equaled or exceeded 95% of the recorded readings. This was a statistical procedure, that, of necessity, assumed a linear and uniform distribution of the points when they were grouped in categories of wind speeds. Using the procedure described below, the wind speeds were converted to wind stress factors.

Converting Wind Speeds to Wind Stress Factors:

The Corps of Engineers' procedure given in the Shore Protection Manual (reference 15) pages 3-26 to 3-30 was followed in preparing wind speed information for use as wind stress factors. That procedure calls for use of five steps:

1. Correction for elevation of the anemometer - The standard height is 10 meters above the ground. if it is less or more than that, the wind speeds are to be adjusted according to the equation given below. The correction tends to be a small one, but can be significant.

Figure A-1. Weather Station Data to be used in Minnesota by area.

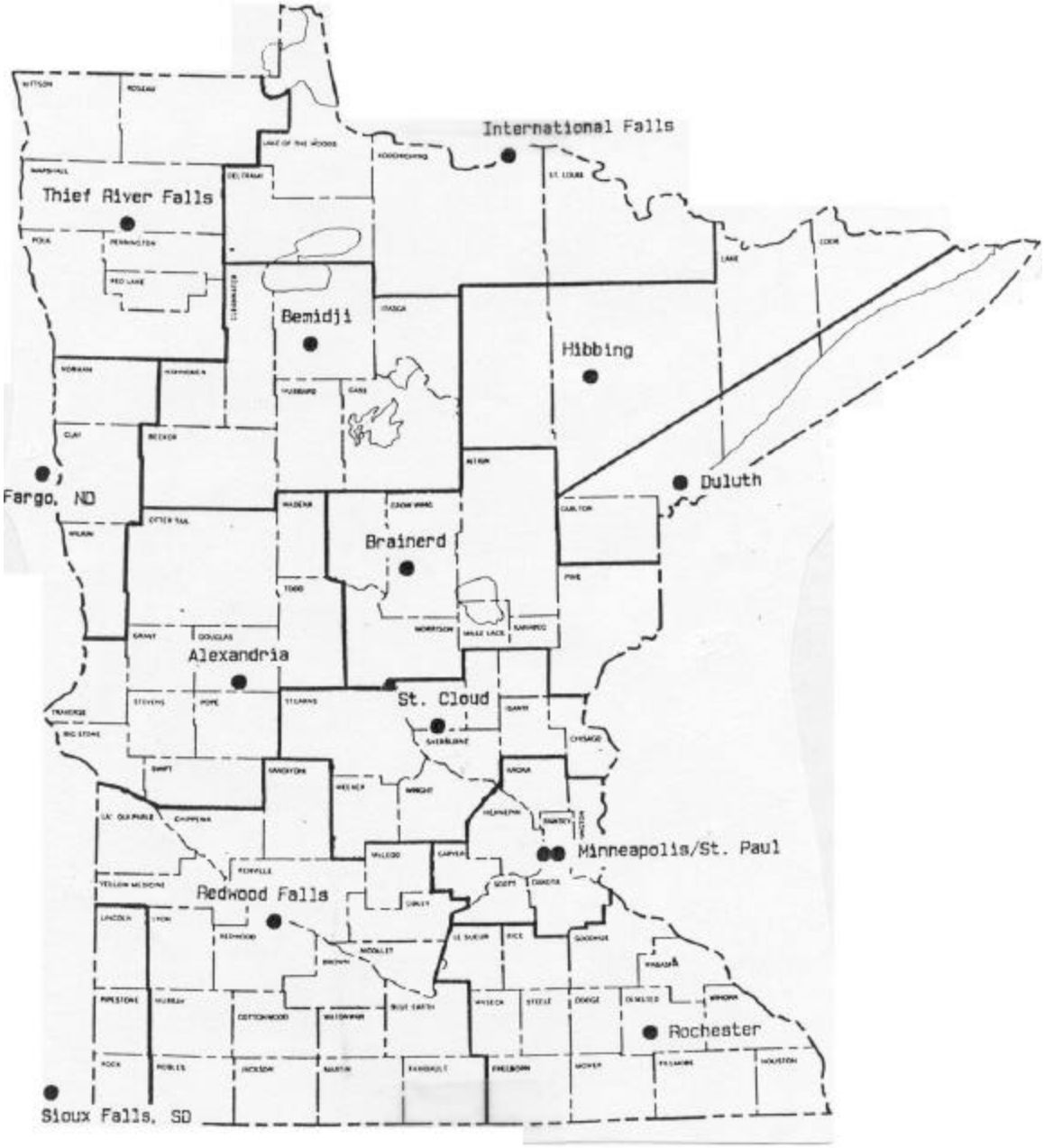


Figure A-2. Ratio, R_L, of windspeed over water, U_W, to windspeed over land, U_L, as a function of windspeed over land, U_L.

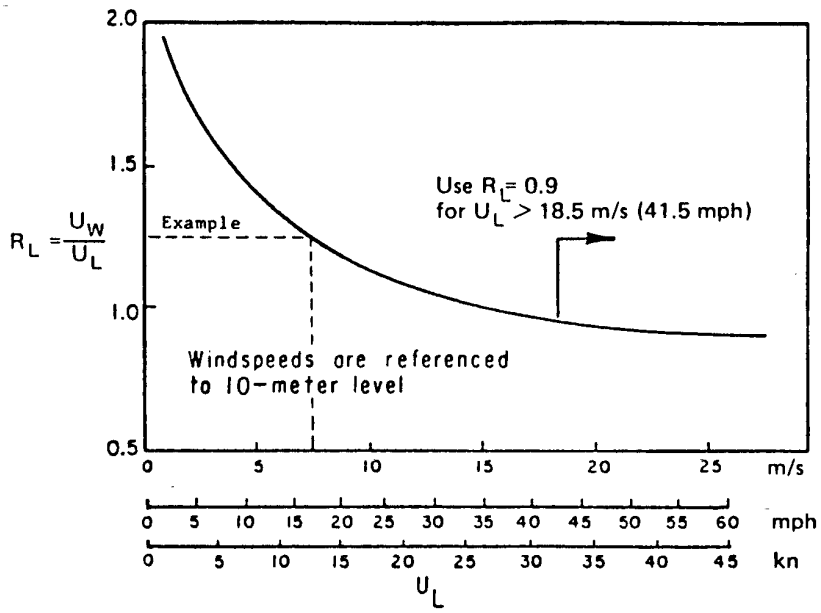
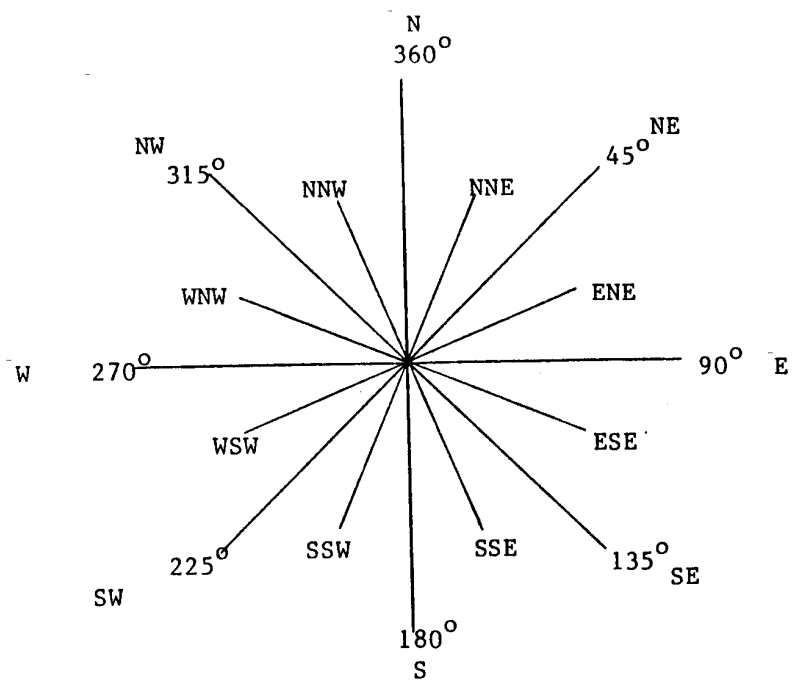


Figure A-3. Compass Rose for Wind Direction



$$U_{10} = U_h(10/h)^{1/7} \qquad \text{Equation A-1}$$

where,

U_{10} = wind speed measured at the 10 meter height
U_h = wind speed measured at height h
h = height above ground where wind speed is measured, meters
U = wind speed (often in miles per hour)

2. The second correction is to use a duration-averaged windspeed instead of the fastest mile windspeed, the value most readily available. Since data is available for Minnesota for wind frequency, this step was ignored and the available data was used.

3. A stability correction is to be applied for a difference in air and sea temperatures. However, with the size of inland lakes in Minnesota that this Technical Release is meant for, this difference is negligible so the correction is ignored.

4. The fourth correction is for location. The wind data is for stations on land, rather than at sea. Wind speeds tend to be faster over water than over land. So Figure 3-15 from the Corps' Shore Protection Manual (reference 15) was used to convert over land speeds to over water speeds. This figure is given as Figure A-2 in this appendix for reference.

5. The final correction is applied after the above four have been multiplied times the wind data. This accounts for the coefficient of drag. The formula below converts the wind speed to a wind stress factor which is used in design. The values given in Table A-1 are wind stress factors (UA), ready to be applied in the design procedure.

$$UA = 0.589\ U^{1.23} \qquad \text{Equation A-2}$$

where,

UA = wind stress factor, miles per hour
U = wind speed, miles per hour

Description of the Records Used:

Alexandria, Minnesota - Records summarized for Dec. 1, 1948 to Dec. 31, 1954, with 53,203 observations. Record was on microfiche with wind speeds in meters per second.

Bemidji, Minnesota - Records summarized for April 1956 through March 1961, with 31, 903 observations. The speeds were given in knots.

Brainerd, Minnesota - Records summarized for January 1958 to December 1962, with 30, 527 observations. The speeds were given in knots. The observations were during daylight hours only.

Duluth, Minnesota - Records were summarized for the years 1973 through 1982. 85, 130 observations were recorded in that time period.

Fargo, North Dakota - Records were summarized for three years in the period of January 1948 to September 1953. Speeds were recorded in miles per hour. 50, 379 observations were included in the record.

Hibbing, Minnesota - Records were given quarterly for the years 1970 through 1972 (months of January, April, July and October). 8851 observations were used in the summary. The speeds were given in miles per hour.

International Falls, Minnesota - Records were summarized for the years of 1949 to 1964, with a total of 100,163 observations. The speeds were given in knots.

Minneapolis/St. Paul, Minnesota - Records were summarized for the years 1974 to 1983, with a total of 87,642 observations. The speeds were given in knots. The anemometer was located at the airport.

Redwood Falls, Minnesota - The records were summarized for November 1, 1949 to December 31, 1954, with a total of 45,020 observations. The wind speeds were recorded in meters per second. The record is on microfiche.

Rochester, Minnesota - The records were summarized for the period September 25, 1960 to December 31, 1978, with a total of 53,365 observations. The speeds were recorded in meters per second. The record is on microfiche.

St. Cloud, Minnesota - The records were summarized for February 14, 1972 to December 31, 1978, with a total of 15, 103 observations. The speeds were recorded in meters per second. The record is on microfiche.

Sioux Falls, South Dakota - The records were summarized for October 1942 to November 1945, with a total of 28, 357 observations. The speeds were recorded in miles per hour.

Thief River Falls, Minnesota - The records are summarized for April 1956 to March 1961 (less January 1959) with a total of 32, 729 observations. The speeds were recorded in knots.

Table A-1. Design Wind Stress Factors in miles per hour

Compass Point	Alexandria	Bemidji	Brainerd	Duluth	Fargo	Hibbing	Int'l Falls	Compass Point
N	27	35	32	27	41	26	27	N
NNE	26	35	29	30	43	25	27	NNE
NE	24	35	33	30	33	24	26	NE
ENE	29	36	34	39	33	26	34	ENE
E	27	34	26	34	32	26	26	E
ESE	26	34	31	28	34	26	27	ESE
SE	24	35	26	27	39	25	27	SE
SSE	27	35	26	27	40	26	27	SSE
S	26	34	26	28	33	26	27	S
SSW	26	34	26	28	33	26	31	SSW
SW	24	35	25	28	32	25	31	SW
WSW	27	36	26	28	32	26	33	WSW
W	29	36	31	28	41	26	34	W
WNW	33	36	36	28	53	29	34	WNW
NW	29	36	36	28	52	32	33	NW
NNW	29	36	36	28	48	26	32	NNW

Compass Point	Mpls. St. Paul	Redwood Falls	Rochester	St. Cloud	Sioux Falls	Thief River Falls	Compass Point
N	33	24	27	23	36	38	N
NNE	34	24	26	23	33	36	NNE
NE	28	25	26	23	32	36	NE
ENE	27	28	24	24	33	36	ENE
E	28	24	26	24	29	35	E
ESE	28	24	27	21	32	36	ESE
SE	28	25	27	20	33	36	SE
SSE	28	28	28	21	34	36	SSE
S	33	27	29	24	33	38	S
SSW	28	27	29	23	33	38	SSW
SW	28	24	28	21	29	36	SW
WSW	28	30	27	20	33	36	WSW
W	33	28	28	24	33	36	W
WNW	33	32	31	24	41	38	WNW
NW	34	30	31	25	41	38	NW
NNW	31	28	29	24	41	38	NNW

Appendix B: Blank Design Forms

APPENDIX B
DESIGN OF LAKESHORE PROTECTION

Page 1

Project Name_____County_____Lake_____

By_____Date_____Ckd By_____ Date_____Job Class_____

Step 1. Hazard: High Moderate Low

Step 2. Effective Fetch Computations:

From a map or aerial photograph, and information gathered, determine the critical open water distance for wave generation (fetch). Consider the dominant wind direction in open water months.

Fe = _____ feet = _____mile(s)

Note: If Effective Fetch (Fe) < 0.5 mile, use Fe = 0.5 mile Use Fe = _____mile(s)

Step 3. Describe fluctuation of lake level:

Still Water Elevation(s)_____

Step 4. **Wind direction along critical fetch** _____ (compass point)

Step 5. First Order Weather Station_____ (Appendix A)

Wind Stress Factor (Ua) _____miles/hour (Appendix A)

Step 6. Wave Period (T) (Eq'n 2-1 or Figure B-1) $T = 0.559[Ua \times Fe]^{1/3}$ = _____seconds

Wave Length (L) (Eq'n 2-2) $L = 5.12\ T^2$ = _____feet

Step 7. Significant Wave Height (Hs) (Eq'n 2-3 or Fig. B-1) $Hs = 0.0301\ Ua\ (Fe)^{0.5}$ = _____ feet

Step 8. Design Factor (DF) (Table 2-2) _____

Design Wave Height (Ho) = Hs x DF = _____ x _____ = _____ feet

Step 9. Slope Ratio _____ (such as 3:1, 4:1) **Ho/L** = _____/_____ = _____

R/Ho (Figure 2-2) _____ If material is not riprap, multiply: R/ Ho x 1.2 = _____ (new R/Ho)

Runup (R) = Ho x R/Ho = _____ x _____ = _____

Setup (S) = 0.1 x Ho = 0.1 x _____ = _____ (not more than 0.5 feet)

Step 10. Lower Limit = 1.5 x Ho = 1.5 x _____ = _____ feet

Upper Limit (WPH) = R + S = _____ + _____ = _____ feet

Step 11. Upper elevation of protection: (upper) SWL + upper limit = _____ + _____ = _____

Lower elevation of protection: (lower) SWL - lower limit = _____ - _____ = _____

RIPRAP DESIGN -

Step 12. Slope Ratio _____ **Design Factor (DF)** (rock size only) (Table 2-2) _____

Ho = Hs x DF = _____x _____ = _____ feet
(Hs is the same as determined in Step 7)

Step 13. Determine W50 (Use Eq'n 2-4 and/or Eq'n 2-5 or select from the chart in Appendix C)
Determine or estimate the density, w_r_____ lbs/ft^3 or specific gravity Gs _____of the rock

Describe rock expected: _____% rounded and _____% angular

$$W_{50} = \frac{w_r \; Ho^3}{(K_D \text{ or } K_{rr})\,(S_r-1)^3 \cot\theta} = _____$$

W50 = _____lbs. = **D50** _____ inches
(Use Table C-4 or C-5 to convert weight to equivalent size, or Eq'n 2-6 below)

$d = 1.15\,(W/w_r)^{1/3}$ = _____ feet (Eq'n 2-6) **Use D50**_____ inches

Step 14.

Gradation calculated for this location:		
D_{100}	2.0 x D_{50} = _____	2.5 x D_{50} = _____
D_{85}	1.6 x D_{50} = _____	2.1 x D_{50} = _____
D_{50}	1.0 x D_{50} = _____	1.5 x D_{50} = _____
D_{15}	0.3 x D_{50} = _____	0.5 x D_{50} = _____

Step 15. Thickness of Riprap = 1.25 x maximum D_{100} = 1.25 x _____ = _____

Step 16. Overtopping Protection

Step a) Elevation of top of bank (determined in field) _____
Step b) Upper elevation of protection (calculated on page 2, step 11)= _____

Step c) If step b is higher than step a, an overtoppping apron is required. {(step b)-(step a)} x 3 = width of apron shoreward (must be $\geq$1.5 feet)

Width of overtopping apron (Wo) = (_____ - _____) x 3 = _____ feet (not less than 1.5 feet)
Use Wo = _____ feet

Ordinary High Water Elevation (OHW) from DNR if available _____

Special considerations related to the OHW elevation:

Step 17. End Protection: Method A _____ Method B _____ (Choose one - see Figure 2-4)
Rationale for this choice:

Step 18. Toe Protection: (Figures 2-5 and 2-6)
Follow steps a through f for an La or Lc toe; use step g for an Lb toe. Use step h for a type d toe.

Step a. 1.25 x D_{50} (riprap) = _____ inches

Step b. Elevation of existing lake bottom near shore = _____

Step c. Lower elevation of protection (computed in Step 11) = _____

Step d. {(step b) - (step c)} x 3 = _____ feet

Step e. Determine whether step a or step d results in a larger value. Write it here. _____

Step. f. The value in step e must not be less than 3 feet (if it is, use 3.0 feet) nor larger than 6 feet (if it is, use 6 feet). This value is the length La or Lc as depicted in Figures 2-5 and 2-6.

La or **Lc** = _____ feet Go to Step 19

Step g. **Lb** = 8 x d50 = _____; use Lb = _____ feet

Step h. **Ld =** the shorter value of 1) 6' (more at engineer's discretion) or 2) the lower elevation of protection calculated in step 11 on page 2. _____ See Figure 2-7.

Step 19. Filter or Bedding Requirements:

Use Geotextile _____ or Use granular filter or bedding _____ (select one)

Granular Filter Design: 1 inch = 25.4 mm

d15 (bedding) > d15 (riprap)/40 > 0.42 mm (No. 40 sieve)
(min.) (max.)

	Minimum	Maximum
d100		
d85		
d50		
d15		

d15 (bedding) < d15 (riprap)/4
(max.) (min.)

d85 (bedding) > d15 (riprap)/4
(min.) (max.)

d50 (bedding) > d50 (riprap)/40
(min.) (max.)

Geotextile:
Woven_____ Non-woven _____
Description:

Appendix C: Rock Weight and Size and Equations

Table C-1. Equivalent Weight for a given Stone Dimension

Stone Dimension				Gs = 2.5						
tenths										
inches	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	0.06	0.08	0.10	0.13	0.16	0.20	0.24	0.29	0.35	0.41
2	0.48	0.55	0.63	0.72	0.82	0.93	1.04	1.17	1.30	1.45
3	1.60	1.77	1.95	2.13	2.33	2.55	2.77	3.01	3.26	3.52
4	3.80	4.09	4.40	4.72	5.06	5.41	5.78	6.17	6.57	6.99
5	7.42	7.88	8.35	8.84	9.35	9.88	10.4	11.0	11.6	12.2
6	12.8	13.5	14.2	14.9	15.6	16.3	17.1	17.9	18.7	19.5
7	20.4	21.3	22.2	23.1	24.1	25.1	26.1	27.1	28.2	29.3
8	30.4	31.6	32.7	34.0	35.2	36.5	37.8	39.1	40.5	41.9
9	43.3	44.8	46.2	47.8	49.3	50.9	52.5	54.2	55.9	57.6
10	59.4	61.2	63.0	64.9	66.8	68.8	70.7	72.8	74.8	76.9
11	79.1	81.2	83.4	85.7	88.0	90.3	92.7	95.1	97.6	100
12	103	105	108	111	113	116	119	122	125	127
13	130	134	137	140	143	146	149	153	156	160
14	163	166	170	174	177	181	185	189	193	196
15	200	204	209	213	217	221	225	230	234	239
16	243	248	253	257	262	267	272	277	282	287
17	292	297	302	308	313	318	324	329	335	341
18	346	352	358	364	370	376	382	388	395	401
19	407	414	420	427	434	440	447	454	461	468
20	475	482	490	497	504	512	519	527	534	542
21	550	558	566	574	582	590	599	607	615	624
22	632	641	650	659	668	677	686	695	704	713
23	723	732	742	751	761	771	781	791	801	811
24	821	831	842	852	863	873	884	895	906	917
25	928	939	950	962	973	985	996	1008	1020	1032
26	1044	1056	1068	1080	1093	1105	1118	1131	1143	1156
27	1169	1182	1195	1208	1222	1235	1249	1262	1276	1290
28	1304	1318	1332	1346	1360	1375	1389	1404	1419	1434
29	1449	1464	1479	1494	1509	1525	1540	1556	1572	1588
30	1604	1620	1636	1652	1669	1685	1702	1719	1735	1752
31	1769	1787	1804	1821	1839	1856	1874	1892	1910	1928
32	1946	1965	1983	2001	2020	2039	2058	2077	2096	2115
33	2134	2154	2173	2193	2213	2233	2253	2273	2293	2314
34	2334	2355	2376	2397	2418	2439	2460	2482	2503	2525
35	2546	2568	2590	2613	2635	2657	2680	2702	2725	2748
36	2771	2794	2817	2841	2864	2888	2912	2936	2960	2984

Weight in pounds

from Chap.7 of Corps' Shore Protection Manual

Table C-2. Equivalent Weight for a Given Stone Dimension

Stone Dimension				Gs = 2.65						
tenths										
inches	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	0.06	0.08	0.11	0.14	0.17	0.21	0.26	0.31	0.37	0.43
2	0.50	0.58	0.67	0.76	0.87	0.98	1.10	1.24	1.38	1.53
3	1.70	1.87	2.06	2.26	2.47	2.69	2.93	3.18	3.45	3.73
4	4.02	4.33	4.65	4.99	5.35	5.72	6.11	6.52	6.95	7.39
5	7.85	8.33	8.83	9.35	9.89	10.5	11.0	11.6	12.3	12.9
6	13.6	14.3	15.0	15.7	16.5	17.3	18.1	18.9	19.8	20.6
7	21.5	22.5	23.4	24.4	25.5	26.5	27.6	28.7	29.8	31.0
8	32.2	33.4	34.6	35.9	37.2	38.6	40.0	41.4	42.8	44.3
9	45.8	47.3	48.9	50.5	52.2	53.9	55.6	57.3	59.1	61.0
10	62.8	64.7	66.7	68.6	70.7	72.7	74.8	77.0	79.1	81.4
11	83.6	85.9	88.3	90.6	93.1	95.5	98.1	100.6	103	106
12	109	111	114	117	120	123	126	129	132	135
13	138	141	144	148	151	155	158	162	165	169
14	172	176	180	184	188	192	196	200	204	208
15	212	216	221	225	229	234	238	243	248	253
16	257	262	267	272	277	282	287	293	298	303
17	309	314	320	325	331	337	342	348	354	360
18	366	373	379	385	391	398	404	411	417	424
19	431	438	445	452	459	466	473	480	488	495
20	503	510	518	526	533	541	549	557	565	574
21	582	590	599	607	616	624	633	642	651	660
22	669	678	687	697	706	716	725	735	745	754
23	764	774	784	795	805	815	826	836	847	858
24	868	879	890	901	913	924	935	947	958	970
25	982	993	1005	1017	1029	1042	1054	1066	1079	1091
26	1104	1117	1130	1143	1156	1169	1182	1196	1209	1223
27	1236	1250	1264	1278	1292	1306	1321	1335	1350	1364
28	1379	1394	1409	1424	1439	1454	1470	1485	1501	1516
29	1532	1548	1564	1580	1596	1613	1629	1646	1662	1679
30	1696	1713	1730	1748	1765	1782	1800	1818	1835	1853
31	1871	1890	1908	1926	1945	1963	1982	2001	2020	2039
32	2058	2078	2097	2117	2137	2156	2176	2197	2217	2237
33	2258	2278	2299	2320	2341	2362	2383	2404	2426	2447
34	2469	2491	2513	2535	2557	2580	2602	2625	2647	2670
35	2693	2717	2740	2763	2787	2810	2834	2858	2882	2907
36	2931	2955	2980	3005	3030	3055	3080	3105	3131	3156

Weight in pounds

from Chap.7 of Corps' Shore Protection Manual

Table C-3. Hudson's Equation for Various Slopes and Rock Angularities

Gs = 2.50		Gs = 2.65	
100% Angular Stone	**Equation**	**100% Angular Stone**	**Equation**
2:1 slope	$W_{50} = 10.505 * Ho^3$	2:1 slope	$W_{50} = 8.348 * Ho^3$
3:1 slope	$W_{50} = 7.003 * Ho^3$	3:1 slope	$W_{50} = 5.565 * Ho^3$
4:1 slope	$W_{50} = 5.253 * Ho^3$	4:1 slope	$W_{50} = 4.174 * Ho^3$
6:1 slope	$W_{50} = 3.502 * Ho^3$	6:1 slope	$W_{50} = 2.783 * Ho^3$
8:1 slope	$W_{50} = 2.626 * Ho^3$	8:1 slope	$W_{50} = 2.087 * Ho^3$
10:1 slope	$W_{50} = 2.101 * Ho^3$	10:1 slope	$W_{50} = 1.670 * Ho^3$
70% Angular, 30% Round		**70% Angular, 30% Round**	
2:1 slope	$W_{50} = 12.164 * Ho^3$	2:1 slope	$W_{50} = 9.666 * Ho^3$
3:1 slope	$W_{50} = 8.109 * Ho^3$	3:1 slope	$W_{50} = 6.444 * Ho^3$
4:1 slope	$W_{50} = 6.082 * Ho^3$	4:1 slope	$W_{50} = 4.833 * Ho^3$
6:1 slope	$W_{50} = 4.055 * Ho^3$	6:1 slope	$W_{50} = 3.222 * Ho^3$
8:1 slope	$W_{50} = 3.041 * Ho^3$	8:1 slope	$W_{50} = 2.417 * Ho^3$
10:1 slope	$W_{50} = 2.433 * Ho^3$	10:1 slope	$W_{50} = 1.933 * Ho^3$
50% Angular, 50% Round		**50% Angular, 50% Round**	
2:1 slope	$W_{50} = 13.595 * Ho^3$	2:1 slope	$W_{50} = 10.803 * Ho^3$
3:1 slope	$W_{50} = 9.063 * Ho^3$	3:1 slope	$W_{50} = 7.202 * Ho^3$
4:1 slope	$W_{50} = 6.797 * Ho^3$	4:1 slope	$W_{50} = 5.402 * Ho^3$
6:1 slope	$W_{50} = 4.532 * Ho^3$	6:1 slope	$W_{50} = 3.601 * Ho^3$
8:1 slope	$W_{50} = 3.399 * Ho^3$	8:1 slope	$W_{50} = 2.701 * Ho^3$
10:1 slope	$W_{50} = 2.719 * Ho^3$	10:1 slope	$W_{50} = 2.161 * Ho^3$
30% Angular, 70% Round		**30% Angular, 70% Round**	
2:1 slope	$W_{50} = 15.407 * Ho^3$	2:1 slope	$W_{50} = 12.244 * Ho^3$
3:1 slope	$W_{50} = 10.272 * Ho^3$	3:1 slope	$W_{50} = 8.162 * Ho^3$
4:1 slope	$W_{50} = 7.704 * Ho^3$	4:1 slope	$W_{50} = 6.122 * Ho^3$
6:1 slope	$W_{50} = 5.136 * Ho^3$	6:1 slope	$W_{50} = 4.081 * Ho^3$
8:1 slope	$W_{50} = 3.852 * Ho^3$	8:1 slope	$W_{50} = 3.061 * Ho^3$
10:1 slope	$W_{50} = 3.081 * Ho^3$	10:1 slope	$W_{50} = 2.449 * Ho^3$
100% Rounded Stone		**100% Rounded Stone**	
2:1 slope	$W_{50} = 19.259 * Ho^3$	2:1 slope	$W_{50} = 15.305 * Ho^3$
3:1 slope	$W_{50} = 12.840 * Ho^3$	3:1 slope	$W_{50} = 10.203 * Ho^3$
4:1 slope	$W_{50} = 9.630 * Ho^3$	4:1 slope	$W_{50} = 7.652 * Ho^3$
6:1 slope	$W_{50} = 6.420 * Ho^3$	6:1 slope	$W_{50} = 5.102 * Ho^3$
8:1 slope	$W_{50} = 4.815 * Ho^3$	8:1 slope	$W_{50} = 3.826 * Ho^3$
10:1 slope	$W_{50} = 3.852 * Ho^3$	10:1 slope	$W_{50} = 3.061 * Ho^3$

Refer to Equations 2-4 and 2-5 in Chapter 2
KD for rounded stone = 1.2
Krr for rough angular quarrystone = 2.2

W50 = median rock weight, pounds
Ho = design wave height, feet

Table C-4. Equivalent Stone Dimension for a known Stone Weight

Gs = 2.5									
Weight	**Size**	**Weight**	**Size**	**Weight**	**Size**	**Weight**	**Size**	**Weight**	**Size**
0.5	2.04	**25**	7.50	**90**	11.49	**250**	16.15		
1	2.56	**30**	7.97	**95**	11.70	**300**	17.16		
2	3.23	**35**	8.39	**100**	11.90	**350**	18.07		
3	3.70	**40**	8.77	**110**	12.28	**400**	18.89		
4	4.07	**45**	9.12	**120**	12.64	**500**	20.35		
5	4.38	**50**	9.44	**130**	12.99	**600**	21.62		
6	4.66	**55**	9.75	**140**	13.31	**700**	22.76		
7	4.90	**60**	10.04	**150**	13.62	**800**	23.80		
8	5.13	**65**	10.31	**160**	13.92	**900**	24.75		
9	5.33	**70**	10.57	**170**	14.20	**1000**	25.63		
10	5.52	**75**	10.81	**180**	14.47				
15	6.32	**80**	11.05	**190**	14.74				
20	6.96	**85**	11.27	**200**	14.99				

Gs = 2.50
Weight n pounds
Size in inches

from Chap.7 of Corps' Shore Protection Manual

Table C-5. Equivalent Stone Dimension for a known Stone Weight

Gs = 2.65									
Weight	**Size**	**Weight**	**Size**	**Weight**	**Size**	**Weight**	**Size**	**Weight**	**Size**
0.5	2.00	**25**	7.36	**90**	11.28	**250**	15.85		
1	2.52	**30**	7.82	**95**	11.48	**300**	16.84		
2	3.17	**35**	8.23	**100**	11.68	**350**	17.73		
3	3.63	**40**	8.61	**110**	12.06	**400**	18.54		
4	3.99	**45**	8.95	**120**	12.41	**500**	19.97		
5	4.30	**50**	9.27	**130**	12.75	**600**	21.22		
6	4.57	**55**	9.57	**140**	13.06	**700**	22.34		
7	4.81	**60**	9.85	**150**	13.37	**800**	23.36		
8	5.03	**65**	10.12	**160**	13.66	**900**	24.29		
9	5.23	**70**	10.37	**170**	13.94	**1000**	25.16		
10	5.42	**75**	10.61	**180**	14.21				
15	6.21	**80**	10.84	**190**	14.46				
20	6.83	**85**	11.06	**200**	14.71				

Gs = 2.65
Weight in pounds
Size in inches

from Chap.7 of Corps' Shore Protection Manual

Appendix D: Glossary

Alongshore - Parallel to and near the shoreline; same as longshore.

Artificial Nourishment - The periodic addition of beaching materials to maintain a beach.

Beach or shore - Zone of sand or gravel extending from the low waterline to a point landward where either the topography abruptly changes or permanent vegetation first appears.

Beach fill - Sand or gravel placed on a beach by a mechanical means.

Beaching - The wave energy dissipation that is provided by the washing of sands and gravels up and down a beach slope within the range of wave effectiveness.

Bedding material - A layer or zone of material placed on the base or foundation to bed the designed structure. The bedding may distribute the applied load, fill the interface voids, or provide a transition in intergranular void size.

Berm - A shelf that breaks the continuity of the slope.

Bluff - High, steep bank at the water's edge. In common usage, the bank is composed primarily of soil. (See Cliff also)

Boulders - Large stones with diameters over 10 inches.

Breaker - A wave as it spills, plunges, or collapses on a shore, natural obstruction, or man-made structure.

Breaker Zone - Area offshore where waves break.

Breaking Depth - The still water depth where waves break.

Breakwater - Structure aligned parallel to shore, sometimes shore-connected, that provides protection 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.

Clay - Extremely fine-grained soil with individual particles less than 0.00015 inches in diameter.

Cliff - High steep bank at the water's edge. In common usage, a bank composed primarily of rock. See Bluff.

Cobbles - Rounded stones with diameters ranging from 3 to 10 inches. Cobbles are intermediate between boulders and gravel.

Crest length, wave - The length of a wave along its crest. See Figure 1-1. Same as wavelength.

Current - Flow of water in a given direction.

Current, longshore - Current in the breaker zone moving essentially parallel to the shore and usually caused by waves breaking at an angle to shore. Also called alongshore current.

D_{50} - The particle diameter corresponding to the point where 50% of the material is finer by dry weight on the gradation curve.

D_{85} - The particle diameter corresponding to the point where 85% of the material is finer by dry weight on the gradation curve.

D_{100} - The particle diameter corresponding to the point where 100% of the material is finer by dry weight.

Deep Water - Area where the surface waves are not influenced by the bottom. Generally a point where the depth is greater than one-half the surface wavelength.

Design Wave Height (Ho) - The wave height used for computing wave protection height (WPH).

Downdrift - Direction of alongshore movement of littoral materials.

Dune - Hill, bank, bluff, ridge or mound of loose wind-blown material, usually sand.

Duration - Length of time the wind blows in nearly the same direction across a fetch (generating area).

Fetch (F) - The continuous distance over which the wind blows upon water in an essentially constant condition, generating waves.

Filter - A layer or combination of layers of pervious material designed and installed in such a manner as to provide drainage, prevent the movement of soil particles due to flowing water, and which will not be leached out through the riprap.

Filter Cloth - Synthetic textile that allows water to pass through but which prevents the passage of soil particles. Also called geotextile.

Flanking - Erosion of the shoreline on either or both sides of a protective measure. See Figure 1-5.

Gravel - Small, rounded granules of rock with individual diameters ranging from 0.18 to 3 inches. Gravels are intermediate between cobbles and sand.

Groin - A shore protection structure usually built perpendicular to the shoreline to trap littoral drift or retard erosion of the shore.

High Water (HW) - The maximum elevation reached by the lake surface.

Impermeable - Not allowing the passage of water.

Lee - Sheltered; part or side facing away from wind or waves.

Littoral - Of or pertaining to a shore.

Littoral drift - The sedimentary material moved in the littoral zone under the influence of waves and currents. Also called littoral material.

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

Littoral zone - Indefinite zone extending from the shoreline to just beyond the breaker zone.

Longshore - Parallel to and near the shoreline; same as alongshore.

Longshore transport rate - Rate at which littoral material is moved parallel to the shore. It is usually expressed as cubic yards per year.

Low water - The lowest elevation that can normally be expected for the lake surface.

Maximum diameter (D_{100}) - The diameter which equals the largest grain size in the material.

Median diameter (D_{50}) - The diameter which marks the point at which 50% of the material is larger and 50% is smaller.

Natural high water - The elevation of the lake under normal circumstances. Also known as still water level.

Normal high water - Same as “natural high water”.

Nourishment - Process of replenishing a beach either naturally by longshore transport or artificially by delivery of materials dredged or excavated elsewhere.

Offshore - Lakeward from the low water elevation.

Onshore - Landward from the landward edge of the beach.

Ordinary High Water (OHW) - The highest elevation which the lake has maintained long enough to leave evidence on the landscape. This is often higher than the still water level or the normal high water.

Overtopping - Passing of water over a structure from wave runup or surge action.

Permeable - Having openings large enough to or simply allowing free passage of appreciable quantities of either (1) sand or (2) water.

Revetment - A facing of stone, concrete, or other materials built to protect a bluff, embankment, shoreline or structure against erosion by wave action or currents.

Riprap - A layer, facing, or protective mound of stones randomly placed to prevent erosion, scour, or sloughing of a structure or embankment; also stone so used.

Runup - The rush of water up a structure or beach as a wave breaks. The amount of runup is the vertical height above still water level that the rush of water reaches.

Sand - Generally coarse-grained soils having particle diameters between approximately 0.003 and 0.18 inches. Sands are intermediate between silts and gravels.

Sandbag - Cloth bag filled with sand or grout and used as a module in a shore protection device.

Setup, wind - Vertical rise in the still water level of a body of water caused by piling up of water on the shore due to wind action. Synonymous with wind tide and storm surge.

Shallow water - Commonly, water of such a depth that surface waves are noticeably affected by bottom topography. It is customary to consider water of depth less than 1/20 of the surface wavelength as shallow water.

Shore - Narrow strip of land in immediate contact with the sea, including the zone between high and low water lines. See also beach.

Significant Wave Height (Hs) - The average of the highest one-third of the waves being generated.

Silt - Generally refers to fine-grained soils having particle diameters between 0.00015 and 0.003 inches. Intermediate between clay and sand.

Slope - Degree of inclination to the horizontal. Usually expressed as a ratio, such as 1:25, indicating 1 unit vertical rise in 25 units of horizontal distance.

Specifications - Detailed description of particulars such as the size of stone, quality of materials, terms, contractor performance, and quality control.

Still Water Level (SWL) - Elevation that the surface of the water would assume if all wave action were absent.

Updrift - Direction opposite the predominant movement of littoral materials in longshore transport. See Figure 1-2.

Wake - Waves generated by motion of a vessel through water.

Wave - Undulation of the surface of a liquid.

Wave crest - Highest part of a wave or that part above the still water level.

Wave direction - Direction from which a wave approaches.

Wave Height (H) - The vertical distance between a crest and the preceding trough. See Figure 1-1.

Wave Length (L) - The horizontal distance between similar points on two successive waves measured perpendicularly to the crest. See Figure 1-1.

Wave Period (T) - The time in seconds for a wave crest to traverse a distance equal to one wave length; also time for two successive wave crests to pass a fixed point.

Wave Protection Height (WPH) - Height above the still water elevation that will be affected by wave action.

Wave runup (R) - The vertical distance above still water level that a wave will run up the slope of a shore as it dissipates its remaining energy.

Wave Steepness (H/L) - The ratio of wave height to its length.

Wave trough - Lowest part of a wave form between successive crests. Also, that part of a wave below the still water level.

Wind Duration - The minimum wind duration, in minutes, required for the generation of the indicated wave height. Same as duration.

Wind Setup (S) - The vertical rise in the still water level on the leeward side of a body of water caused by wind pressure stresses on the surface of the water. See Figure 1-7.

Windward - Direction <u>from</u> which the wind is blowing.

Appendix E: Nomenclature and Symbols

a Wave amplitude, feet
C Velocity, feet/second (also called celerity)
Cd Drag coefficient, dimensionless
COE U.S. Army Corps of Engineers
d Depth of lake, feet
D_{100} Diameter of maximum rock size, inches or feet
D_{50} Diameter of median rock size, inches or feet
D_{85} Diameter of rock in inches or feet, where 85% of the rock is smaller than this size
DNR Minnesota Department of Natural Resources, a regulating agency for Minnesota lakeshores
F Fetch, miles
Fe Effective fetch, miles
g Acceleration due to gravity, 32.16 ft/sec^2
G Specific gravity of rock, dimensionless
h height above the ground where the wind speed is measured
H Wave height, feet
Ho Design wave height, feet
Hs Significant wave height, feet
K Median grain size (D_{50}) of riprap, feet
K_D Stability coefficient for armor, used in Table 2-4
K_{rr} Stability coefficient for angular, graded riprap; see Table 2-4
L Wave length, feet
LL Liquid limit
m Dimension for riprap end protection, feet (See Figure 2-6)
NRCS Natural Resources Conservation Service, an agency in the United States Department of Agriculture, formerly the Soil Conservation Service (SCS)
OHW - Ordinary High Water; defined by DNR for a given lake; stated in feet of elevation
p Dimension for riprap end protection, feet (See Figure 2-6)
PI Plasticity Index
R Wave runup, feet
S Wind setup, feet
SCS Soil Conservation Service, the former name for the Natural Resources Conservation Service (NRCS)
SF Safety factor related to endangering valuable property if the lakeshore protection measure were to fail. See Tables 2-1 and 2-2.
SWL Still water level, elevation in feet
t Time, seconds
tB Thickness of bedding, feet
tr Thickness of riprap, feet
T Wave period, seconds
U Wind speed, in miles per hour, meters per second or knots
U_{10} Wind speed at a height of 10 meters above the ground (standard)
UA Wind stress factor, miles per hour
Ud Design wind velocity, miles per hour
UL Overland wind velocity, miles per hour
USGS United States Geological Survey
UW Overwater wind velocity, miles per hour
U*h* Wind speed at a height of *h* meters above the earth, miles per hour
W_{50} Weight of the median size rock, pounds
W_{max} Maximum rock size in a gradation, pounds
W_{min} Minimum rock size in a gradation, pounds
Wo Width of overtopping protection, feet (See Figure 2-6)
WPH Wave protection height, feet
z slope of a bank, where z units horizontal change occurs in one unit of vertical change, dimensionless

Conversion Factors:
1 knot = 1.152 miles per hour
1 meter per second = 2.237 miles per hour
1 kg = 2.205 lbs.
1 foot = 0.3062 meter

Appendix F: References

1. American Railway Engineering Association, Bulletin No. 591, Proceedings Volume 66, February 1965. (Table taken from page 525)

2. Minnesota Department of Natural Resources, Division of Waters, “Sand Beach Blankets”, Information Sheet, 1987.

3. U. S. Army Corps of Engineers, “Coastal Engineering Research Center - Its Mission and Capabilities, May 1980, 28 pages.

4. U. S. Army Corps of Engineers, “Construction Materials for Coastal Structures”, by Moffatt and Nichol, Special Report No. 10, February 1983, 427 pages.

5. U. S. Army Corps of Engineers, “Help Yourself” brochure.

6. U. S. Army Corps of Engineers, “Low Cost Shore Protection... a Guide for Engineers and Contractors”, 1981, 173 pages.

7. U. S. Army Corps of Engineers, “Low Cost Shore Protection... a Guide for Local Government Officials”, 1981, 108 pages.

8. U. S. Army Corps of Engineers, “Low Cost Shore Protection... a Property Owner’s Guide”, 1981, 159 pages.

9. U. S. Army Corps of Engineers, “Low Cost Shore Protection: Final Report on the Shoreline Erosion Control Demonstration Program”, Office of the Chief of Engineers, 1981b.

10. U. S. Army Corps of Engineers, “Shore Protection Guidelines”, Part of the National Shoreline Study, August 1971, 59 pages.

11. U. S. Army Corps of Engineers, New Orleans District, “Shoreline Erosion Control Demonstration Program”, 1981, colored pamphlet.

12. U. S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, “Intermittent Ice Forces Acting on Inclined Wedges”, by Per Tryde, October 1977, 26 pages.

13. U. S. Army Corps of Engineers, Coastal Engineering Research Center, “A Primer of Basic Concepts of Lakeshore Processes”, January 1975, by David Duane, Lee Harris, Richard Bruno, and Edward Hands, Miscellaneous Paper No. 1-75, 29 pages.

14. U. S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, “Shoreline Erosion Processes - Orwell Lake, Minnesota”, December 1984, 101 pages.

15. U.S. Army Coastal Engineering Research Center, Department of the Army Corps of Engineers, “Shore Protection Manual”, Volumes 1 and 2, 1984.

16. U.S. Army Corps of Engineers Waterways Experiment Station, “Revetment Stability Study, Fort Fisher State Historic Site, North Carolina”, November 1982, 93 pages.

17. U.S. Department of Agriculture, Soil Conservation Service, “Riprap for Slope Protection against Wave Action”, Technical Release No. 69, February 1983, 53 pages.

18. Baker, Donald G., “Climate of Minnesota: Part 14 - Wind Climatology and Wind Power”, Technical Bulletin AD-TB1955; Agricultural Experiment Station, University of Minnesota, 1983, 48 pages.

19. Sorenson, Robert M., “Investigation of Ship-Generated Waves”, Journal of the Waterways and Harbors Division, Proceedings of the American Society of Civil Engineers (ASCE), February

1967, Volume 93, No. WW1, pages 85 to 99.

20. Sorenson, Robert M., "Water Waves Produced by Ships", Journal of the Waterways, Harbors, and Coastal Engineering Division, Proceedings of the American Society of Civil Engineers, Volume 99, No. WW2, May 1973, pages 245 to 256.

21. Lubinski, Kenneth, Henry Seagle, Nani Bhowmik, and others, "Information Summary of the Physical, Chemical, and Biological Effects of Navigation", submitted to the Environmental Work Team, Master Plan Task Force, Upper Mississippi River Basin Commission, May 7, 1981.

22. Weckman, Javier, and John M. Scales, "Design Guidelines for Cabled Block Mat Shore Protection Systems", Coastal Structures '83, Editor: J. Richard Weggel, American Society of Civil Engineers, Proceedings of the Conference held March 9-11, 1983, pages 295-306.

23. Kenter, den Boer, and Pilarczyk, "Large Scale Model Tests on Placed Block Revetment", Coastal Structures '83, Editor: J. Richard Weggel, American Society of Civil Engineers, Proceedings of the Conference held March 9-11, 1983, pages 307-319.

24. Broderick, Laurie, "Riprap Stability - A Progress Report", Coastal Structures '83, Editor: J. Richard Weggel, American Society of Civil Engineers, Proceedings of the Conference held March 9-11, 1983, pages 320-330.

25. Eckert, James., "Design of Toe Protection for Coastal Structures", Coastal Structures '83, Editor: J. Richard Weggel, American Society of Civil Engineers, Proceedings of the Conference held March 9-11, 1983, pages 331-341.

26. Downie, K.A. and H. Saaltink, "An Artificial Cobble Beach for Erosion Control", Coastal Structures '83, Editor: J. Richard Weggel, American Society of Civil Engineers, Proceedings of the Conference held March 9-11, 1983, pages 846-859.

27. Ahrens, John P., "Wave Runup on Idealized Structures", Coastal Structures '83, Editor: J. Richard Weggel, American Society of Civil Engineers, Proceedings of the Conference held March 9-11, 1983, pages 925-938.

28. Thompson, E. F., and C. L. Vincent, "Prediction of Wave Height in Shallow Water", Coastal Structures '83, Editor: J. Richard Weggel, American Society of Civil Engineers, Proceedings of the Conference held March 9-11, 1983, pages 1000-1008.

29. Shoreline Protection -- Proceedings of a Conference Organized by the Institution of Civil Engineers and held at the University of Southampton on Sept. 14-15, 1982, Published by Thomas Telford, Ltd., London, 1983, 248 pages. (Several articles discuss the use of groins and artificial nourishment. Several papers discuss problems unique to the United Kingdom.)

30. "Technologies for Coastal Erosion Control", by the Department of International Economic and Social Affairs, Ocean Economics and Technology Branch of the United Nations, New York, 1982.

31. Kobayashi, Nobuhisa, and Brian K. Jacobs, "Riprap Stability Under Wave Action", Journal of Waterway, Port, Coastal and Ocean Engineering, American Society of Civil Engineers, Volume 111.3, May 1985, pages 552-566.

32. Bhowmik, Nani G., "Development of Criteria for Shore Protection Against Wind-Generated Waves for Lakes and Ponds in Illinois", Illinois State Water Survey, Urbana, IL, Water Resources

Center Research Report No. 107, January 1976.

33. Thorne, Colin, Steven Abt, Frans Barends, Stephen Maynord, and Krystian Pilarczyk, Editors, River Coastal and Shoreline Protection: Erosion Control Using Riprap and Armourstone, John Wiley and Sons, 1995, 764 pages.

34. U. S. Department of the Army, Corps of Engineers, Engineering Manual EM-1110-2-1614, "Design of Coastal Revetments, Seawalls, and Bulkheads", April 30, 1985.

35. Department of the Army, U.S. Army Corps of Engineers, Engineering Circular EC 110-2-289, September 30, 1996 (draft), Coastal Engineering Manual, Part II, Hydrodynamics.

36. Department of the Army, Corps of Engineers, Cold Regions Research and Engineering Laboratory, CRREL Report 96-12, "Ice Action on Riprap", by Devinder Sodhi, Sharon Borland, and Jesse Stanley, September 1996.

37. Ashton, G.D., Editor, *River and Lake Ice Engineering*, Water Resources Publications, Littleton, Colorado, 1986.

38. Gray, Donald and Andrew T. Leiser, Biotechnical Slope Protection and Erosion Control, Van Nostrand Reinhold Company, New York, 1982, 263 pages.

39. Soil Conservation Service, Engineering Field Handbook Chapter 18: " Soil Bioengineering for Upland Slope Protection and Erosion Reduction", October 1992, 50 pages.

40. Gray, Donald and Robbin Sotir, Biotechnical & Soil Bioengineering Slope Stabilization: A Practical Guide for Erosion Control, John Wiley & Sons, 272 pages, 1996.

41. Natural Resources Conservation Service, Engineering Field Handbook Chapter 16: "Streambank and Shoreline Protection", December 1996, 134 pages.

42. Fuller, Doug, "Understanding, Living With, and Controlling Shoreline Erosion: A Guide Book for Shoreline Property Owners", Tip of the Mitt Watershed Council, Conway, Michigan, 1995, 90 pages.

43. Soil Conservation Service, Technical Release No. 56, "A Guide for Design and Layout of Vegetative Wave Protection for Earth Dam Embankments", Washington, DC, 1974, 28 pages.