7.8 Bank Protection (Type B Channels)

7.8.1 Purpose

One of the hazards of placing a highway near a river or stream channel or other water body is the potential for erosion of the highway embankment by moving water. If erosion of the highway embankment is to be prevented, bank protection must be anticipated and the proper type and amount of protection must be provided in the right locations.

Four methods of protecting a highway embankment from bank erosion are available to the designer. These are listed in descending order of desirability:

- relocating the highway away from the stream or water body
- protecting the embankment from erosion
- changing the direction of the current with training works
- moving the water body away from the highway (channel change)

This section provides procedures for the design of revetments to be used as channel bank protection and channel linings on larger streams and rivers **(i.e., having design discharges generally greater than 1.4 m^3/s (50 cfs))**. Procedures are also presented for riprap protection at bridge piers and abutments. For small discharges, procedures presented in the roadside channel section should be used. Emphasis in this section has been placed on rock riprap revetments due to their costs, environmental considerations, flexible characteristics and widespread usage. Other channel stabilization methods such as spurs, guide banks retard structures, longitudinal dikes and bulkheads are discussed in "Stream Stability at Highway Structures," Hydraulic Engineering Circular No. 20.

7.8.2 Erosion Potential

Channel and bank stabilization is essential to the design of any structure affected by the water environment. The identification of the potential for bank erosion, and the subsequent need for stabilization, is best accomplished through observation. A three level analysis procedure is provided in FHWA Hydraulic Engineering Circular No. 20. This procedure is described in Section 7.5.2. The three level analysis provides a rigorous procedure for determining the geomorphological characteristics, evaluating the existing conditions through field observations and determining the hydraulic and sediment transport properties of the stream. If sufficient information is obtained at any level of the analysis to solve the problem, the procedure may be stopped without going on to the other levels.

Observations provide the most positive indication of erosion potential. Observation comparison can be based on historic information, or current site conditions. Aerial photographs, old maps and surveying notes and bridge design files and river survey data that are available as described in the Data Collection chapter, as well as gaging station records and interviews of long-time residents can provide documentation of any recent and potentially current channel movement or bank instabilities.

In addition, current site conditions can be used to evaluate stability. Even when historic information indicates that a bank has been relatively stable in the past, local conditions may indicate more recent instabilities. Local site conditions which are indicative of instabilities may include tipping and falling of vegetation along the bank, cracks along the bank surface, the presence of slump blocks, fresh vegetation laying in the channel near the channel banks, deflection of channel flows in the direction of the bank due to some recently deposited obstruction or channel course change, fresh vertical face cuts along the bank, locally high velocities along the bank, new bar formation downstream from an eroding bank, local headcuts, pending or recent cutoffs, etc. It is also important to recognize that the presence of any one of these conditions does not in itself indicate an erosion problem; some bank erosion is common in all channels even when the channel is stable.

7.8.3 Symbols And Definitions

To provide consistency within this section as well as throughout this manual the following symbols will be used. These symbols were selected because of their wide use in many bank and shore protection publications. Where the same symbol is used for more than one definition, the symbol will be defined where it is used.

Table 7-6 Symbols And Definitions

Symbol	Definition	Units
AOS	Apparent opening size in filter cloth	mm (inches)
A	Coefficient used to determine the apparent opening size	
C	Coefficient, relates free vortex motion to velocity streamlines for unequal radius of curvature	-
C_u	Uniformity coefficient	
D_{50}	The median bed material size	m or mm (ft or inches)
D_{15}	The 15% finer particle size	m or mm (ft or inches)
D_{85}	The 85% finer particle size	m or mm (ft or inches)
d_{avg}	Average flow depth in the main flow channel	m (ft)
d_s	Estimated probable maximum depth of scour	m(ft)
g	Gravitational acceleration (9.81 m/s^2)	m/s^2 (ft/s^2)
H	Wave height	m (ft)
k	Permeability	cm/s or mm/s (inches/s)
K_1	Correction term reflecting bank angle	-
n	Manning's roughness coefficient	-
O_{95}	Opening size in the geotextile material for which 95% of the openings are smaller	mm (inches)
Q_{mc}	Discharge in the zone of main channel flow	m^3/s (ft^3/s)
R	Hydraulic radius	m (ft)
R	Wave runup	m (ft)
R_o	Mean radius of the channel centerline at the bend	m (ft)
S_f, S	Friction slope or energy grade line slope	m/m (ft/ft)
SF	Stability factor	-
S_s, s	Specific gravity of the riprap material	-
T	Topwidth of the channel between its banks	m (ft)
V	Velocity	m/s (ft/s)
V_a	Mean channel velocity	m/s (ft/s)
W_{50}	Weight of the median particle	kg (lb)
Z	Superelevation of the water surface	m (ft)
γ	Unit weight of the riprap material	kg/m^3 (lb/ft^3)
θ	Bank angle with the horizontal	degrees
Φ	Riprap material's angle of repose	degrees

7.8.4 Design Criteria

To provide an acceptable standard level of service, the Department traditionally employs widely-used pre-established design frequencies which are based on the importance of the transportation facility to the system and the allowable risk for that facility. This would be true of revetment protection. In addition, design standards of other agencies that have control or jurisdiction over the waterway or facility concerned should be incorporated or addressed in the design.

The criteria for the design of channels is found in the hydrology chapter and Section 7.3.3.

7.8.5 Bank And Lining Failure Modes

Potential Failures

Prior to designing a bank stabilization scheme, it is important to be aware of common erosion mechanisms and revetment failure modes, and the causes or driving forces behind bank erosion processes. Inadequate recognition of potential erosion processes at a particular site may lead to failure of the revetment system.

Many causes of bank erosion and revetment failure have been identified. Some of the more common include abrasion, debris flows, water flow, eddy action, flow acceleration, unsteady flow, freeze/thaw, human actions on the bank, ice, precipitation, waves, toe erosion and subsurface flows. However, it is most often a combination of mechanisms which cause bank and revetment failure and the actual mechanism or cause is usually difficult to determine. Failures are better classified by failure mode including:

- particle erosion
- translational slide
- modified slump
- slump

Particle Erosion

Particle erosion is the most commonly considered erosion mechanism. Particle erosion results when the tractive force exerted by the flowing water exceeds the bank material's ability to resist movement. In addition, if displaced stones are not transported from the eroded area, a mound of displaced rock will develop on the channel bed. This mound has been observed to cause flow concentration along the bank, resulting in further bank erosion.

A special type of particle erosion results in loss of the underlying material resulting in undermining and eventual collapse of the revetment protection. Usually the underlying material is lost through the revetment or piped under the toe of the revetment protection. This failure is very common in and extremely damaging to rigid types of protective linings. Providing a suitable filter, either natural or fabrics in conjunction with hydrostatic relief features will prevent this failure.

Another frequent type of particle erosion failure occurs at the edges of the protective feature. The interface creates turbulence which in turn increases the tractive stresses placed on the protective layer, underlying layers, and the natural bank material beyond the revetment. This failure area needs to receive special attention since extension of the protective feature usually only moves, not eliminates, the failure.

Translation Slide

A translational slide is a failure of riprap caused by the downslope movement of a mass of stones, with the fault line on a horizontal plane. The initial phases of a translational slide are indicated by cracks in the upper part of the riprap bank that extend parallel to the channel. As the slide progresses, the lower part of riprap separates from the upper part, and moves downslope as a homogeneous body. A resulting bulge may appear at the base of the bank if the channel bed is not scoured.

Modified Slump

The failure of riprap referred to as modified slump is the mass movement of material along an internal slip surface within the riprap blanket; the underlying material supporting the riprap does not fail. This type of failure is similar in many respects to the translational slide, but the geometry of the damaged riprap is similar in shape to initial stages of failure caused by particle erosion.

Slump

Slump is a rotational-gravitational movement of material along a surface of rupture that has a concave upward curve. The cause of slump failures is related to shear failure of the underlying base material that supports the riprap revetment. The primary feature of a slump failure is the localized displacement of base material along a slip surface, which is usually caused by excess pore pressure that reduces friction along a fault line in the base material.

7.8.6 Revetment Types

Common Types

The types of slope protection or revetment commonly used for bank and shore protection and stabilization include:

- riprap
- gabions
- concrete block slope protection
- concrete slope pavement
- articulating block mat systems

Riprap

Riprap has been described as a layer or facing of rock, dumped or hand-placed to prevent erosion, scour, or sloughing of a structure or embankment. Materials other than rock are also referred to as riprap; for example, rubble, broken concrete slabs and preformed concrete shapes (slabs, blocks, rectangular prisms, etc.). These materials are similar to rock in that they can be hand-placed or dumped onto an embankment to form a flexible revetment.

Gabions

Wire-enclosed rock, or gabion, revetments consist of rectangular wire mesh baskets filled with rock. These revetments are formed by filling pre-assembled wire baskets with rock, and anchoring to the channel bottom or bank. Wire-enclosed rock revetments are generally of two types distinguished by shape: rock and wire mattresses, or blocks. In mattress designs, the individual wire mesh units are laid end to end and side to side to form a mattress layer on the channel bed or bank. The gabion baskets comprising the mattress generally have a depth dimension which is much smaller than their width or length. Block gabions, on the other hand, are more equal-dimensional, having depths that are approximately the same as their widths, and of the same order of magnitude as their lengths. They are typically rectangular or trapezoidal in shape. Block gabion revetments are formed by stacking the individual gabion blocks in a stepped fashion.

Concrete Block Slope Protection

Pre-cast concrete block revetments are a recent development. The pre-formed sections which comprise the revetment systems are butted together or joined in some fashion; as such, they form a continuous blanket or mat. The concrete blocks which make up the mats differ in shape and method of articulation, but share certain common features. These features include flexibility, rapid installation and provisions for establishment of vegetation within the revetment. The permeable nature of these revetments permits free draining of the bank materials; the flexibility, although limited, allows the mattress to conform to minor changes in the bank geometry. Their limited flexibility, however, makes them subject to undermining in environments characterized by large and relatively rapid fluctuations in the surface elevation of the channel bed and/or bank. Unlike wire-enclosed rock, the open nature of the pre-cast concrete blocks does promote volunteering of vegetation within the revetment.

Concrete Slope Pavement

Concrete pavement revetments (concrete slope pavement) are cast in place on a prepared slope to provide the necessary bank protection. Like grouted rock, concrete pavement is a rigid revetment which does not conform to changes in bank geometry due to a removal of foundation support by subsidence, undermining, outward displacement by hydrostatic pressure, slide action, or erosion of the supporting embankment at its ends. The loss of even small sections of the supporting embankment can cause complete failure of the revetment system. Concrete pavement revetments are also among the most expensive streambank protection designs. In the past, concrete pavement has been best utilized as a subaqueous revetment (on the bank below the water surface) with vegetation or some other less expensive upper-bank treatment.

7.8.7 Flow Resistance

The hydraulic analysis performed as a part of the riprap design process requires the estimation of Manning's roughness coefficient. Physical characteristics upon which the resistance equations are based include the channel base material, surface irregularities, variations in section geometry, bed form, obstructions, vegetation, channel meandering, flow depth and channel slope. In addition, seasonal changes in these factors must also be considered. See Section 7.4.11, for a discussion of the selection of Manning's n values.

7.8.8 Extent Of Protection

Extent of protection refers to the longitudinal and vertical extent of protection required to adequately protect the channel bank.

Longitudinal Extent

The longitudinal extent of protection required for a particular bank protection scheme is highly dependent on local site conditions. In general, the revetment should be continuous for a distance greater than the length that is impacted by channel-flow forces severe enough to cause dislodging and/or transport of bank material. Although this is a vague criteria, it demands serious consideration. Review of existing bank protection sites has revealed that a common misconception in streambank protection is to provide protection too far upstream and not far enough downstream.

One criteria for establishing the longitudinal limits of protection required is illustrated in Figure 7-21. As illustrated, the minimum distances recommended for bank protection are an upstream distance of 1.0 channel width and a downstream distance of 1.5 channel widths from corresponding reference lines. All reference lines pass through tangents to the bend at the bend entrance or exit. This criteria is based on analysis of flow conditions in symmetric channel bends under ideal laboratory conditions. Real-world conditions are rarely as simplistic.

In actuality, many site-specific factors have a bearing on the actual length of bank that should be protected. A designer will find the above criteria difficult to apply on mildly curving bends or on channels having irregular, non-symmetric bends. Also, other channel controls (such as bridge abutments) might already be producing a stabilizing effect on the bend so that only a part of the channel bend needs to be stabilized. In addition, the magnitude or nature of the flow event might only cause erosion problems in a very localized portion of the bend, requiring that only a short channel length be stabilized. Therefore, the above criteria should only be used as a starting point. Additional analysis of site-specific factors is necessary to define the actual extent of protection required.

Field reconnaissance is a useful tool for the evaluation of the longitudinal extent of protection required, particularly if the channel is actively eroding. In straight channel reaches, scars on the channel bank may be useful to help identify the limits required for channel bank protection. In this case, it is recommended that upstream and downstream limits of the protection scheme be extended a minimum of one channel width beyond the observed erosion limits.

In curved channel reaches, the scars on the channel bank can be used to establish the upstream limit of erosion. Here a minimum of one channel width should be added to the observed upstream limit to define the limit of protection. The downstream limit of protection required in curved channel reaches is not as easy to define. Since the natural progression of bank erosion is in the downstream direction, the present visual limit of erosion might not define the ultimate downstream limit. Additional analysis based on consideration of flow patterns in the channel bend may be required.

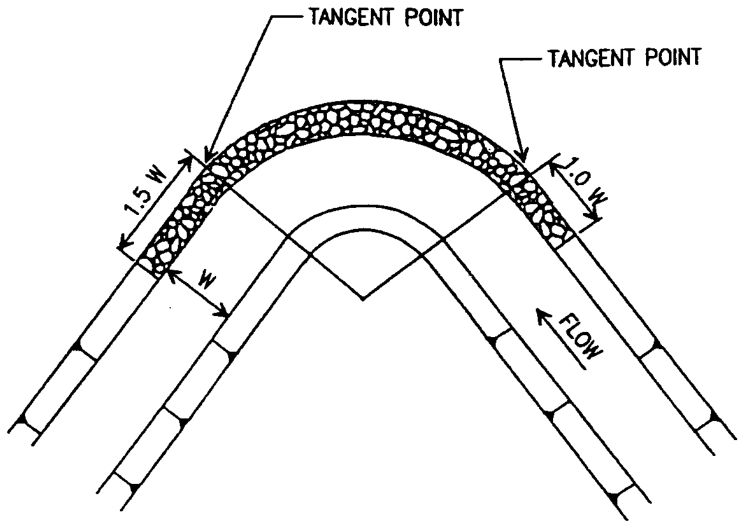


Figure 7-21 Longitudinal Extent Of Revetment Protection

Vertical Extent

The vertical extent of protection required of a revetment includes design height and foundation or toe depth.

Design Height

The design height of a riprap installation should be equal to the design highwater elevation plus an allowance for freeboard, generally 0.3 – 0.6m (1-2 ft). Freeboard is provided to ensure that the desired degree of protection will not be reduced by unaccounted factors. Some such factors include:

- wave action (from wind or boat traffic)
- superelevation in channel bends
- hydraulic jumps
- flow irregularities due to piers, transitions and flow junctions

In addition, erratic phenomena such as unforeseen embankment settlement, the accumulation of silt, trash and debris in the channel, aquatic or other growth in the channels and ice flows should be considered when setting freeboard heights. Also, wave run-up on the bank must be considered.

Wave Action

The prediction of wave heights from wind and boat generated waves is not as straightforward as other wave sources. Figure 7-22 provides a definition sketch for the wave height discussion to follow. The height of boat generated waves must be estimated from observations. The height of wind generated waves is discussed in Appendix A of this chapter.

It is necessary to estimate the magnitude of wave runup which results when waves impact the bank. Wave runup is a function of the design wave height, the wave period, bank angle and the bank surface characteristics (as represented by different revetment materials). For wave heights less than 0.6 m (2 ft), wave runup can be computed using Figure 7-23 and Table 7-7. The runup height (R) given in Figure 7-23 is for concrete pavement. Correction factors are provided in Table 7-7 for reducing the runup magnitude for other revetment materials. The correction factor is multiplied times the wave height to get the resulting wave runup (R).

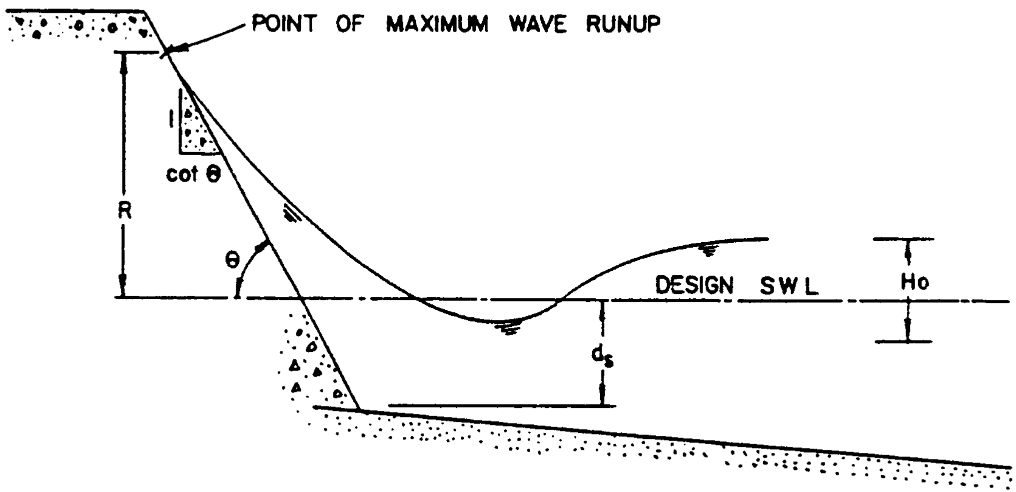
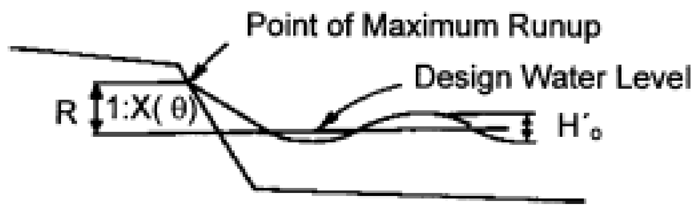
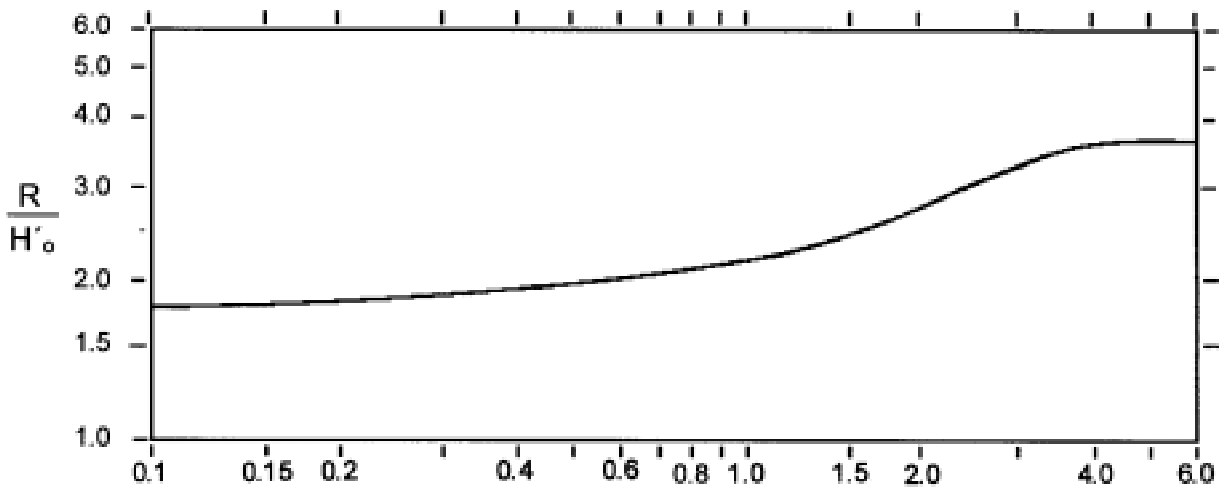


Figure 7-22 Wave Height Definition Sketch



R = Wave Run Up Height (m)
H´o = Wave Height (m)
θ = Bank Angle with the Horizontal



X(COT θ)

Figure 7-23 Wave Run-Up On Smooth, Impermeable Slopes

Table 7.7 Correction Factors For Wave Run-Up

Slope Surface Characteristics	Placement Method	Correction Factor
Concrete pavement	—	1.00
Concrete blocks (voids < 20%)	fitted	0.90
Concrete blocks (20% < voids > 40%)	fitted	0.70
Concrete blocks (40% < voids > 60%)	fitted	0.50
Grass	—	0.85 - 0.90
Rock riprap (angular)	random	0.60
Rock riprap (round)	random	0.70
Rock riprap (hand placed or keyed)	keyed	0.80
Grouted rock	—	0.90
Wire enclosed rocks/gabions	—	0.80

Flow In Channel Bends (Superelevation of Flow)

Flow conditions in channel bends are complicated by the distortion of flow patterns in the vicinity of the bend. In long, relatively straight channels, the flow conditions are uniform and symmetrical about the center line of the channel. However, in channel bends, the centrifugal forces and secondary currents produced lead to non-uniform and non-symmetrical flow conditions.

Special consideration must be given to the increased velocities and shear stresses that are generated as a result of non-uniform flow in bends.

Superelevation of flow in channel bends is another important consideration in the design of revetments. Although the magnitude of superelevation is generally small when compared with the overall flow depth in the bend (usually less than 0.3 m) it should be considered when establishing freeboard limits for bank protection schemes on sharp bends. The magnitude of superelevation at a channel bend may be estimated for subcritical flow by the following equation:

$$\mathbf{Z = C\,[(V_a^2 T)/(gR_o)]} \qquad \textbf{(7.33)}$$

where: Z = superelevation of the water surface, m (ft)
C = coefficient that relates free vortex motion to velocity streamlines for unequal radius of curvature,
V_a = mean channel velocity, m/s (ft/s)
T = water-surface width at section, m (ft)
g = gravitational acceleration - 9.81 m/s^2 (32.2 ft/s^2)
R_o = the mean radius of the channel centerline at the bend, m (ft)

The coefficient C has been evaluated by the U.S. Geological Survey (USGS) and ranges between 0.5 and 3.0, with an average value of 1.5.

Freeboard

As indicated, there are many factors which must be considered in the selection of an appropriate freeboard height. As a minimum, it is recommended that a freeboard elevation of 0.3 (1 ft) be used in unconstricted reaches, and 0.6m (2 ft) in constricted reaches. When computational procedures indicate that additional freeboard may be required, the greater height should be used. In addition, it is recommended that the designer observe wave and flow conditions during various seasons of the year (if possible), consult existing records, and interview persons who have knowledge of past conditions when establishing the necessary vertical extent of protection required for a particular revetment installation.

Toe Depth

The undermining of revetment toe protection has been identified as one of the primary mechanisms of revetment failure. In the design of bank protection, estimates of the depth of scour are needed so that the protective layer is placed sufficiently low in the streambed to prevent undermining. The ultimate depth of scour must consider channel degradation as well as natural scour and fill processes.

The relationships presented in Equation 7.34 and 7.35 can be used to estimate the probable maximum depth of scour due to natural scour and fill phenomenon in straight channels, and in channels having mild bends. In application, the depth of scour, d_s, should be measured from the lowest elevation in the cross section. It should be assumed that the low point in the cross section may eventually move adjacent to the protection (even if this is not the case in the current survey).

$$\mathbf{d_s = 3.66\ m\ (12\ ft) \qquad for\ D_{50} < 1.5\ mm\ (0.06\ in)} \tag{7.34}$$

$$\mathbf{d_s = 1.738\ D_{50}^{-0.11m} m \qquad (\ d_s = 3.72\ D_{50}^{-0.11}\ (ft\ ))\quad for\ D_{50} > 1.5\ mm\ (0.06\ in)} \tag{7.35}$$

Where: d_s = estimated probable maximum depth of scour, m (ft)

D_{50} = median diameter of bed material, mm (inch)

The depth of scour predicted by Equations 7-34 and 7.35 must be added to the magnitude of predicted degradation and local scour (if any) to arrive at the total required toe depth.