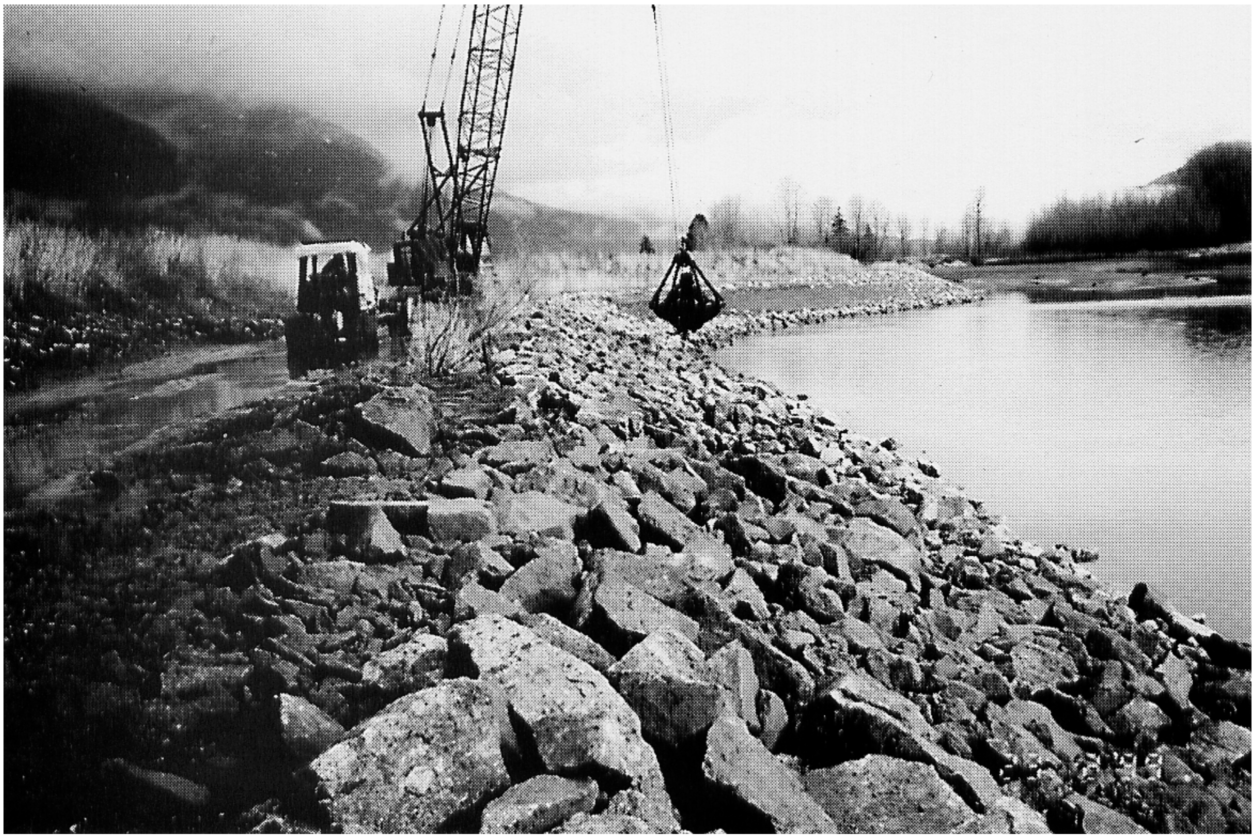
Riprap Design and Construction Guide



Public Safety Section
Water Management Branch

Province of British Columbia
Ministry of Environment, Lands and Parks

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BRITISH COLUMBIA

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1.
General

The purpose of this guide is to assist Diking Authorities, Local Authorities, and other agencies in the design and construction of slope or bank protection works and to provide current information on the design and construction of riprap in British Columbia for use by owners and design professionals. The guide addresses design and construction of repairs to existing works, design and construction of new works, and construction of emergency works.

The guide is a summary of the technical report included as Appendix A. The technical report provides details for the design and construction of riprap revetments.

1.1 Bank Protection in British Columbia

This guide addresses the design and construction of protective works to prevent erosion of river banks and dike slopes from stream flow. The bank protection structures that are discussed in this guide are classified as “blanket revetments”. Blanket revetments, constructed of broken rock or other material, are laid on suitably-shaped and aligned slopes and usually parallel the flow.

British Columbia has some special circumstances that affect riprap design and construction. The potential for ice and debris damage to riprap revetments is an important consideration in design. Stream banks are often composed of non-cohesive sand and gravel that require a filter layer to prevent their erosion, and subsequent failure of the revetment. Also, high velocities are very common. Adequate toe protection is vital to the stability of the revetment. In extreme circumstances, grouting of the riprap may be required to provide adequate resistance to movement.

Riprap is the most commonly used bank protection material in British Columbia. In some cases and also in some other jurisdictions, revetments are constructed of concrete blocks, gabions, concrete bags or mattresses, jacks or similar structures, articulated concrete slabs, rigid pavements, timber piles or fences, bio-engineering, or woody debris, such as trees, root boles, or brush. Design of blanket revetments with these other, less common, materials is not considered in this guide.

The advantages of riprap are that it is highly durable, has a history of use, and is available in most of British Columbia. Structures built from riprap are flexible, do not fail under minor shifting, and can be easily constructed and repaired. The main limitations of riprap revetments are that they are not suitable for steep slopes that cannot be re-graded to a lower angle and that they may cause opposite bank erosion if they encroach substantially into the stream. As well, their construction may damage aquatic or riparian habitat resulting in costs for mitigation or compensation, their construction may be limited to a narrow time period during the fisheries window, and, some people find riprap revetments aesthetically unappealing.

2.
Legislation and Regulatory Controls

The construction and repair of bank protection works are regulated by various provincial and federal Acts. The Province requires Approvals under the *Water Act* and, possibly the *Dike Maintenance Act*, prior to construction. The proposed works must also satisfy the Canada *Fisheries Act*. Other relevant legislation may include the provincial *Land Act* or the federal *Navigable Waters Protection Act.*

2.1 Water Act

All riprap work in and about a stream or watercourse is subject to approval under the *Water Act*, through the Regional Water Management Office of MELP. The approval will regulate the period when construction may be undertaken and may restrict the activities or nature of the activities that can be carried out within the stream. Note that in the Fraser River estuary, an approval from the Fraser River Estuary Management Program (FREMP) incorporates an approval under the *Water Act.* Both DFO and provincial Fish and Wildlife may review and comment on a submission for construction of bank protection works through the Application for a *Water Act* Approval. In some regions, separate applications are required to Fish and Wildlife and to DFO.

2.2 Dike Maintenance Act

The principal legislation in BC pertinent to flood protection works is the *Dike Maintenance Act.* Under this Act, written approvals are required from the Deputy Inspector of Dikes for any works in and about flood protection dikes. The approval is based on drawings and a written description submitted well prior to the planned date of construction.

The *"Guidelines for Management of Flood Protection Works in British Columbia"* (Water Management Branch 1999b) provide additional information for repair and construction of bank protection works associated with flood protection works.

2.3 Canada Fisheries Act

All work in and about streams, which contain waters frequented by fish, requires approval under the Canada *Fisheries Act*. The federal Department of Fisheries and Oceans (DFO) manages anadromous salmon and operates under a policy of "No Net Loss of Habitat" (DFO 1986). They require mitigation to eliminate potential habitat loss from any proposed works or compensation to replace habitat that would be damaged by the bank protection works. The provincial Fish and Wildlife is responsible for management of steelhead, trout, char and other non-salmonid freshwater species under the *Fisheries Act*.

2.4 Land Act

The BC *Land Act* affects the removal of gravel from streambeds, and may subject the removals to a royalty. Whether the stream bed is on Crown Land or private land, the permission of the land owner is required.

2.5 Canada Navigable Waters Protection Act

Bank protection works within, above, or under the surface of navigable waters will be subject to review under the *Navigable Waters Protection Act.*

3. Considerations for Design and Construction

3.1 Failure of Riprap Revetments

Rock riprap resists erosion through a combination of stone size and weight, stone durability, and the gradation and thickness of the riprap blanket. The interlocking of angular rocks provides resistance to movement for the individual blocks in the revetment. Stream characteristics also strongly affect the stability of riprap revetments. Local scour, as affected by stream characteristics and bed materials, determines the protection required against undermining of the toe of the revetment; channel slope and alignment affect the impingement of flows on the bank and the hydraulic conditions that the rock must resist.

The four most common types of riprap failure are particle erosion, translational sliding, modified slumping and slumping (Blodgett 1986). Particle erosion results from the displacement of individual rocks and is often a result of under-sized rock, debris impact or direct impingement of flow. Translational sliding, where the revetment fails parallel to the side slope, generally results from toe scour and loss of support along the base of the revetment. Modified slumping, where the blanket moves without toe failure, usually results from oversteep slopes. Slumping is a rotational failure of the bank beneath the revetment, that generally occurs on high, unstable banks.

3.2 Typical Bank Protection Problems

The typical bank protection problems encountered by a Diking Authority or other local authority are:

- minor repair of existing embankments, typically requiring less than 100 m^3 or so of riprap;
- major repairs of existing embankments, often requiring re-construction of the bank line and reconstruction or replacement of several hundred m^3 of riprap;
- extension of existing embankments, upstream or downstream, to address erosion;
- erosion protection for natural banks to prevent damage to dikes or flood protection structures or to other resources; and
- emergency erosion protection placed during floods.

In some instances, restoration or repair may require other river engineering works in addition to, or instead of, embankment reconstruction and protection. Where severe damage to erosion protection works occurs, or where major changes are evident in the channel and its characteristics, a review by a professional engineer, with an appropriate speciality, should be part of the design and construction of the new riprap embankment.

3.3 Limitations of the Guide

The Guide provides advice on design and construction practices based on current research that may not be appropriate for all circumstances. Limitations of the various recommended procedures and techniques are indicated, where they are known.

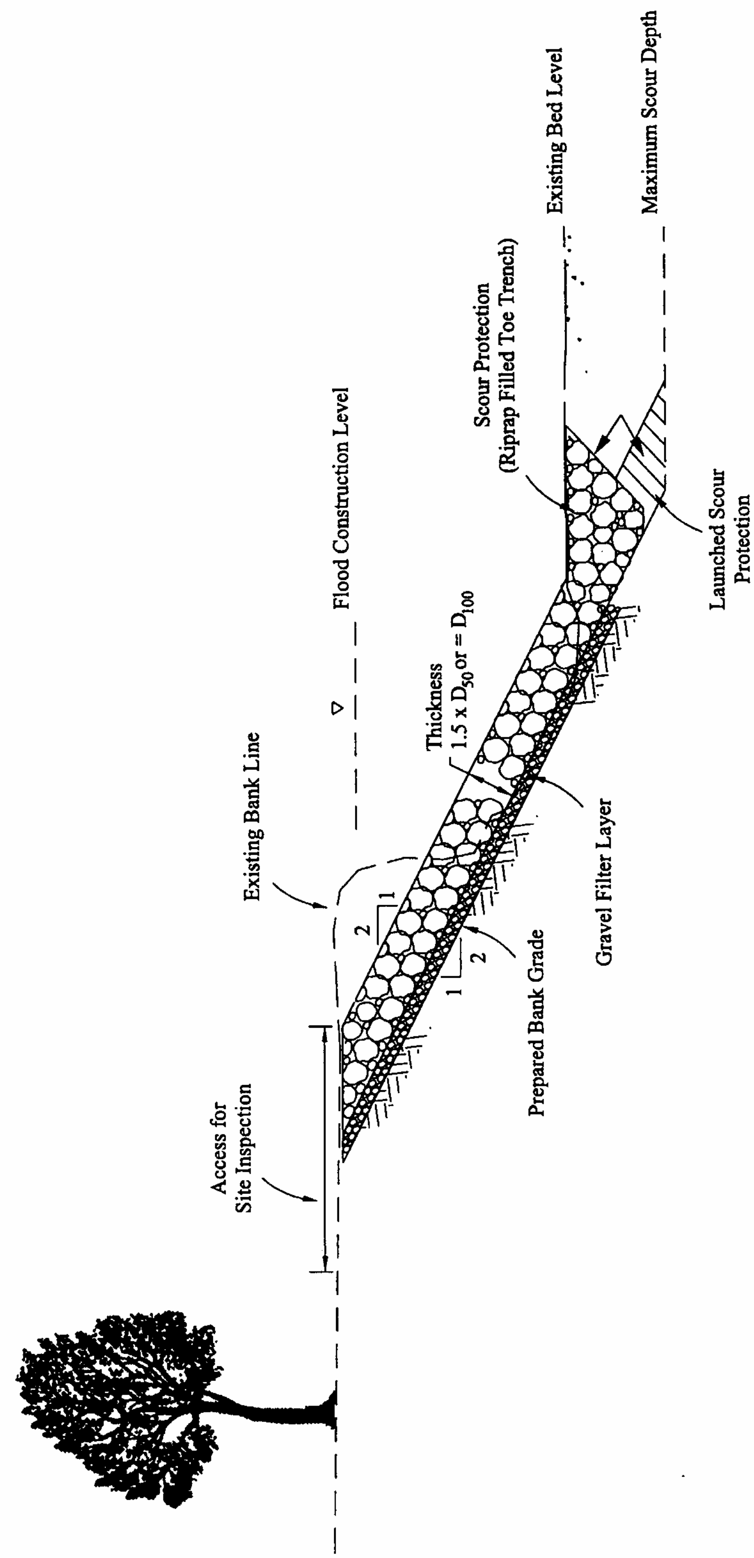

Figure 1: Cross Section of Typical Riprap Revetment

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4. Rip Rap Design

4.1 Characteristics Requiring Design

The following features of riprap revetments require consideration during design. Appendix A to the guide provides technical details.

- Length and alignment of bank protection
- End treatment and top treatment of bank protection
- Rock shape, size, gradation and blanket thickness
- Bank slope and the vertical height (extent) of protection
- Toe treatment, or protection against scour or undermining
- Filter layer

Repairs of riprap revetments generally do not need to consider the first two items in detail. However, they are key issues in the successful design of works for banks that have not been previously protected, in re-design of works following their complete, or near-complete, failure, and in long extensions of existing revetments. Consultation with a professional engineer that specializes in river engineering works is advised for major repairs or new construction.

4.2 Background to Design

The design of riprap revetments is based on the nature of the streambank and the hydraulic characteristics of the stream at the design flood. As a result, the following background information is usually required as part of design:

- An inspection of the banks and river channel, the extent of recent erosion, potential hard points (inerodible materials along the bank), and the general behaviour of the river near the proposed bank protection site.

- For most projects, cross sections of the bank, stream channel and floodplain are required. If the stream has been previously surveyed for design of bank protection works or floodplain mapping, then these would be repeated.

- Maps, air photographs, bed and bank material descriptions, channel surveys, design briefs for floodplain mapping and previous studies for bank protection all provide valuable information on channel characteristics and behaviour (see USACE 1994).

- Hydrologic analyses, either of a local Water Survey of Canada gauge record on the stream, or a regional analysis, is often required to predict the design discharge for the stream. In British Columbia, this is almost always the 200-year instantaneous maximum discharge.

  Design briefs for floodplain mapping, or previous engineering studies for bank protection works may provide a suitable design discharge.

- Hydraulic analyses, at the design or other discharges, are required to predict design water levels, and maximum average velocities and depths. A key aspect of the hydraulic analysis is to predict the maximum average velocity that occurs along the channel and, by extension, the bank where protective works are to be constructed.

4.3 Scour Depth

A key aspect of the design of riprap revetment is to adequately protect its toe from undermining by scour, where this refers to a lowering of the channel bed below some observed level.

Local scour often occurs at bends, changes in flow direction, obstructions, constrictions, sills, control structures, piers or abutments. In addition, general bed lowering may result from long-term degradation, perhaps downstream of a large dam, or from the effects of long-term gravel mining (Galay 1983). The general bed lowering is added to the local scour to predict design scour depth.

A variety of publications provide methods to predict scour depths (Hoffmans et al 1997; Breusers and Raudkivi 1991). The proposed revisions to the "*Guide to Bridge Hydraulics*" provide methods that are thought to be particularly applicable to British Columbia (Neill 1973).

4.4 Alignment of Revetments

A key question is whether or not the revetment is to be placed along the existing bank. Often, following a large flood, bank retreat and channel shifting may cause high velocities to impinge directly on the bank or they may cause a poor flow alignment into the next bend, into a bridge crossing, or into another hydraulic structure. Alternatively, the bank may have retreated close to valuable infrastructure or buildings. In these cases, re-aligning the channel may be required as part of bank protection, prior to re-construction or construction of a riprap revetment.

4.5 End Treatments and Top Treatments of Revetments

The most suitable end treatment is to extend the revetment to join an inerodible bank or to extend it to where velocities are non-eroding. When the revetment terminates where velocities are still erosive, or may be erosive following channel shifting or bar aggradation, the usual end treatment is to thicken the upstream and downstream edges of the revetment, or turn ("key") the revetment into the natural bank.

These treatments may not provide a long term solution to bank erosion, where the channel is unstable and shifting its point of attack. In these circumstances, the end treatments will help reduce bank erosion upstream or downstream and help ensure that a major flood does not outflank the revetment. Emergency protection may be required at the upstream or downstream ends of the revetment during a major flood.

Where a revetment can be overtopped by extreme floods, some form of erosion protection is often required on the top of the embankment to prevent erosion by escaping or return flows. A layer of riprap may be placed on the top of the bank to prevent erosion; alternatively, filter layers beneath the riprap may be designed to prevent erosion of the bank by the escaping or returning flows. Top treatments using sod or other materials to prevent erosion are described by Chamberlin and Meyers (1995).

4.6 Riprap Dimensions

4.6.1 The Size of Riprap

The sizes of individual rocks are expressed by the dimensions of their three axes. The long axis, *a*, is the maximum length of the stone. The intermediate axis, *b*, is the maximum width, perpendicular to the long axis. The short axis, *c*, is the thickness of the stone perpendicular to the plane of the *a* and *b*-axes. The size of an individual rock is usually expressed as its *b*-axis dimension.

The use of rock or stone size is preferred for riprap dimensions; however, weight is commonly used. The relationship of size to weight depends on stone shape and also on the specific weight or density of the rock. Typically, space the rock used for riprap is not spherical and its shape lies between that of a sphere and a cube.

4.6.2 Rock Shape

Rocks used for riprap should be blocky and angular, with sharp clean edges and relatively flat faces. It is generally recommended that individual pieces be close to equi-dimensional, rather than elongate, although this may not always be practical. Typically, the average ratio of the long axis, *a,* to the thickness, *c,* for an individual rock should be less than 2.

USACE (1991) notes that if rounded stones are used for riprap that they should be placed on flatter slopes (not exceeding 2.5H:1V) and that the predicted or recommended median rock diameter be increased by 25%, with a comparable increase in the thickness of the revetment.

4.6.3 Rock Density

The density of rock used for riprap typically varies from about 2,400 kg/m^3 (150 lb/ft^3) to 2,800 kg/m^3 (175 lb/ft^3), with a density of about 2,600 kg/m^3 (162.5 lb/ft^3) common for the granitic or granodioritic rocks that are often quarried in British Columbia.

4.7 Determining the Required Rock Size

Rock dimensions may be successfully designed to resist failure based on local experience, empirical guidelines, or hydraulic relationships that predict stable riprap sizes, based on bank slope and stream characteristics. In this guide, the design of riprap size is based on the latter approach, which requires hydrologic and hydraulic analysis as part of the design process.

Nearly all the riprap sizing methods that are commonly used in North America are based on stream velocity, usually predicting rock size as a power of the velocity against the riprap embankment (Brown and Clyde 1989, CALTRANS 1997, Maynord et al 1989, USACE 1991). As a result, the estimated bank velocity is often the most important factor in determining rock size.

Care is recommended when calculating mean channel velocities and careful consideration is required when selecting the ratio used for converting mean velocities to bank velocities. Stream behavior resulting in direct impingement of flow on the bank, where bank velocities may be much larger than the mean velocity, is often a critical factor for riprap design.

The relative merits of the various riprap sizing equations are described in Meville and Coleman (2000). Following the practice of the proposed revisions to the *"Guide to Bridge Hydraulics"* (Neill 1973), the USACE (1991) method for rock sizing is described in detail in Appendix A to this guide. Other riprap sizing equations may work equally well in British Columbia.

4.8 Riprap Gradation

The riprap specifications in Section 205 of MOTH (1999) provide a suitable range of standard sizes for use in British Columbia.

Their specifications meet typical standards for graded mixtures, provide a range of specifications up to 4 tonnes nominal size and are commonly produced by quarries in British Columbia. MOTH bases their specifications on rock weight, converted to a median diameter, D_{50}, by assuming a spherical shape for the individual pieces.

The USACE (1991) method predicts the D_{30} riprap diameter, which would be converted to the required median rock diameter, D_{50}, by multiplying by 1.25. The appropriate specification is then selected from MOTH (1999) as that gradation whose median diameter is equal to or larger than the required D_{50} predicted by the USACE method. This approach will provide a conservative riprap gradation.

4.9 Thickness

The revetment should be thick enough to include all the rocks in the specified gradation within the layer. Oversize stones that project through the layer may contribute to failure by creating turbulence. Based on Brown and Clyde (1989), the riprap thickness normal to the slope should meet the following criteria:

- Not less than 350 mm,
- Not less than 1.5 x D_{50}; and
- Not less than a D_{100}.

The above specifications are roughly equivalent to the thicknesses recommended in MOTH (1999).

4.10 Bank Slope and the Vertical Extent of Protection

The design slope should not be steeper than 1V:2H, except in special circumstances. Further limits on side slope steepness may be imposed by slope instability, groundwater flows, or rapid water level recession and piping failure, all of which should be carefully considered in slope design.

Rock riprap revetments are normally continued to the top of the bank or to design water level, plus a freeboard, if the bank is not over topped. Freeboard is added to account for wave runup, superelevation, profile irregularities, floating debris, ice and surface waves. In British Columbia, the typical freeboard is usually 0.6 m though there may be justification to increase this, in steep streams with critical or supercritical flow. Dotson (1991) provides a discussion of freeboard practice and design considerations in the United States. Section 4.5 provided recommendations for treatments of banks that are overtopped.

4.11 Toe Treatment or Protection Against Scour

Toe scour, along revetments, is thought to be the most common cause of failure.

Six methods are commonly used to prevent undermining, as described below (see Apendix A for further information):

- The slope is excavated and covered with rock riprap to below expected scour levels. This method is the most permanent, but it may be impractical or uneconomical if the lower limit is deeply buried. Extensive disturbance of the stream bed is often strongly opposed by the environmental agencies.

- The slope is excavated and covered with rock riprap to meet inerodible material found above expected scour levels. The toe of the riprap is “keyed” into the inerodible material to prevent unravelling of the slope and revetment failure.

- A flexible "launching apron" is laid horizontally on the bed at the foot of the revetment with a height of about 1.5 times the predicted revetment thickness. The intention is that when scour occurs, the apron will settle and cover the side of the scour hole on a natural slope.

- A rock-filled toe trench or toe berm is constructed at the foot of the slope. This is a variant of the launching apron since the rock in the trench launches as scour develops. This method requires encroachment into the river channel, however a toe trench can be re-buried beneath native stream bed materials.

- A sheetpile cutoff wall is installed from the toe of the revetment down to an inerodible material or to below the expected scour level. Such walls tend to provoke deeper local scour than armoured slopes, and often need to be tied back to deadmen or anchors to ensure stability.

- The entire streambed is paved with riprap or other materials. This method has been used mainly for small steep, streams. The paving should not be raised above normal stream bed levels. Scour tends to occur at the downstream edge of the paving unless it is tied into a natural inerodible formation or unless a stilling basin is provided.

4.12 Riprap Filters

In British Columbia, where riprap is often placed on banks composed of sand and fine gravel, a filter layer is necessary to avoid loss of bank material through the riprap. The traditional filter material is gravel or crushed rock. Geotextiles are also an alternative because they may be cheaper and easier to install in certain circumstances.

For gravel or rock filters, Brown and Clyde (1989) recommend the following sizing criterion:

$$D_{15c}/D_{85f} < 5 < D_{15c}/D_{15f} < 40$$

where D_{15} and D_{85} refer to the 15% and 85% sieve passing sizes, and subscripts "c" and "f" refer to the coarse and finer layers respectively. The criterion should be imposed at the interfaces between the underlying material and the filter, and between the filter and the overlying riprap. If a single filter layer cannot meet the criterian at both interfaces, two or more layers may be required.

4.13 Ice Debris and Other Considerations

Increasing the safety factor for the USACE (1991) design procedure (see Appendix A) is suggested where there is potential for ice or debris impact, particularly for revetments that are less than 450 mm thick, or for severe freeze-thaw conditions. USACE (1991) notes that there are no design guidelines at present for riprap exposed to ice or debris damage. As a general rule of thumb they recommend increasing the design revetment thickness by 15 to 30 cm, with a corresponding increase in the median rock size, and limiting slopes to a maximum of 2.5H:1V. The Cold Regions Laboratory is currently monitoring revetments along the Tanana River in Alaska for design guidance but no results have been published yet.

In urban areas, or near population centres, movement or removal of the rock riprap by people is a factor in design. Here, the minimum rock size should be greater than about 50 kg. Grouting may be one approach to prevent revetments composed of small riprap from being damaged.

5.
Riprap Revetment Construction Practices

5.1 Approvals and Instream Construction Windows

Instream construction, which includes nearly all bank protection works, is limited to specific windows or time periods, based on utilization of the stream by different life stages of fish. Construction windows are typically in the summer but on the Lower Fraser River they occur in February, when water levels are lowest.

Applications for Approvals of Instream Works from MELP require a design showing layout, profiles and cross sections of the works. The application is normally submitted well in advance of the desired date for the start of construction, preferably several months in advance. An on-site meeting with DFO and MELP to discuss potential mitigation requirements and other issues is recommended prior to submission.

5.2 Environmental Management Program

An environmental management plan is often required as part of the approval of instream construction works. The plan addresses salvage of fish, sediment management, access management, environmental monitoring and site restoration. A fisheries biologist is often engaged to assist with developing this plan, if one is required.

The requirements for an environmental management plan vary from region to region in British Columbia and the contents would be based on discussion with DFO and MELP.

5.3 Site Preparation

Clearing and grubbing should be kept to the minimum required to meet the specifications shown on design drawings, with slopes left free of brush, trees, stumps or other objectionable materials and dressed to a smooth surface.

Banks are to be trimmed uniform slope, as indicated on drawings. Loose, soft or spongy material, and large rocks projecting through the slope are removed and the resulting minor potholes or hollows filled with selected non-cohesive materials and compacted as directed. If a toe trench for scour protection is required, it is constructed during site preparation.

5.4 Placing Filter Layers

The materials for gravel filter layers are inspected for quality (hardness and durability of rock and presence of fines) and compliance with gradation by the site engineer. The filter layer materials are spread evenly on the prepared bank, to the dimensions on the drawings. They are sometimes extended beneath launching aprons or toe berms. The layers are usually placed by techniques that do not result in segregation of the rock mass. Compaction is not required but the surface should be smooth and free of mounds, dips or windrows.

5.5 Quality

Stone used for rock riprap should be hard, durable, angular in shape, resistant to weathering and water action, free from overburden, spoil, silt and clay or organic material and meet the specified gradation. Dirty rock, which contains clay, silt, soil, or organic material , but is otherwise acceptable, is usually washed prior to delivery to the site.

Specifications for rock used as riprap typically include rock density or specific weight, rock shape, and rock hardness and durability.

5.6 Gradation

Control of the size and gradation of rock riprap placed on a bank is one of the most important aspects of riprap construction yet it can be very difficult to achieve (Galay et al 1987).Visual inspection of individual loads of rock delivered to the site is an important part of quality control. The following techniques also help ensure that gradation is met.

- For large projects, a sample of rock in the quarry that meets the specified gradation can be provided as a visual reference for the machine operators. Marked samples of the D_{100}, D_{85}, D_{50}, and D_{15} rocks are often particularly helpful. A similar sample can be placed at the construction site for reference.

- Daily, or more frequent, line sampling of in-place riprap provides a check on gradation. The procedure is to lay a measuring tape across the surface of the riprap and measure the dimensions (usually the b-axis) of each stone that falls under a fixed spacing, such as every 2 m along the tape (Kellerhals and Bray 1971). Measure at least 50 rocks for each line sample. Tabulate the stone dimensions from largest to smallest, calculating the percent finer for every fifth rock in the sample.

  Plot a curve of percent finer by diameter and compare it to the gradation curve. If the sample rock appears undersized, additional sampling is required. If further sampling confirms that the rock is undersized, construction can be stopped and the procedures in the quarry re-evaluated.

5.7 Rock Riprap Placement

The rock is transported and placed by methods that avoid segregation: end dumping, dumping into chutes placing or moving by dragline buckets, or spreading by bulldozers are generally not acceptable construction practices. Care should be taken to prevent cracking or breaking of rock riprap by crushing under machine tracks. Each truckload of rock brought to the site should provide a complete range of the rock sizes in the gradation.

Rocks are placed by bucket load to the required thickness, providing a reasonably well-graded mass with the minimum of voids. Large stones are placed along the toe or distributed evenly throughout the mass. Clusters of small or large stones are avoided.

For above water work, stones are placed from the base of the slope to the top in one operation. For high banks, it may be most suitable for two excavators to complete the work, one at the base of the bank and one at the top. Care is required in placing rock to avoid disturbing the filter layer(s).

For underwater placement, clamshells are typically used to place rock on the streambed or the toe of the bank. Dumping of rock is not recommended as it produces a poor distribution of material. Quality control, which is often based on GPS-controlled soundings or dive inspections, is beyond the scope of this document.

Often the surface of the rock is left rough. However, in some circumstances, quarry spalls are used to fill voids in the revetment surface creating a smoother surface.

6. Environmental Design and Mitigation

6.1 General

Bank protection works often encroach into streams and may damage fish habitat by removing riparian vegetation, changing the angle and general nature of the stream bank, increasing the size of materials exposed along the water line, and covering part of the bed and bank with coarse angular rock. Bank protection projects may also cause secondary effects, such as bed scour near the works and coarsening of the bed material, or opposite bank erosion that may also be detrimental to fish habitat.

Should the bank protection project potentially damage fish habitat, DFO may require either mitigation, by altering the design to reduce damage to habitat, or compensation, by creating additional habitat elsewhere, through their policy of "No Net Loss of Habitat" (DFO 1986). Mitigation is preferred and can often be achieved by modifying the riprap design.

A fisheries biologist can provide an initial review of potential impacts on habitat, liaise with DFO, MELP, and other concerned agencies, and help develop mitigative measures. A site visit, with the appropriate agencies, to review the design and discuss potential mitigative measures is often an important step in the approval process and should occur before proceeding to final design.

6.2 Examples of Modifications to Riprap Revetments for Mitigation

Often, riprap revetments can be modified to reduce their impact on fish habitat or features added to the revetment to replace the habitat that is damaged or destroyed. Mitigative measures are site specific, as they must address the particular species and their life stages that utilize the habitat affected by the bank protection works. Consequently, the following examples may not be appropriate throughout British of Columbia.

A number of modifications are thought to be consistent with stability of the riprap revetment, if designed and constructed properly. These include such features as scalloping the low water shoreline, placing large rock at the toe of the revetment, increasing the size of the rock over that required for hydraulic stability, adding short spurs to the revetment, adding planting baskets or eco-pockets, or building stepped revetments, with a bench for planting riprarian species.

7. Emergency Construction or Repair Practices

7.1 General

Emergency construction or repair includes both the planning and organization carried out prior to a flood as well as the construction work completed during the flood. Pre-flood planning is often a critical component of emergency repair. Design of riprap sizes, estimation of volume required per unit length of bank, and stockpiling of appropriate reserves in a central location are key tasks that can be undertaken prior to the emergency. Where sites have failed in the past, or where they are expected to be unstable as a result of channel shifting, riprap can be stockpiled nearby. This allows rapid emergency response and eliminates the difficulty of moving the rock to the site rapidly enough to manage erosion damage.

A suitably sized excavator, with a hydraulic thumb, should be used to place the riprap. Dumping of rock from the top of the bank is often a waste of limited resources, using far more rock to stop erosion that would be required if it were placed. If it is not safe for a machine to work near the top of the bank, a windrow of rock may be placed behind the bank that will launch as the bank retreats. This may be the only feasible option to stop bank erosion. Much larger volumes per unit length of bank are required than would normally be expected based on standard designs. Alternatively, repair work could be completed as water levels drop after the peak of the flood.

Identifying the start and end points of the emergency construction works for protection of eroding banks, particularly those have never been protected, is often difficult. Emergency works should start at a hard point or at some distance upstream of the eroding area. However with rapid bank retreat, erosion may quickly outpace placement of erosion protection. Water Management Branch (1999b) recommends construction of a key trench at the upstream end of the work as a first priority to help prevent outflanking of the revetment. Emergency spur construction may also be considered as an alternate approach. Another issue is reconstruction of emergency works after the flood. Emergency works are usually not built to the standard that would be recommended under other circumstances. Rock sizes may be smaller than design, filter layers are usually missing, and toe protection is either not installed or may be of insufficient volume. As part of post-flood inspections, design criteria for the protective work should be re-assessed and the works upgraded, as required.

7.2 Emergency Repair of Revetment Washouts

The California Department of Transportation (Racin 1997) recommends an emergency repair procedure for road washouts. Suitable rock riprap is stockpiled on site, or nearby, and repair starts with construction of a toe berm by an excavator working near the river or from the top of the bank. The berm joins with the upstream and downstream revetment sections and is raised high enough to reduce velocities on the eroded bank.

The bank is then reconstructed in lifts using local material (without de-watering); a very tough filter fabric is placed on the fill, and then riprap is placed directly on the filter fabric to design dimensions. Bedding layers that are usually recommended between the rock and the fabric are omitted.

A similar technique is often used for emergency repair in British Columbia. A toe berm, is constructed moving from upstream to downstream, and starting at a stable section of bank, as the first step. The toe berm is constructed of the largest available rocks, individually placed by an excavator. Once stable, the berm is continued above water level to grade, using normal sized rock.


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8. Maintenance

8.1 General

Riprap revetments require inspection and survey, particularly after major floods, in order to check their performance and upgrade them if necessary. Where appropriate, underwater works should be inspected, either by detailed soundings or by divers.

Many streams in British Columbia are unstable and continually shift their point of attack on banks. Frequent inspections are required to identify minor damage and specify repairs before major damage occurs. Ideally, inspection of the revetments should be part of a formal monitoring program that also includes periodic technical review and re-assessment of the design criteria of the bank protection works.

8.2 High Water Patrols

Water Management Branch (1999a) provides standard forms and procedures for high water inspections. While these forms emphasize dike inspections they also include sections to describe problems with bank protection, such as loss of rock, settlement, or slumping. These forms are suitable both for inspection of bank protection works associated with dikes and also for other bank protection works.

8.3 Post-Flood Inspections

High water patrols will identify loss of rock or slumping of riprap revetments. Post-flood inspections, preferably during low water levels, will identify loss of rock from the toe of the revetment. Detailed surveys or diver inspections may be required if the toe extends into deep water.

These inspections should examine launching of toe rock, and if it has occurred ensure that an adequate volume of rock was placed in the toe
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berm or launching apron. Toe rock may not be visible as it may have launched into scour holes formed during the flood peak, which have subsequently re-filled with bed material deposits. If rock has been lost from the toe, or if scour is deeper than anticipated, it would be prudent to add additional riprap. It may also be valuable to re-assess the required rock sizes and gradation based on observations following a large flood.

8.4 Minor Repair

It is critical that small slumps or displacements of rocks from revetments are repaired soon after they are observed. Large pieces that project from the bank or holes in the protective layer can result in further damage leading to progressive failure of the revetment. An excavator with a hydraulic thumb is the best equipment to re-arrange rock, adding additional rock if needed.

For large slumps or loss of rock from a continuous section of revetment, it is important to assess the cause of failure before repair. A re-evaluation of the design criteria and the recommended rock sizes and gradation may be in order, particular if channel shifting has changed the angle of attack on the bank. In these circumstances, grouting might be considered as a reinforcing measure if the bank is to be re-constructed from salvaged rock.

If the revetment failure is deep and appears to originate as a rotational slump on a failure plane well behind the revetment and filter layer, it may result from instability in the bank materials. In this case, a geotechnical engineer should be engaged prior to reconstruction of the bank. Note that failure of the rock revetment from toe scour and subsequent rapid erosion of the underlying bank material may create a deep pocket that appears to be a slump

8.5 Riprap Stockpiling

Stockpiling of riprap is an important part of a strategy for repairs of eroding unprotected banks or revetments. Riprap should be sized for the "worst" conditions that might occur on streams in the region. It may be worthwhile to stockpile very large, uniformly-graded rock separately, as it is often required for toe construction during emergency works.

Specifications for stockpiled well-graded riprap should provide larger sizes than strictly required based on expected velocities and depths, to account for segregation and breakage during stockpiling and transportation.

8.6 Management of Vegetation

Trees, shrubs and other vegetation growing through the riprap – excluding plants in eco-pockets grown as part of mitigation – may require treatment in order to provide access for inspections and to ensure that large trees do not displace or damage riprap. MELP and DFO (1999) provide advice for these activities

9.
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If you have comments, suggestions or wish to share your experiences, please contact the

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RIPRAP DESIGN AND CONSTRUCTION GUIDE

APPENDIX A
TECHNICAL REPORT

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1. INTRODUCTION

1.1 PURPOSE OF THE TECHNICAL REPORT

The purpose of this Technical Report is to assist Diking Authorities, local authorities, or other agencies in the design and construction of slope or bank protection works. It provides the technical details on the guidelines for riprap design and construction in British Columbia that are not included in the *"Riprap Design and Construction Guide"*. Similar to the guide, the Technical Report addresses design and construction of repairs to existing works, design and construction of new works, and construction of emergency works.

Other guides issued by the Ministry of Environment, Lands and Parks (MELP) may assist in the design and construction of bank protection. Both the *"Guidelines for Management of Flood Protection Works in British Columbia"* (Water Management Branch 1999b) and the *"Flood Planning and Response Guide for British Columbia"* (Water Management Branch 1999a) provide additional information related to the development and management of flood protection works. The *"Environmental Guidelines for Vegetation Management on Flood Protection Works to Protect Public Safety and the Environment"* (MELP and DFO 1999) also may have implications for some features of design. The *"Guidelines for Management of Flood Protection Works in British Columbia"* recommends professional engineering advice for major repairs, such as dike and bank protection rebuilding, and for permanent repair work after emergency conditions or construction.

1.2 DEFINITIONS

Bank Erosion is "the removal of soil particles or a mass of material from a bank surface, primarily by the action of flowing water. Other factors such as weathering, ice and debris abrasion, chemical reactions, and land use on the top of the bank may also contribute to erosion."

Bank protection works are "treatments of slopes of dikes, and banks of streams, lakes or other water bodies by placement of riprap or other forms of protection to prevent erosion by surface runoff, stream flows or wave action."

Blanket (bank) revetment is "erosion-resistant materials placed directly on a prepared stream bank to protect it from erosion."

Dikes are "embankments, walls, fills, pilings, pumps, gates, floodboxes, pipes, sluices, culverts, canals, ditches, drains or any other thing that is constructed, assembled or installed to prevent flooding of land."

Revetment is "rigid or flexible armour placed to prevent lateral erosion or scour."

River training consists of "engineered works, with or without revetment, that direct or lead flow into a prescribed channel."

Riprap is "an engineered layer of graded broken rock pieces placed for bank protection."

Scour is "erosion or removal of streambed material usually considered as including local scour and long-term bed degradation."

Spurs are "permeable or impermeable structures that project into a channel from the bank to alter flow direction, induce deposition, or reduce flow velocities along the bank."

1.3 LEGISLATION AND REGULATORY CONTROLS

We refer the reader to Chapter 2 of the *"Riprap Design and Construction Guide"* for details.

1.4 STRUCTURES AND MATERIALS

The Technical Report addresses the design and construction of erosion protection for river banks and dike slopes and is directed to erosion resulting from flow currents: erosion protection from waves is not considered. The erosion protection structures that are discussed in this report are classified as either "blanket revetments" or "spurs". Blanket revetments, constructed of broken rock or other material, are laid on suitably-shaped and aligned slopes and usually parallel the flow. Spurs are short structures, constructed of broken rock or other materials, which project from the bank and are often aligned roughly perpendicular to the flow. Only a brief description of spurs is provided.

Riprap is the material most often recommended for construction of the blanket revetments or spurs and is the most commonly used bank protection material in British Columbia. In high-velocity streams, riprap may be grouted to improve its resistance to movement. In some parts of BC, and in other jurisdictions, other materials are used for construction of erosion protection: concrete blocks, gabions, concrete bags or mattresses, jacks or similar structures, articulated concrete slabs, rigid pavements, timber piles or fences, bio-engineering or woody debris such as trees, root boles, or brush. Design of blanket revetments or spurs with these other, less common, materials is not considered in this report, but references are provided to other documents.

Some advantages of riprap are that it is highly durable, has a long history of use, and is available at a reasonable price in most of British Columbia. Structures built from riprap are flexible, do not fail under minor shifting, and can be easily constructed and repaired. Some limitations of revetments and spurs are that:

- blanket revetments are not suitable for steeply sloped banks (greater than 1V:1.5H) that cannot be re-graded to a lower angle;
- revetments or spurs may cause opposite bank erosion if they encroach substantially on the stream;
- construction may damage aquatic or riparian habitat resulting in costs for mitigation or compensation,
- construction is often limited to a narrow time period during the fisheries window, and,
- some people find riprap revetments aesthetically unappealing.

1.5 TYPICAL DESIGN AND CONSTRUCTION PROBLEMS

Typical problems encountered by a Diking Authority or other local authority that are covered by this report are:

- minor repair of existing embankments, typically requiring less than 100 m^3 or so of riprap;
- major repairs of existing embankments, often requiring reconstruction of the bank line and reconstruction or replacement of several hundred m^3 of riprap;
- extension of existing embankments, upstream or downstream, to address erosion;
- erosion protection for natural banks to prevent damage to dikes or flood protection structures or other facilities; and
- emergency erosion protection placed during floods.

Emergency works should normally be reviewed and assessed after the flood emergency and, if appropriate, re-designed and re-constructed to meet the guidelines in this report.

The two flow charts on the following pages summarize the design process both for minor repairs, and for major repairs or extensions to existing revetments. The subsequent chapters of the report provide details on the steps that are required.

In some instances, restoration following a flood may require other river engineering works in addition, or instead of, embankment reconstruction and protection. Gravel removal, bank re-alignment or re-construction on a new alignment, river diversion or major training works may be required to restore damage and prevent future erosion of flood protection works. Where severe damage to erosion protection works occurs, or where major changes are evident in the channel and its characteristics, a review is recommended by a professional engineer, with an appropriate speciality, before proceeding to design and construction.

1.6 LIMITATIONS OF THE REPORT

The Technical Report is based on current research and practices and may not be appropriate for all circumstances. Limitations of the various recommended procedures and techniques are indicated throughout the guide, where they are known.

The report does not provide a general discussion of theoretical concepts applicable to river engineering or describe other approaches to river management, though it does briefly describe some aspects that are appropriate to the design and construction of riprap.

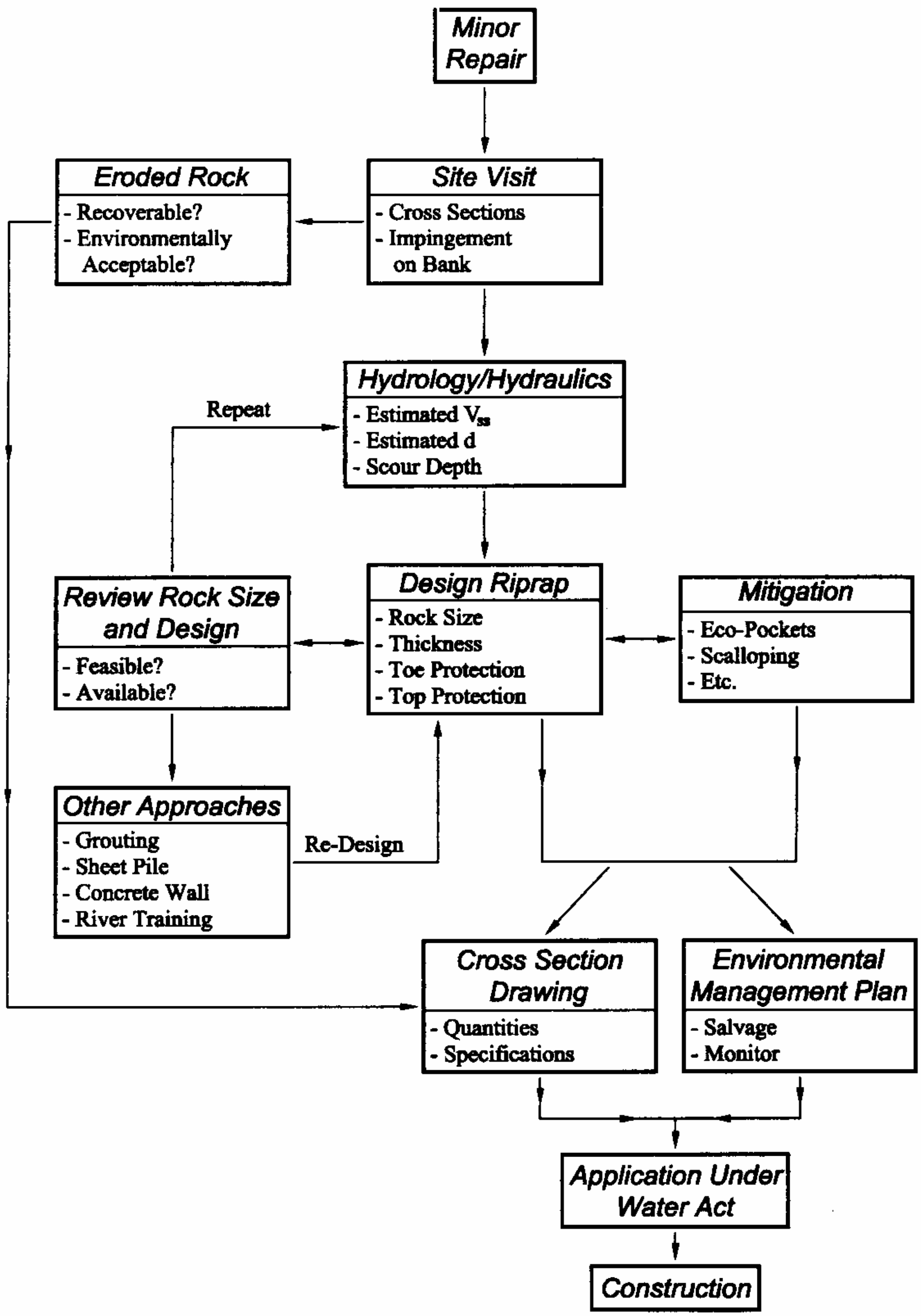

Figure 1-1: Flowchart for Design of Minor Repairs

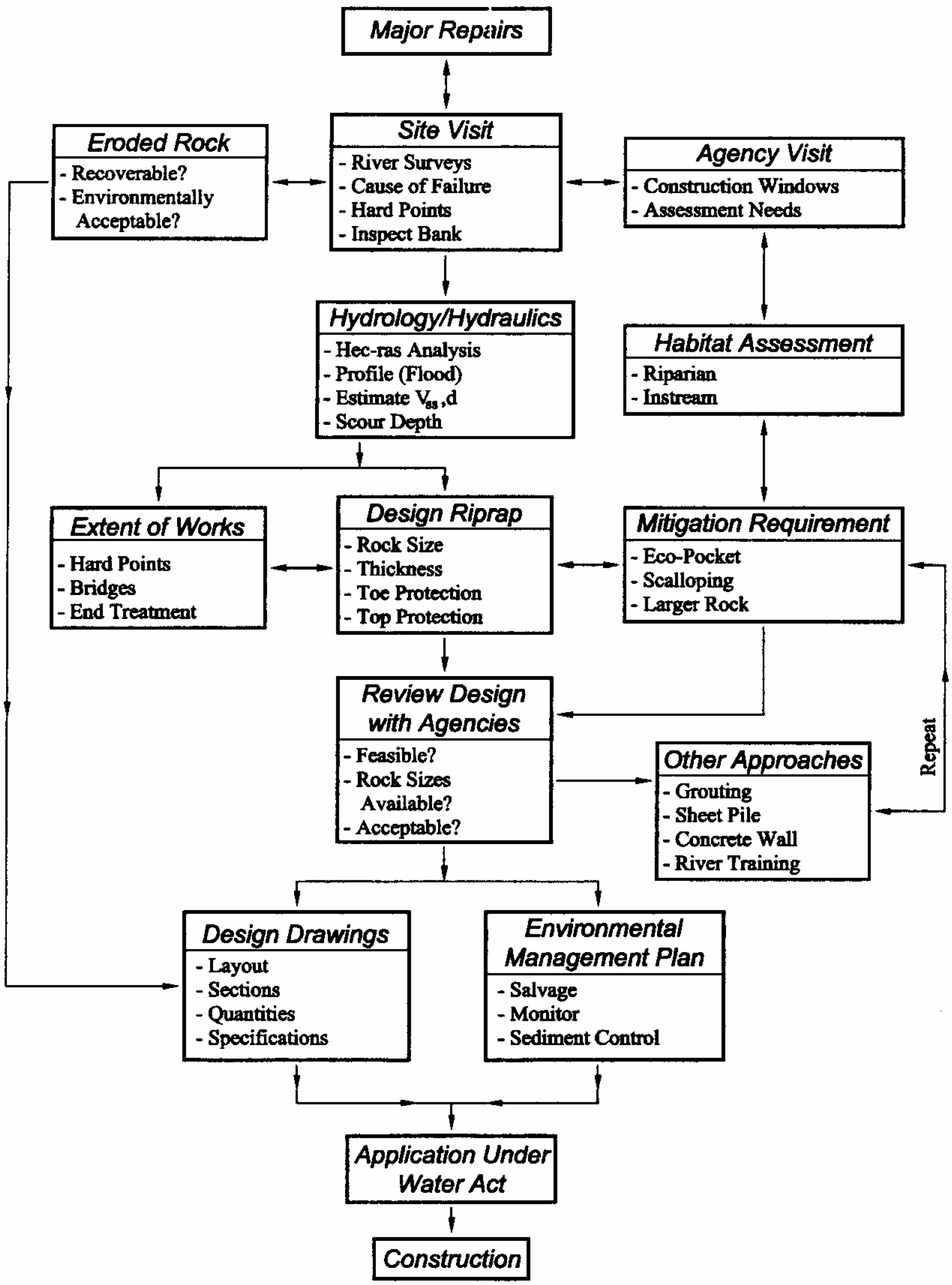

Figure 1-2: Flowchart for Design of Major Repairs

2. DESIGN AND CONSTRUCTION PRACTICES IN BC AND ELSEWHERE

Chapter 2 briefly summarizes typical design and construction practices in British Columbia, Alberta, and the western United States, based on discussions with a few individuals and a review of reports, documents, and websites. It is not intended to be a detailed survey of practices in other jurisdictions.

2.1 MINISTRY OF ENVIRONMENT, LANDS AND PARKS

The Ministry's riprap design procedures are found in *"Design and Construction of Rock Riprap Bank Protection"* prepared by Woods (1982). Rock size is selected from a chart that relates velocity against the stone to the equivalent mean diameter of the stone, for side slopes ranging from 1V:12H to 1V:1H. Velocity against the stone is calculated by adjusting the mean velocity in the channel, as recommended by California Highways (1970) and repeated in other publications since then. The same chart is in the Ministry of Transportation and Highway's *"Highway Engineering Design Manual"* (MOTH 1999) and is based on curves originally published by the American Society of Engineers in 1948. For side slopes of 2H:1V, the design curve is very similar to one published by Searcy (1967) - see Neill (1973).

The Ministry also provides a reference gradation curve. A particular gradation can be designed by drawing a curve parallel to the reference, passing through the median (D_{50}) size obtained from the above-mentioned chart. Diameters are converted to rock weight on the basis of an equivalent spherical relationship and the gradation is expressed as percent finer, either by weight or diameter. The reference curve provides a typical ratio of D_{85}/D_{15} of about 3.

Woods (1982) provides guidance on project planning, design of revetment thickness, side slopes and the design of filter layers. His manual also provides advice on construction, quality control, and maintenance and also provides typical specifications for a "light" and "heavy" riprap.

2.2 MINISTRY OF TRANSPORTATION AND HIGHWAYS

The Ministry's riprap design procedures are contained in their *"Highway Engineering Design Manual"* (MOTH 1999) in a chapter on Hydraulics and Structures. Design is based on a chart that relates riprap class (expressed as the median weight of rock) to the velocity against the bank for side slopes ranging from 1V:1H to 1V:12H. The velocity against the bank is adjusted from the mean stream velocity, at the design discharge, by applying one of three factors that reflect the severity of impingement of the flow on the bank, following procedures recommended by California Highways (1970). The chart does not provide for interpolation; instead, the next larger riprap class is selected.

Section 205 of the Ministry of Transportation and Highways *"Standard Specifications for Highway Construction"* provides specifications for various riprap classes. It defines nine classes, ranging from 10 to 4,000 kg median weight, and provides a weight-based gradation defined for the 85%, 50% and 15% quantiles. It also specifies a nominal thickness measured at right angles to the slope for each riprap class and indicates equivalent average dimensions, based on a spherical conversion (Appendix 1A).

Section 205 also provides standard specifications for the construction of machine-laid and hand-laid riprap revetments.

2.3 MINISTRY OF FORESTS

Based on discussions with Ministry personnel, it appears that the Ministry of Forests does not have a standard riprap design procedure. Recommendations for design of revetment for bridge abutments and approaches, as well as abbreviated specifications, are included in the *"Forest Service Bridge Design and Construction"* (Ministry of Forests 1997). The *"Stream Crossing Guidebook for Fish Streams"* (Poulin and Argent 1997) prepared with the BC Ministry of Employment and Investment, BC Ministry of Environment, Lands and Parks and the Federal Department of Fisheries and Oceans provide advice on sizing and design of rock riprap protection that conflicts to some degree with that of other Ministries.

2.4 ALBERTA (ALBERTA ENVIRONMENT, ALBERTA TRANSPORTATION AND UTILITIES)

A search of the Alberta Transportation and Utilities *"Procedure Manuals"* did not reveal one that provided design and installation advice for riprap protection. Reviews of riprap design and construction procedures were prepared for Alberta Environment (**nhc** 1982) and Alberta Transportation and Utilities (**nhc** 1988) but these reports have not been widely circulated. Alberta Environment does not have a standard riprap design manual.

Standard practice in Alberta often follows the *"Guide to Bridge Hydraulics"* (Neill 1973), which recommends three stone riprap gradations– called "Classes I, II and III" – appropriate for maximum local or bank velocities of up to 3 m/s, 4 m/s or 4.5 m/s and side slopes of 2H:1V. The recommended gradations are based on weight and converted to equivalent spherical diameters for a standard specific weight of 2.65. These classes have also been used as standard gradations for some projects in British Columbia.

2.5 WASHINGTON, OREGON AND CALIFORNIA

The US Army Corps of Engineers (USACE 1991), Federal Highway Administration (Brown and Clyde 1989) and California State Department of Transportation (CALTRANS 1997) all have their own detailed riprap design and construction procedures. The procedures developed by a particular agency are normally used to design bank protection projects that they fund.

The California Department of Transportation now recommends a somewhat unusual approach to design of riprap revetments (CALTRANS 1997). After predicting a minimum stone weight from the bank velocity, and adjusting for specific gravity and bank slope, the revetment is designed as a series of layers overlying a geotextile fabric. The median weight of the standard riprap class for the outer layer is selected to exceed the minimum stable stone weight. Once the outer layer is specified, a standard table then recommends up to two inner layer riprap classes and one or two backing layer riprap classes for the revetment. The report also provides construction methods and specifications for rock riprap, geotextile fabrics, and grouted rock riprap, as extracted from the California Highway Design Manual.

The California Department of Transportation also provides recommendations for emergency repairs through a memorandum titled "Emergency Repairs of Road Washouts along Streams with a History of Washouts" (Racin 1997). Their emergency procedures are based on their standard riprap design procedure and include recommendations for preparation prior to storms and for construction procedures for road reconstruction. The procedure, which is based on construction of a toe berm prior to placement of fill, is discussed further in Chapter 6 of the Technical Report.

3. RIP RAP DESIGN

3.1 RIPRAP CHARACTERISTICS REQUIRING DESIGN

This document provides guidance on the design of the following characteristics of riprap for bank protection works:

- Length and alignment of revetment
- End treatment and top treatment of revetment
- Rock shape, size, gradation and blanket thickness
- Bank slope and the vertical height (extent) of protection
- Toe treatment, or protection against scour or undermining
- Filter layer, either gravel or geotextile
- Grouting

The first two items refer to the layout and design of revetments or spurs. When repairing riprap revetments it is generally unnecessary to consider these two items in detail. However, they are key issues in the successful design of works for banks not previously protected, in re-design of works following their failure, and in long extensions of existing revetments. Unfortunately, the required length and alignment of the revetment or spurs fields are highly dependent on local conditions and river behaviour. It is difficult to provide general guidance applicable to all the river situations that will be encountered in British Columbia. For major projects, consultation with a professional engineer that specializes in river engineering works is recommended.

The next four items in the above list refer to the design of the revetment in cross section (Figure 3-1). Detailed advice is provided herein, contingent an adequate knowledge of the hydrology, hydraulics and bank materials of the stream.

Only a general discussion of grouting of riprap is provided, with references to design procedures. Grouting may provide a satisfactory solution to repair of revetments where undersized rock has failed under high, imposed velocities.

A brief discussion of the design features of spurs is included in the final section of this chapter. Incorporating environmental mitigation into riprap design is discussed in Chapter 5.

3.2 RESISTANCE TO EROSION OF ROCK RIPRAP

The characteristics of rock riprap affecting resistance to erosion include stone size, shape and weight, stone durability, gradation and thickness. Local stream characteristics also strongly affect the stability of riprap revetments. Local scour, as affected by stream characteristics and bed materials, requires that protection be provided against undermining of the toe of the revetment. Channel slope and alignment affect the degree of impingement of flows on the bank and the hydraulic conditions that the rock must resist.

Blodgett (1986) identified four modes of riprap failure, as described on the second following page:

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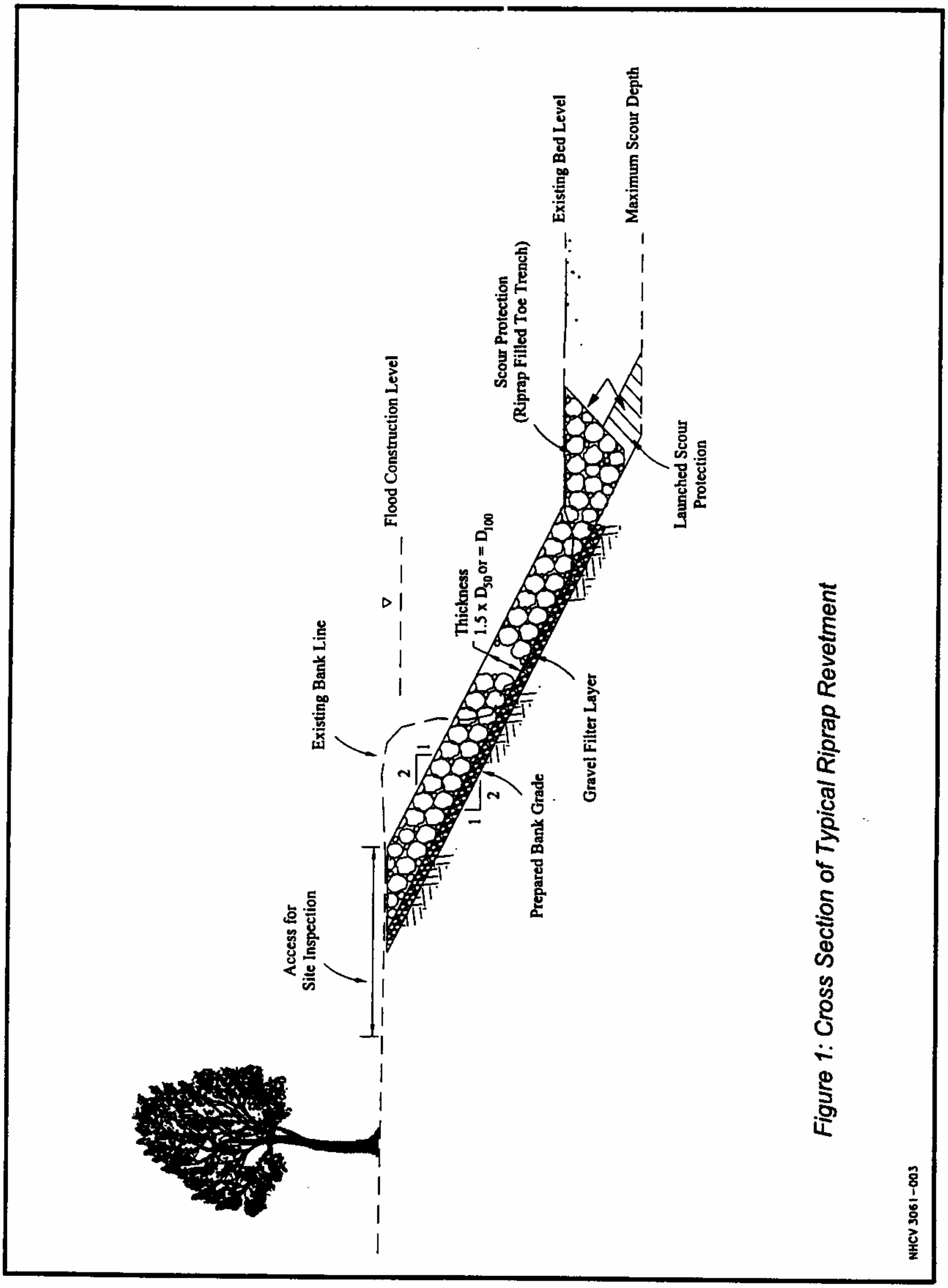

Figure 1: Cross Section of Typical Riprap Revetment

- Particle erosion, involving the removal of individual rocks by velocities or tractive forces. It may be a result of under-sized rock, debris impact, or changes in the channel that result in direct impingement of flows on the bank. Side slopes that are too steep often cause failure of the revetment. Often the largest stones remain on the bank while the smaller eroded rock may be deposited along the nearby streambed, directing flow back towards the bank.

- Translational sliding, consisting of sliding of the riprap along failure planes parallel to the side slope. It generally results from toe scour and loss of support at the base of the revetment and is aggravated by steep slopes and high pore pressures in the slope behind the riprap. Failure by toe scour is thought to be the most common cause of failure of revetments.

- Modified slumping, consisting of movement of the riprap blanket without failure or displacement of the toe. The most probable cause is too steep a side slope.

- Slumping, caused by a rotational failure of the bank underlying the rock revetment. High, steep banks composed of cohesive sediment are particularly susceptible, if the underlying materials are unstable.

The design of riprap to resist failure may be based on successful local experience on the stream, empirical guidelines, or hydraulic relationships. In this report, the design approach is based on the hydraulic characteristics of the stream or river and may require detailed hydrologic and hydraulic analysis as part of the design process. However, for many small streams, local experience or empirical guidelines may also provide successful designs, particularly where detailed knowledge of the hydrologic or hydraulic character of the stream is difficult to obtain or the project is too small to justify detailed engineering design.

A conservative approach should normally be taken to design. Usually, riprap is designed for the most severe conditions along the reach to be protected and these dimensions are then used along the entire reach, and usually extended to the top of the bank. This approach may result in over-design of part of the works for the existing conditions. However, it is possible that the locus of the highest velocities, as well as the impingement point of the river on the protected bank, will change over time requiring that the entire bank protection works be designed to resist them. It is theoretically possible to vary the design of the riprap according to the expected hydraulic forces but the apparent cost saving from this approach may be largely offset by the additional costs for design and construction.

3.3 Background to Design

The extent of review and analysis required prior to design of riprap characteristics depends in part on the nature of the project. For repair or extension of existing revetments the design process may be relatively simple: usually, hydrologic and hydraulic analyses have been previously completed, and the length and alignment of the rebuilt bank will be partly or completely fixed by the remaining revetment. However, it is important to determine the reasons for failure– was it caused by inadequate rock sizes, lack of toe protection, or changes in channel alignment and flow impingement? Any deficiencies should be addressed in the re-design and re-construction of the revetment. Surveys of the eroded bank, and a field visit, are minimum requirements prior to design.

When designing revetment for a previously unprotected bank, it is likely that all, or nearly all, of the steps outlined below will be required for a successful design.

Field Visit

A site inspection can provide information that can not be obtained from maps and air photographs. We recommend photographing the site, interviewing maintenance personnel or local residents, and identifying typical bed and bank materials. We also recommend inspecting the banks and river channel upstream and downstream of the site to identify the extent of recent erosion, potential hard points (inerodible materials along the bank) and the general behaviour of the river near the site.

Channel Surveys

As a minimum, we recommend cross-section and layout surveys of the eroded stream bank and adjacent streambed. For many projects, cross sections of the stream channel and floodplain are also required. If the stream has been previously surveyed as part of design of bank protection works or floodplain mapping, we recommend re-locating and repeating surveys along the previous cross section alignments. Otherwise, the layout of the cross sections will depend on the hydraulic analysis to be done. For uniform-flow calculations (where these are justified) a few cross sections are required to establish typical river cross sections and the streambed slope. Where gradually-varied flow analysis (HEC-RAS) is required, the engineer undertaking the work should lay out the required cross section surveys on a map or air photograph, based on site observations.

Channel Stability Analysis

Maps, air photographs, bed and bank material descriptions, channel surveys, design briefs for floodplain mapping from MELP, and previous studies for bank protection may all provide valuable information on channel characteristics and behaviour. Maps and air photographs in particular can provide a historic perspective on channel shifting and instability. USACE (1994), *"Channel Stability Assessments for Flood Control Projects"* provides details on analytic techniques.

Hydrologic Analysis

Hydrologic analysis, either of a local WSC gauge record on the stream, or of regional flood characteristics, is required to predict the design discharge for the stream. In British Columbia, this is almost always based on the 200-year maximum instantaneous discharge. Design briefs for floodplain mapping, or previous engineering studies for bank protection works, may already provide a suitable design discharge.

Department of Public Works (1999) provides recommended guidelines on flood frequency analysis for gauging stations; Watt et al (1989) provide general guidelines on hydrologic analysis. The level of effort for hydrologic analysis should be closely related to the value of the project – stringent analyses are required for projects of major public significance, but lesser efforts are usually appropriate for local bank protection projects.

Hydraulic Analysis

The purpose of the hydraulic analysis is to predict, for the design discharge or other discharges, the hydraulic parameters needed to design the rock revetment or spur, including water levels, velocities and depths. We recommend predicting these parameters on the basis of a one-dimensional numerical model such as HEC-RAS, based on channel surveys and field estimates of channel roughness (Manning's n). In some circumstances, uniform flow calculations based on the Manning formula may provide adequate estimates of water levels, velocities and depths, particularly for small projects that are only of local significance.

A key aspect of the hydraulic analysis is to predict the maximum average velocity in the channel and along the bank. Although velocities often continue to increase after banks are overtopped, this may not always be the case. In some streams, downstream controls may result in velocities at the design discharge being less than at a lower discharge. In braided streams, the highest velocities may occur well below bankfull, when flows impinge directly on a bank as they pass over and around bars. Consequently, we recommend examining velocities for a range of discharges, especially where local experience indicates that highest velocities may occur below design flood.

It is also important to re-calculate design velocities and depths for the condition with the riprap revetment or spur field in place. As a rule of thumb, riprap revetments or spur fields that occupy more than 10 to 15% of the bankfull cross sectional area in a particular stream may cause opposite bank erosion or bed scour. It may also be important to re-evaluate flood levels if rock riprap is extended across most of, or all, the channel bed. Particularly in small streams, the increased roughness may lead to higher design water levels.

SCOUR ANALYSIS

A key requirement in the design of riprap revetment is to adequately protect its toe from undermining and failure by scour, where this refers to a lowering of the channel bed below it normal level. Scour depths predicted from the hydraulic analysis are required in order to design toe protection.

Scour as discussed below refers to local deepening of a stream channel associated with bends, changes in flow direction, obstructions, constrictions, sills, control structures, abutments, piers or other local conditions. In addition, overall bed lowering may result in some cases from long-term degradation, perhaps downstream of a large dam or from the effects of long-term gravel mining as described by Galay (1983). Such bed lowering due to degradation should be added to the local scour to predict a total scour depth for revetment design.

The following recommendations are based on a proposed revision of the *"Guide to Bridge Hydraulics"* (Neill 1973). Estimation of scoured depths near banks and channel control works in large alluvial rivers was addressed by the "regime" literature from the Indian subcontinent in the early 20th century. This approach has been summarized by Inglis (1949), Blench (1957, 1969) and Joglekar (1971), among others. Maximum scoured depths (below flood water level) were treated as multiples of "regime" depth, which can be viewed as a natural average depth for a specified flow. On the basis of field observations, multipliers were recommended for various situations and features. Some Canadian field data have been analyzed in similar terms (see for example Neill 1976; several papers in Harrington and Gerard 1983; Galay et al 1987). Breusers and Raudkivi (1991) refer to various laboratory studies on guide banks and spurs, and suggest a somewhat similar approach for practical estimation.

The following method based on Blench (1969) is adapted with slight modifications from Neill (1973):

1. Estimate the average (design) flood discharge intensity q_f (velocity x depth) at the location of the feature in question. Generally, q_f is estimated as total discharge divided by net depth-averaged width at the location.

2. Calculate a form of "regime" depth corresponding to the flood discharge intensity q_f :

$$y_f = (q_f^2/F_{b0})^{1/3}$$

   where F_{b0} is an empirical parameter dependent on bed-material grainsize as described in Blench (1969).

3. For purposes of scour protection design, estimate maximum scoured depth below flood level at the feature in question as Z x y_f, where the multiplier Z may range as follows:

flow parallel to a bank	1.5 to 2.0
flow impinging directly on a bank	2.0 to 2.5
nose of a guide bank or spur	2.2 to 2.8

These ranges of Z leave considerable scope for judgement (see also Galay et al 1987). Local experience based on measurements at sites with deep scour, or physical modelling, may provide additional guidance in some cases. If the calculated results provide unexpectedly deep or shallow scour depths, we recommend consultation with a professional river engineer.

3.4 ALIGNMENT AND LENGTH OF REVETMENTS

A key question is whether the revetment or spur field should be placed along the existing bank or set out at some distance into the stream. Often, following a large flood, bank retreat or channel shifting may cause high velocities to impinge directly on the bank or it may cause a poor flow alignment into the next bend, into a bridge crossing, or into another hydraulic structure. Alternatively, the bank may have retreated close to valuable infrastructure or buildings. In such cases, re-establishing the previous channel alignment may be advisible to prevent further damage.

In these circumstances river training, involving re-aligning the channel over a considerable distance with spurs, guide banks, excavation, bend cut-offs, or a combination of techniques, may be required prior to placing bank protection. Obviously, the river training works will profoundly affect the flow conditions in the channel and the design of any revetment. General guidance for river training is provided in various publications; however, consulting a professional engineer specializing in river engineering is recommended, if these types of works are thought to be required.

It is often difficult to determine the required extent of revetment. Published guidance for the length of protection is generally lacking. As a general rule, the revetment should extend well upstream and downstream of the area that is eroded. Physical or numerical hydraulic modelling, if sufficiently detailed, may provide an indication of where velocities along the bank fall below critical values that might initiate erosion or scour.

Alternatively, inspection of the bank may identify scars from past erosion or other evidence that shows the likely extent of present erosion. In curved reaches, the scars are helpful to identify the upstream limit of erosion (Brown and Clyde 1989), but meander progression in bends makes them less helpful for determining the required downstream extent of protection. Historic studies of meander behavior using air photos or maps may be helpful in this regard. As a minimum, bank protection should be extended at least one channel width upstream and downstream of the limits indicated by erosion scars.

Brown and Clyde (1989) and USACE (1991) note, based on laboratory tests, that the highest velocities often occur just downstream of bends. They recommend that outer bank protection for severe bends should extend at least one channel width upstream and 1.5 channel widths downstream of the tangent points (Figure 3-2). However, they also note that it is difficult to apply these criteria on natural streams with mildly or irregularly curving bends, and they recommend additional analysis of site-specific factors to define the extent of protection required. As is noted in both references, a common mistake is to provide protection too far upstream and not far enough downstream.

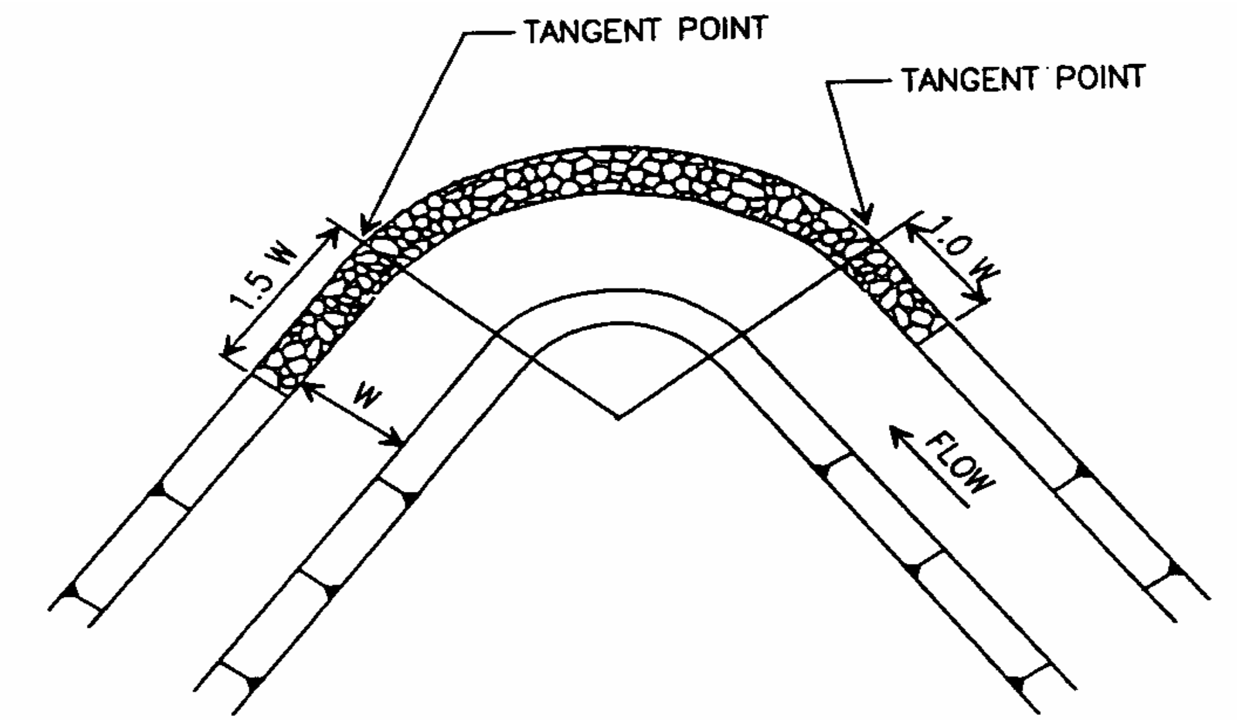

Figure 3-2: Extent of Protection Required for Symmetrical Bends (Brown and Clyde 1989)

Long term channel behavior should also be considered in determining the extent of protection. In meandering streams, the revetment can be extended downstream to a riffle or "crossing" where flow vectors cross the channel towards the opposite bank. In wandering or braided streams, consideration should be given to future bar building or changes in alignment resulting from upstream erosion, and their effect on average velocities and the locus of greatest velocities along the bank. Projection of future channel behaviour from sequences of historic air photographs, or local experience on other nearby sites, may provide the best guidance.

Channel controls or "hard points" are also useful in establishing the limits of protection. Bridge abutments often act as erosion control points, and protective works can often be ended at the abutments or integrated with the scour protection for the bridge. Brown and Clyde (1989) provide recommendations on how far to extend protection through a bridge opening depending on the contraction in the opening, or expansion downstream. Bedrock projections, existing bank protection, or erosion-resistant deposits such as tills, may also provide convenient end points.

3.5 END TREATMENTS AND TOP TREATMENTS OF REVETMENTS

The most suitable end treatment is to extend the revetment to an inerodible bank or to areas where velocities are non-eroding. USACE (1991) provides recommends on reducing the median size and thickness of the riprap in areas of lower velocities.

When the revetment terminates where velocities are still erosive, or may become erosive following channel shifting or bar aggradation, the usual end treatment involves thickening the upstream and downstream edges of the revetment, or turning ("keying") the revetment into the natural bank. These treatments often do not provide a permanent solution to erosion along the bank. However, they help reduce bank erosion rates beyond the limits of the protection and help ensure that a major flood does not outflank the revetment before emergency rock can be placed. Figure 3-3 provides details on end treatments recommended by Brown and Clyde (1989).

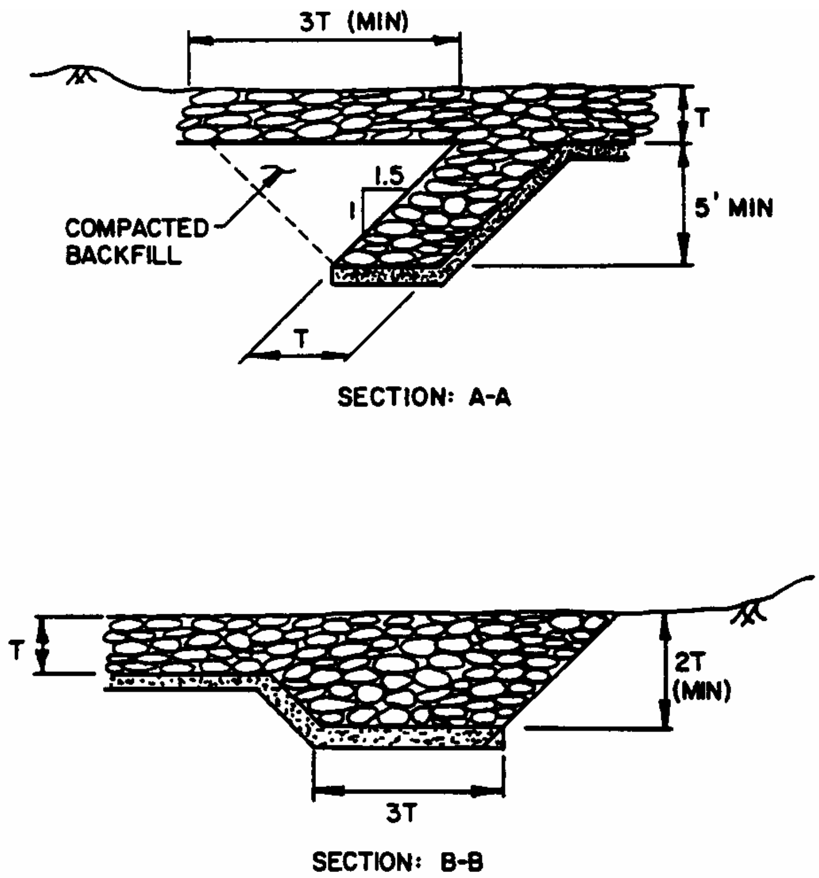

Figure 3-3: End Treatments for Riprap Revetments (Brown and Clyde 1989). Sections are through the revetment, parallel to the banktop. Section A-A is upstream; B-B, downstream.

Where revetment is applied to an embankment or other structure that can be overtopped by extreme floods, some form of erosion protection should be provided on the top of the embankment and down the back slope to prevent erosion by escape or return flows. Filter layers beneath the revetment may be designed to prevent erosion of the bank by escape or return flows passing beneath the riprap layer. Chamberlin and Meyers (1995) provide various top treatments that use sod or other materials to prevent erosion.

3.6 RIPRAP DIMENSIONS

DEFINING RIPRAP SIZE AND WEIGHT

The dimensions of individual rocks are defined by their three axes. The long axis, a, is the length of the stone. The intermediate axis, b, is then the maximum width perpendicular to the long axis. The short axis, c, is the maximum thickness of the stone perpendicular to the plane of the a and b axes. The size is usually expressed as the b-axis dimension.

Although stone size is preferred for specifying riprap dimensions, stone weight is sometimes used. The relationship of weight to nominal size depends on stone shape and also on the density of the rock. A spherical relationship is generally assumed between diameter and volume, as follows:

$$W = \frac{\pi D^3 \gamma_s}{6} \tag{3.1}$$

where D is the b-axis dimension, W is the weight of the stone, and γ_s is the specific weight (weight per unit volume). Figure 3-4 illustrates the above relationship along with one for cubes.

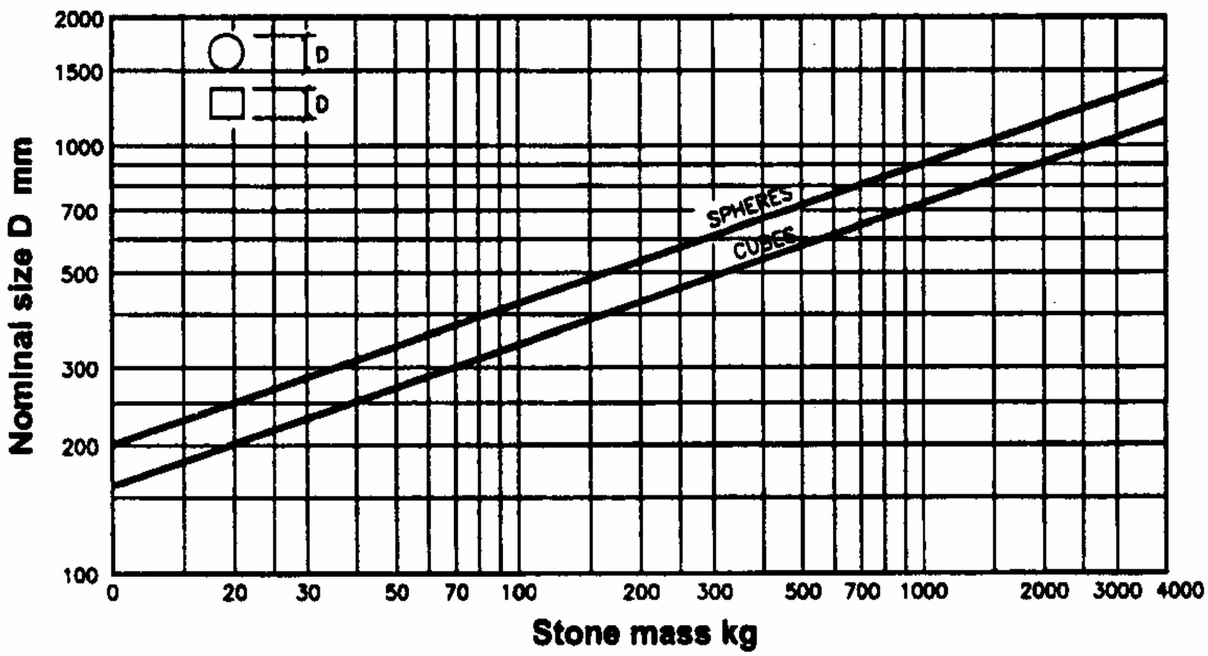

Figure 3-4: Riprap Size and Weight for a Specific Weight of 2.65

Typically, the rock used for riprap is not spherical and its shape lies between that of a sphere and a cube (Figure 3-4). In that case Eq. 3.1 will underestimate the actual weight of a rock of a specified b-axis diameter. On the other hand, if riprap is originally specified by weight, Eq. 3.1 will give a conservatively large b-axis dimension.

ROCK SHAPE

Rocks used for riprap should generally be blocky and angular or sub-angular, with sharp clean edges and relatively flat faces. It is generally recommended that rocks should be close to equi-dimensional rather than elongate, although this is not always possible. Typically, the average ratio of the long axis, a, to the thickness, c, should be less than 2. USACE (1991) further recommends the following specifications for rock shape:

1) Less than 30% of the stones with $a/c > 2.5$;
2) Less than 15% of the stones with $a/c > 3$; and
3) No stones with $a/c > 3.5$.

The reference notes that if rounded stones are used, they should be placed on slopes not exceeding 2.5H:1V, and the size should be increased by 25%, with a proportional increase in the thickness.

ROCK DENSITY

The density of rock used for riprap typically varies from about 2,400 kg/m^3 (150 lb/ft^3) to 2,800 kg/m^3 (175 lb/ft^3). A value of about 2,600 kg/m^3 is fairly common for the granitic or granodioritic rocks that are often quarried in British Columbia. Most relationships that predict rock size from hydraulic characteristics are sensitive to specific weight, γ_s. The resistance of stones to movement underwater depends on submerged specific weight, expressed as (γ_s -1). Because of this dependence, an increase in the relative density of the rock used for riprap may be more advantageous than it appears. For example, on the basis of the USACE Eq. 2A-1 **(Appendix 2A)**, a 10% increase in relative density, from 2.4 to 2.65, reduces the required nominal rock size by nearly 20%; in a similar fashion, a 10% decrease in relative density would require rock sizes to increase by about 20%.

Where the type of rock to be used for construction is not known, it is conservative to assume a density near the lower end of the range for specification purposes. If denser rock is ultimately used for construction then slightly smaller sizes can be allowed on site.

3.7 PREDICTING THE REQUIRED ROCK SIZE

The following recommendations are based on a proposed revision of the *"Guide to Bridge Hydraulics"* (Neill 1973). Numerous analytical and experimental studies have been conducted to determine the required rock sizes for given hydraulic conditions (see for example Stevens et al 1976, Ulrich 1987, Maynord et al 1989, Escarameia and May 1995, Froelich and Benson 1996). The problem is theoretically complex, because the required size for stability depends on local boundary shear stress, intensity and scale of turbulence, rock density and shape, packing arrangement and slope angle. In many formulations, shear stress is replaced by velocity and depth, which are easier to visualize and usually easier to measure or estimate.

Certainly, nearly all the most commonly-used rock sizing methods in North America are based on stream velocity, usually predicting rock size as function of the velocity against the riprap embankment, raised to a power greater than one (see recent summary in Melville and Coleman 2000). As a result, all the equations are very sensitive to the estimated bank velocity, which is usually calculated from the average channel velocity. Average channel velocities should be carefully calculated and the ratio used for converting to bank velocities selected from a site inspection. Stream behavior resulting in direct impingement of flow on the bank, where bank velocities may be much larger than the mean velocity, is often a critical factor for design.

The relative merits of the various commonly-used hydraulic relationships are described in Meville and Coleman (2000). Following the practice of the proposed revision to the *"Guide to Bridge Hydraulics"* we have adopted USACE (1991), which provides a comprehensive method for rock sizing.

US CORPS OF ENGINEERS RELATIONSHIP (1991)

Following an extensive large-scale experimental study at the Waterways Experiment Station of the U.S. Army Corps of Engineers, a velocity-based method for sizing riprap bank protection was presented by Maynord (1988) and Maynord et al (1989). A variant of the method has been incorporated in a USACE Manual for flood control channels (USACE 1991) and associated computer programs for river analysis.

Their hydraulic relationship **(see Appendix 2A)** is intended for subcritical flow in channels of fairly regular gradient and cross-section with slopes of less than 2%. Maynord (1994) provides guidance for more severe conditions, particularly for impinging flows, as occur in braided streams. USACE (1991) provides no guidance for additional allowances for supercritical flow at relatively shallow depths, or for severe large-scale turbulence resulting from obstructions, irregularities or abrupt bends. Such factors could be allowed for by increasing the safety factor S_f or by adopting alternative design procedures (Maynord 1994).

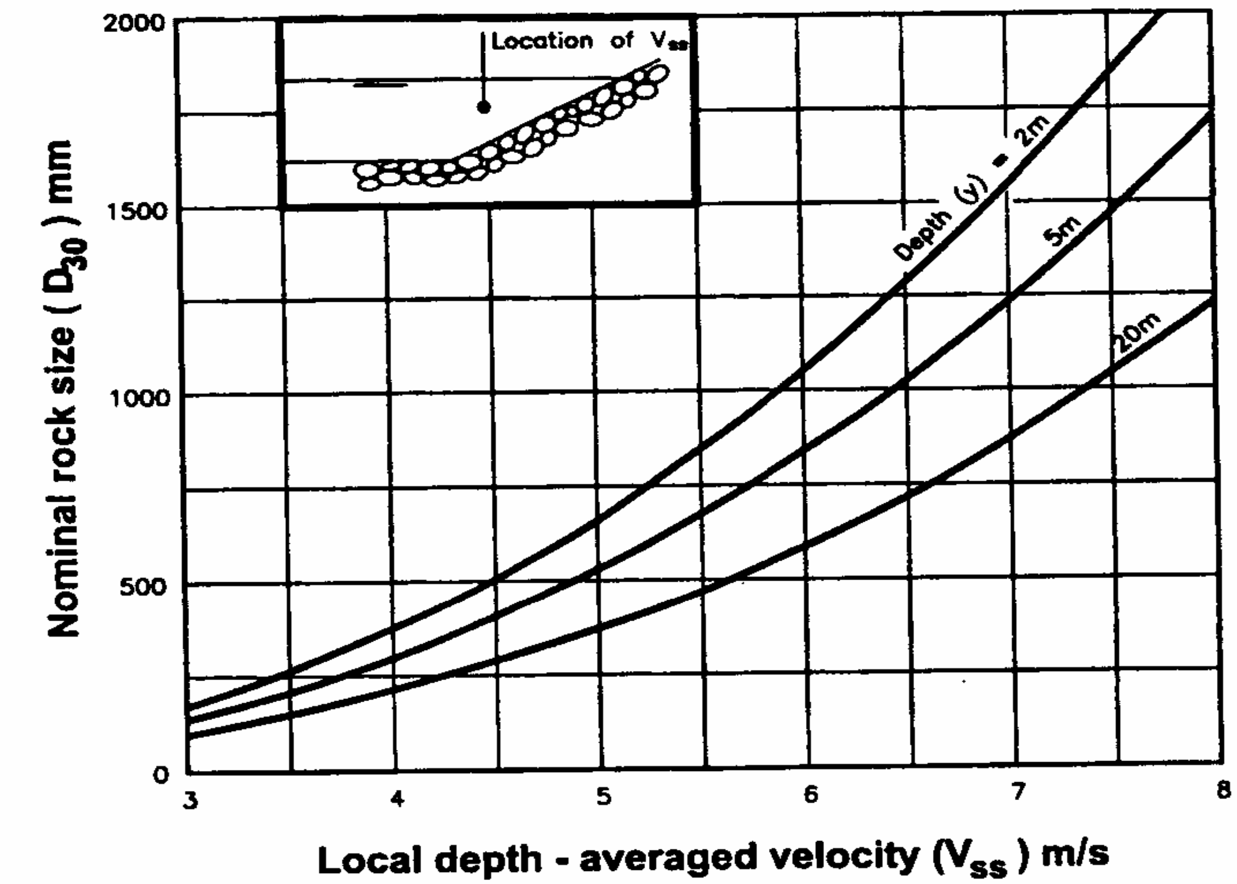

Figure 3-5: Required Rock Sizes for a Range of Velocities and Depths

The basic equation from the 1991 reference is included in Appendix 2A, which provides a detailed description of the procedure to estimate rock size. Figure 3-5, above, provides a graphic method to solve the relationship between required rock size and the local velocity, Vss, for a range of depths and a typical set of design parameters: a safety factor of 1.2; a stability coefficient of 0.3, a velocity distribution coefficient of 1.0, a thickness coefficient of 1.0, a side slope coefficient of 0.9 for a slope of 2H:1V and a specific weight of rock of 2.5 **(Appendix 2A)**.

Guidelines for selecting or calculating rock size, velocity and depth are discussed below. The required rock size can be adjusted for other values of the coefficients and factors by referring to the adjustments in Appendix 3A, or by directly calculating the required rock size from Equation 2A-1 of Appendix 2A.

Rock size D. The nominal, just-stable size D predicted by **Eq. 2A-1** is considered to be D_{30}, the size in a mixture than which 30% is finer, by weight. The use of D_{30} as the basic size criterion differs from most earlier hydraulic relationships that use the median diameter, or D_{50}. For moderately graded riprap mixtures ($D_{85}/D_{15} < 3$ or so), D_{50} is typically about 25% larger than D_{30}; consequently, the rock size selected from Figure 3-5 or calculated from **Eq. 2A-1** can be multiplied by 1.25 as an approximate adjustment. For more widely graded mixtures, a grading curve is required for conversion.

Local velocity V_{ss}. The reference suggests that local velocity, V_{ss}, for use in Figure 3-5 should be the depth-averaged velocity V_{ss} at a point inshore from the toe of the bank slope by 20% of the slope length. This parameter is difficult to estimate from ordinary river data, though USACE (1991) and Maynord (1994) note that it can be measured in the field, calculated from two-dimensional numerical flow models, or for straight or mildly sinuous reaches, estimated from partitioning of the cross section in a one-dimensional numerical flow model such as HEC-RAS and calculating the velocity distribution.

The bank velocity is commonly estimated from the average channel velocity, V_{avg}, by relationships between channel curvature and the ratio of V_{ss}/V_{avg}. Figure 3-6, below, provides such as relationship for natural channels (USACE 1991).

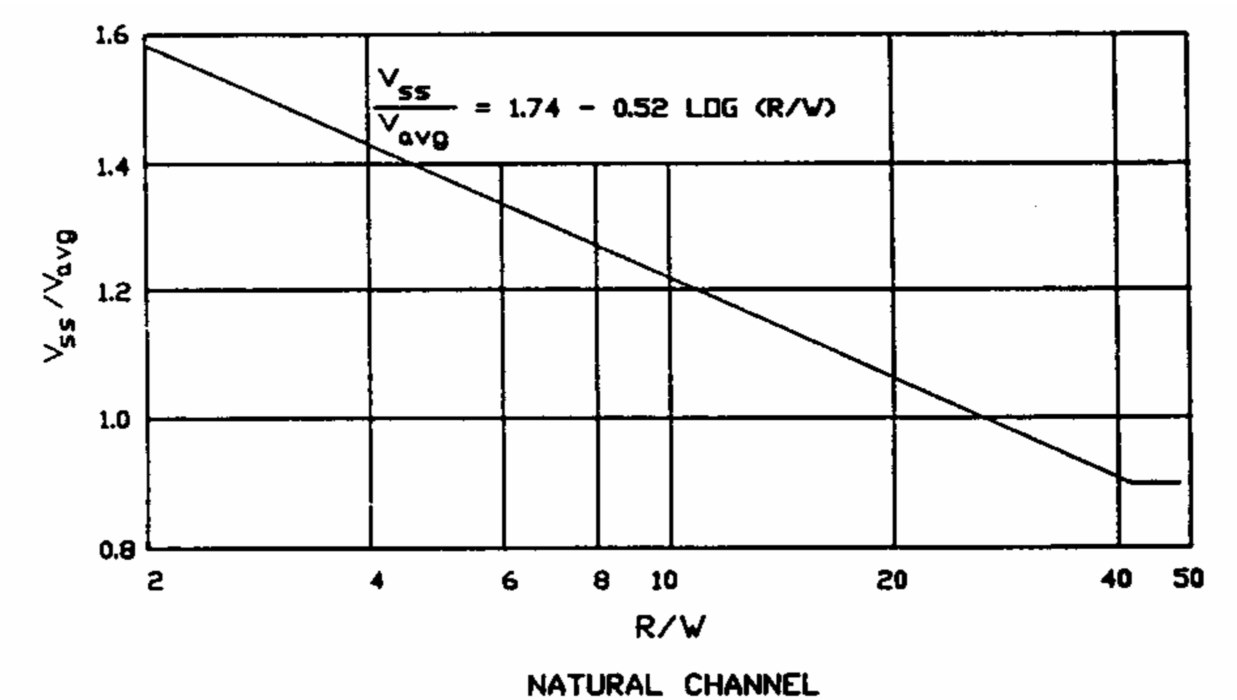

Figure 3-6: Ratio of V_{ss}/V_{avg} for Natural Bends of Various Curvatures (USACE 1991)

Values of the ratio range from 0.9 for straight natural channels to 1.6 for abrupt natural bends. As noted above, Maynord (1994) also recommends 1.6 for direct impingement on the stream bank, as often occurs in wandering or braided rivers. He also recommends increasing the velocity distribution coefficient, C_v, to 1.25. As described previously in Chapter 2, the typical ratios for estimating bank velocities from average velocities in British Columbia have been either 0.67 or 1.33.

Local flow depth y. This is given in the reference as the local flow depth near the toe of the revetment. The rock size predicted by the formula decreases with increasing depth (at a constant velocity) though the formula is relatively insensitive to depth, being inversely proportional to the 0.25 power of y. In cases of uncertainty, it is conservative to underestimate the depth. Figure 3-5 requires interpolation for depths different than shown on the three curves.

The rock size predicted by Figure 3-5 can be adjusted to other coefficients, side slopes, or specific weights, based on the correction factors shown on the graphs in Appendix 3A, from USACE (1991). In each case, the rock size is adjusted by multiplying it by all the required correction factors.

3.8 RIPRAP GRADATION

The gradation of a riprap mixture is usually characterized by the ratio D_{85}/D_{15}. In the Corps of Engineers terminology (USACE 1991), uniform riprap has a ratio of less than 1.4; well-graded mixtures fall in the range of 1.4 to 3; and quarry-run material may have ratios of up to 7. According to the reference, any of these types may be used provided that stability is assessed on the basis of their D_{30} size.

Quarry-run material may eliminate the need for an underlying filter, but for a given median size it requires a greater thickness in order to enclose the largest sizes. It also requires careful placement to avoid segregation. It should not contain silt or other fine material that could wash out and degrade aquatic habitat and, generally, the portion of gravel and sand should be less than the void volume of the larger rock, or likely less than 20% by weight. Gap-graded material is not suitable for quarry-run riprap.

USACE (1991), and most other references on riprap design, provides standardized gradations, based on $D_{85}/D_{15} < 3.0$. In British Columbia, we recommend adopting the standardized specifications provides by Section 205 of the "*Highway Engineering Design Manual"* (MOTH 1999; Appendix 1A). These meet the standards for graded mixtures described above, provide a range of standard specifications up to 4 tonnes nominal size, and are commonly produced by quarries in British Columbia. Their specifications are based on weight, converted to a dimension, by a spherical conversion.

To select an appropriate standard specification, the USACE method is used to predict the D_{30} riprap diameter, which is then converted to the required median rock diameter, D_{50}, by multiplying by 1.25. The appropriate specification is then selected from MOTH (1999) as that gradation whose median diameter is equal to or larger than the required D_{50} predicted by the USACE method. This approach will provide a conservative riprap gradation.

3.9 THICKNESS

The basic criterion is to that all stones in the gradation should be contained within the layer thickness. Oversize stones that project through the layer may cause failure by creating turbulence. Based on Brown and Clyde (1989), we recommend that the riprap thickness normal to the slope meet the following criteria:

- Not less than 350 mm;
- Not less than 1.5 x D_{50}; and
- Not less than D_{100}.

The above specifications are roughly equivalent to those recommended in the MOTH *Highway Engineering Design Manual*. USACE (1991) further recommends that thickness should be increased by 50% for underwater placement. As discussed in a later section, it may also be prudent to increase thickness where potential damage from floating debris or ice is expected.

3.10 BANK SLOPE AND THE VERTICAL EXTENT OF PROTECTION

Maximum bank slopes should be limited to no steeper than 2H:1V, except for special circumstances or cases of hand-placed, well-keyed riprap. Hand placing typically limits maximum rock dimensions to less than 350 mm, or to weights of less than 50 kg. Further limits on side slope steepness may be imposed by slope instability, groundwater flows, or rapid water level recession and piping failure, all of which should be considered in design.

If the bank is overtopped, riprap is normally continued just to the top of the bank. If the bank is higher than design water level, riprap is carried up to design water level, plus a freeboard to account for wave runup, superelevation, hydraulic jumps or other profile irregularities, floating debris, ice and surface waves. In British Columbia, the typical freeboard is 0.6 m, though there may be justification for increasing this, particularly in steep streams with critical or supercritical flow. Dotson (1991) provides a detailed discussion of freeboard practice and design considerations for the United States. Section 3.5 herein provides recommendations for treatments for banks that are subject to overtopping.

Theoretical arguments can be made for reducing the size of riprap protection with height; however, it is common to use the same gradation over the full height of protection. Additional costs for analysis and design and the production of two more riprap gradations is generally not thought to justify the potential cost savings, though further research may indicate otherwise.

3.11 TOE TREATMENT OR PROTECTION AGAINST SCOUR

Toe scour along the foot of the revetments is thought to be the most common cause of failure. Five methods used to prevent undermining are described below and illustrated on Figure 3-6:

- The slope is excavated and covered with rock riprap to below expected scour levels (Method a). This method is the most permanent, but it may be impractical or uneconomical if the lower limit is deeply buried. Extensive disturbance of the stream bed is often strongly opposed by the Department of Fisheries and Oceans or the MELP Fish and Wildlife.

- The slope is excavated and covered with rock riprap to inerodible material. The toe is “keyed” into the inerodible material to prevent unravelling of the slope and revetment failure (Method a).

- A sheetpile cutoff wall is installed from the toe of the revetment down to an inerodible material or to below the expected scour level (Method b). Such walls tend to provoke deeper local scour than armoured slopes, and often need to be tied back to deadmen or similar anchors to ensure stability. These walls may be environmentally acceptable in some channels and they have been installed on the lower Fraser River.

- A flexible "launching apron" is laid horizontally on the bed at the foot of the revetment with a thickness of about 1.5 times the desired revetment thickness (Method c). The intention is that when scour occurs, the apron will settle and cover the side of the scour hole on a natural slope. This method has been widely used for granular channel beds where deep scour is expected, and is discussed in more detail below. Aprons should be wide enough that after launching, they will extend to or beyond the limits of the deepest scour expected.

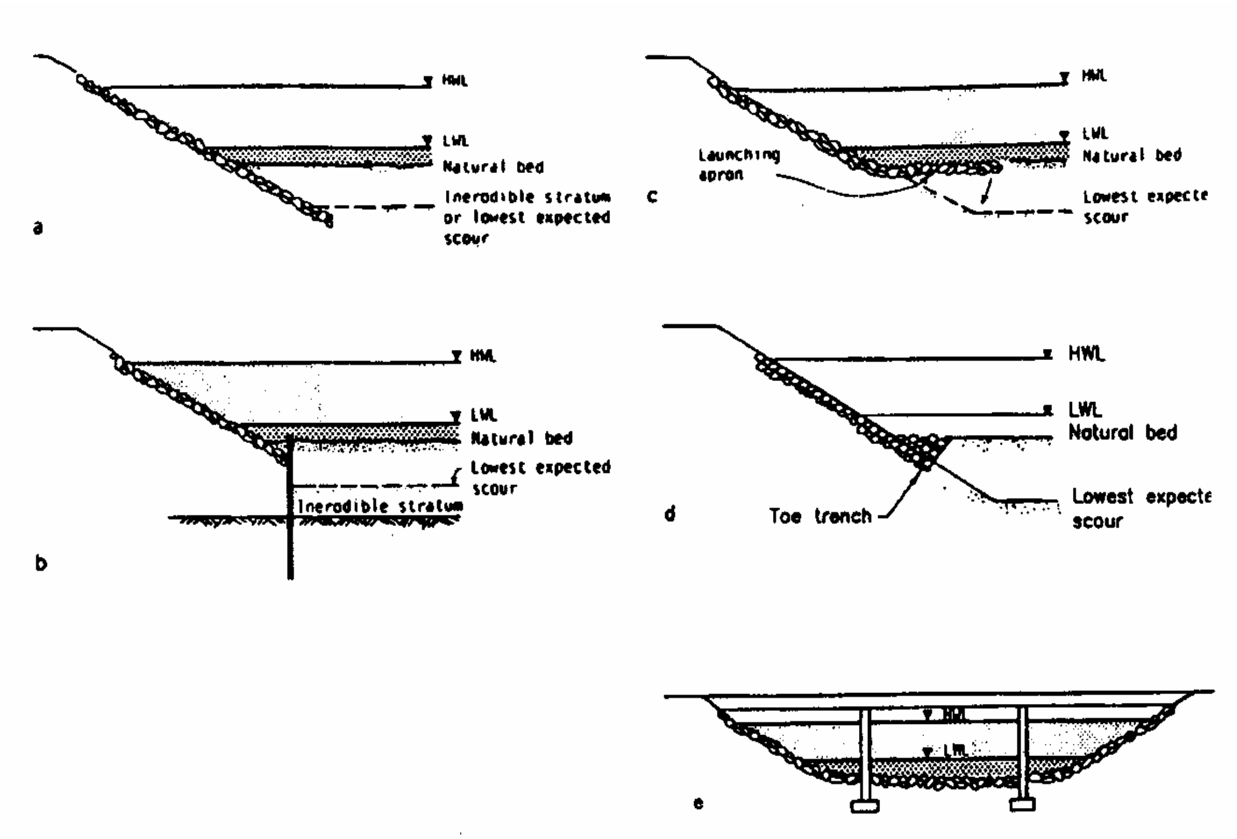

Figure 3-6: Five Methods of Toe Protection for Revetments (Neill 1973)

- A rock-filled toe trench or toe berm is provided at the foot of the slope (Method d). This is basically a variant of the launching apron since the trench material is expected to launch as scour develops. It involves less construction encroachment into the river channel. Typically, the height of the toe trench is greater than twice the calculated riprap thickness and is at least 1.5 times the length of the excavation.

- The entire streambed is paved with riprap or other materials (Method e). This method has been used mainly for relatively small streams. The paving should not be raised above normal stream bed levels. Scour tends to occur at the downstream edge of the paving unless it is tied into a natural inerodible formation or unless a stilling basin is provided. Strong objections may be expected from environmental agencies and it may potentially raise design water levels.

Launching aprons are designed on the assumption that in granular channel beds the stone will settle to a slope of 2 horizontal to 1 vertical (2H:1V), extending to the depth of scour. The volume should be increased so that it is sufficient to cover the scoured slope to about 1.5 times the required revetment thickness, T. On this basis, Brown and Clyde (1989) calculate the volume, V_T, of rock per metre of bank required for the toe trench, toe berm, or launching apron as:

$$V_T = 3.35T \times D_s \qquad (3\text{-}2)$$

where D_s is the estimated depth of scour below the streambed. Launching aprons or toe trenches do not perform well on cohesive channel beds, where scour tends to cause slumps with steep slip faces. In such cases riprap should be continued down to the expected lowest scour elevation and then backfilled.

In some circumstances, where environmental considerations prevent riprap from being placed on the stream banks or along the toe of the bank, the revetment rock can be placed in a trench behind the top of the bank, or stacked as a windrow on the top of the bank. The rock will then launch as the bank erodes.

3.12 RIPRAP FILTERS

When riprap is placed on top of sand or fine gravel, a filter layer is necessary to avoid loss of material through the riprap that may lead to bank failure. (In the case of quarry-run material, a separate filter layer may be unnecessary.) The traditional filter material is gravel or crushed rock and the Ministry of Environment, Lands and Parks recommends this approach. Geotextiles are sometimes used as an alternative because they are cheaper and easier to install; however, they require additional care in placing rock riprap to prevent damage to the geotextile.

For gravel or rock filters, Brown and Clyde (1989) recommend the following sizing criteria:

$$D_{15c}/D_{85f} < 5 < D_{15c}/D_{15f} < 40 \quad (3\text{-}3)$$

where D_{15} and D_{85} refer to 15% and 85% sieve passing sizes, and subscripts "c" and "f" refer to the coarse and finer layers respectively. The criteria should be imposed at the interfaces between the underlying material and the filter, and between the filter and the overlying riprap. If a single filter layer cannot meet the criteria at both interfaces, two or more layers may be required.

Extensive design information for geotextiles in a variety of applications is presented by Koerner (1994), but discussion of erosion control applications is limited. When used as a filter, care should be taken to avoid puncture or damage during installation and rock placement, to provide adequate laps or seams, and to key in the fabric at the top and bottom of slopes, often by wrapping it around the toe rock (CALTRANS 1997). Geotextiles should be avoided if there is a significant potential for displacement (as for example in launching aprons) or for exposure, since some fabrics degrade in sunlight. Generally, non-woven fabrics have better filtering properties and are more resistant to damage than woven ones. CALTRANS (1997) and Brown and Clyde (1989) discuss the advantages and disadvantages of geotextile filters in more detail, and CALTRANS provides detailed specifications for their preferred materials.

3.13 ICE , DEBRIS, AND OTHER CONSIDERATIONS

In the USACE (1991) design procedure **(Appendix 2A)** an increased safety factor is suggested where there is ice or debris impact, particularly for revetments that are less than 450 mm thick or for severe freeze-thaw conditions. However, it is noted that there are no design guidelines at present for riprap exposed to ice or debris damage. As a general rule of thumb USACE recommend increasing the design thickness by 15 to 30 cm, with a corresponding increase in the median rock size, and limiting slopes to a maximum of 2.5H:1V. The USACE Cold Regions Laboratory is currently monitoring revetments along the Tanana River in Alaska for design guidance but no results have been published yet.

In urban areas, disturbance of the rock by people is a factor to consider in design. In these circumstances, the minimum rock size should be about 50 kg. Grouting may prevent damage to revetments composed of small riprap.

3.14 GROUTED RIPRAP

In British Columbia, the design velocities in some streams, particularly on Vancouver Island and the Mainland Coast, require riprap with sizes well in excess of 1.2 m. Use of such very large rock and the large volumes required per metre of bank protection may be impractical; also, it may be too expensive to produce, deliver, and install.

For grouted riprap, a smaller rock size than is hydraulically stable is placed and integrated by pouring grout or concrete on to the surface and rodding or tamping the material into the voids, generally leaving the larger stones projecting to maintain a rough surface. Grouted riprap must be securely protected against toe scour or undermining (see previous sections). It will not self-repair like ordinary riprap.

Grouting provides an alternative where ordinary riprap is ruled out by the large sizes and thicknesses required. However, environmental concerns regarding leaching of concrete mix into streams may prevent this application, unless special precautions are taken during construction.

USACE (1992) provides general advice on the design and construction of grouted riprap, while Brown and Clyde (1989) provide detailed design advice. The California Highway Design Guide provides detailed specifications (CALTRANS 1997). Design of grouted riprap requires consideration of bank slope and preparation, rock size and blanket thickness, rock gradation and quality, grout quality, edge and toe treatment, filter design, and pressure relief.

Grouted rock is rigid, but not very strong, and the underlying bank supports it. Careful attention is required to bank preparation, often with bank materials filled and compacted, a sub-base or foundation layer placed beneath the rock, a permeable filter layer, and pressure relief or drainage pipes provided through the grout.

Brown and Clyde (1989) provide recommendations on the required thickness of the grouted rock blanket for bank velocities up to 7 m/s. They also provide typical gradations, and minimum grout penetration depths, which are equivalent to those of CALTRANS (the California State Department of Transportation). Typically, the gradations are deficient in the finer sizes, to allow grout penetration. Rock that is suitable for ordinary riprap installations is usually adequate for grouted riprap, but rock that could potentially react chemically with the cement should be avoided.

Grouting may be a suitable technique for repair of riprap revetments that fail from exposure to high velocities, particularly if the bank revetment is to be re-constructed with salvaged rock. It is important to be sure of the cause of failure before grouting the salvaged rock to repair the embankment.

3.15 SPURS

USES AND MATERIALS

Spurs, also called “groins” in some references, may be used instead of continuous revetment to prevent or slow the erosion of road embankments, dikes, or natural river-banks. As an alternative to bank revetment, they may not provide complete protection and they are more likely to provoke objections and claims on grounds of downstream riparian erosion. In certain circumstances, spurs are thought to provide better fish habitat than revetments and are environmentally preferred; spurs were constructed as environmental mitigation to create specific habitat types, as part of the CN Rail Environmental Design Program (Lister et al 1995).

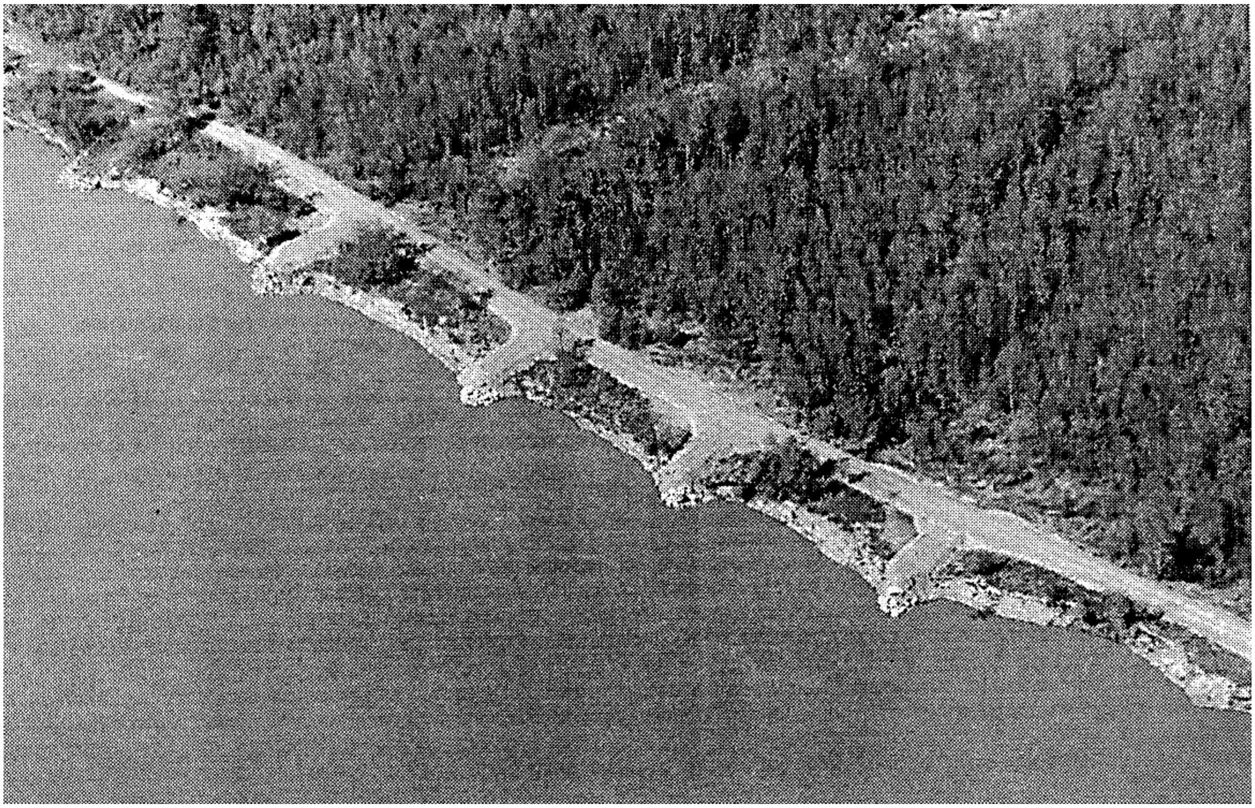

Figure 3-7: Spurs along Seabird Island, Fraser River

Advice on the design of spurs is beyond the scope of this report. Spurs are normally used in groups, although exceptions can be admitted in certain circumstances. Potential adverse effects on navigation, ice passage, log transport and fish passage, and potential liability for accelerated erosion of nearby riparian property, should receive careful consideration in design. Riprap revetments are usually preferred to spurs, where they can be constructed, though spurs may provide river training that is not easily accomplished with a revetment.

4. RIPRAP REVETMENT CONSTRUCTION PRACTICES

4.1 APPROVALS AND INSTREAM CONSTRUCTION WINDOWS

Instream construction in British Columbia, which includes nearly all bank protection works, is limited to specific windows or time periods, based on utilization of the stream by different life stages of fish. The local Ministry of Environment, Lands and Parks office can provide an appropriate window for streams in their region. Construction windows are typically in the summer, but on the Lower Fraser River they occur in February, when water levels are lowest.

Applications for Approvals of Instream Works from the Ministry of Environment, Lands and Parks usually require a detailed design showing layout, profiles and cross sections of the works based on a survey of the site. The application should be submitted well in advance of desired date for the start of construction, preferably several months in advance. We also recommend an on-site meeting with the Department of Fisheries and Oceans and MELP Fish and Wildlife prior to submission, to discuss potential mitigation requirements and other issues. In order to accommodate this meeting and provide time to prepare final drawings, preliminary design should be completed about 90 days prior to start of construction.

4.2 ENVIRONMENTAL MANAGEMENT PROGRAM

An environmental management plan is often required as part of the approval of instream construction works. We recommend engaging a fisheries biologist to assist with developing such a plan.

An environmental management program may include any or all of the following components:

- Salvage of fish prior to construction if work is within the wetted perimeter.
- Sediment management if work is carried out in the wetted perimeter. Plans would be required to separate the work site from the stream with silt fences or other suitable techniques or to divert flow away from the work site, treat turbid water, and provide emergency response for sudden flooding or high water.
- Access management including roads for equipment, showing trees that are to be removed.
- Environmental monitoring, specifying duties and qualifications for an on-site monitor.
- Restoration plans, for seeding and replanting of the site after construction.
- Detailed scheduling for construction.

The requirements for an environmental management plan vary from region to region in British Columbia and the contents would be based on requirements from the Department of Fisheries and Oceans and Ministry of Environment, Lands and Parks.

4.3 SITE PREPARATION

Clearing and grubbing should be kept to the minimum required to meet the specifications shown on design drawings with slopes cleared of brush, trees, stumps or other objectionable materials and dressed to a smooth surface. Areas should be trimmed to a uniform slope, or as indicated on drawings. Loose, soft or spongy material, and large rocks projecting through the slope should be removed and resulting minor potholes or hollows filled with selected non-cohesive materials and compacted. Typically, if a toe trench is required as part of design it is constructed during site preparation.

Brown and Clyde (1989) recommend a maximum allowable tolerance for the constructed slope of 6-inches (15 cm), although they note that depressions can be filled during placement of the filter layer or riprap. It is not common to provide a tolerance for slope grading for riprap installations in British Columbia.

4.4 PLACING FILTER LAYERS AND ROCK RIPRAP

Gravel filter layers should meet the design specifications and are generally inspected for gradation and quality (hardness, durability, and absence of fines) by the site engineer. The filter layers should be spread evenly on the prepared bank. They may sometimes be extended beneath a launching apron or toe berm, though it is not clear if there is any benefit to this. Filter layers should be placed by techniques that do not result in segregation of the rock mass. Compacting is not required but the surface should be reasonably smooth when complete.

Filter fabrics for riprap revetments are typically non-woven geotextile or geosynthetic materials. Specifications for tensile strength, burst strength and opening sizes can be obtained from MOTH (1999), or from other publications. Contractors are typically able to provide a fabric that is certified to meet these specifications.

Heavy riprap may stretch and rip the filter fabric as it settles. Brown and Clyde (1989) recommend a gravel layer between the riprap and filter fabric, if the median rock diameter is greater than 900 mm. Standard practice in California (CALTRANS 1997) is to place a coarse backing layer over the filter fabric before placing the riprap. Alternatively, it may be simpler and cheaper to place a gravel filter layer.

Typically, the filter fabric is extended beneath the riprap toe and launching apron or toe berm. Brown and Clyde (1989) seem to recommend wrapping the filter fabric around the toe of the stone if the revetment is extended to scour depth. Filter fabric is laid in rows along the bank with overlap between sheets. Brown and Clyde (1989) recommend overlaps of 30 to 90 cm, with smaller overlaps for light riprap and larger overlaps for underwater placement of large stone. Securing pins are placed at regular intervals along the mid-point of the overlap. Folds are usually left in the sheets to prevent stretching and tension from placement and subsequent settling of the riprap.

Brown and Clyde (1989) recommend that rock placement start from the bottom of the slope and proceed to the top. Filter fabric may be ruptured if stones are dropped from a height greater than 0.6 m, though the risk is less if stones are dropped into water.

Rock may be placed by two machines; one placing the toe material from a berm or bench, and the following behind, placing the slope material to the top of the bank (Figure 4-1).

Figure 4-1: Placing Rock Riprap Over a Filter Layer on a 2H:1V Slope

4.5 ROCK RIPRAP QUALITY

Stone used for rock riprap should be hard, durable, angular in shape, resistant to weathering and water action, free from overburden, spoil, silt and clay or organic material. Dirty rock which contains clay, silt, soil, or organic material but is otherwise acceptable should be washed prior to delivery to the site.

Specifications for rock riprap typically include density or specific weight, shape, hardness and durability, and gradation. Quality control checks undertaken by the site engineer are discussed in the following sections.

SPECIFIC WEIGHT OR DENSITY

Specific weight or density should meet or exceed the value assumed in calculating stable stone sizes. If disputed, the specific gravity (density relative to water) is determined from standard tests and multiplied by 1,000 kg/m^3 to calculate the specific weight.

ROCK SHAPE

Rocks should be roughly equi-dimensional. Chapter 3 provides maximum limits for elongate or platy rocks, as calculated from the ratios of the axes. We recommend visually inspecting rock in the quarry for shape. If disputes arise, the dimensions of a standard load of rock can be measured and compared to the specifications. Highly rounded stones or boulders are generally not acceptable, unless the revetment was designed specifically for these materials.

ROCK HARDNESS AND DURABILITY

Stone should be durable and abrasion resistant and free from seams, cracks, and cleavage planes. Typically shale and rocks with shale seams are not acceptable; sandstone, conglomerate, breccia, and other sedimentary rocks may also be questionable. Matheson (1988) noted that some limestone and sandstone riprap deteriorated rapidly when exposed to freeze-thaw.

Lutton et al (1991) ranked rock types from best to worst as granite (including granodiorite), quartzite, basalt, limestone and dolomite, rhyolite and dacite, andesite, sandstone, breccia and conglomerates. Note that durability of rocks from the same source can vary because of changes in rock character over the exposure, different blasting techniques and, even, the time when the rock was quarried: rock quarried in winter is often thought to produce inferior riprap (Wuebben 1995).

If previous experience does not confirm that the hardness or durability of rock from a particular quarry is adequate, various tests may be appropriate to measure these parameters. McElroy and Lienhart (1993) provide a summary of common tests and their utilization throughout the United States. Abrasion can be tested by tumbling small rocks according to ASTM Test C 535 (McElroy and Lienhart 1993; Brown and Clyde 1989). Freeze-thawing resistance is based on a standard test developed at the USACE Waterways Experimental Station, which is used as guide to resistance to weathering, based on rock loss after a number of freeze-thaw cycles (McElroy and Lienhart 1993). As Lienhart et al (1995) note all of these tests have drawbacks; they are time-consuming and not necessarily good predictors of durability.

GRADATION

Control of the size and gradation of rock riprap as placed is one of the most important aspects of riprap construction, yet it can be difficult to achieve. Visual inspection of individual loads of rock delivered to the site is an important part of quality control, however we also recommend:

- For large projects, separating a large sample of rock that meets the specified gradation as a visual reference for the machine operators in the quarry. Marked samples of the D_{100}, D_{85}, D_{50} and D_{15} rocks are particularly helpful. A similar sample can be placed at the construction site (Galay et al 1987).

- Line sampling of in-place riprap to check gradation. The basic procedure is to lay a measuring tape across the surface of the riprap and measure the dimensions (usually the b-axis) for each stone that falls under a fixed spacing, such as every 2 m, along the tape (Figure 4-2). At least 50 rocks should be measured for each line sample. A curve of percent by number finer versus size is plotted on semi-logarithmic paper and compared to the gradation curve. The sample curve should fall very close to the design curve with a similar or larger D_{50} and D_{85} size. If the sample appears undersized, additional sampling is required. If further sampling confirms that the riprap is undersized, construction should be halted and the quarry operations reviewed.

  As shown by Kellerhals and Bray (1971), a distribution curve by number determined by the line sampling methods described above is approximately equivalent to a standard sieve curve showing percent by weight finer versus size.

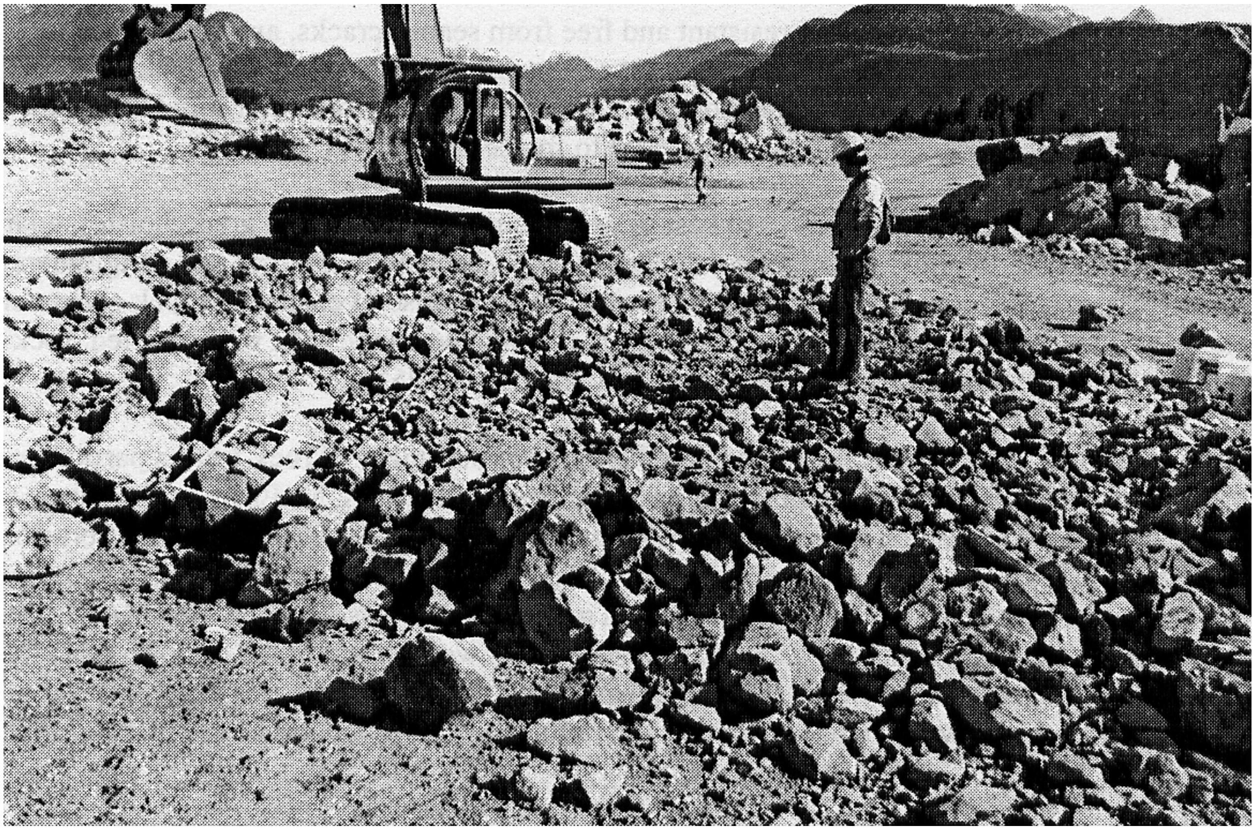

Figure 4-2: Preparing for Sampling Rock Gradations in a Quarry

4.5 ROCK RIPRAP CONSTRUCTION

Each truckload of rock brought to the site should meet the specified gradation. Stone should be transported and placed by methods that avoid segregation: end dumping, dumping into chutes, placing or moving by dragline buckets, or spreading by bulldozers are generally not acceptable. Care should be taken to prevent cracking or breaking of rock under machine tracks.

In above-water placement, stones are placed typically from the base of the slope to the top to the slope in one operation. For high banks, it may be preferable to use two machines, one at the base of the bank and one at the top (Figure 4-1). Care is required to avoid disturbing the filter layer(s) or filter fabric, if used instead of a filter layer. Rocks should be placed by bucket load to the required thickness, providing a well-graded mass with a minimum of voids. Larger stones should be placed along the toe with the remainder distributed evenly throughout the mass. Clusters of small or large stones should be avoided.

Often the surface of the rock is left rough. In some cases, however, quarry spalls are used to fill voids and create a hydraulically smoother surface.

For underwater placement, clamshells typically place the rock on the streambed or the toe of the bank (Figure 4-3, following). Dumping of rock is not recommended as it produces a poor distribution of material. Quality control may be by line sampling in the quarry, detailed GPS-controlled soundings, dive inspections, or other techniques. Details are beyond the scope of this document.

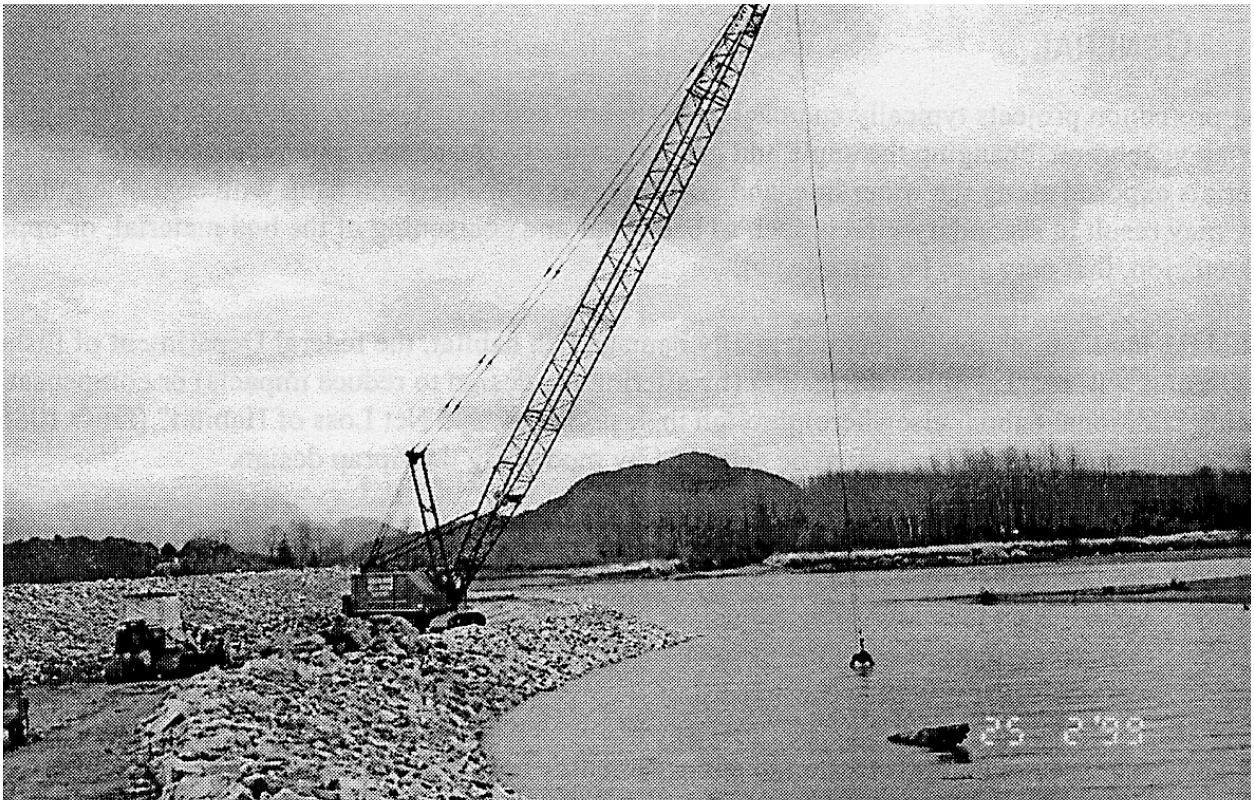

Figure 4-3: Placing of Toe Rock along Nicomen Island, Fraser River (1999)

4.6 GROUTED RIPRAP

The user is referred to USACE (1992) or other publications for detailed specifications and construction practices.

5. ENVIRONMENTAL DESIGN AND MITIGATION

5.1 GENERAL

Bank protection projects typically encroach into streams and may damage fish habitat by removing riparian vegetation, changing the angle and general nature of the stream bank, changing the size of materials exposed along the water line, and covering part of the bed and bank with coarse angular rock. They may result in secondary effects such as bed scour and coarsening of the bed material, or opposite bank erosion, that may also be detrimental.

Should the bank protection project potentially damage fish habitat, the federal Department of Fisheries and Oceans, will request either mitigation (by altering the design to reduce impacts) or compensation (by creating additional habitat elsewhere) through their policy of "No Net Loss of Habitat" (DFO 1986). Mitigation is preferred and can often be achieved by modifying the riprap design.

We recommend engaging a fisheries biologist to provide an initial review of potential impacts on habitat, liaise with the Department of Fisheries and Oceans, Ministry of Environment, Lands and Parks, or other concerned agencies, and help develop mitigative measures. A site visit with the appropriate agencies to review the design and discuss potential mitigative measures is often an important step in the approval process.

Compensation through habitat creation or enhancement is not discussed herein. Where required, detailed biological and other studies would be needed to develop appropriate measures in negotiation with the appropriate agencies.
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5.2 EXAMPLES OF MODIFICATIONS TO RIPRAP REVETMENTS FOR MITIGATION

Riprap revetments can often be modified to reduce their impact on fish habitat or other amenities, or features can be added to the revetment to replace the habitat that is damaged. Mitigative measures are site specific, as they must address the particular species and life stages of those species that utilize the habitat. Consequently, the following examples may not be appropriate for all cases throughout the Province of British of Columbia.

The following modifications are thought to be consistent with stability of riprap revetments designed and constructed according to Chapters 3 and 4:

- Scallop the low water shoreline. Small embayments are created along the waterline by increasing and decreasing the slope of the revetment. The embayments typically create about 10 m^2 of low-velocity rearing habitat with eddies and shear zones. This approach is most suitable in steep, gravel bed streams that lack areas of low velocity. A recent example has been constructed on the Campbell River, just upstream of the new Island Highway Bridge.

- Place large rocks at the toe of the revetment along the low water shoreline. As in the above example, the large rocks, which typically exceed 1 m diameter, provide flow diversity along the shoreline, creating low velocities, eddies and shear zones that are attractive for rearing salmonids (Lister et al 1995). This approach is recommended when there is a toe trench or riprap is extended to scour depth, particularly where the channel is shallow (Lister et al 1995). It may be most appropriate in steep, gravel bed stream and it was used as part of the CN Rail Environmental Design Program.

- Increase the size of rock over that required for hydraulic stability. Lister et al (1995) found that the riprap larger than 300 mm median size supported greater densities of rearing salmonids than smaller rock. This form of mitigation works best at sites where riprap sizes smaller than 300 to 400 mm are adequate for hydraulic stability; often rock sizes and revetment thickness can be increased without much additional cost.

- Replace the rock revetment with spurs, or add short spurs to the revetment. Short spurs, with projection lengths less than 5 m, function like embayments creating areas of low velocity. One or two spurs may provide adequate mitigation. The spurs may be engineered to overtop at high flows. Spurs require suitable design to ensure stability and longevity.

- Planting baskets or "eco-pockets" within the riprap revetment. The eco-pockets consist of soil retaining gabions or other containers placed within the riprap revetment. After construction the pockets are planted with suitable riparian species, usually trailing vegetation or low shrubs. We recommend consultation with a riparian vegetation specialist to select appropriate species and locations. The pockets have been used at several sites along the Fraser River.

- Retain or preserve riparian trees by filling rather than cutting over-steep banks. Fill and riprap are placed against the eroded bank, supporting trees on the top of the bank. This design is most appropriate for low banks. As filling causes additional encroachment on the channel cross section, when compared to a typical design, it is important to evaluate the potential for erosion of the opposite bank and to provide a smooth transition to the existing bank line upstream and downstream.

Figure 5-1: Planted Bench in Revetment along Nicomen Island, Fraser River

- Provide a stepped revetment. A bench is formed, usually by excavation rather than fill, part way up the revetment slope (Figure 5-1). In the Fraser River estuary, these benches are planted with suitable species and at an elevation relative to the tidal cycle recommended by a riparian ecologist. Benches can also be used as walking trails or bike paths to mitigate loss of recreational opportunities.

- Modify revetments for recreational purposes. Typically, this includes lowering the angle of the revetment to a maximum of 3H:1V for access and safety, and may also include placing gravel over the riprap to provide a suitable surface for walking and fishing. GVRD Parks has adopted this approach along the Fraser River, replacing the gravel every few years as required.

- Combine a riprap revetment with timber or pile walls. Timber walls have two uses when combined with riprap. Pile and plank walls can be used on the upper sections of high banks to reduce the length of slope encroachment into streams. Large rocks, for scour protection and habitat mitigation, are placed at the base of the wall. An open timber pile wall can be used in front of an eroding bank to reduce or prevent erosion while maintaining fish access and riparian vegetation. Such designs have been used for banks on the lower Fraser River.

5.3 BANK PROTECTION WORKS THAT INCORPORATE HABITAT FEATURES

Various publications, including some from the Province of BC's Watershed Restoration Program, provide designs for bank restoration projects that incorporate habitat features. The stability of these designs, compared to riprap revetments, is usually not well documented and the range of velocities, depths or shear stresses that they can withstand is often not known. Their design lives are also often unknown. Subtle differences in layout and alignment seem to affect the performance of some of these designs. Doyle (1992) discusses the stability of some alternate bank protection designs in detail.

Non-riprap alternate designs are appropriate where the main objective is to restore fish habitat rather than prevent bank erosion and damage to facilities. However, in some circumstances, particularly where failure of the protective works will not result in severe damage, they may also be appropriate to treat bank erosion, if riprap revetments or spurs are not environmentally acceptable. We typically recommend restricting these structures to low to moderate velocities, less than 3 m/s, and carefully considering their effect on opposite bank erosion and on downstream structures should they fail catastrophically. The cost per unit length for alternate designs that includes large woody debris with root wads may be greater than for riprap revetments.

The following types of designs are now commonly constructed in British Columbia, often as part of Watershed Restoration Program (WRP) projects:

- Tree revetments. Babakaiff et al (1997) provides designs for tree revetments, supposedly for low, moderate and high, energy environments. The designs consist of large woody debris (LWD) pieces with attached root balls pointed upstream in the flow. The spacing along the bank, the use of footer logs, and the size and number of anchor rocks varies from one design to another. Acheson (1968) provides similar designs using willows, for low and moderate energy environments.

  The high energy design, with LWD with root wads incorporated into a riprap revetment, and vegetated geogrids on the upper slope, is thought to be the most appropriate for British Columbia. The concept sketch in the reference does not incorporate launching rock for scour; however we recommend adding a launching apron or other scour protection as part of design. We also recommend sizing the rock and constructing the lower revetment following the procedures in Chapters 3 and 4.

- LWD crib walls or structures. The typical crib structures that are used for bridge abutments on forestry roads can also be modified for habitat-friendly bank protection. The primary modification involves LWD pieces with root wads projecting through the structure and into the stream. The root wads provide cover and create low-velocity habitat. These structures are scour susceptible: a toe trench of appropriately sized riprap or other scour defence is recommended. If the logs on the face of the wall are staggered, bushes or other vegetation can be planted in the crib fill material.

- LWD log structures. A common structure for habitat restoration is the logjam or LWD spur (Slaney et al 1997). These are built of LWD pieces with or without root wads, attached to boulder or riprap anchors. The structures are built either as single projecting logs, triangular log spurs consisting of two pieces projecting into the stream and joined together, or jams spaced along a bank (Figure 5-2). The triangular log spurs seem to be the most common design. The LWD structures may not provide adequate bank protection. The structures are open and velocities may accelerate between the tip of the structure and the bank. Also, they are normally overtopped during the design event, potentially directing flows at the bank.

  A design procedure to determine the required anchor weights to counteract buoyancy and resist drag on the structure is provided in D'Aoust and Miller (1998). Spacing of the structures along the bank can be based on the criteria proposed for spurs in Neill (1973) or other references therein.

Figure 5-2: Construction of LWD Log Jam along the Mahatta River, Vancouver Island

- Geosynthetics. Koerner (1994) provides detailed advice on design with geosynthetics in various environments, but provides no designs for erosion protection against flowing water. As noted, these materials may be incorporated with rock, soil, or large woody debris in mitigative designs.

- BioEngineering. Schiechtl and Stern (1994) and Donat (1995) provide detailed advice on bioengineering techniques for streambank and shoreline protection. Many of their techniques depend on re-sloping of the bank and adding toe protection, often using riprap, for successful performance. Their report provides detailed advice on the use of vegetation in bank protection systems.

6. EMERGENCY CONSTRUCTION OR REPAIR PRACTICES

6.1 GENERAL

Emergency construction or repair includes both planning and organization carried out prior to a flood, and the actual construction work during the flood. Pre-flood planning is often a critical aspect of emergency repair. Design of riprap sizes, estimation of volume required per unit length of bank, and stockpiling of appropriate reserves in a central location are key tasks that can be undertaken prior to an emergency. Where sites have failed in the past, or are expected to become unstable as a result of channel shifting, riprap can be stockpiled nearby. This allows rapid emergency response and eliminates the difficulty of mobilizing rock rapidly enough to control erosion damage.

A suitably sized excavator with a hydraulic thumb should be used to place the riprap. Dumping of rock from the top of the bank is often a waste of limited resources, requiring far more rock that if it were placed. If it is unsafe for a machine to work near the top of the bank, a windrow of rock may be placed behind the bank to launch as the bank retreats. This may be the only feasible option to stop bank erosion. However, much larger volumes per unit length of bank are required than for standard designs. Alternatively, repair work can be completed as water levels drop after the peak of the flood.

Identifying the start and end points of emergency bank protection, particularly on banks that have never been protected, is often difficult. Preferably, work should start at a hard point or at some distance upstream of the eroding area. However with rapid bank retreat, erosion may quickly outpace placement of erosion protection. Water Management Branch (1999a) recommends construction of a key trench at the upstream end of the work as a first priority to help prevent outflanking of the revetment. Emergency spur construction may also be considered, as an alternate approach.

Another issue is reconstruction of emergency works after the flood. Emergency works are usually not built to the standard that would be applied under other circumstances. Rock sizes may be smaller than design, filter layers are almost always missing, and toe protection is often not installed or of insufficient volume. As part of post-flood inspections, design criteria for the protective works should be assessed and the works should be upgraded, as required.

6.2 EMERGENCY REPAIR OF REVETMENT WASHOUTS

The California Department of Transportation (Racin 1997) recommends an emergency repair procedure for road washouts, partly based on their layered riprap design. Suitable riprap is stockpiled on site, or nearby. Repair starts with construction of a toe berm by an excavator working in the river or from the top of the bank. The berm joins with the upstream and downstream revetment sections and is raised high enough to reduce velocities on the damaged bank. The bank is then reconstructed in lifts using local materials (without de-watering); a very tough filter fabric is placed on the fill, and then riprap is placed directly on the filter fabric to design dimensions. Bedding layers between the rock and the fabric are usually omitted.

A similar approach was used for emergency repair of a road along the Indian River following a flood in 1995 (Photo 6-1). The excavator worked from upstream to downstream, starting at a stable forested section of bank, and first placed the largest available rock as toe stone (Photo 6-2). The berm was then built above water levels and to road grade with smaller rock and fill. After bank re-construction, the road was re-built.

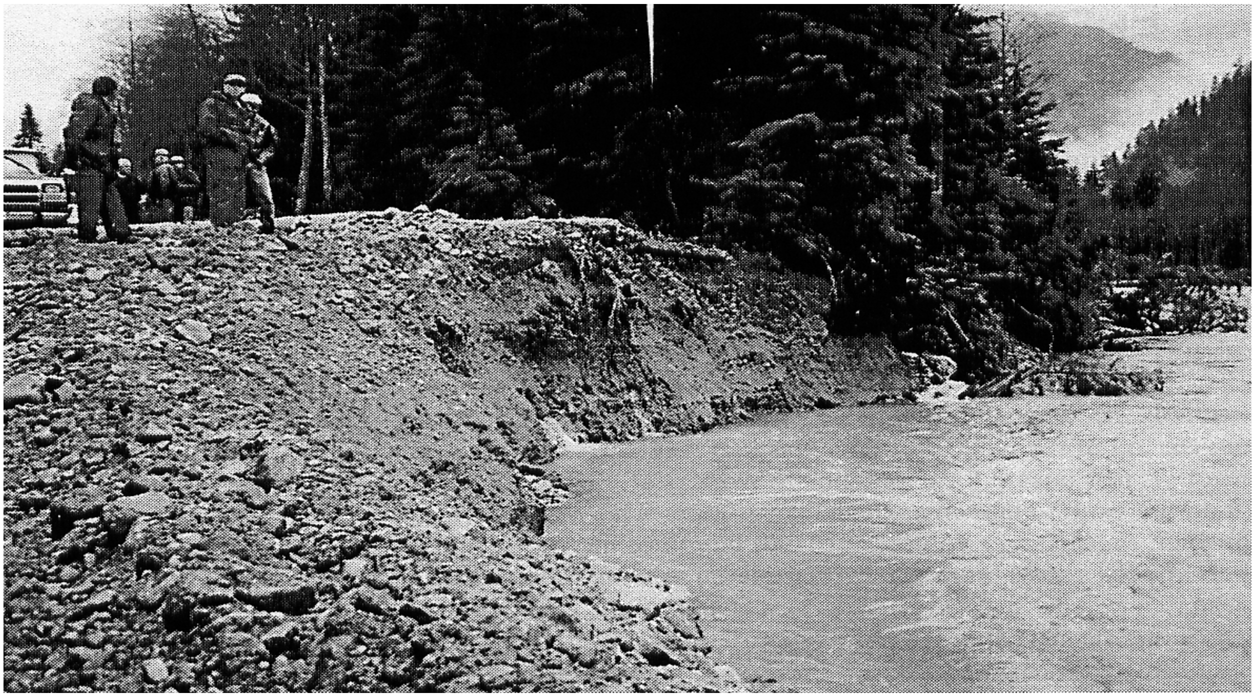

Figure 6-1: Eroding Road Bank along the Indian River, looking upstream

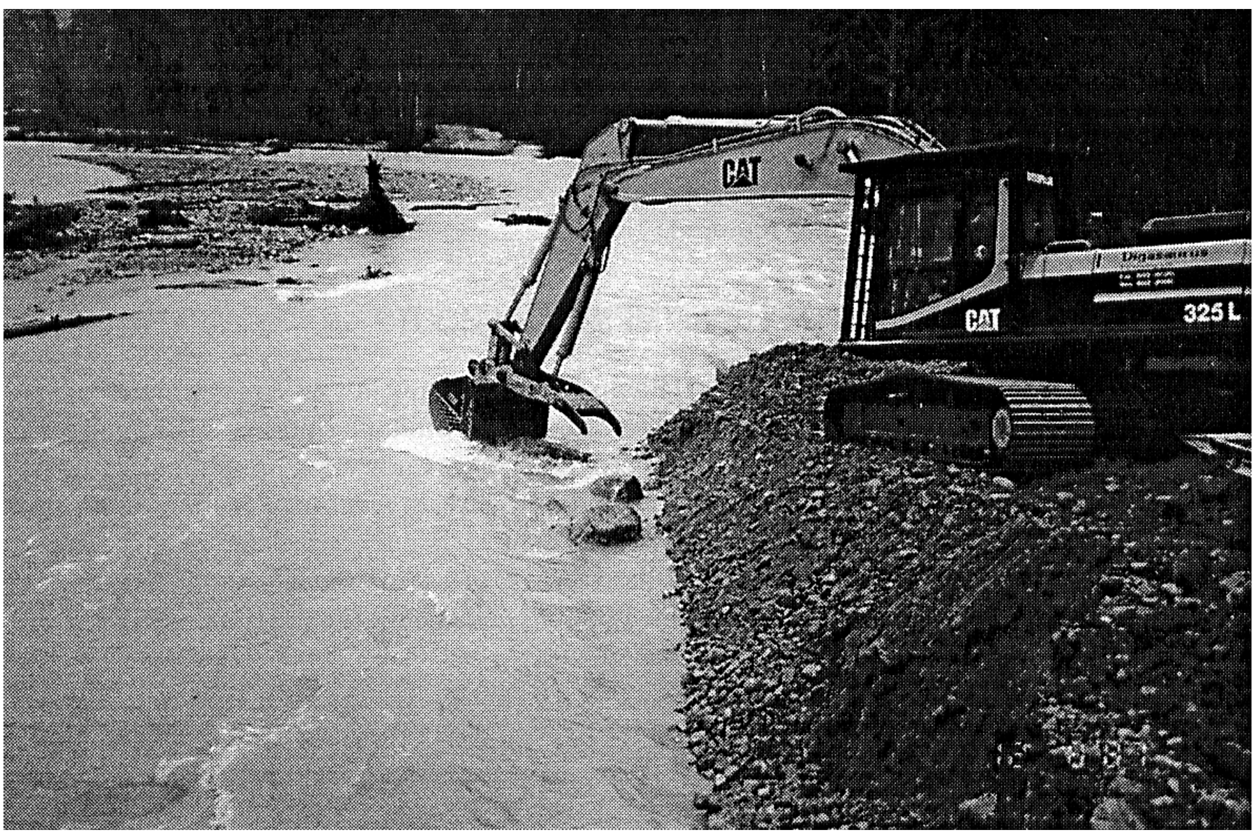

Figure 6-2: Placing Toe Rock for Berm with Excavator, Indian River

6.3 EMERGENCY REPAIR OF BANK EROSION WITH SPURS

During the 1990 flood on the Chilliwack River, channel shifting and erosion on the outside of a bend threatened the main road along the valley and partly undermined the foundation of a residence. The emergency works consisted of a revetment and two spurs (Figure 6-3). A spur was first constructed out perpendicular to the bank just upstream of the house. This spur extended past the house's foundation with very large rock placed at the toe and on the face (see Figure 6-4). Rock revetment was placed along the upstream bank, from the point of attack, guiding the flow to another spur that projected in the flow but was pointed downstream (see Figure 6-3). Later, the bank between the two spurs was filled with coarse material, reconstructing the bank closer to its original alignment (Figure 6-4).

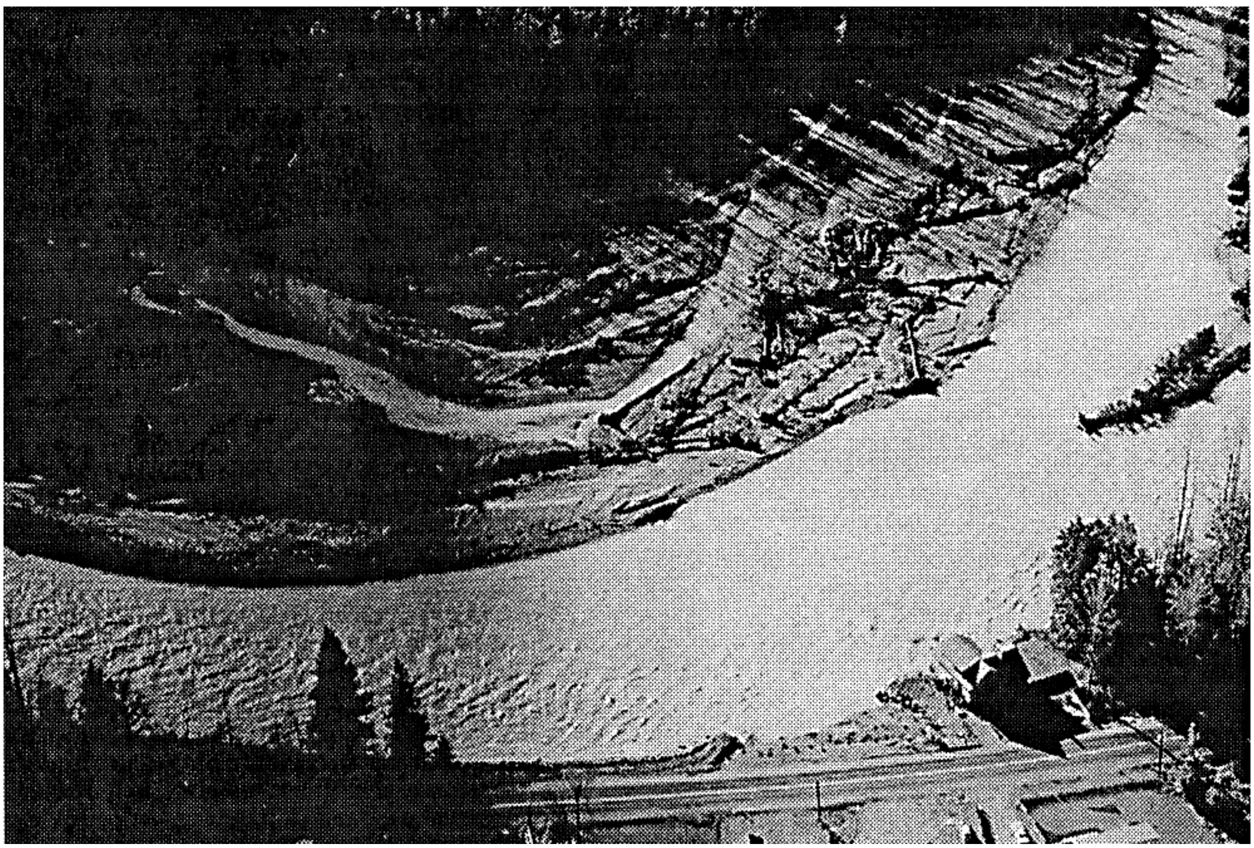

Figure 6-3: Emergency Spur Construction along the Chilliwack River

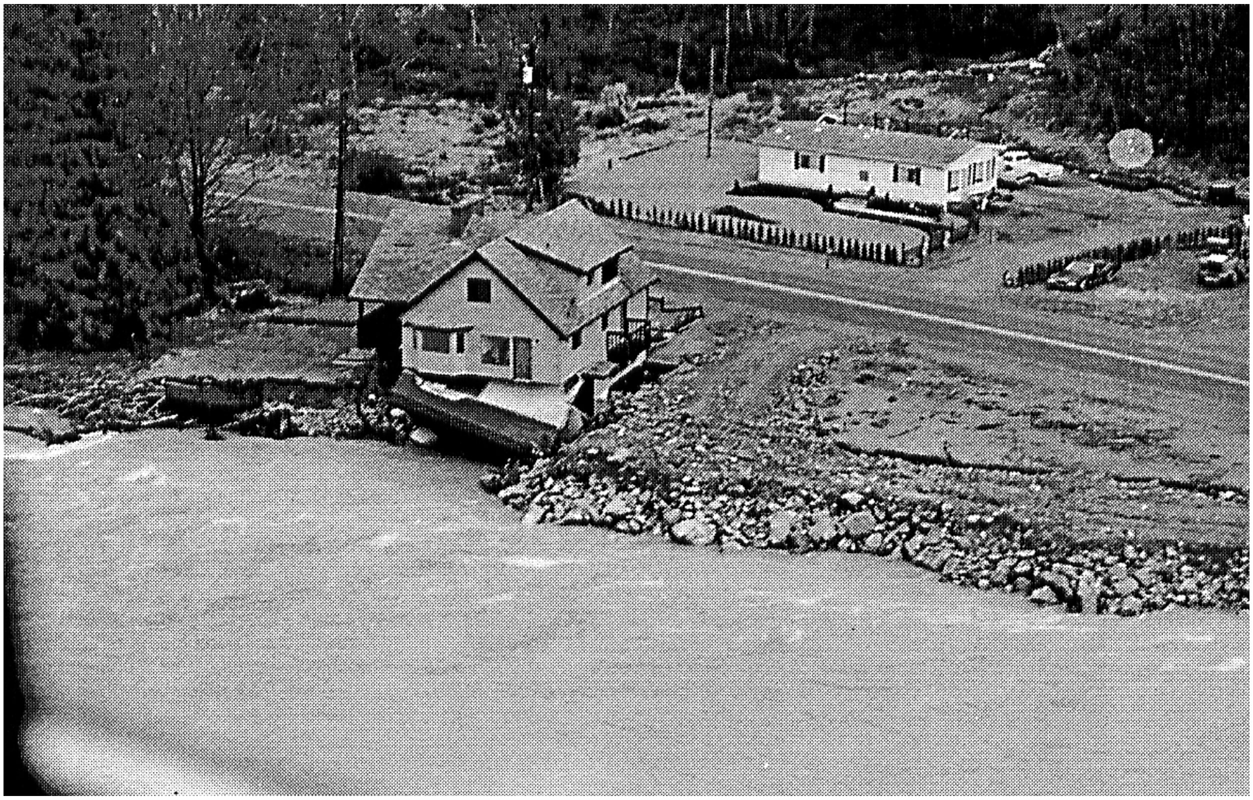

Figure 6-4: View of Riprap Placed Between Spurs to Reconstruct Bank Line

7. MAINTENANCE

7.1 GENERAL

Constructed revetments require inspection and survey, particularly after major floods, in order to check their performance and upgrade them if necessary. Where appropriate, underwater works should be inspected, either by detailed soundings or by divers.

Many streams in British Columbia are unstable and continually shift their point of attack on banks. Frequent inspections are required to identify minor damage and specify repairs before major damage occurs. Ideally, inspection of the revetments should be part of a formal monitoring program that also includes periodic technical review and re-assessment of the design criteria of the bank protection works.

7.2 HIGH WATER PATROLS

Water Management Branch (1999a) provides standard forms and procedures for high water inspections. While these forms emphasize dike inspections, they include sections to describe problems with bank protection, such as loss of rock, settlement, slumping, etc. We recommend use of these forms for all high water inspections of bank protection, whether or not associated with dikes.

7.3 POST-FLOOD INSPECTIONS

High water inspections will identify immediate problems with loss of rock or slumping. We also recommend post-flood inspections, preferably during low water levels, of the revetment toe and launching apron. Detailed surveys or diver inspections may be required if the toe extends into deep water.

These inspections should examine whether toe rock has launched, and if so ensure that an adequate volume of rock was placed in the toe berm or launching apron. Toe rock may not be visible, as it may have launched into scour holes that formed during the flood peak and have subsequently re-filled with bed material. Probing with a rod or minor excavation of the stream bed may be necessary to confirm the presence of the launched rock.

If rock has been lost from the toe, or if scour is deeper than anticipated, it would be prudent to add additional riprap. It may also be appropriate to re-assess the required rock sizes and gradation on the basis of post-flood observations.

7.4 MINOR REPAIR

It is important to repair small slumps or displacements of rocks as soon as possible after they are observed. Large projecting pieces can result in further damage, leading to progressive failure of the rock blanket. We recommend using an excavator with a hydraulic thumb to re-arrange rock as required, adding additional material if needed.

In the case of large slumps or loss of rock from a continuous revetment, it is important to assess the cause of failure before repair. A re-evaluation of the design criteria and the recommended rock sizes and gradation may be in order, particular if channel shifting has changed the angle of attack on the bank. In these circumstances, grouting might be considered as a reinforcing measure if the bank is to be re-constructed from salvaged rock.

If the revetment failure is deep and appears to originate as a rotational slump on a failure plane well behind the revetment, it may result from instability in the underlying bank materials. In this case, we recommend contacting a geotechnical engineer prior to reconstruction of the bank. However, failure of the rock revetment from toe scour and subsequent rapid erosion of the underlying bank material may create a deep pocket that looks like a rotational slump.

7.5 RIPRAP STOCKPILING

Stockpiling of riprap is an important part of a strategy for emergency repairs of eroding unprotected banks or revetments. In the case of regional stockpiles, riprap should be sized for the "worst" conditions that might occur in the region. It may be worthwhile to stockpile very large, uniformly graded rock separately, as it is often required for toe construction during emergency works. Specifications for stockpiled well-graded riprap should provide somewhat larger sizes than strictly required for the expected velocities and depths, to allow for segregation and breakage during stockpiling and transportation.

7.6 MANAGEMENT OF VEGETATION

Trees, shrubs and other vegetation growing through riprap – excluding plants in eco-pockets grown deliberately as part of mitigation – may require treatment in order to provide access for inspections and to ensure that large trees do not displace or damage riprap. MELP and DFO (1999) provide advice for these activities.

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RIPRAP DESIGN AND CONSTRUCTION GUIDE

APPENDIX 1A
TO THE TECHNICAL REPORT

Ministry of Transportation and Highways (1999)
Riprap Gradations

SECTION 205

RIPRAP

205.01 General - This Section of the Province of British Columbia "Standard Specifications for Highway Construction" (BCH) covers the protection by riprap of embankments and channels at the locations and of the type and class shown on the Drawings or required by the Ministry Representative.

Work within any watercourse shall generally be carried out in conformity with the environmental protection provisions to the satisfaction of the Ministry Representative.

205.02 Material - Rock shall be hard durable angular quarry rock of a quality that will not disintegrate on exposure to water or the atmosphere. The gradation of rock sizes (mass in kg) in each class of riprap, as specified or directed, shall conform to Table 205-A.

* The thickness of riprap, measured at right angles to the slope, for the class specified, shall be the nominal thickness stated, unless otherwise shown on the Drawings or required by the Ministry Representative.

Rocks generally shall be evenly graded, approximately the stipulated sizes, and individual rocks shall have a thickness greater than one-third their length and none shall have a mass greater than five times that of the specified class mass.

For visual comprehension only, Table 205-B indicates the approximate average dimension of an angular rock for each specified rock class mass.

TABLE 205-A GRADATION OF ROCK SIZES IN EACH CLASS OF RIPRAP

CLASS OF RIPRAP (kg)	*NOMINAL THICK-NESS OF RIPRAP (mm)	ROCK GRADATION; PERCENTAGE LARGER THAN GIVEN ROCK MASS (kg)		
		85%	50%	15%
10	350	1	10	30
25	450	2.5	25	75
50	550	5	50	150
100	700	10	100	300
250	1000	25	250	750
500	1200	50	500	1500
1000	1500	100	1000	3000
2000	2000	200	2000	6000
4000	2500	400	4000	12000

205.03 Preparation - Areas to receive riprap shall be trimmed to a uniform surface and to the slope(s) indicated on the Drawings or as directed by the Ministry Representative.

Before rock placement commences, loose material shall be removed and minor pot-holes and hollows filled with selected materials well tamped-in to the approval of the Ministry Representative.

205.04 Foundations - To provide a stable foundation and protection against any undercutting, the riprap shall be thickened at the toe, laid horizontally to form an apron and/or keyed into the bed of the watercourse, all as indicated on the Drawings or as directed by the Ministry Representative.

205.05 Filter Blankets - Filter blanket material and placement, where required, shall be as specified in the Special Provisions or as directed by the Ministry Representative.

TABLE 205-B APPROXIMATE AVERAGE DIMENSION OF AN ANGULAR ROCK FOR EACH SPECIFIED ROCK CLASS MASS

kg	10	25	50	100	250	500	1000	2000	4000
mm	200	300	350	450	600	800	1000	1200	1500

205.06 Loose Riprap - The controlled placement of rock of the class specified shall produce a rock mass of the nominal or required thickness over the area indicated. The rock shall be manipulated as necessary to provide mass stability and a regular surface with a minimum of voids.

205.07 Hand-Laid Riprap - Hand-laid riprap, normally Class 10 or 25, shall conform to the size, gradation and requirements set out in Subsection 205.02. Individual rocks too large to handle shall be manipulated for satisfactory setting and spacing.

At the toe of sloped riprap, a sufficient number of the larger rocks shall be placed to form a firm foundation approximately 50% thicker than the required nominal riprap thickness. The remaining larger rocks shall be regularly spaced, at least one to every 2.5 m^2, when placing the general rock mass to the nominal or required thickness over the area indicated. Smaller rocks or spalls shall be well hammered in to fill the interstices and to form a closely massed regular surface.

Where riprap is required in two layers, the rocks shall be laid up and generally lap jointed between the regularly spaced larger rocks placed as through headers.

205.08 Grouted Riprap - Where grouted riprap is shown or required, the surfaces of the rocks shall be cleaned and wetted and the interstices filled with cement mortar, well rodded and pounded in for a minimum mortar depth of 300 mm or as otherwise detailed or required by the Ministry Representative. The mortar shall consist of one part Portland cement to three parts well-graded clean fine aggregate mixed to a proper consistency.

205.09 Measurement and Payment - Measurement shall be made by multiplying the facial area by the average thickness dimensions as shown on the Drawings or as directed by the Ministry Representative. No allowance will be made for the quantity of rock placed in excess of these dimensions.

Payment shall be on the basis of the price bid per cubic metre for the type and class of riprap specified or required. The price bid shall be accepted as full compensation for everything completely furnished and done in connection therewith, but shall not include the excavation for foundation, which shall be paid for under "Foundation Excavation", nor for excavation of rock for riprap which shall be paid for under "Roadway and Drainage Excavation", nor for haul which shall be paid for under "Overhaul" in accordance with Subsection 201.20.

RIPRAP DESIGN AND CONSTRUCTION GUIDE

APPENDIX 2A
TO THE TECHNICAL REPORT

US Army Corps of Engineers (1991)
Detailed Riprap Design Procedure

APPENDIX 2A
DETAILED RIPRAP DESIGN PROCEDURE

US ARMY CORPS OF ENGINEERS (1991) PROCEDURE

The following discussion is based on a proposed revision to the "Guide to Bridge Hydraulics" (Neill 1973). Based on an extensive large-scale experimental study at the Waterways Experiment Station of the U.S. Army Corps of Engineers, a comprehensive velocity-based method for sizing riprap bank protection was presented by Maynord (1988) and Maynord et al (1989). A variant of the method is incorporated in a manual for flood control channels (USACE 1991) and associated computer programs for river analysis. The basic equation in the 1991 reference may be written in re-arranged form as:

.... Eq. [2A-1]

$$\frac{D}{y} = S_f C_s C_v C_T \left[\frac{V^2}{(s-1)K_1(gy)} \right]^{1.25}$$

where D is nominal rock size, V is local (depth-averaged) flow velocity, y is local flow depth near the bank, S_f is a safety factor, C_s is a stability coefficient, C_v is a velocity distribution coefficient, C_T is a thickness coefficient, s is dry rock density relative to water, K_1 is a side-slope factor and g is gravitational acceleration. The equation is dimensionally homogeneous and can be used with any consistent system of units.

Rock size D. The nominal size D given by **Eq. 2A-1** is considered to be D_{30}, the size in a mixture than which 30% by mass is finer. On the basis of experiments covering a wide range of gradings, this was found to give the most consistent relationship with velocity. The use of D_{30} as the basic size criterion contrasts with many earlier hydraulic relationships that use D_{50}. For moderately graded riprap mixtures ($D_{85}/D_{15} < 3$ or so), D_{50} is typically about 25% larger than D_{30}. For more widely graded mixtures, a grading curve should be used for conversion.

Local velocity V_{ss}. The reference suggests that local velocity V_{ss} for insertion in **Eq.2A-1** should be the depth-averaged velocity V_{ss} at a point inshore from the toe of the bank slope by 20% of the slope length. This parameter is difficult to estimate from ordinary river data, though USACE (1991) and Maynord (1992) note that it can be measured in the field, calculated from two-dimensional numerical flow models, or estimated from partitioning of the cross section in a one-dimensional flow model such as HEC-RAS and calculating the velocity distribution. We only recommend using the one-dimensional flow model in straight or mildly sinuous reaches.

The bank velocity is most commonly estimated from the average channel velocity, based on ratios of V_{ss} to cross-sectional average velocity V_{avg} for trapezoidal and natural channels of various curvatures, as shown in Figure 2A-1. Values of the ratio range from 0.9 for straight natural channels to 1.6 for abrupt natural bends.

Maynord (1992) also recommends 1.6 for direct impingement on the stream bank, as often occurs in wandering or braided rivers. As described in Chapter 2 of the Technical Report, the typical ratios for estimating bank velocities from average velocities in British Columbia have been either 0.67 or 1.33.

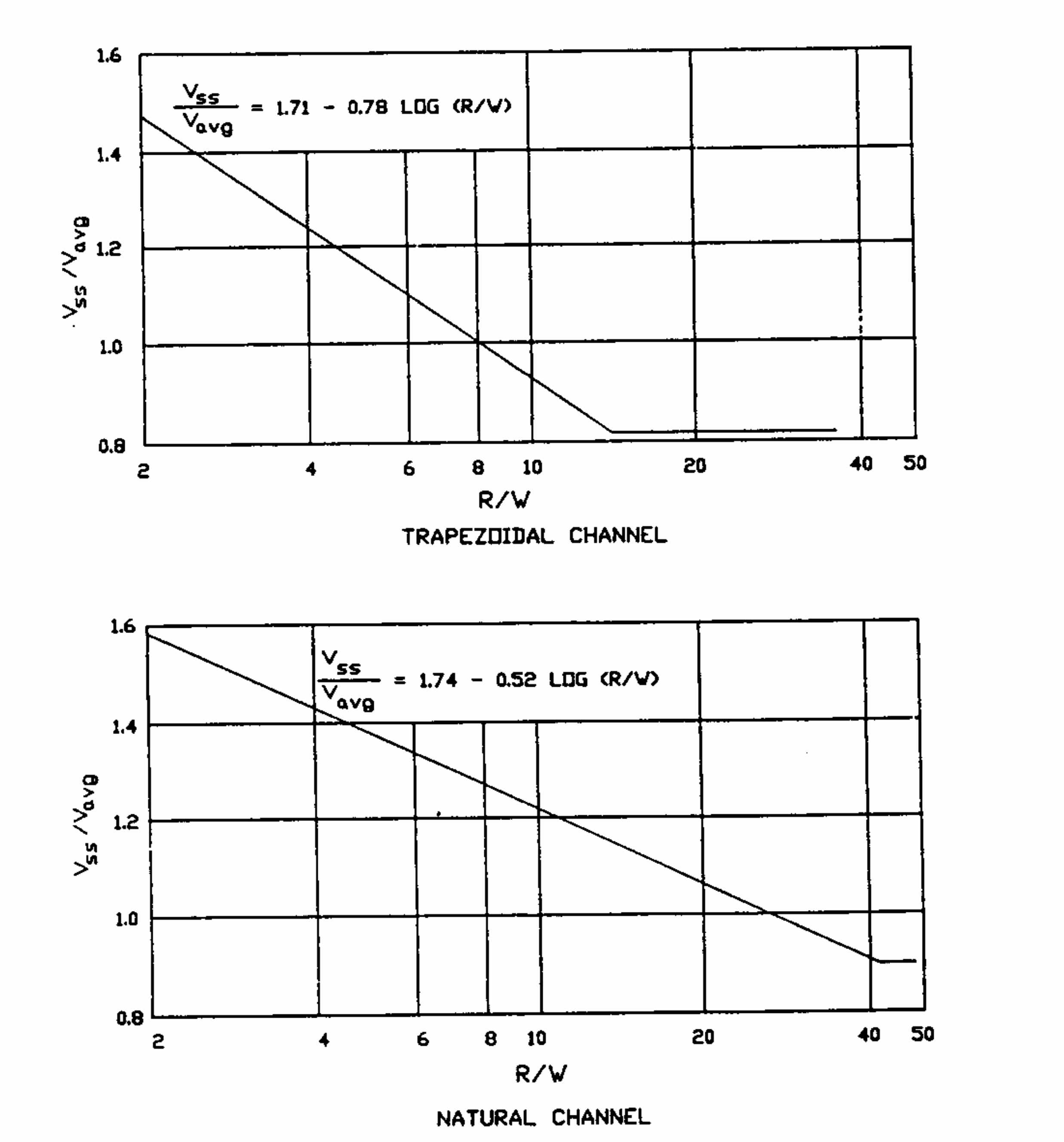


Figure 2A-1: Estimating V_{ss} As a Ratio of V_{avg} for Bends of Various Curvatures (USACE 1991)

Local flow depth y. This is given in the reference as the local flow depth. The rock size predicted by the formula decreases with increasing depth (at a constant velocity), although the formula is relatively insensitive to depth, being inversely proportional to the 0.25 power of y. In cases of uncertainty, it is more conservative to underestimate the depth.

Safety factor S_f. The basic equation provides a "just stable" rock size for the imposed hydraulic conditions; the minimum value suggested by USACE (1991) is 1.1. Where velocities or depths are estimated conservatively, the safety factor should not be increased. However, it may be increased to reflect uncertainty in these estimates.

The use of higher values is suggested where there is ice or debris impact, particularly for revetments less than 450 mm diameter, or severe freeze-thaw conditions, but no further numerical guidance is given. USACE (1991) notes that there are no design guidelines at present for riprap exposed to ice or debris damage. As a general rule of thumb they recommend increasing the design thickness by 15 to 30 cm, with a corresponding increase in the median rock size, and limiting slopes to a maximum of 2.5H:1V.

They also recommend increasing the safety factor when riprap is stockpiled prior to, or during, construction to account for segregation and pockets of undersized stone.

Stability coefficient C_s. Values suggested in the reference are 0.30 for angular rock and 0.36 for rounded rock. Maynord (1992) later corrected the value for rounded rock to 0.375, which increases the stable rounded rock diameter by 4% over that predicted with the smaller coefficient.

Vertical velocity distribution coefficient C_v. Suggested values are 1.0 for straight channels and 1.25 downstream of concrete-lined sections, at the ends of dikes, and for impinging flows. The following formula provides the coefficient at the outside banks of bends of varying curvature:

$$C_v = 1.283 - 0.2 \log_{10}(R/W) \qquad \text{Eq. [2A-2]}$$

where R is bend centreline radius and W is water-surface width. Maximum values for the velocity coefficient in bends, for R/W of 2, will be about 1.22, as shown on **Figure 2A-2**.

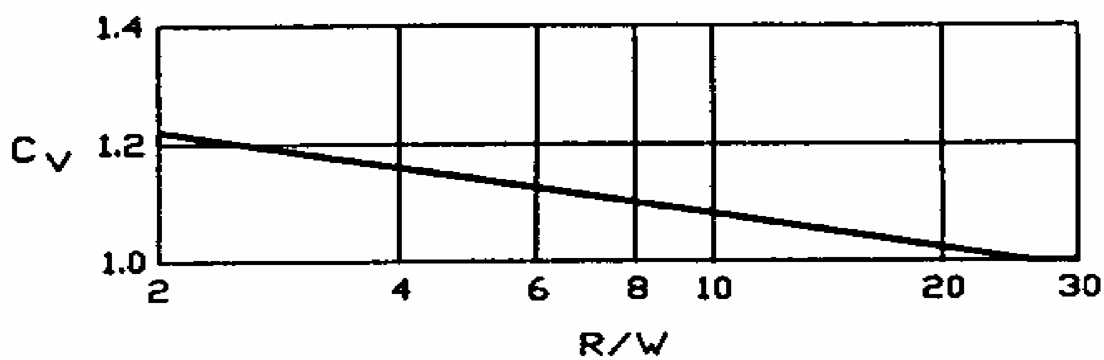


Figure 2A-2: Vertical Velocity Distribution Coefficient and Bend Curvature (USACE 1991)

Thickness coefficient C_T. The basic value is 1.0 for a basic minimum in-situ thickness normal to the slope of D_{100}, or 1.5 x D_{50} - whichever is greater. **Figure 2A-3**, following, allows reductions for greater thicknesses.

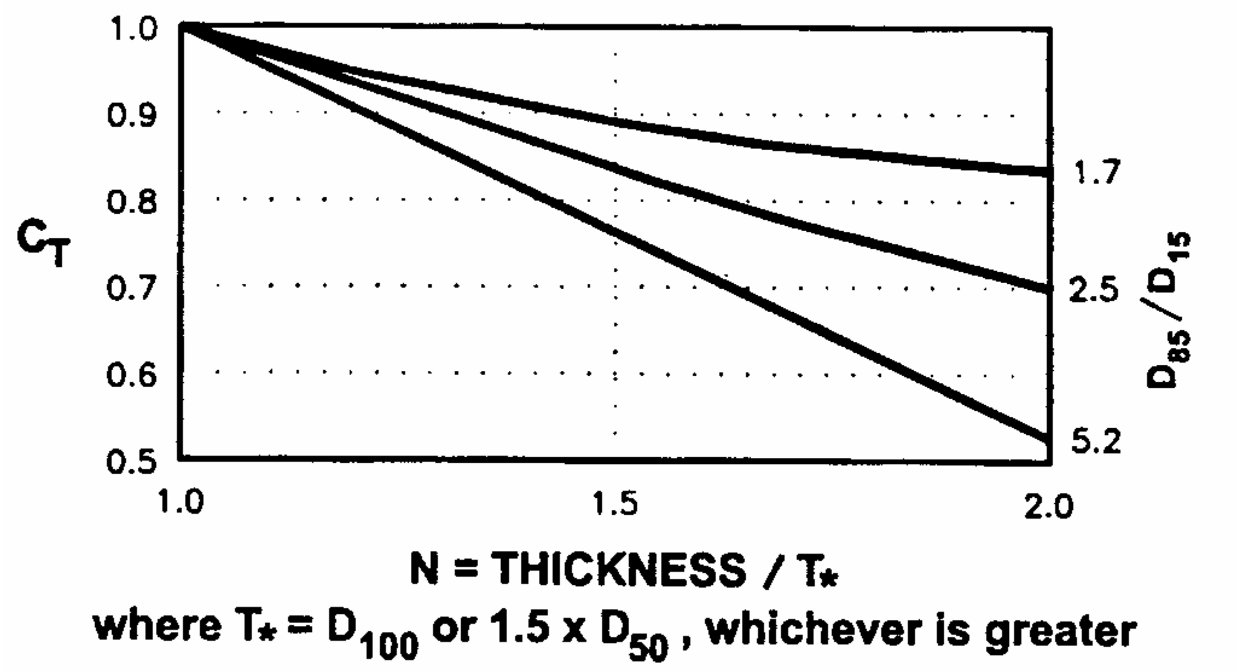


Figure 2A-3: Riprap Thickness Coefficient for Greater Than Standard Thickness

Side-slope factor K_1. Recommended values, as defined by Figure 2A-4, are as follows, for typical side slope angles:

Side-slope (H/V)	K_1
3:1 or flatter	1.0
2:1	0.9
1.75:1	0.8
1.5:1	0.7

Side slopes steeper than 1.5:1 are not recommended, unless stones are placed by hand and keyed into the bank.

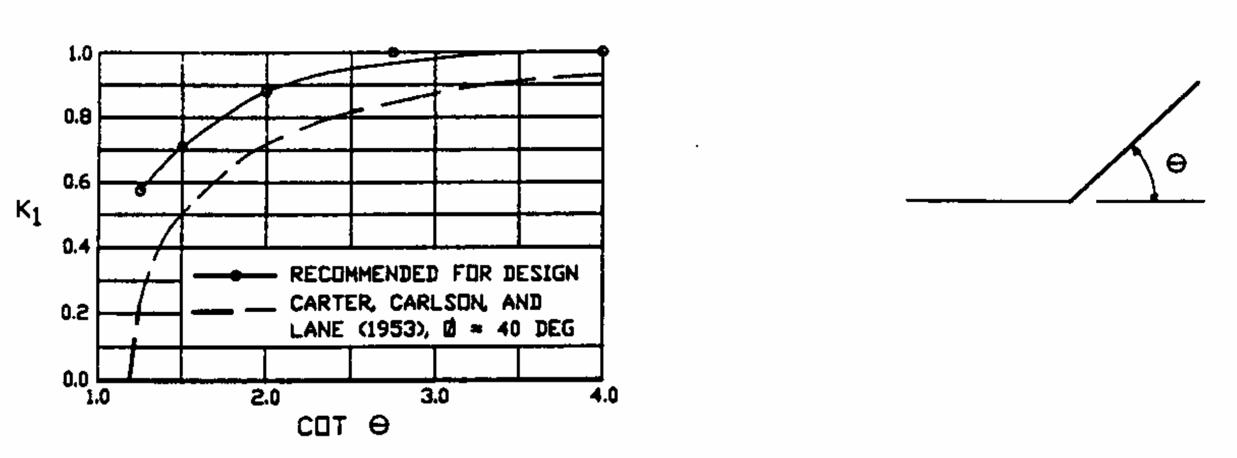


Figure 2A-4: Side Slope Factor K_1 for Various Bank Angles (USACE 1991)

RIPRAP DESIGN AND CONSTRUCTION GUIDE

APPENDIX 3A
TO THE TECHNICAL REPORT

US Army Corps of Engineers (1991)
Correction Factors for Figure 3-5

APPENDIX 3A
CORRECTION FACTORS FOR FIGURE 3-5

US ARMY CORPS OF ENGINEERS (1991) PROCEDURE

This Appendix provides correction factors to adjust the result from Figure 3-5 to other values of specific weight, vertical velocity distribution and thickness coefficients, side slopes or ssafety factors. Figure 3-5 is based on specific weight of 2.5, a velocity distribution coefficient of 1.0, a thickness coefficient of 0.30, a side slope coefficient of 0.9 for a slope of 2H:1V, and a safety factor of 1.2.

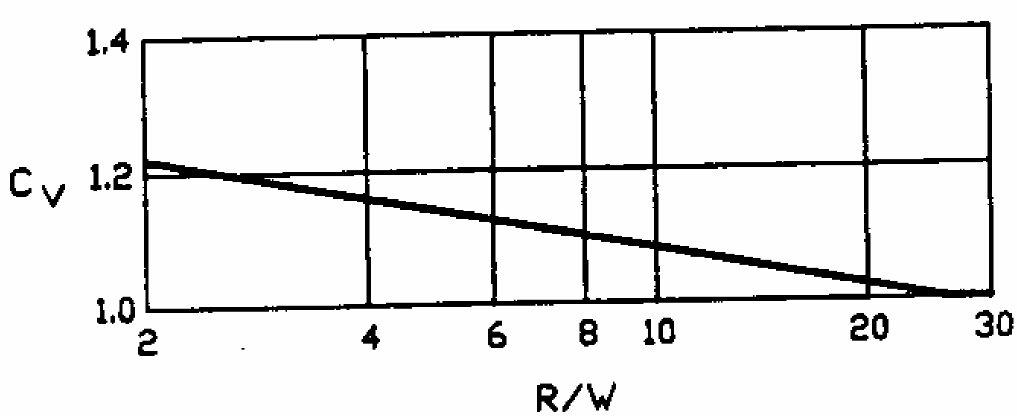
1. Correction for Specific Weight of Rock

(Multiply the D_{30} from Figure 3-5 by the appropriate Correction Factor C_1 from the following table)

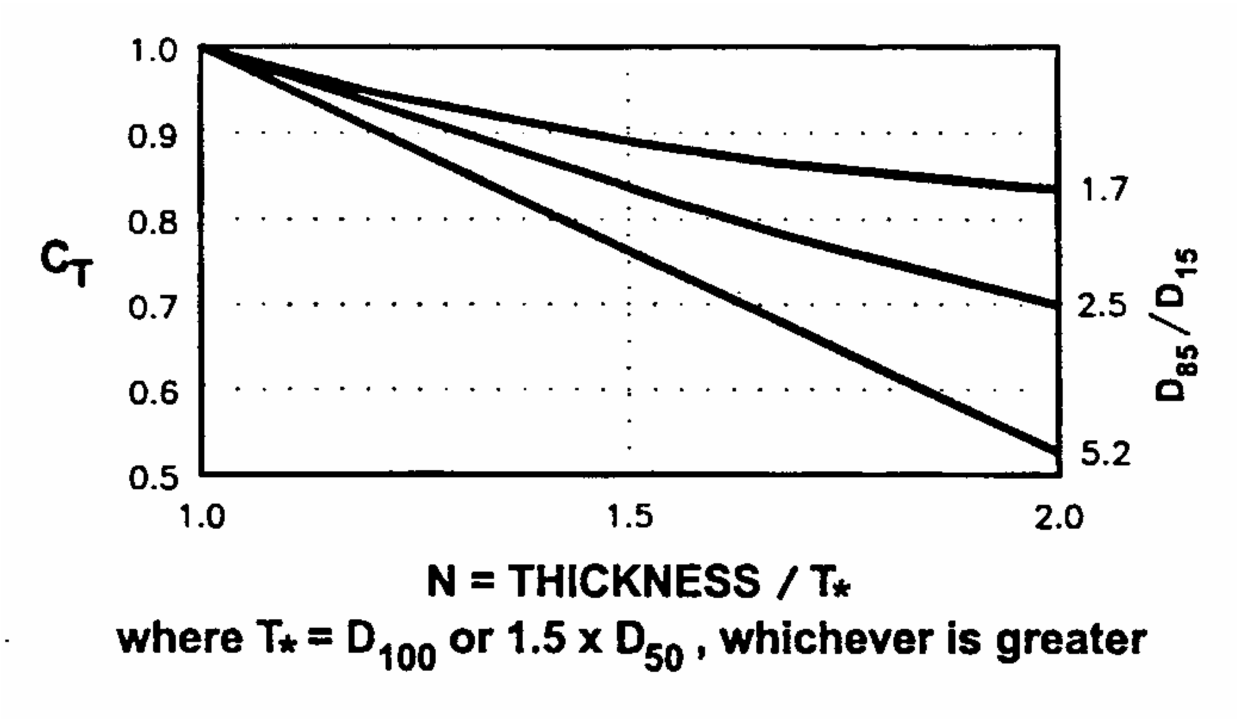
Specific Weight	*Correction Factor C_1*
2.4	1.09
2.5	1.0
2.6	0.93
2.65	0.89
2.7	0.86
2.8	0.79

2. Correction for Vertical Velocity Distribution Coefficient

(Multiply the D_{30} from Figure 3-5 by the Correction Factor C_v)



3. Correction for Thickness Coefficient
(Multiply the D_{30} from Figure 3-5 by the Correction Factor C_T)



4. Correction for Side Slope Angle
(Multiply the D_{30} from Figure 3-5 by the appropriate Correction Factor C_A from the following table.)

Side Slope	***Correction Factor C_A***
1.5H:1V	1.25
2H:1V	1.0
2.5H:1V	0.92
3H:1V	0.86
4H:1V	0.85

5. Correction for Safety Factor

(Multiply the D_{30} from Figure 3-5 by the appropriate Correction Factor C_s from the following table.)

Safety Factor	Correction Factor C_s
1.0	0.83
1.1	0.92
1.2	1.0
1.3	1.08
1.4	1.17