Chapter 6: Physical Methods for River Training

Flash flood mitigation in the upstream part of a catchment is aimed at reducing the occurrence of flash floods and focuses on reducing slope instability, reducing the amount and velocity of runoff, and preventing erosion. In the downstream areas, the focus is on mitigating the effects and impact of any flash flood that occurs. Some rivers are particularly prone to flash floods ('flashy rivers') and it is possible to plan mitigation interventions, even though the timing of individual flash floods cannot be predicted. This chapter looks at some structural measures in the downstream areas.

The morphology of a river is a strong determinant of flow, and can thus serve to intensify or mitigate flood waves and torrents. At the same time, when rivers flow in an alluvial plain they often become meandered or braided, and at times of flood, this morphology leads to excessive bank cutting which can destroy agricultural land and human settlements.

'River training' refers to the structural measures which are taken to improve a river and its banks. River training is an important component in the prevention and mitigation of flash floods and general flood control, as well as in other activities such as ensuring safe passage of a flood under a bridge. For flash flood mitigation, the main aim is to control the water discharge regime in the watercourse by limiting its dynamic energy, thereby controlling the morphological evolution of the watercourse (Colombo et al. 2002). River training measures also reduce sediment transportation and thus minimize bed and bank erosion. Many river training structures are implemented in combination with bioengineering techniques to lessen the negative effects on environment and landscape (see Chapter 3). There are a number of types of river training structure. The selection and design of the most appropriate structure depends largely on the site conditions.

River training structures can be classified into two main categories: transversal protection structures and longitudinal protection structures.

Transversal Protection Structures

Transversal protection structures are installed perpendicular to the water course. They are used to lower the river gradient in order to reduce the water velocity and protect the river bed and banks from erosion. Most of the rivers in the Hindu Kush Himalayan region originate in the high mountains, where they have steep gradients giving the flow a massive erosive power. Moreover, intense rainfall and breakout events can accelerate the river flow to such an extent that the water has a significant impact on the watercourses and surrounding areas. Transversal protection structures are effective for controlling the velocity of rivers and streams and reducing the development of flash floods. The major structures likely to be useful in the region are described briefly in the following.

Check dams

Check dams are described in detail in the previous chapter, mainly in relation to gully control. The dams used along river courses follow the same principles. They can be made of gabions, concrete, logs, bamboo, and many other materials. These dams decrease the morphological gradient of the torrent bed and reduce the water velocity during a flood event by increasing the time of concentration of the hydrographic basins and reducing the flood peak and solid transportation capacity of the river. They also help to reduce erosion and debris flow. The main purpose of check dams on rivers is to stabilize the riverbed over a long distance. Check dams generally require additional protection structures in the bed or on the banks to hinder undermining.

Spurs

A spur, spur dyke, or groyne is a structure made to project flow from a river bank into a stream or river with the aim of deflecting the flow away from the side of the river on which the groyne is built. Two to five structures are typically placed in series along straight or convex bank lines where the flow lines are roughly parallel to the bank (McCullah and Gray 2005).

Spurs help train a river to flow along a desired course by preventing erosion of the bank and encouraging flow along a channel with a more desirable width and alignment (Julien 2002). They are used to control natural meandering at a river bend, to channel wide rivers, and to convert poorly defined streams into well defined channels. The spurs create a zone of slack flow which encourages silting up in the region of the spur to create a natural bank. They generally protect the riparian environment and often improve the pool habitat and physical diversity.

Spurs can be made from many materials including stone, for example in the form of gabions (Figure 42) or in bamboo 'cages' (Figure 43); tree trunks and branches (Figure 44); concrete; or any material that is not easily detached by the river and is strong enough to withstand the flow and the impacts of debris. They can be categorized on the basis of permeability (Figure 45), submergence (Figure 46), orientation (Figure 47), and the shape of the head (Figure 48).

Some guidelines for designing and constructing spurs are provided in Box 16.

Sills

A sill (also called a bed sill or ground sill) is a transverse gradient control structure built across the bed of a river or stream to reduce bed or headward erosion. Sills are installed along river stretches with a medium to low morphological gradient. The purpose is similar to that of a check dam, but a sill is much lower. A sill is usually constructed together with other hydraulic structures such as bridges to prevent them from being undermined and increase their durability. Sills can be built with different shapes, for example stepped or sloping, and from a variety of materials including concrete, stone, gabions, wood, and rock. The selection of material depends on morphological and ecological factors. Sills made from wood, rock, and gabions tend to be more environmentally friendly than those made from concrete or cemented stones. The most common types of sills are the following.

Figure 42: Gabion spurs with sandbags along the bank

Source: Mercy Corps

Figure 43: Low-cost bamboo and stone spurs

Source: Deepak, DSCWM

Figure 44: Low-cost spurs made from tree trunks and branches

Source: Mercy Corps

Figure 45: Permeable and impermeable spurs

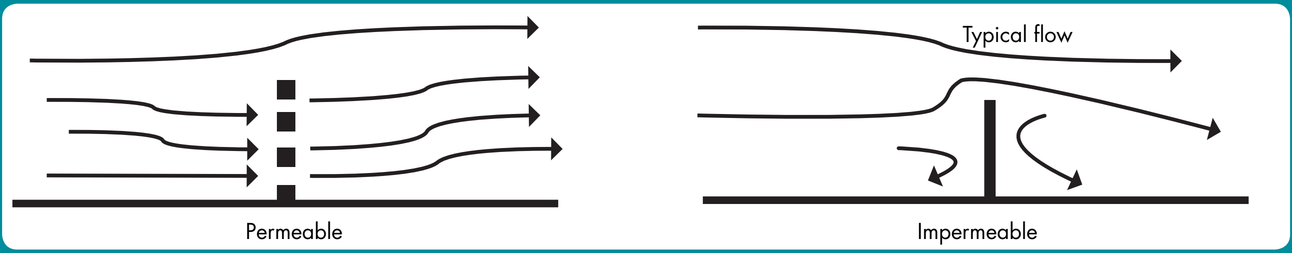


Figure 46: Submerged and non-submerged spurs

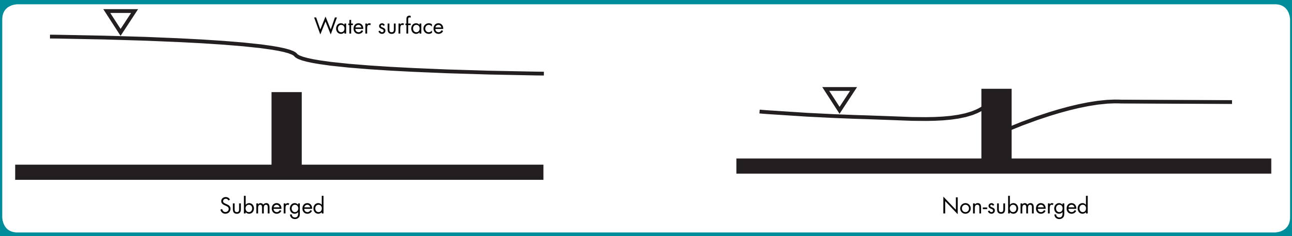


Figure 47: Different orientation of spurs

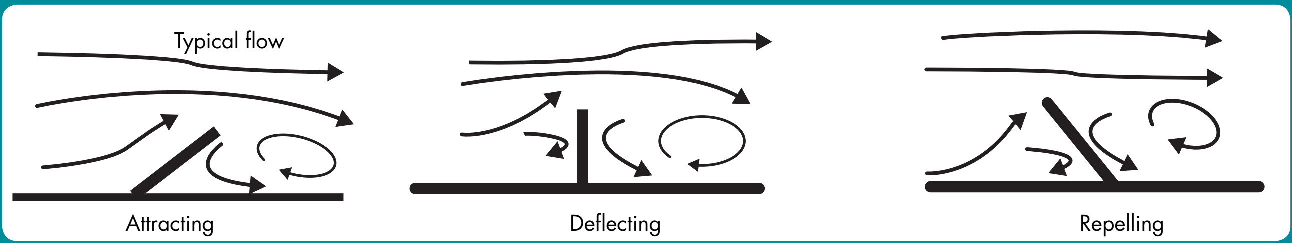
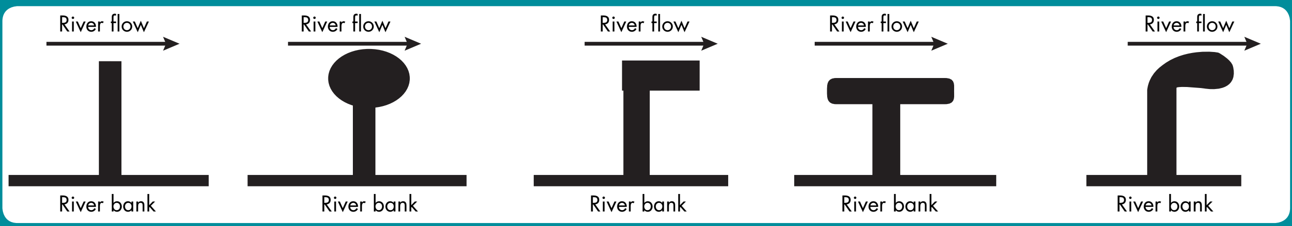


Figure 48: Different shapes of spur



Concrete or stone sills. Sills made of concrete or concreted stone are easy to construct and relatively common, even though the construction cost is generally higher than for other types. This type of sill can be used for a wide range of morphological conditions, and is particularly suitable for lower reaches. They are often used in combination with structures such as bridges or walls.

Gabion sills. Sills made with gabions can be installed under many different hydrodynamic conditions. The gabions can be filled with rock from along the river or stream bed. Gabion sills are considered environmentally less harmful than concrete sills for the natural riverine environment and ecology because of their greater width and limited height.

Wood and rock sills. Sills are often made of local wood and rock in the mountainous reaches of watercourses or at sites with morphological constraints. Any kind of water resistant wood can be used, the most suitable being chestnut, larch, and natural or treated resinous plants. This type of sill has a low environmental impact because of its tendency towards naturalization, which favours the ecology and environment of the watercourse.

Box 16: **General guidelines for spur design and construction**

Spurs should not be used where the river is already narrow or where the alignment of the river banks cannot be modified or reduced. It is also not advisable to use spurs where the opposite bank is exposed to transverse flows, which create unacceptable erosion. In such cases continuous longitudinal protection is required (Maccaferri Australia n.d.).

The effectiveness of a spur depends on its design and location, and the resources available. The location of the upstream starting point and the downstream termination point also influence the success of spur installation. The main characteristics to be considered are summarized in the following.

Permeability

Spurs can be permeable or impermeable (Figure 45). Impermeable spurs are built of local soil, stones, gravel, rocks, and gabions, while permeable spurs usually consist of one or several rows of timber, bamboo, or similar. An impermeable spur blocks and deflects the river flow, while a permeable spur allows water to pass through but reduces the water velocity.

Spur height

Spurs can be designed to be higher than the water level at all times (non-submerged), or submerged during the time of floods, emerging only when the flood recedes (Figure 46). In general, submerged spurs are designed to be permeable, whereas non-submerged spurs are impermeable.

The height of non-submerged spurs should not exceed the bank height because erosion at the end of the spur in the overbank area could increase the probability of outflanking when the water level (stream stage) is high. If stream stages can be greater than or equal to the bank height, the spurs should be equal to the bank height. If flood stages are always lower than the bank height, the spurs should be designed so that overtopping will not occur at the bank (DSCWM 2005).

Submerged spurs should have a height between 1/3 and 1/2 of the water depth (Jha et al. 2000).

Spur orientation relative to the river axis

Spurs can be attracting, deflecting, or repelling according to their inclination as shown in Figure 47. An attracting spur points downstream and attracts the flow towards its head and thus to the bank, maintaining a deep current close to the bank. A deflecting spur changes the direction of the flow without repelling it and creates a wake zone behind. A repelling spur points upstream and diverts the flow away from itself. The first spur in a bend should always be attracting to minimize the impact of the flow.

Spur shape

Spurs are basically bar shaped, but the end protruding into the water flow can be shaped differently (Figure 48). An oval or elliptical spur, with the wider portion towards the bank, can change the hydraulic efficiency and reduce the direct impact of the flood water on the spur body. Investigations have shown that the shape of the spur can affect the bed stress distribution and the scour depth around a spur. For example, the extension of the high shear stress zone is smaller in T-shaped spurs (Safarzadeh et al. 2010), whereas the maximum scour depth is less around L-shaped spurs (Hashemi Najafi et al. 2008).

Spur length

When choosing the length of a spur, it is important to consider the safety of the opposite bank. If a spur is too long, it may guide the river current during a flash flood to the opposite bank which will cause damage; if it is too short, it may cause erosion of the near bank. As a general rule, the length of a spur should be no more than 1/5 the river width and no less than 2.5 times the scour depth. Sometimes a spur is made long and strong with the aim of changing the river course by repelling it towards the opposite bank, in which case the opposite bank should also be protected. Both the river width and the width of the main flow channel to be deflected should be considered when designing the length of a spur (Jha et al. 2000)

The scour depth is given by

$$R = 1.35\,(q^2 f)^{1/3},$$

where
R = the normal scour depth below high flood level (HFL),
q = discharge intensity in m^3/s per metre width, and
f = Lacey's silt factor, which depends upon the grain size of the river bed material (given for different materials in Table 14).

The value of q can be obtained from $q = \dfrac{Q_f}{\text{Water width}}$ in $m^3/s/m$, where the water width is the flood water width in the river and

$Q_f = 1.2Q - 1.24Q,$

where Q is the discharge.

Spacing

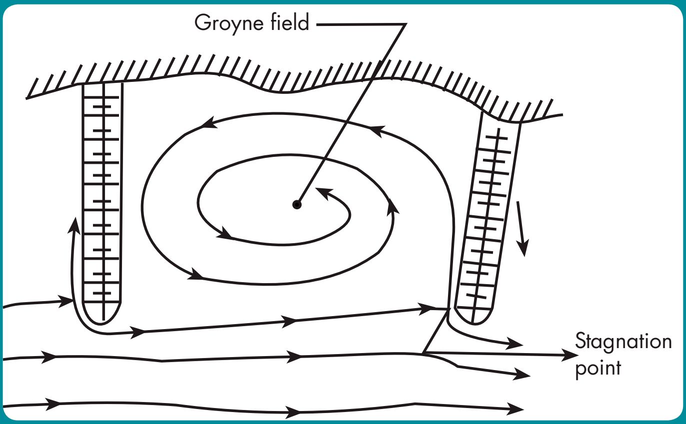
The effect of a group of spurs depends on their length and spacing. The spacing between two spurs depends on the length of the spurs. The effect on flow is best fulfilled if one strong eddy is created between each pair of spurs (Figure 49). If the spacing is too wide, the effect of the spurs will be insufficient as parts of the bank will remain unaffected. A spacing less than the optimum is wasteful as it does not increase the effect. The length of bank protected by a spur is generally at least twice the length of the spur projecting perpendicular to the river water current; thus spurs do not need to be closer than twice their projecting length. More exact calculations can be made using the formulae for eddy stability and energy loss of river flow (HMGN 1990). In general, the spacing between two spurs should be 2–2.5 times the spur length along a concave bank and 2.5–3 times the spur length along a convex bank. In the case of a revetment with spurs, the spacing can be increased without causing harm to the bank (Jha et al. 2000).

Table 14: Lacey's silt factor for different materials

Type of material	Size of grains (mm)	Silt factor (f)
Silt		
Very fine	0.052	0.4
Fine	0.081	0.5
Medium	0.158	0.7
Standard	0.323	1.0
Sand		
Medium	0.505	1.25
Coarse	0.725	1.50
Gravel		
Medium	7.28	4.75
Heavy	26.1	9.0
Boulders		
Small	50.1	12.0
Medium	72.5	15.0
Large	183.8	24.0

Source: Varshney et al. 1983

Figure 49: Formation of eddy between two spurs



Source: HMGN 1990

Number of spurs along the stream bank

The number of spurs depends on the length of stream bank to be protected and the calculated space between spurs.

Launching apron

A launching apron should be constructed to protect the spur from scouring at the base. 'Scouring' is the name given to the removal of the bed or bank of a watercourse by the action of flowing. When river training works are carried out to protect a river bank, the obstruction of high flow discharge and the associated changed water flow pattern can lead to scouring in the form of a deep depression in the river bed close to the river training structure. Scouring can destabilize the structure and thus measures need to be taken to counteract the effect. A launching apron is a flexible stone cover placed on the bed of the river which settles into the scouring area as scouring takes place and covers the base and side of the scour hole, preventing it from developing further. An example of an apron placed to protect a bank is shown diagrammatically in the section below on guide banks.

Scouring is common around spurs and can result in their destruction. For an impermeable spur, the scour hole can reach a depth of up to 1.0–1.7 times the design flow upstream of the pool, but it is much less for permeable spurs. A launching apron should be constructed to protect impermeable spurs from scouring. For permeable spurs, it is sufficient to bury material below the spur to fill the site of the potential scour hole.

Screen dams and beam dams

Screen dams and beam dams are sediment retention structures. They are designed to trap medium to large size debris and boulders carried downstream in flood events in order to reduce the impact downstream. This type of dam is often installed in alluvial fans, along stretches with a steep slope, in wooded areas, in areas with frequent mass movements, and along narrow channel beds at the end of a valley just before the stream or river enters an alluvial fan or plains area.

The dams themselves must be constructed with strong materials such as concrete or cement to withstand the impact of heavy debris, whereas the retention portion can be built with other materials. Other supporting structures must also be constructed to protect the banks and foundation. The dams require regular maintenance; trapped debris and sediment should be removed at regular intervals and after flood events to maintain the storage capacity. These structures can have a significant environmental impact depending on their size and the materials used for construction. The most common types of screen dams and beam dams are the following.

Screen dam with vertical bars. This type of dam is mainly made to retain vegetative materials such as tree trunks and branches. The vertical bars are usually constructed from steel or concrete, although wood can also be used in dams for small torrents and water channels. The dam offers a high resistance to the debris.

Beam dam with pylon bars, vertical opening, and horizontal steel bars. These dams are constructed with concrete and steel. The main purpose is to control mass transportation of sediments that could affect settlements or other infrastructure.

Porcupines

Porcupines are a form of permeable structure designed to reduce flow and trap sediment. They have pole-like projections in all directions, resembling a porcupine with its quills sticking into the air. They are used as flood control structures, and for river bank and bed protection. Porcupines can be used in a line forming a spur into a river, as silting aprons for larger spurs, and in a longitudinal line along an embankment. Originally such devices were made of timber or bamboo (Figure 50), but these have a limited lifespan. The use of wooden and bamboo

Figure 50: Bamboo porcupines used to form a spur

Source: Rajendra Prasad Adhikary

Figure 51: RCC porcupines along a river bank (top) and combined with sandbags to form a bar projecting into the Koshi river (bottom)

Source: Mitra Baral (top) and Shiva Kumar Sharma (bottom) porcupines combined with vegetation to form a green wall is described in the chapter on bioengineering. This section describes porcupines made of concrete.

There are two kinds of concrete porcupine in common use: reinforced cement (RCC; Figure 51) and pre-stressed cement (PSC). Quality control of RCC struts is difficult because each strut cannot be tested separately, although a rebound hammer can be used to test the uniformity of strength throughout. PSC porcupines are better in terms of size, shape, strength, concrete mix, and steel used.

Porcupines can be constructed in two shapes, tetrahedral and prismatic (Box 17). The following are their main uses.

Bank protection as a bar. Porcupines can be used as a pro-siltation protection device for a natural river bank or an embankment (Figure 54). The structures are flexible, which ensures stability against extreme water forces and even earthquakes. Porcupines reduce the flow velocity, intercept and break eddies formed by floodwater, and fill up scour holes with silt.

Porcupines are most commonly used as bars across, and aligned 2–5° upstream of, the flow. Each bar consists of single, double, or triple rows based on the velocity of flow, the width of the bank line channel, and the spacing between bars (Figure 54); the higher the velocity, the higher the number of rows. Single or double rows are used when the bars are close to each other. The porcupines are generally placed so that they touch each other at the base, and with the lines staggered if there are multiple rows. The bar extends from the highest flood level line to

Box 17: **Porcupine design**

Tetrahedral porcupines

The most common shape is tetrahedral. The porcupine is formed by assembling six concrete struts of the same length in a tetrahedral pattern (Figure 52). Individual struts are bolted together, projecting beyond the joint. The bolts are passed through holes made at the appropriate point using cheap polythene tubes during casting.

The size of a porcupine is denoted by the length of the individual struts, for example a 2 m porcupine or 3 m porcupine. The struts of 2–3 m porcupines have a cross-section of 10 x 10 cm. The individual struts are at 60 degrees to each other, thus a 2 m porcupine is about 1.7 m high and a 3 m porcupine 2.6 m high. The most common sizes in use are 2, 2.5, and 3 m. Mounted or long boom cranes are necessary to handle anything larger.

Prismatic porcupines

Prismatic porcupines are made with nine concrete struts joined in the form of a prism (Figure 53). Two end triangles are formed first and then joined together with three struts placed at the vertices. Struts are bolted together as for tetrahedrons.

Figure 52: Tetrahedral porcupine (dimensions in metres, shown here for a 3 m porcupine)

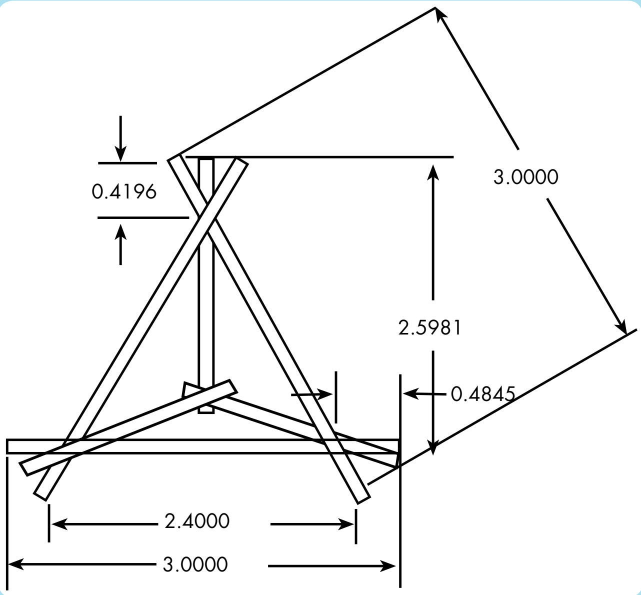


Figure 53: Prismatic porcupine

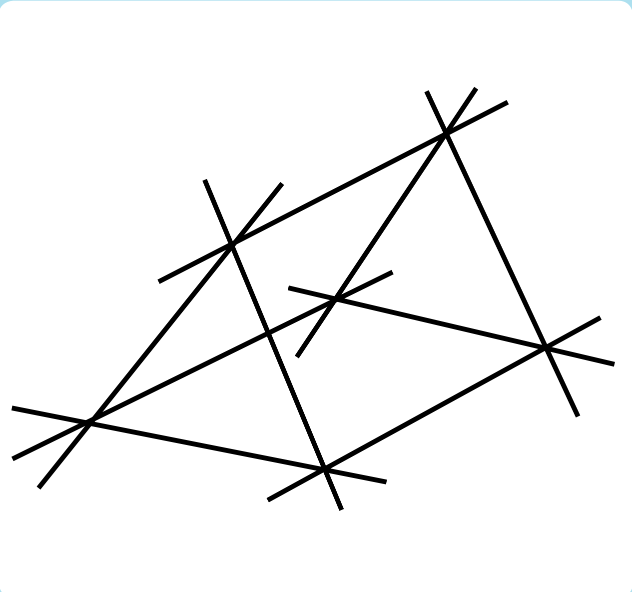
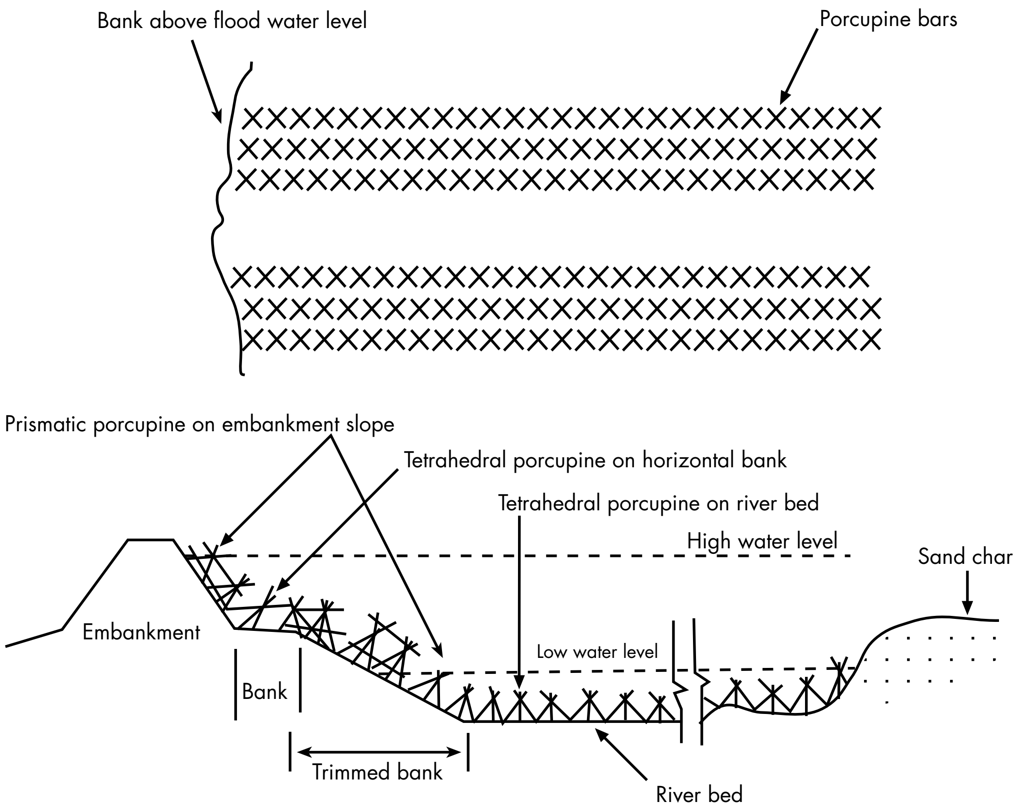


Figure 54: Plan (above) and cross-section (below) of a porcupine bar for embankment protection



the deepest scour point of the bank line channel plus a marginal distance as a factor of safety. The bars may be extended to link up with the continuous non submerged river bank or road – above the highest flood level – to avoid out flanking. To reduce costs, the extension can be for an alternate or every third bar only.

Spacing between bars is not usually the same as for spurs. The main purpose of the bar is to obtain continuous deposition of silt and not to deflect the flow away from the bank. However, wide spacing may create sand bars around each bar leaving lagoons in between, thus closer spacing is preferred. When the curvature of the eroding bank is sharp and the flow velocity is high, bars should be spaced less than 10 m apart.

Silting apron. Concrete porcupines are also used as silting aprons for spurs. Used in the form of a sunray, they have shown encouraging results for filling scour pits around spurs.

Longitudinal Protection Structures

Longitudinal protection structures are installed on river banks parallel to the river course, generally with the aim of protecting adjoining areas from inundation, erosion, and river meandering. They are usually constructed on natural banks and extend for a considerable distance. The most common structures are embankments or levees in the form of guide bunds or banks, afflux bunds, and approach embankments. Very often, spurs are constructed together with longitudinal structures to protect the latter. Some common longitudinal structures are described in the following.

Levees or earth fill embankments

Levees, or marginal embankments, are dam-like earthen structures constructed along a river in order to protect the surrounding countryside from flooding and/or to confine the course of a river to provide higher and faster water flow (Figures 55 and 56). They are usually constructed for long stretches along a river in low lying areas with an extended floodplain (Figure 57).

Figure 55: Levee along the Rapti River in Nepal

Source: Rajendra Prasad Adhikary

Figure 56: Extension of flooded river before and after levee construction

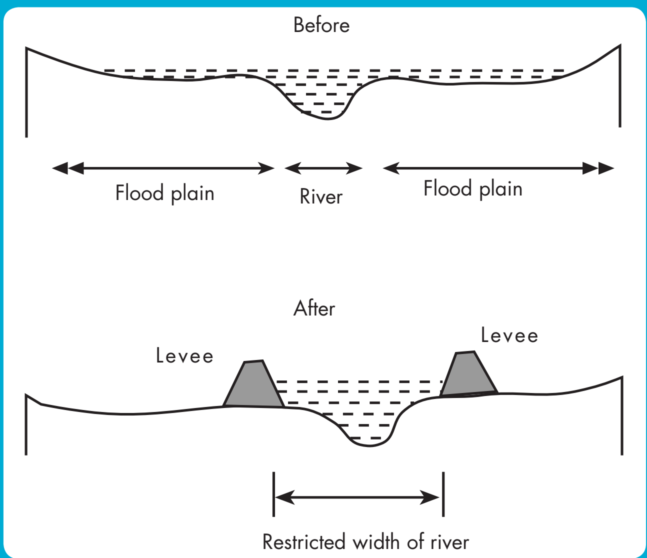
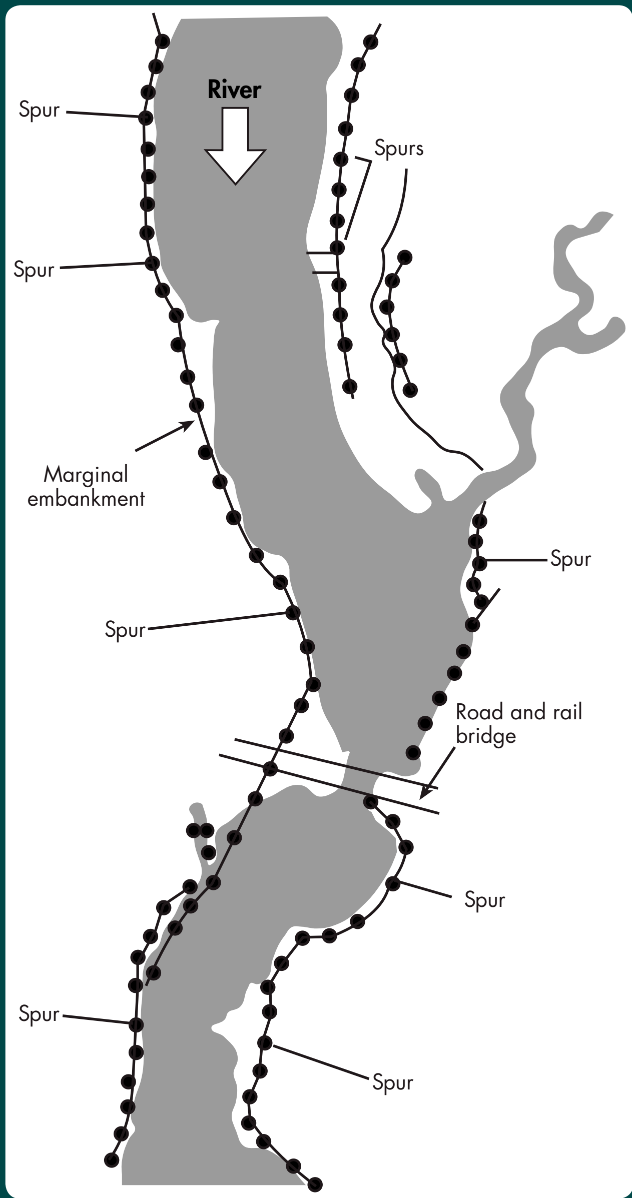


Figure 57: Levees (marginal embankments) protected by spurs along a river in the plains



Levees are usually constructed by piling earth on a cleared level surface. The type of fill material used for construction usually depends on the materials available in the local area. The levee must be designed and constructed very carefully as failure can result in catastrophic impacts.

- Both sides of the levee should be properly constructed. The slope is fixed to ensure stability, and ultimately depends on the material that the levee is made of and its height. The sides should be strengthened with riprap (see below) to prevent erosion.
- The slopes of the upstream and downstream faces of the embankment should be flat enough to provide sufficient width at the base to ensure that the maximum shear stress under flood conditions will remain well below the corresponding maximum shear strength of the soil, in order to provide a suitable factor of safety.

Specific design criteria for levees are given in Box 18.

Guide banks and other approach embankments

Guide banks are structures built to guide a stream or river through a bridge opening or towards other hydraulic structures such as weirs, especially when river flow level is markedly higher than usual. The aim is to confine the

Box 18: **Design criteria for levees**

Freeboard

The minimum vertical distance between the maximum flood level and the top of the levee (the crown or crest) is generally taken to be 1.5 times the height of the wave (hw), which is calculated from the following:

$hw = 0.032\sqrt{VF} + 0.763 - 0.271\,(F)^{1/4}$ (for $F < 32$ km)
or
$hw = 0.032\sqrt{VF}$ (for $F > 32$ km),

where
V = velocity of wind km/hr, and
F = straight length of water surface in km.

Width

The top width of the embankment should be sufficient to keep the seepage line well within the levee. For a small levee, this top width is generally governed by the minimum roadway width requirements.

The minimum top width (A) of an earthen levee can be calculated as follows:

$A = H/5 + 3$	for a very low levee,
$A = 0.55\sqrt{H} + 0.2H$	for a levee lower than 30 m, or
$A = 1.65\,(H + 1.5)^{1/3}$	for a levee higher than 30 m,

where H is the height of the levee.

river within a reasonable waterway and direct the flow in a manner that ensures its safe and expeditious passage (Varshney et al. 1983). They also reduce or eliminate local scour at the embankment and adjacent piers (Julien 2002). In a wide river lined by levees, a series of diversion structures may be used to guide and narrow the water course and protect the levee or highway embankment, where a highway or other bridge crosses the river. These consist of an afflux embankment or bund, an approach embankment, and the guide banks themselves (Figure 58).

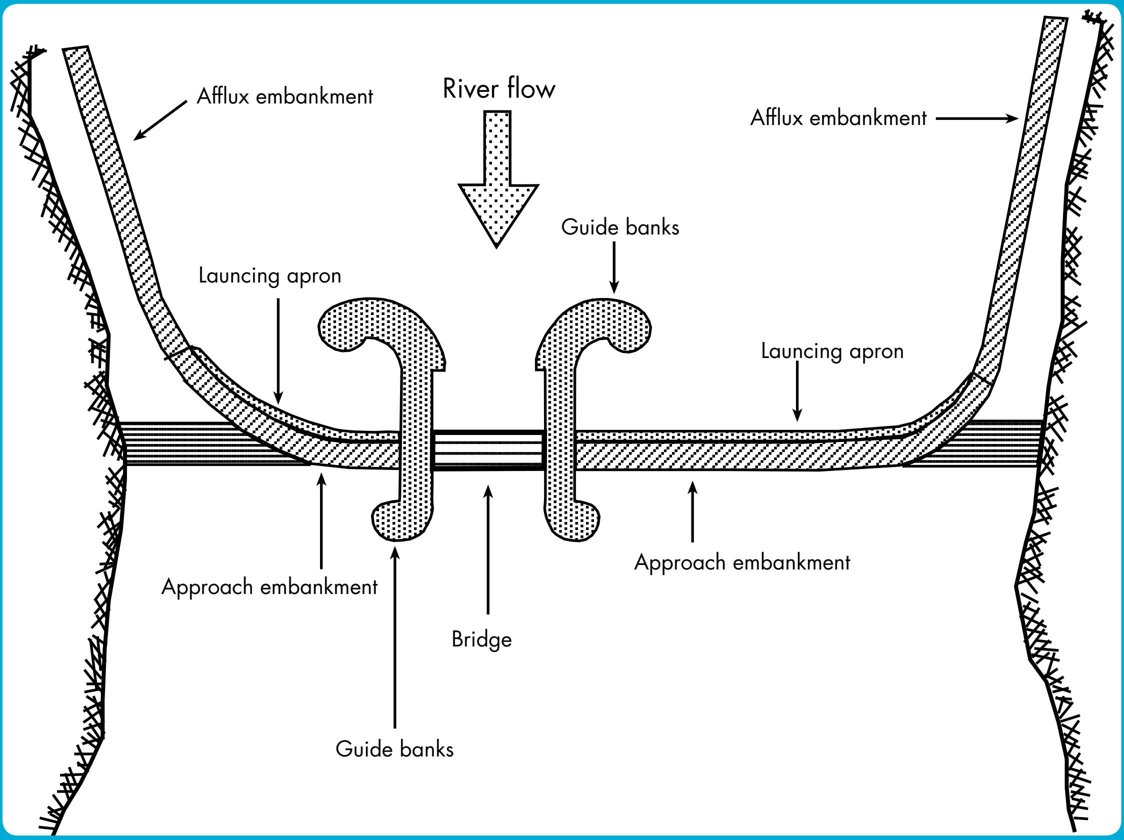
Guide banks are constructed in a river in order to:

- confine the flow to a single channel,
- improve the distribution of discharge across the width of a river thus controlling the angle of attack by a flash flood,
- protect weirs, barrages, or other hydraulic structures constructed in the river such as intakes from flash floods,
- control the meander pattern of a river,
- control overtopping of natural embankments in a flash flood and protect adjacent land from flooding,
- reduce erosion of banks by the water current,
- prevent sliding of soil as a result of the draw down effect of the flood water level,
- facilitate smooth transportation of water, and
- prevent piping of water through the banks.

Two guide banks are generally required when the waterway opening is in the middle of a wide flood plain or is a braided stream where the direction of the main flow can shift from side to side. A single guide bank may be sufficient at a location where the river is confined to one side of a valley and it is possible to take advantage of a natural non-erodible bank such as a hard rock exposed surface. It is essential to check the load bearing capacity of the river bed sub-soil before choosing the location of a guide bank. The minimum width between the guide banks should be sufficient to provide the required waterway opening during the anticipated flash flood discharge.

The design of guide banks is described in Box 19.

Figure 58: Guide banks and other approach embankments



Box 19: **Design of guide banks**

Length

For shifting alluvial rivers, the length depends on the distance necessary to secure a straight run for the river, and the distance necessary to prevent the formation of a bend in the river so as to avoid the angle of attack of the anticipated flash flood.

Plan shape

Ideally, the guide bank should have a converging curved shape forming a bell mouth entry to the waterway. The axis should be parallel to the principle direction of flood flow through the opening. This shape is particularly suitable where the direction of flow can vary. In most cases, the main sections of the two banks are constructed parallel to each other, but other forms are possible, for example curved or converging.

Embankment section

The angle of the embankment slope is calculated according to the subsoil conditions, the angle of repose of the embankment material, and the type of slope revetment provided (see below): the slope should usually have a vertical to horizontal ratio of between 2:1 and 3:1 (Singh 1980). In general, the top of the embankment is made wide enough to accommodate vehicles for construction and maintenance purposes. Guide banks should normally extend above the design high water level with a freeboard allowance of 1–1.5 m depending upon the discharge condition (Singh 1980). Lower guide banks that can be overtopped under high flood discharge condition may be preferred in some cases. Under these conditions, the top of the bank and outside slope must be protected against erosion.

Spacing between the guide banks

The layout of the guide banks should be such as to guide the flood smoothly throughout the guide bank length. Generally, the guide banks are constructed to form a symmetrical pair. They should confine the river within a reasonable channel that can ensure safe and rapid passage of water during a flash flood. The confined width of the river between the guide banks in an alluvial river can be calculated using Lacey's formula (Singh 1980):

$L = 4.75\ Q½$,

where
L = constrained width of the river in m, and
Q = maximum discharge in m^3/s of the river during a flash flood.

This equation is for finding the wetted perimeter. In practical cases, the width is slightly more than the wetted perimeter, and the formula is modified to:

$L = 5\ Q½$.

The calculated waterway should be multiplied by 3–6 to give the spacing between the embankments; the exact number depends on the width, nature, river characteristics, and level of protection to be provided (Jha et al. 2000).

Pitching

The inside slope of the embankment is subjected to erosion from the river flow, particularly during floods and flash floods. The continuous movement of water saturates the embankment material as a result of pore water pressure. Sudden increases and decreases in the water level can change the water inflow and outflow in the embankment material and damage the embankment. Hence, the inside slope should be protected by stone pitching. The usual thickness of the pitching varies from 40–60 cm. The thickness can be determined from the formula $t = 0.60\ Q^{1/3}$, where t is the thickness in metres and Q is the maximum river water discharge in m^3/s (Varshney et al. 1983).

Launching apron

Stone pitching protects the face of the bank. However, floods can induce scouring at the toe which would undermine the pitching and cause its collapse. To prevent this, a stone cover or launching apron is laid beyond the toe of the bank on the horizontal river bed (Figure 59). As the scour undermines the apron starting at its farther end and working back towards the slope, the apron falls to cover the face of the scour, with the stones forming a continuous carpet below the permanent slope of the guide bank. The apron must have sufficient stone to ensure complete protection of the whole of the scour face. The length of the scoured face is equal to $5\sqrt{D}$, where D is the anticipated scour depth below the apron.

The scouring effect is a function of the gradation of the silt available in the river bed and the discharge of the flowing water. It can be calculated using the following formula (Varshney et al. 1983):

Lacey's silt factor is:

$f = 1.76\ mr½$,

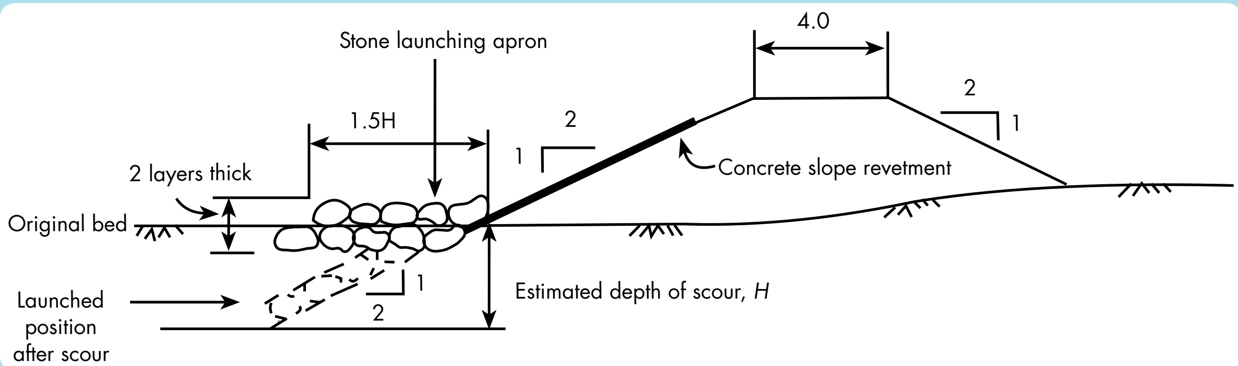
where mr is the average diameter of the river bed material.

Depth of scour (R) is given by

$R = 0.47\ (Q/f)^{1/3}$,

where Q = is the maximum discharge in m^3/s of the river during a flash flood.

Figure 59: Cross-section through guide bank (numbers indicate relative values for any given size



Source: HMGN 1990

Concrete embankments

Concrete embankments are made from cemented bricks, stones, or concrete. These are thin but strong embankments usually installed in urban reaches of water courses where there is not enough space to build more massive structures. They can also be combined with earth fill structures. The construction cost of concrete embankments is higher than that of earth fill embankments and such an embankment has a significant impact on the environment and often destroys the ecology of riparian areas.

Revetments and rock riprap

Revetment refers to a continuous artificial surface on a river bank or embankment slope and part of the river bed which is designed to absorb the energy of the incoming water and protect against erosion by the river current. Revetments are usually placed along the concave side of a river bend where river velocities are high. Upstream from barrages, revetments may be used to hold approaching river banks in their existing positions. Revetments can be flexible or rigid. They can be constructed from various materials including rock, stones, stone-filled gabions, concrete slabs, timber piles, bamboo piles, old tyres, and sandbags.

If there is a potential for scour at the toe, the revetment must be extended down to the expected level of the scour and sufficient material added in the form of a thickened toe or horizontal apron such that the toe material will launch to a stable slope as the bed scour develops.

Rock riprap is one of the most common types of material used to make a revetment (see, for example, FHWA 1989; MDEP 1997). Riprap is a layer or facing of loose rough rock or other material used to armour embankments, streambeds, bridge abutments, pilings, and other structures subject to erosion by wave action and impact damage from debris carried by the waves. Riprap absorbs and deflects the energy of floodwater and debris before it reaches the defended structure, while the gaps between the rocks trap and slow the flow of water. Riprap has structural flexibility and can be constructed with locally available materials.

A riprap revetment is composed of three sections: an armour or stone layer, an underlying filter layer, and a toe protection layer. Armour is the outer layer of rough angular rock. The underlying filter layer supports the stone against settlement, allows groundwater to drain through the structure, and prevents the soil beneath from being washed through the armour by waves or groundwater seepage. The toe protection prevents downward movement of the riprap and is constructed by trenching in the riprap at the toe of the slope. Figure 60 shows the cross-section through a typical riprap revetment. Various designs can be used for toe protection depending on the exact requirements and physical location (Figure 61). The design considerations for a rock riprap revetment are described in Box 20. More detailed information can be found in FHWA (1989). This approach can be adapted for other types of revetment.

Apart from rock riprap, reformed flexible ‘mattresses’ can also be used to form revetments. They can be prepared from a variety of materials including willow and timber, reinforced asphalt, soil, cement, and articulated concrete. The design and construction method depend on the type. Reinforced asphalt mattresses are the most durable and abrasion resistant of the above types but highly mechanized techniques are required for their manufacture and placing. Gabion mattresses consist of flat mattresses fabricated from wire mesh and filled with stone. Mattresses are generally used to protect a bank against high velocities where stone sizes are very small.

Bags filled with sand or concrete can also be used as revetment. This type of protection is used where gravel is available but large stones are rare. This protection is rigid and almost all the failures are due to undermining of the toe at the ends of the protection.

Porcupines used as embankment protection

Transversal arrangements of porcupines are used to reduce water velocity and encourage siltation, as described in the first part of this chapter. Longitudinal arrays of porcupines can also be used as a pro-siltation device to stabilize a river bank (Figure 63). The porcupines can be made of timber or bamboo as well as concrete. The bamboo and timber structures have a shorter life than concrete porcupines but can be more environmentally acceptable. They

Figure 60: Cross-section of typical rock riprap revetment

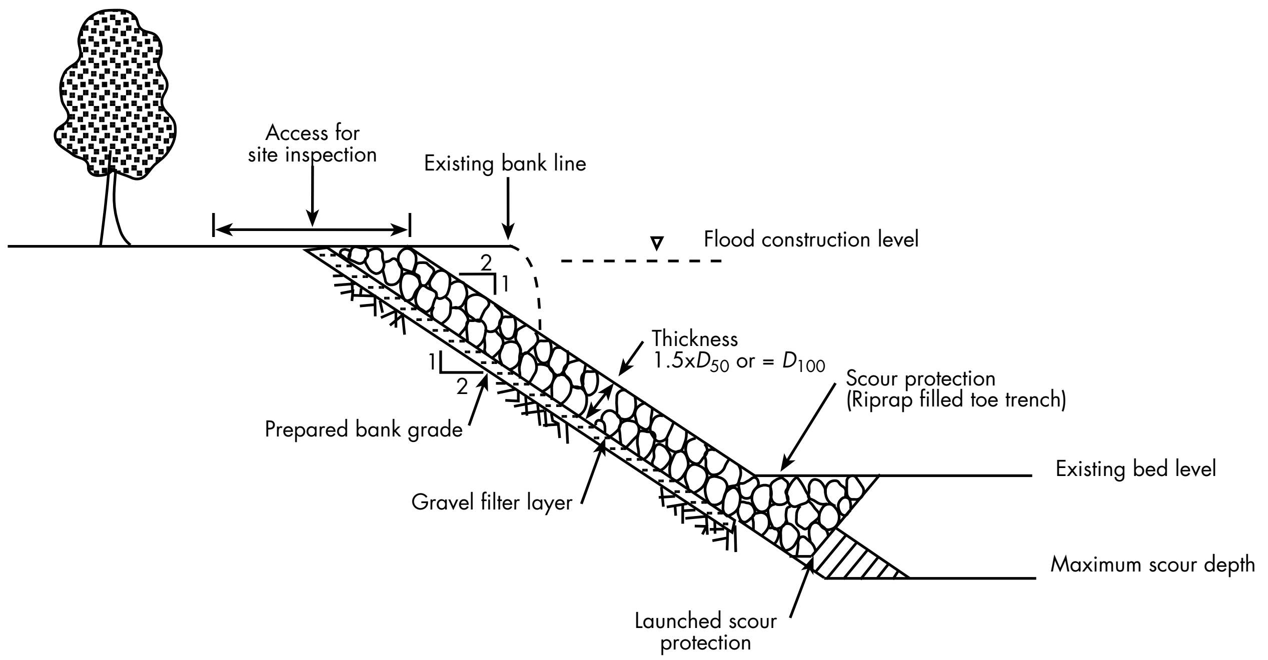
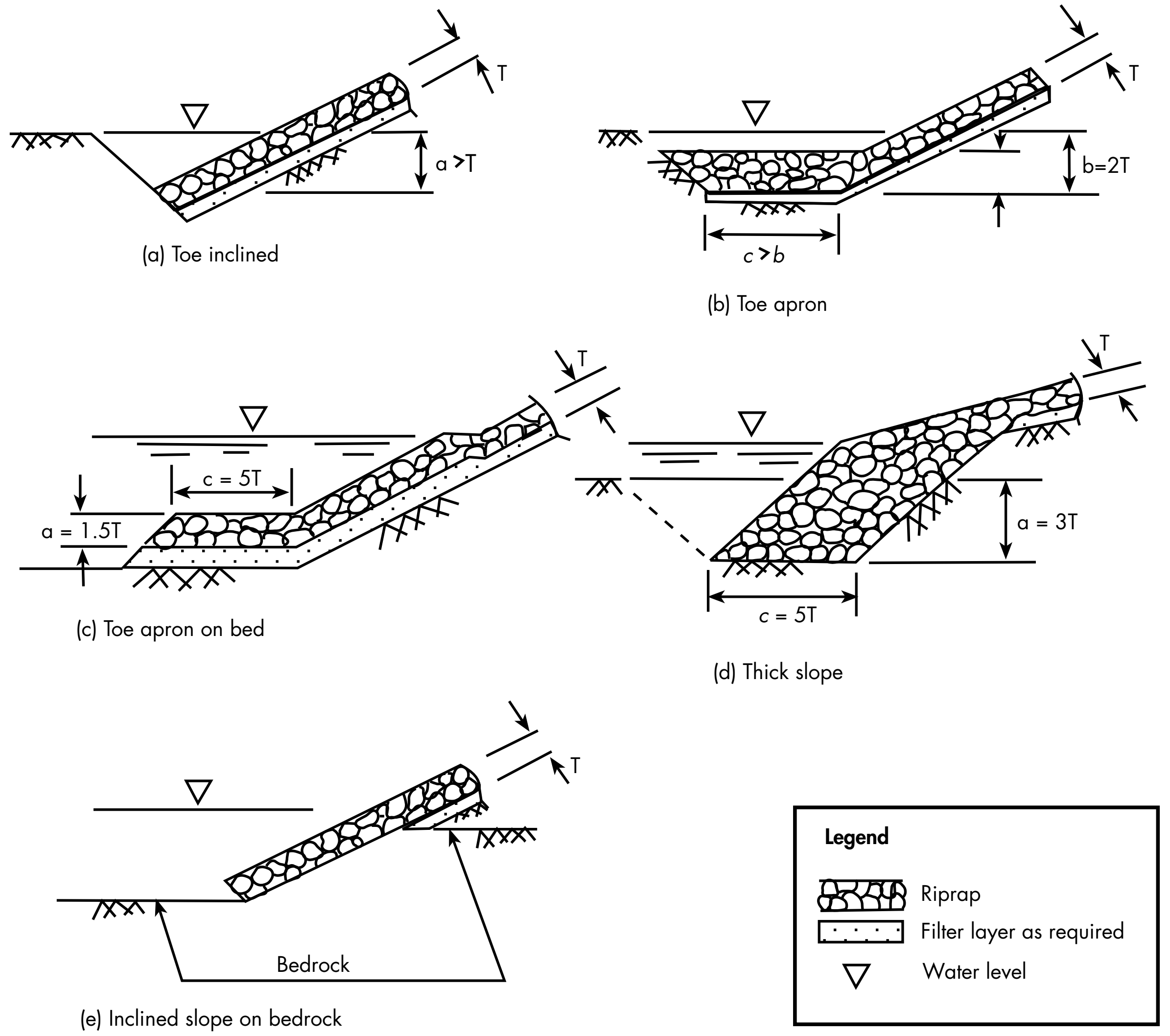


Figure 61: Different designs for the toe of a rock riprap revetment



Box 20: **Design considerations for rock riprap revetments**

Rock size

Riprap is classified as either graded or uniform. Graded riprap contains a mixture of stones which vary in size; uniform riprap contains stones which are similar in size. For most applications, graded riprap is preferred to uniform riprap. Graded riprap forms a fexible self-healing cover, while uniform riprap is more rigid and cannot withstand movement of the stones. Graded riprap is cheaper to install, requiring only that the stones be dumped so that they remain in a well-graded mass (MDEP 1997). Graded riprap is described in terms of the median diameter D_{50}: in a mixture of stones, 50% of the rock by weight will have a diameter above D_{50} and 50% below. The largest stones should not exceed 1.5 times the D_{50} specified.

The stability of the structure is provided by the well graded rock layer and the average rock diameter. Rock riprap on a stream bank is affected by the hydrodynamic drag and lift forces created by the velocity of flow past the rock. These effects are resisted by the force components resulting from the submerged weight of the rock and its geometry. The required D_{50} is determined from the expected maximum velocity of flow under flood conditions as shown in Table 15.

Table 15: Determining median diameter (D_{50}) of riprap from maximum flow velocity

Maximum flow velocity (cfs)	Riprap D_{50}	
	cm	inches
16	91	36
13	61	24
11	46	18
10	38	15
8	25	10
6	15	6
4	7.5	3

Source: MDEP 2003

Rock shape

Stones should be shaped so that the least dimension of the stone fragment is not less than one-third of the greatest dimension of the fragment. Flat rocks should not be used for riprap. Blocky and angular shaped rocks with sharp clean edges and relatively flat faces are good. If rounded stones are used, they should be placed on flatter slopes (not exceeding 2.5:1 horizontal to vertical) and the recommended median rock diameter should be increased by 25% with a comparable increase in the thickness of the revetment (USACE 1991).

Thickness

The minimum thickness of the riprap layer should be 2.2 times the maximum stone diameter for a D_{50} of 30 cm or less, but not less than 15 cm, and twice the D_{50} for a specified D_{50} greater than 30 cm.

Figure 63: Bamboo porcupines as protection along an embankment

Source: Rajendra Prasad Adhikary

can be intertwined with living plants to form a stable structure as silt builds up and the plants root into the ground (see Chapter 4).

Other Protection Structures

Sandbagging

Sandbags can be used to reinforce structures (e.g., Figure 51) and to build (emergency) dikes (Hellevang 2011). They are widely used to control or reduce the devastating effects of floods particularly in plains areas. Figure 64 shows a typical use of sandbags in a toe wall along an embankment.

Sandbags can also be stacked to make a barrier against rising flood water as well as in areas where flash floods are likely (Figure 65). The sandbag wall or barrier should be constructed on a firm flat surface to prevent seepage. A trench can be dug and the bottom

Filter blanket

A geo-textile or stone filter blanket should be placed under the riprap to prevent water from removing the underlying soil material through voids in the riprap. Generally, the filter blanket is made from a layer of well-graded gravel or sand-gravel, or synthetic filter fabric materials. The design of a gravel filter blanket is based on the ratio of the particle size in the overlying filter material to that of the base material in accordance with the following criteria (Brooks 1989, cited in PBC 2000):

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

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.

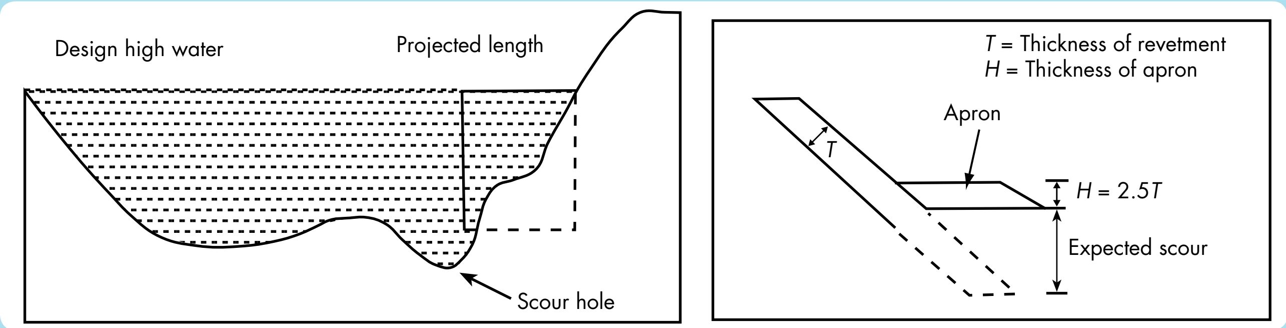
Geo textiles can also be used as filters in place of or in combination with gravel filters. They are both cheaper and easier to install.

Toe design and scour depth

The revetment toe must be protected from undermining by scour. A deep scour hole can form at the tip of the revetment where the flow velocity is much higher than the average channel velocity (Figure 62). The scour hole can undermine the bank leading to a collapse of the whole structure. An apron can be constructed to fill the scour hole (Figure 59).

This method is recommended for cohesionless channel beds in which deep scour is expected. In cohesive channel beds, the bank revetment should be continued down to the expected worst scour level and the excavated area refilled as shown in Figure 59 (Julien 2002).

Figure 62: Scour hole and expected scour



layer of bags placed in it to improve stability. Plastic sheets can be used to help seal the dike if available. It is important to construct the barrier properly to ensure that the result is effective; Hellevang (2011) provides detailed instructions. Bags can be made from various materials and in different sizes but woven polypropylene is the most common. Bags with a filled weight of no more than 30–40 pounds (14–18 kg) are easier to handle. Sand is the easiest and most available material for filling and shaping the bags. Silt and clay can also be used, but working with these materials is more difficult.

Whatever the final use, it is important to fill the bags properly. The bags should be about one-half full and tied near the top so that the sand can move easily (Figure 66). Overfilled bags and bags tied too low lead to gaps in the dike or wall, which allows water to seep through.

Figure 64: Toe wall constructed from bamboo and sandbags

Source: Mercy Corps

Figure 65: Sandbag dike

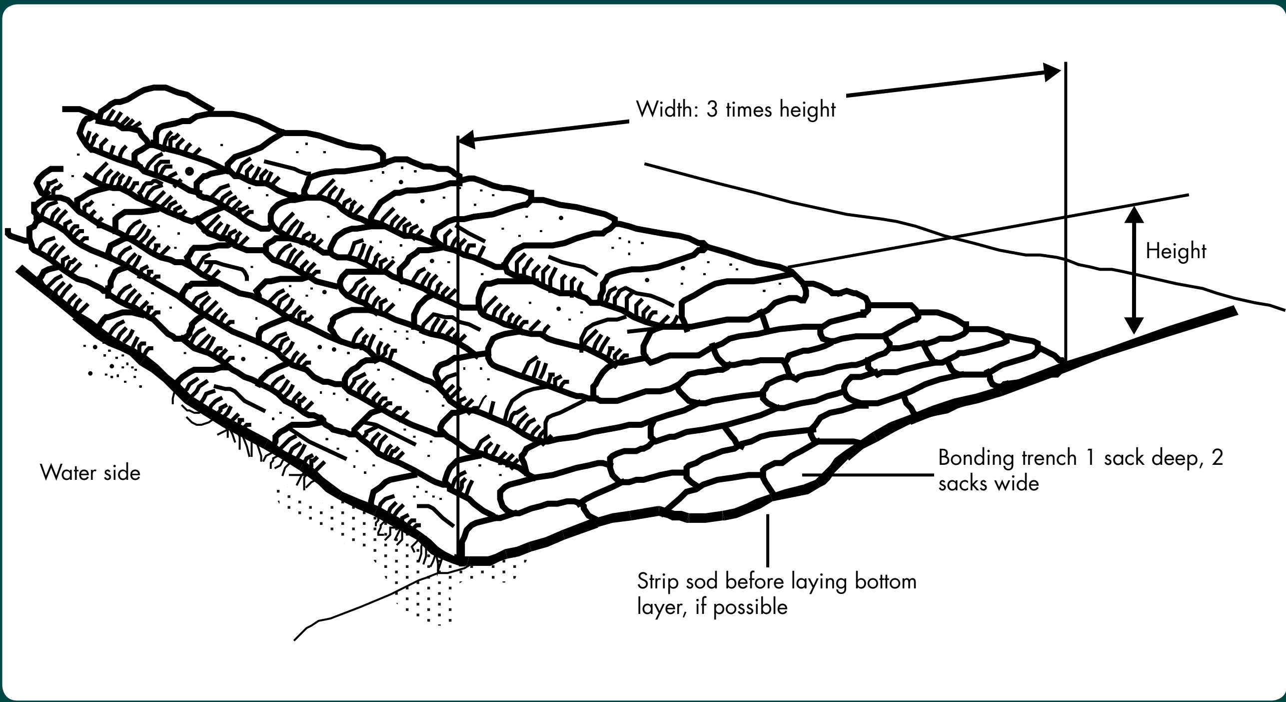
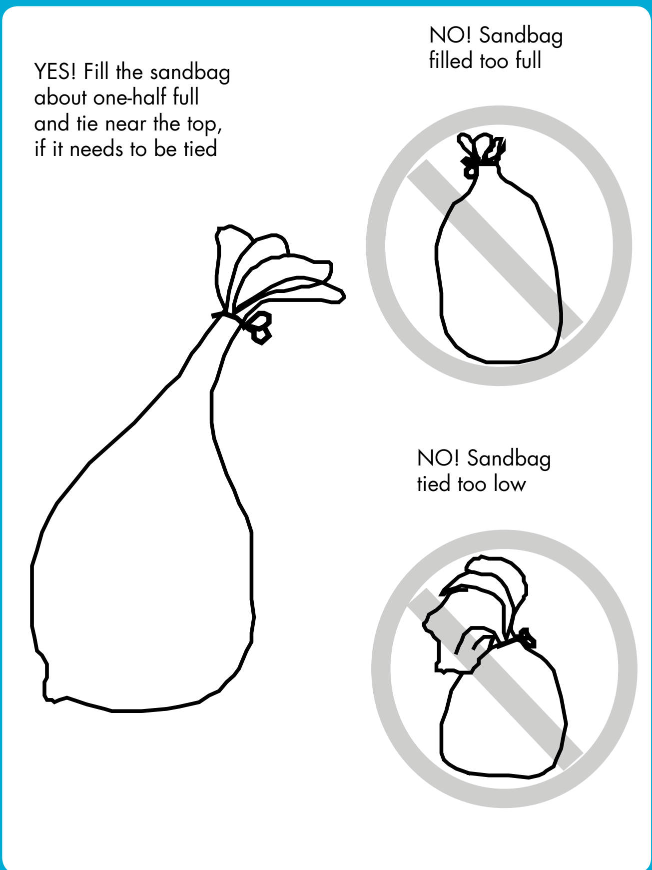


Figure 66: Correct way to fill sandbags



Source: Hellevang 2011

Figure 67: Concrete channel lining

Source: Nabin Baral

Channel lining

Channel lining is a protective layer used to protect the banks and bed of a watercourse against erosion. Channel lining can help increase the velocity of flow to ensure easy transport of sediment and reduce deposition in the channel bed. It is recommended in catchments highly prone to erosion, particularly in urban and alluvial fan reaches. However, channel lining can have a marked environmental impact and the necessity and the type of structure should be carefully assessed.

Channel lining structures can be made from many materials including concrete (Figure 67), gabions, and wood, as well as earth, rocks, asphalt, and plastic. Concrete and cement linings have a higher environmental impact, natural materials generally a lower one. Wood channel linings are usually cheaper to install and maintain than those made of other materials.

Bamboo piles

Bamboo can be used in the form of piles to strengthen a foundation or stabilize a flood embankment or river bed. The rows of bamboo piles should be firmly fixed with a rope or iron wire. Piling in wet soil is very easy but may otherwise require more strength. It may be necessary to excavate small holes in boulder covered parts of the river bed. Two parallel rows of piles can be prepared and the space between them filled with boulders and pebbles as a toe protection measure for flood embankments (Box 21).

Box 21: **How to use bamboo piles to develop a protection structure**

Materials

- Bamboo piles
- Digging tools, hammer
- Boulders or pebbles

Installation

1. Drive piles into the ground at least 1 m deep by hammering. The piles should be about 40 cm apart and driven in to leave about 1–1.5 m exposed at the top.
2. Where there are boulders, excavate a small area and hammer the pile in. Fill in around the pile.
3. Tie the piles together with rope or iron wire.
4. Fill the space between parallel rows of piles with boulders and pebbles as a toe protection measure.