Chapter 5: Physical Methods for Slope Stabilization and Erosion Control

The bioengineering methods for slope stabilization and erosion control described in the previous chapter have a number of advantages. They are generally low cost and easy to install, and rather than disintegrating over time, their strength increases as root systems develop and the structures become more stable. However, such methods are not usually sufficient to withstand the volume of debris involved in mass failure, and are not appropriate for all the interventions required to reduce flash flood risk. Physical structures and techniques are also required for slope stabilization and erosion control. Various types of construction can be used to help retain soil and improve slope stability. The selection of measures always depends upon the site, the topography, and the required result. Proper selection and design of any measures plays a very important role in slope stabilization and the control of erosion and measures should only be undertaken as the result of an integrated planning process. Physical measures are often combined with bioengineering approaches to obtain the maximum effect.

Some of the major physical methods are described in this chapter. They can be divided broadly into measures to reduce runoff (terracing, diversions, grassed waterways, conservation ponds), methods to stabilize slopes and reduce erosion (retaining walls, drop structures, sabo dams), and integrated methods to address specific problems (gully control, trail improvement), although they all tend to have multiple functions.

Terracing

Terracing is the technique of converting a slope into a series of horizontal step-like structures (Figure 22) with the aim of:

- controlling the flow of surface runoff by guiding the runoff across the slope and conveying it to a suitable outlet at a non-erosive velocity;
- reducing soil erosion by trapping the soil on the terrace; and
- creating flat land suitable for cultivation.

Terracing helps prevent the formation of rills, improves soil fertility through reduced erosion, and helps water conservation.

Figure 22: A terraced slope in Nepal

Source: Jack Ives

Types of terrace

Terraces can be made in a variety of ways. The best approach depends on many factors including the steepness of the slope, the intended use, and the soil. The terraces are constructed with light equipment or by hand. The spacing between the terraces depends on the slope of land; the distance between terraces goes down as the slope increases. The three main types of terrace are bench, level or contour, and parallel or channel.

Level or contour terraces are constructed along slope contours with the main aim of retaining water and sediment. The terrace edge is planted with trees, small plants, and grass, usually with trees on the outward facing edge to increase stability.

Bench terracing is similar to contour terracing with the difference that the terraces do not strictly follow the contour line and runoff may run along as well as across the terrace. Bench terraces are primarily constructed to enable crops to be grown on sloping land, rather than to retain water and sediment. Bench terraces are recommended for slopes with gradient of up to 33%, but as a result of pressure on land are constructed on slopes up to 50–60% (Sharda et al. 2007).

Parallel or channel terraces are mainly used in heavy rainfall areas. They are also known as graded terraces as they have a constant slope or gradient along their length which is used to convey excess runoff at a safe velocity into a grassed waterway or channel.

Of these three, bench terraces are the most common type found in the mountain and hill areas of the Hindu Kush Himalayan region. Following is a brief description of bench terraces and a type of contour terracing that is particularly useful for stabilization. The construction of bench terraces is described in more detail in Box 7.

Bench terraces

Bench terraces are particularly suitable where marked seasonal variations exist in the availability of water. The approach consists of converting relatively steep land into a series of horizontal steps running across the slope. These steps can be constructed by simply digging out the clayey soil, or they can be reinforced with locally available mud, stone, or brick. The terraces help conserve moisture during the long dry season, which is especially important where there are sandy and loam types of soil, and they help to slow and drain away runoff during the heavy rainfall monsoon season, which also helps counteract the tendency for sliding. There are three main types (Figure 23):

- outward sloping terraces, which are used to reduce a steep slope to a gentle slope;
- level terraces, which are used to impound water for paddy cultivation; and
- inward sloping terraces, which are the most suitable for steep slopes because they guide the surface runoff towards the hillside rather than down the slope.

Rainwater can be drained from outward sloping terraces along a ditch constructed along the toe of the riser. In inward sloping terraces, the riser is kept free from flowing water and is protected by a cover of grass.

Terrace design is influenced by the following factors (Sharda et al. 2007):

- soil depth and distribution of the top soil;
- slope of land;
- amount and distribution of rainfall; and
- farming practices and proposed crops to be grown.

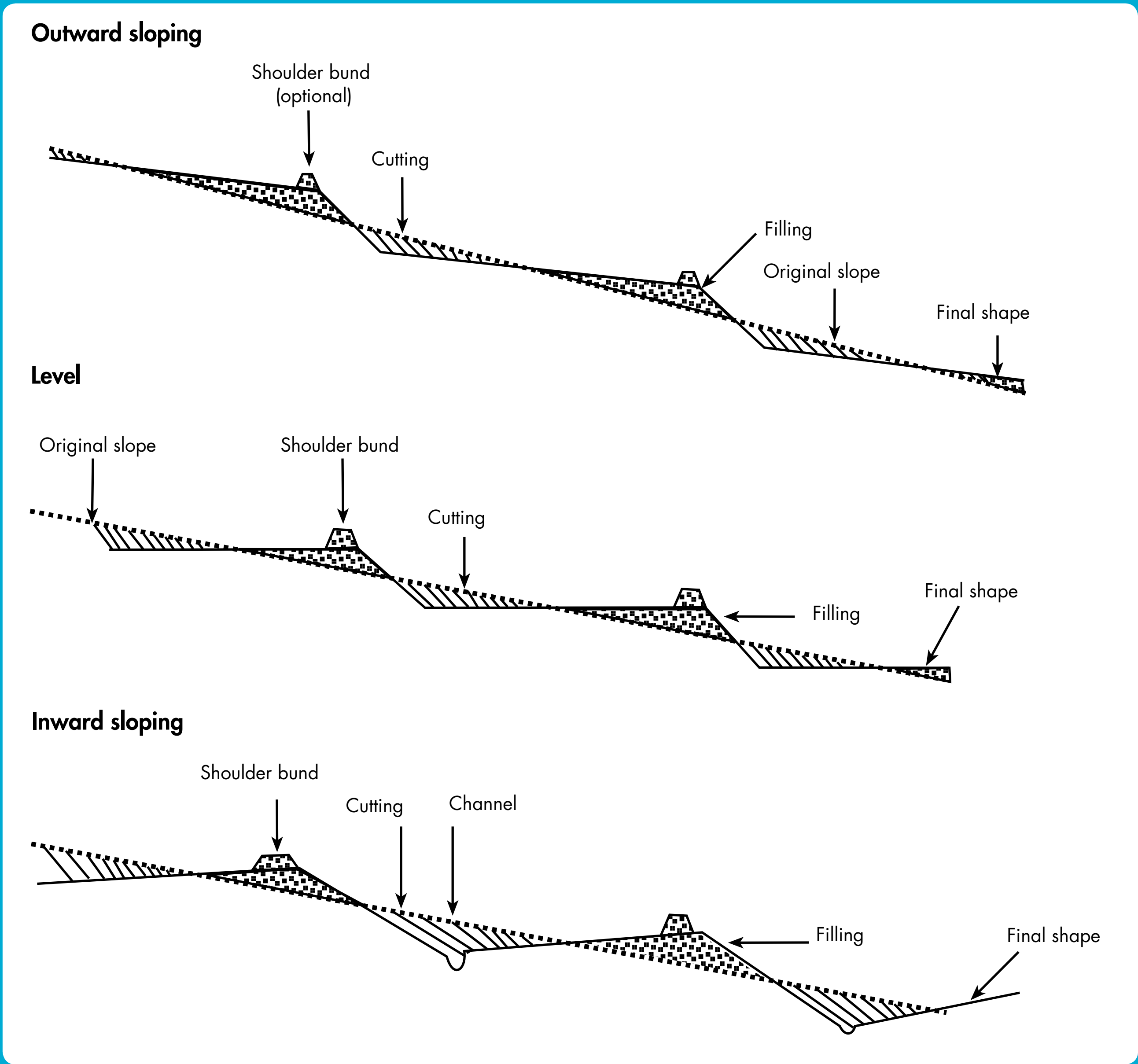
When designing the terrace, it is necessary to select the type and determine the desired width, vertical interval and spacing, length, gradient, and cross-section (Box 7).

Contour terraces

The main aim of contour terraces is to retain water and sediment. Contour terraces are similar to bench terraces, with the major difference that the terrace is formed along the contour, so that runoff flows across but not along the terrace. In addition, the terrace edge is planted with trees, small plants, and grass to stabilize it and trap sediment. The terraces can be constructed by excavating soil from the upper half and using it to fill in the lower half as for bench terraces, or can be allowed to form naturally using a technique called sloping agricultural land technology (SALT), or contour hedgerow intercropping (agroforestry) technology (CHIAT).

SALT combines the strengths of terracing with the strengths of natural vegetation to stabilize sloping land and make it available for farming. Double hedgerows of fast growing perennial nitrogen-fixing tree or shrub species are

Figure 23: Types of bench terrace



planted along the contour lines on a slope at a distance of 4–6 metres to create a living barrier that traps sediment carried downslope by runoff (Tang 1999; Tang and Murray 2004). As the sediment builds up, the sloping land is gradually transformed to terraced land. The space between the contour hedgerows is used for subsistence and cash crops. The hedgerows both markedly reduce soil erosion and contribute to improving and/or maintaining soil fertility through nitrogen fixation at the roots and incorporation of the hedgerow trimmings into the soil. SALT can be established on farmland slopes with gradients of 5–25% or more.

A combined approach has also been developed for improved terraces in which retaining walls are first constructed along the contours using cement bags filled with soil supported by bamboo cuttings along the contour. The soil is then excavated from the upper part of the terraces and used to build up the lower part above and behind the terrace riser wall to create a level bed; the fertile top soil is kept aside and later spread over the newly terraced fields. Grass and hedgerow species are then planted on the outermost margins of the terraces above the risers (ICIMOD 2008). The vegetation improves the terrace stability and increases moisture retention, while the construction means that the terraces are immediately ready for use, unlike the original SALT technique.

Box 7: **Design and construction of bench terraces**

Step 1: Selection of type

The type is selected according to the rainfall and soil conditions of the area. In general, outward sloping terraces are constructed in low rainfall areas with permeable soils; level terraces in areas with medium rainfall and/or highly permeable soils, or for growing rice; and inward sloping terraces in areas of heavy rainfall and less permeable soils.

Step 2: Width

The width of the terraces is determined based on the soil depth, slope, amount and distribution of rainfall, and intended farming practices. Construction of very wide terraces is more costly, requires deep cutting, and results in a higher riser. However, at least two metres width is required for ploughing using bullocks (DSCWM 2005).

The formula for calculating the width of the terrace is given by Sharda et al. (2007) as

$$W = \frac{200 \times d}{S}$$

where
W = width of the terrace in metres
d = maximum depth of the cut (metres)
S = slope of land (%)

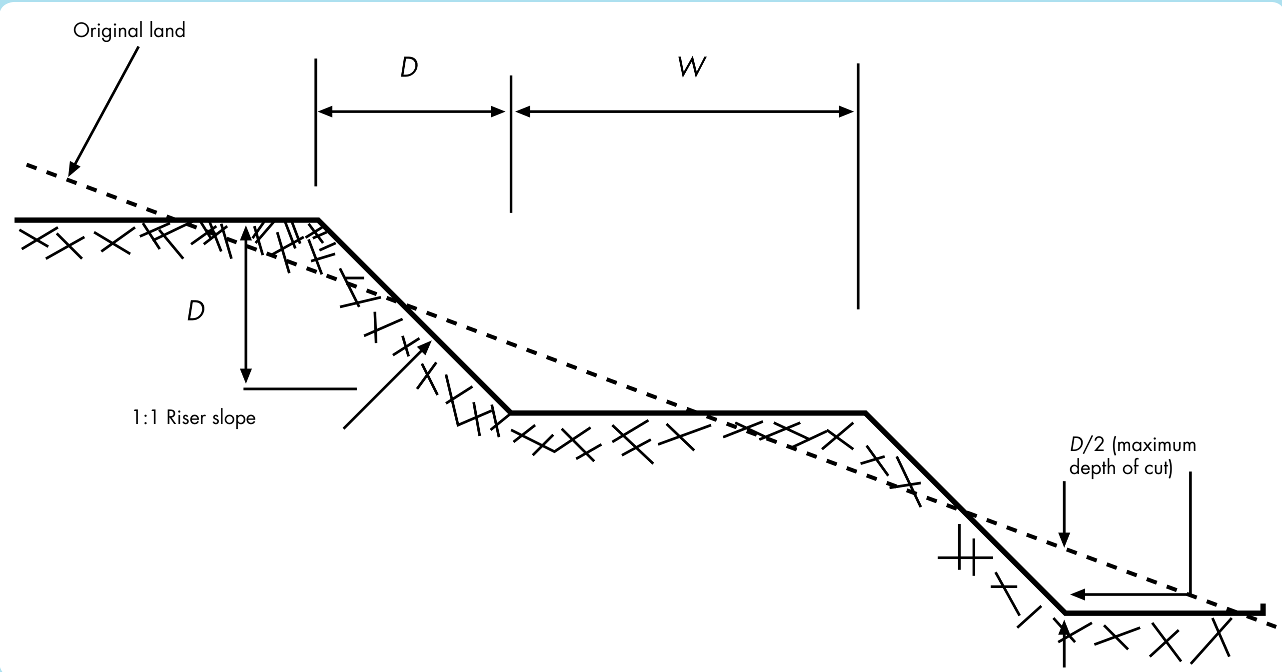
Step 3: Spacing

The spacing is the vertical interval (*VI*) between two terraces. The terrace spacing depends on the soil type, slope, surface condition, gradient, depth of cut, and agricultural use. The depth of cut and fill have to be balanced, thus the interval is equal to double the depth of cut. The depth of cut must not be so deep as to expose the bed rock. The spacing is also linked to the terrace width.

The soil depth limits the maximum depth of cut and thus the maximum possible vertical interval. At the same time, the width of the terrace should permit economic agricultural operation. The following steps should be followed to take the different factors into account (Mal 1999).

- Ascertain the maximum depth of the productive soil by taking soil samples from different locations.
- Decide which crops are to be grown in order to calculate the depth of soil required and thus the maximum possible depth of cut. The depth of cut should be such that at least a minimum convenient width of terrace is obtained.
- If d is the maximum depth of cut, the vertical drop between two consecutive terraces is $2d = D$ (Figure 24). And the corresponding horizontal distance is $100D/S$ or $200d/S$.
- If W is the width of the bench terrace and the riser slope is 1:1, the horizontal distance for a drop D is $(W + D)$.

Figure 24: Design procedure for a bench terrace



Therefore,
$W + D = 100D/S$ (Mal 1999).

If the riser slope is 1:1,

$$VI = D = \frac{S \times W}{100 - S}$$

Similarly, for a riser slope of 0.5:1, the horizontal distance for a drop D is ($W + D/2$).

Therefore,
$W + D/2 = 100D/S$

or $$VI = D = \frac{2W \times S}{200 - S}$$

Note: For a given slope, the greater the VI, the greater the width. For a given VI, the steeper the slope, the smaller the width.

Step 4: Length

The length of the terrace is determined by many factors including the shape and size of the land, degree of dissection of the land, and permeability and erodibility of the soil. Longer terraces are more efficient for agriculture and cost less to install, but they may increase the velocity of surface runoff thus increasing erosion (DSCWM 2005).

Step 5: Gradient

It is also important to determine the gradient along the terrace. It would be best to select the gradient in accordance with the rainfall intensity, soil permeability, and width and length of the terrace. But it can also be determined using the simpler approach of 1 m for every 100 m terrace length, or not more than 1%. In low rainfall areas with highly permeable soil, the gradient can be lower than 0.5%, whereas in high rainfall areas with low permeable soil, 1% is preferable to reduce excess run-off. The gradient can also vary, for example for a terrace around 100 m long, 0.25% for the first 25 m, 0.5% for the next 50 m, and 1% for the remainder.

Step 6: Cross-section

In bench terraces, soil excavated from the upper half is deposited on the lower half. In other words, the volume of cut is equal to the volume of fill (Mal 1999). The volume of soil after excavation is calculated in terms of loose cubic metres (LCM), and is more than the volume before excavation (banked cubic metres or BCM). All calculations should be done in BCM. Filling in LCM should be calculated such that the proper height will be obtained after settling. For land with a slope in the range 10–15%, a platform approximately 8 m wide should be constructed. The width is reduced to about 5–8 m for a slope of 15–25%, and about 3 m for a slope of 25–33%. The shoulder bund is constructed with a trapezoidal shape (1:1 side slope) and a height of 15–30 cm. A bottom width of 75 cm is provided for stability (Figure 25).

Figure 26 shows the typical appearance of bench terraces shortly after construction and some years later.

Worked example (adapted from Mal 1999)

Problem: Design a 120 m long bench terrace for a sandy loam soil with an average slope of 16%. The entire width of the terrace acts as a channel which is provided with a uniform gradient of 0.6%. Rainfall intensity for a 10 year recurrence interval and the time of concentration is 24 cm/hr. (The time of concentration is the time needed for water to flow from the most remote point in the watershed to the watershed outlet.)

Solution: An inward sloping terrace should be used (Figure 25). As the average slope is 16%, the width of the terrace is selected as 6 m or W = 6 m. A final slope of 5% is provided so that the inner side of the terrace is 30 cm lower than the outer side.

Average slope (S) = 16%, width of the terrace (W) = 6 m.

The terrace spacing (VI) is given by

$$VI = \frac{S \times W}{100 - S} \quad \frac{16 \times 6}{100 - 16} = 1.143 \text{ m.}$$

The following standard dimensions are assumed: riser side slope = 1:1, shoulder bund height = 30 cm, bottom width = 75 cm, side slope = 2:1

The area of the terrace that has to be drained by the channel is calculated using the formula:

$$A = \frac{L \times W}{10{,}000}$$

where

A = area to be drained (ha)

L = length of terrace (m)

W = width of terrace (m)

Thus, the area of terrace, $A = \frac{120 \times 6}{10{,}000}$ m^2 = 0.072 ha.

Figure 25: Design of (inward sloping) bench terrace (not to scale)

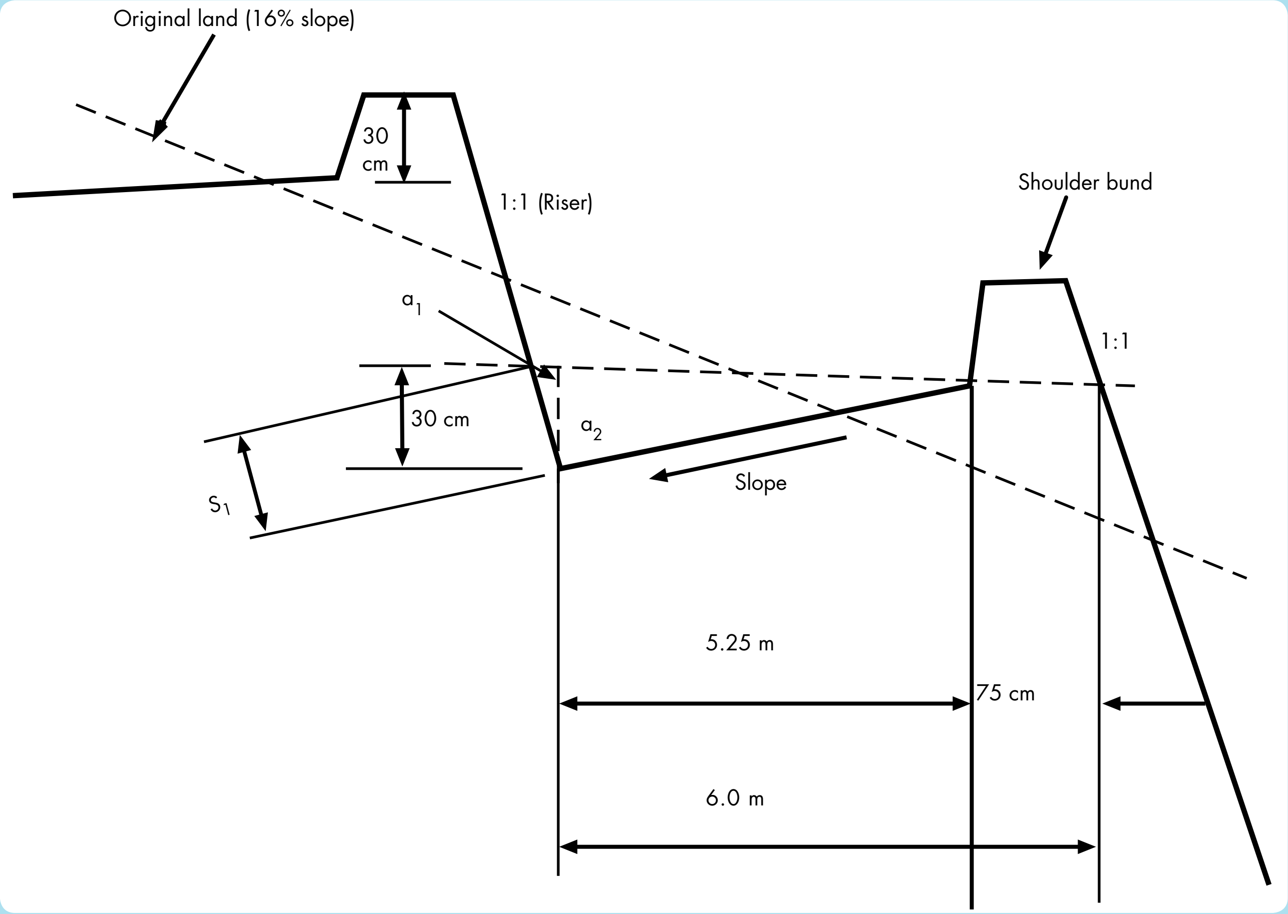


Figure 26: Newly constructed bench terraces on a slope (left) and the same terraces some years later (right)

Source: DWIDP

For a sandy loam soil, the runoff coefficient = 0.3. The peak discharge to be handled is obtained from the rational runoff formula:

$$Q = \frac{C \times I \times A}{36} \text{ (Mal 1999)},$$

where
Q = rate of runoff in cubic metres per second,
I = rainfall intensity, that is the rate of rainfall in mm/hr for a designed frequency for a duration equal to the time of concentration (tc),
A = area of watershed in hectares, and
C = dimensionless runoff coefficient.

Thus,

$$Q = \frac{0.3 \times 24 \times 0.072}{36} = 0.0144 \text{ m}^3 \text{ per second}$$

The area of flow can be calculated from Figure 25:
a_1 = ½ × 0.30 × 0.30 = 0.045 m^2,
a_2 = ½ × 5.25 × 0.30 = 0.7875 m^2.

The total area of flow is $a = a_1 + a_2$ = 0.8325 m^2.

$s_1 = \sqrt{(30^2+30^2)}$ = 42 cm = 0.42 m; s_2 $\sqrt{(0.30^2+5.25^2)}$ = 5.259 m,

where s_1 and s_2 are the perimeter of water flow.

The wetted perimeter (P) is calculated as:
$P = s_1 + s_2$ = 5.679 m,
$R = a/P$ = 0.8325/5.679 = 0.147 m.

Using Manning's formula, the velocity of flow (V) can be calculated from

$$V = \frac{1}{n} \times R^{\frac{2}{3}} \times S^{\frac{1}{2}}$$

$$V = \frac{(0.147)^{\frac{2}{3}} \times (0.006)^{\frac{1}{2}}}{0.04} = 0.538 \text{ m/s}.$$

The velocity is non-erosive. The discharge carrying capacity $Q = aV$ = 0.8325 × 0.538 = 0.45 m^3/s. When the terrace acts as a channel it has sufficient carrying capacity.

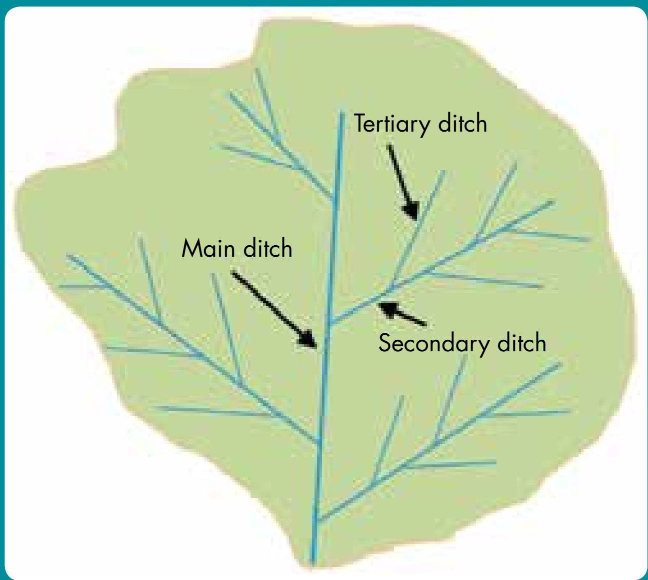
Diversions

Diversions are ridges of soil or channels with a supporting ridge on the lower side. They are built across the slope to intercept runoff and dispose of it at a selected location. They are used to break up long slopes, to direct water away from active erosion sites, to direct water around agricultural fields or other sites, and to channel surface runoff to suitable outlet locations. Safe passage of the surface runoff to prevent slope failure can be achieved by installing drainage ditches, or by cross drainage work for road structures.

Slope drainage

The simplest way to safely drain off springs and surface water is to use an open ditch (drain) or a system of open ditches. The main ditch is located in the direction of the slope gradient (downhill); secondary or lateral ditches are located in a fishbone pattern (Figure 27). Water should be collected as

Figure 27: Arrangement of ditches on the slope



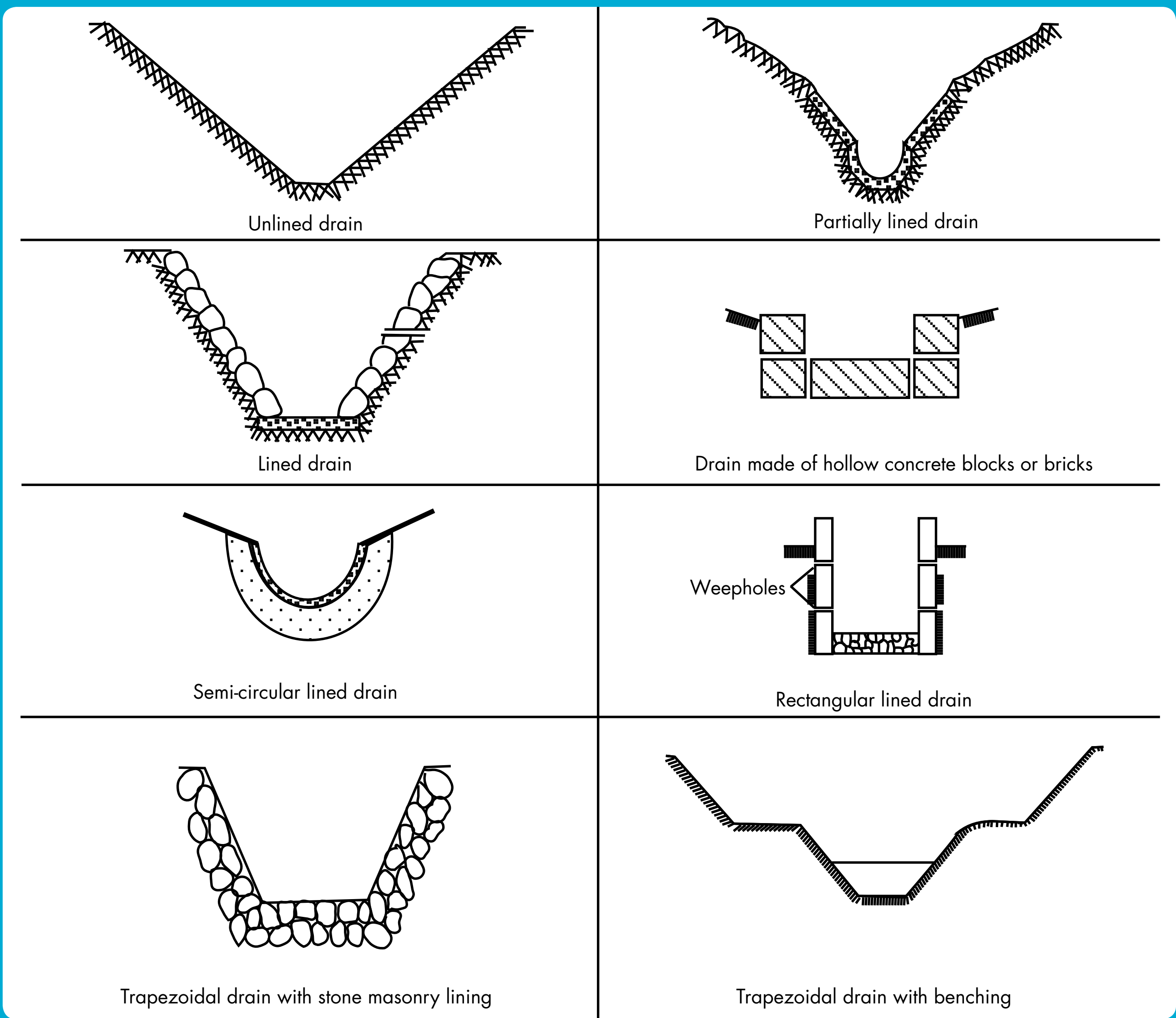
close as possible to its origin and channelled to a side drain, culvert, or any other nearby water course. Ditch excavation should start at the lowest point and work up in order that the accumulating water may drain off immediately. The most common types of drain are stone or gravel-filled drains with or without pipes.

Pipe drains are the most efficient and effective, but they are more expensive and often not locally available. Normal stone drains may silt up over time and it is advisable to form a drainage channel of stones, or place a bundle of brushwood, at the bottom of the drain. The top of the drain should be covered with a layer of grass to prevent siltation.

Simple drainage ditches

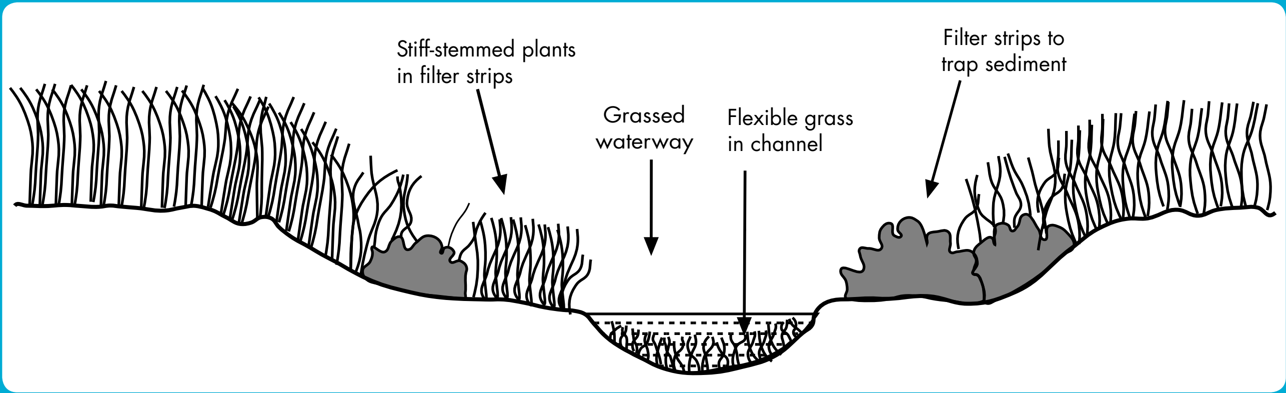
Drainage ditches can be constructed with different shapes and sizes (Figure 28). The appropriate size and shape for a particular site depends upon such factors as the expected runoff, site condition, and availability of resources and construction materials.

Figure 28: Simple designs for drainage channels



Source: based on WHO/UNEP 1991

Figure 29: Grassed waterway



Source: Modified from Bentrup 2008

Grassed Waterways

(adapted from Sharda et al. 2007)

Grassed waterways are natural or artificially constructed water courses shaped or graded to the required dimensions and planted with suitable vegetation (Figures 29 and 30). Grassed waterways generally run down a slope and are designed to conduct surplus water safely into natural drainage courses. They are usually made broad and shallow, although the shape and size can vary depending on the size of the drainage area, slope of the land, and soil type. The channels help surface water to flow across the land without causing soil erosion. They are used as outlets to prevent rill and gully formation. The vegetation in the channel helps control the water flow and reduces channel surface erosion. Properly designed grassed waterways can safely transport large volumes of water to the down slope. They are also used as filters to prevent sediments entering into nearby water bodies. Grassed waterways are used as

- outlets for diversions and emergency spillways;
- to safely convey runoff from contour and graded bunds and bench terraces;
- as outlets for surface and sub-surface drainage systems on sloping land;
- to carry runoff from natural drains and prevent formation of gullies; and
- to dispose of water collected in road ditches or discharged through culverts.

Figure 30: Grassed waterway

Source: Keshar Man Sthapit

The design of grassed waterways is described in Box 8.

Conservation Ponds

Conservation ponds, also known as farm ponds, are small reservoirs constructed for the purpose of collecting and storing water from surface runoff. Storing water runoff during excessive rainfall helps to reduce the peak flow and surface erosion and thus reduce the probability of floods. It is also useful for providing supplemental irrigation for agriculture, water for domestic purposes, and fish farming. Conservation ponds play a significant role in areas with rainfed agriculture, and construction of a large number of ponds in a catchment area can have a significant effect

Box 8: **Design of grassed waterways**

When designing a grassed waterway, it is first necessary to determine the required shape, size, and gradient.

Shape

Usually a waterway can be triangular, trapezoidal, or parabolic. A parabolic shape is hydrologically more efficient and easier to construct. The other two shapes tend to become parabolic over time as a result of bank erosion and deposition of sediments across the channel section.

Size of waterway and calculation of peak discharge

The size of the waterway is calculated on the basis of the peak rate of runoff expected from a ten-year return period storm without scour or fill. The peak runoff rate can be estimated using the rational method. The rational runoff coefficient varies according to land use and soil type (Table 4). The catchment area of the grassed waterway increases towards the outlet and the size of the waterway should be increased accordingly.

The rational equation, in imperial units, is

$$Q = C \times i \times A$$

where
Q = peak discharge in cubic feet per second (ft^3/s),
C = rational method runoff coefficient,
i = rainfall intensity, inches/hr, and
A = drainage area in acres.

The rational method runoff coefficient (*C*) is a function of the soil type and drainage basin slope. The rainfall intensity (*i*) is typically found from intensity/duration/frequency curves for rainfall events in the geographical region of interest. The duration is usually equivalent to the time of concentration of the drainage area. The resultant *Q* can be divided by 35.3 to convert from ft^3/s to m^3/s.

Table 4: Rational method runoff coefficients (*C*) for different land cover areas and soil types

Land use and topography	Soil type		
	Sandy loam	Clay and silt loam	Tight clay
Cultivated land			
Flat	0.30	0.50	0.60
Rolling	0.40	0.60	0.70
Hilly	0.52	0.72	0.82
Pasture land			
Flat	0.10	0.30	0.40
Rolling	0.16	0.36	0.55
Hilly	0.22	0.42	0.60
Forest land			
Flat	0.10	0.30	0.40
Rolling	0.25	0.35	0.60
Hilly	0.30	0.50	0.60
Populated area			
Flat	0.40	0.55	0.65
Rolling	0.50	0.65	0.80

Note: The value of the rational method runoff coefficient can vary from close to 0 to 1.0. A low *C* value indicates that most of the water is retained for a time on the ground surface and soaks into the ground, where as a high *C* value means that most of the rainwater runs off immediately.

Source: Suresh 1997

Flow velocity

The flow velocity in a grassed waterway depends upon factors such as the soil type, water quality, and ability of the vegetation to resist erosion. Similarly, the permissible velocity of flow in a waterway varies with the type, condition, and density of vegetation. The maximum permissible velocities recommended by the Central Water and Power Research Station (CWPRS) Pune for canals for different types of soils are shown in Table 5. Permissible velocities for sod forming grasses are higher than those for bunch grasses or other non-uniform grasses. In a grassed waterway, the average flow velocity near the top is always higher than the velocity in contact with the channel bed, as surface roughness is greater at the bed.

Gradient

The slope of the land normally determines the gradient of the waterway. Usually, a gradient of less than 5% is preferred; in a normal course it should not exceed 10%.

Design of the cross-section

The catchment area of the grassed waterway increases towards the outlet and the size of the waterway should be increased accordingly. The cross-sectional area is calculated from the formula

$A=Q/V$

where
A = cross-sectional area of flow,
Q = peak discharge, and
V = cross-sectional average velocity.

Table 5: Recommended maximum permissible velocity for different soils

Soil type	Maximum permissible velocity (m/s)
Ordinary soils	0.6–0.9
Very light loose to average sandy soil	0.3–0.6
Sandy loam, black cotton soil, and similar soil	0.6–0.9
Hard soil	0.9–1.1
Gravel and disintegrated rock	1.5

Source: NABARD 2012

Q is calculated using the rational method (above) and V is calculated using Manning's formula to calculate the cross-section average velocity flow in an open channel:

$$V = \frac{1}{n} \times R^{\frac{2}{3}} \times S^{\frac{1}{2}}$$

where
V = cross-sectional average velocity (m/s),
n = Manning's roughness coefficient,
R = hydraulic radius (A/P) (m),
A = cross-sectional area of flow (m^2),
P = wetted perimeter (m), and
S = slope (m/m).

The value of n can be taken as 0.035, or 0.04 for freshly constructed earthen channels.

Assume either the width or the depth and calculate the dimensions of the channel from A. Check whether the computed velocity of flow is within the permissible limits. If not, adjust the channel dimensions to bring the velocity of flow within the permissible limits. Add a suitable freeboard (height between water level and top of the bank) of 20% extra depth or a minimum of 15 cm to the design depth of the waterway as obtained above to account for any higher flood.

on downstream flow and control of floods. Water storage is a topic of increasing importance in the Hindu Kush Himalayas as the focus turns toward adaptation to climate change, and conservation ponds and other storage mechanisms are likely to play an increasing role in future development activities (Vaidya 2009; Upadhya 2009).

Conservation ponds can be broadly classified into embankment type ponds and dugout type ponds.

Dugout ponds

The types of dugout ponds range from the very simple, which require no explanation, to forms specifically designed to collect water on a slope for infiltration and recharge purposes. Some selected types are described below.

Simple earthen ponds are cheap and durable but have high seepage losses that reduce effectiveness. Vertical and horizontal seepage loss can be significantly reduced by compacting a 30 cm deep layer of heavy clay on the floor and walls of the pond. Addition of cow-dung and puddling will help seal seepage pores. Watering of buffaloes in such ponds also helps reduce seepage. High density polythene sheet or SILPAULIN (multi-layered, cross laminated, ultraviolet stabilized plastic sheet) can also be used to reduce seepage (Figure 31).

Figure 31: Earthen ponds laminated with plastic sheet

Source: ICIMOD 2007

Eyebrow pits are a special type of dugout pond used to reduce runoff across a slope and thus stabilize degraded slopes and increase infiltration and recharge of springs. Small curved trenches around 2 m long and 50 cm wide in the shape of an eyebrow are dug at intervals facing inward to the slope to catch water and slowly return it to the soil. Grass and fodder species are planted along the lower ridges of the pits (ICIMOD 2007).

Embankment type ponds

(adapted from Sharda et al. 2007)

Embankment type ponds are constructed to collect runoff at the base of a slope. They can be constructed across dry water beds or courses with a gentle to steep slope that fill when it rains. Usually, an earthen dam is constructed between two hillsides to hold back the water from overland runoff. The pond bottom and dam should be made up of soil that prevents excess seepage. Embankment ponds should not be built by damming any stream with permanent flow, no matter how small. The dimensions depend on the volume of water to be stored. The location should be sufficiently depressed to enable the maximum storage volume to be obtained with the least requirement for earthworks.

The design of embankment type ponds is described in Box 9, and the steps in their construction are elaborated in Box 10.

Seepage control. Seepage is almost inevitable in any dam or embankment structure. It mainly occurs through the embankment and under the foundation. The following methods can be used to control seepage.

- **Core wall:** A core wall is constructed using impervious materials and checks the flow of water in the dam. The main purpose of the wall is to add strength to the bund and increase the seepage gradient length through the embankment.
- **Filter and toe drains:** These drains are constructed by including a layer of coarse material in the dam section to attract the flow of water and bring the saturation line down to the level of the drain.
- **Berm:** A berm is a horizontal structure built on the lower part of the downstream (outward) face of the dam to prevent seepage from the face and keep the seepage line within the base of the dam section. It increases the base width of the embankment.
- **Cut off wall:** A cut off wall is constructed to join the impervious foundation to the base of the dam and prevent piping.

Spillway. A spillway is an opening constructed in the embankment to allow water to exit the pond once it is at the desired level. The size and type of spillway depends upon the size and characteristics of the watershed and the site conditions. There are two types of spillway: mechanical and emergency. A mechanical spillway is used to let out

Box 9: Design of an embankment type pond

Designing the pond involves calculating the dimensions (height, width, side slopes), and considering how to control seepage and provide a spillway.

Height

The dam height should be no more than 16 m, otherwise special design criteria for stability must be used. The height of the dam is also called the top bund level (TBL) of the embankment. It is calculated using the formula:

TBL = FTL + flood depth + freeboard + settlement allowance,

where
FTL = the full tank level of the reservoir. This is the required storage volume and is determined by the depth capacity curve for the location where the dam is to be constructed.

Freeboard = height added to the dam as a safety factor to prevent waves and runoff from storms greater than the design frequency from overtopping the embankment. Normally, 10–15% of the height is added as freeboard to the highest flood level of the dam, with a minimum of 50 cm.

The height of the earth fill along the central line of the dam is determined from the cross-section profile of the ground at the central line and the calculated height of the embankment.

Top width

The top width is calculated from the formula:

$W = (H/5) + 1.5$,

where
W = the top width, and
H = height of the dam.

In general, a minimum top width of 2.5 m is recommended for dams up to 5 m high.

Side slope

The slope used for the sides depends upon the nature of the fill materials. When fill materials are stable, the side slopes can be steeper and vice versa. The recommended side slopes for earthen embankments are shown in Table 6.

Table 6: Side slopes for embankments made of different materials

Type of material	Upstream slope	Downstream slope
Homogeneous well-graded material	2.5:1	2:1
Homogeneous coarse silt	3:1	2.5:1
Homogeneous silty clay or clay • Height less than 15 m • Height more than 15 m	 2.5:1 3:1	 2:1 2.5:1
Sand or sand and gravel with clay core	3:1	2.5:1
Sand or sand and gravel with reinforced cement concrete (RCC) core wall	2.5:1	2:1

Source: Sharda et al. 2007

Box 10: **Construction of an embankment type pond**

Step 1

Completely clear large stones, bushes, and tree stumps from the site of the pond and plough and excavate the top soil to a depth of 10 cm. Stockpile the excavated soil on the downward (outward) side of the dam. It can be used later to provide a base for adding grass sod on the downward side.

Step 2

Mark out the layout for the main embankment, core wall, and mechanical and emergency spillways using stakes or lime powder.

Step 3

Excavate a cut-off trench along the bottom length of the dam as per the design depth, bottom width, and side slopes. Excavation is generally at least down to the layer of impervious material.

Step 4

Fill the cut-off trench with the best available clay, compacting layer by layer, up to the desired height to form the core wall.

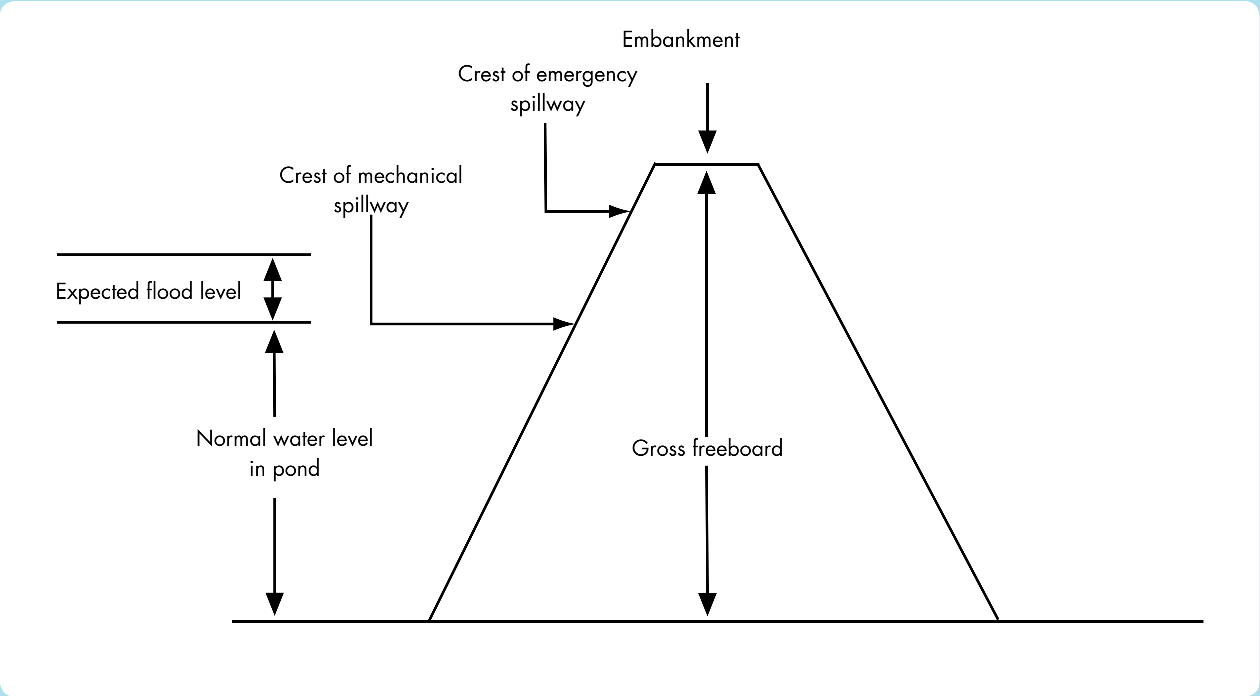
Step 5

Cover the core wall with layers of excavated earth, compacting each layer, to form a bund of the selected dimensions. Compaction is normally achieved using rollers with pneumatic tyres and sheep foot rollers after slightly moistening the earth fill to achieve optimum moisture content.

Step 6

Start constructing the mechanical spillway when the embankment construction reaches the bottom level of the spillway (Figure 32). Take special care to compact the material around the spillway components to avoid unequal settling. Place pipes, anti-seep collars, and other equipment, and then back fill with earth. Cover the pipe with at least 1 m of earth before allowing any heavy equipment such as trucks or tippers to pass over it. Proceed in the same way with the emergency spillway.

Figure 32: Location of mechanical and emergency spillways



Source: Sharda et al. 2007

excess storage water safely; whereas an emergency spillway is used as a safeguard for the earthen embankment against overtopping when the inflow exceeds the capacity of the mechanical spillway.

Retaining Walls

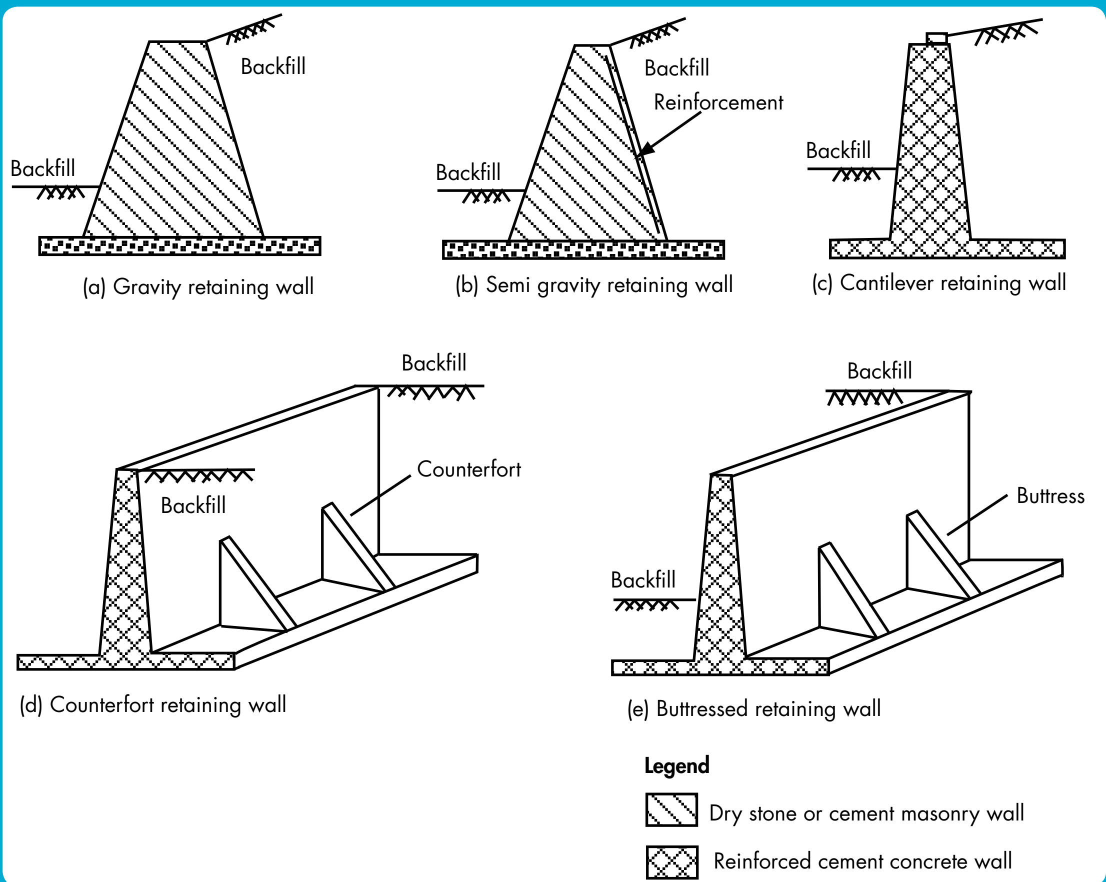
Retaining walls are artificial structures that hold back soil, rock, or water from a building, structure, or area. Retaining walls prevent down slope movement and soil erosion, and provide support for vertical or near-vertical changes in gradient. The walls are generally made from timber, masonry, stone, brick, concrete, vinyl, steel, or a combination of these. Retaining walls act to support the lateral pressure exerted by a soil mass which may cause slope failure. Retaining walls are strongly recommended where the toe of slope has collapsed and the slope failure is likely to progress upward along the slope. Retaining walls should be constructed on a stable foundation. Their design is described in Box 11.

Retaining walls are categorized in two ways: based on the mechanics of performance, and based on the construction material.

Types based on the mechanics of performance

Gravity retaining wall. A gravity retaining wall is low and depends on its own weight or mass to hold back the earth behind it (Figure 33a). It is constructed with a large volume of material in such a way that, when stacked together, the weight and friction of the interlocking material exceeds the forces of the earth behind. The wall supports the pressure from the earth by means of its dead weight, and generally requires a good foundation with sufficient bearing capacity. The wall is thicker at the bottom than at the top; the thickness at the base should be between one-half and three-quarters of the height. Gravity walls are very cumbersome to construct because they require large amounts of material. They are usually constructed with concrete and masonry. The size of the section

Figure 33: Types of retaining wall based on the mechanics of performance

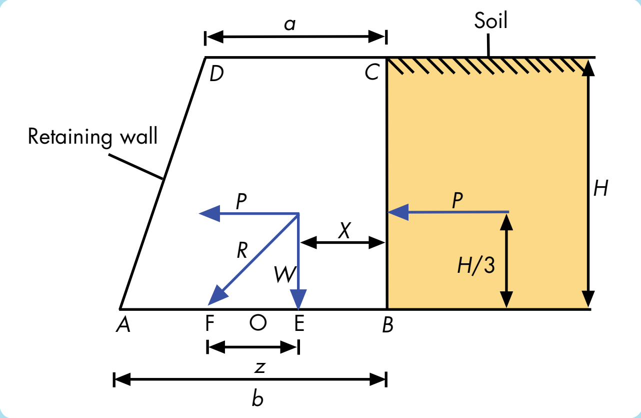


Box 11: **Designing a retaining wall**

The design of a retaining wall mainly consists of the estimation of the load and active pressure acting on the structure and the design of the structure to withstand this load and pressure. The forces acting on the wall are the lateral pressure and the self weight of the wall. The self weight of the wall is responsible for supporting the lateral earth pressure.

Consider as an example the case of a gravity retaining wall as shown in Figure 34. The wall is supporting the soil mass with no surcharge.

Figure 34: Gravity retaining wall showing the dimensions (black arrows) and the forces acting on it (blue arrows)



The first step is to estimate the pressure of the earth on the wall. Rankine's formula can be used to calculate the pressure as follows:

$$P = \frac{\gamma s\, H^2 (1 - \sin\phi)}{2(1+\sin\phi)}$$

where
P = pressure in kg/m² (the pressure acts at $H/3$ above the base [DSCWM 2005]),
H = height of the wall in metres,
γs = density of the soil in kg/m³, and
ϕ = angle of earth in degrees.

The weight of the wall per metre length is given by:

$$W = \frac{(a+b) \times H \times \gamma m}{2}$$

where
W = weight of wall per metre length in kg/m (the weight acts at a distance X from the face BC),
γm = density of wall material in kg/m³,
a = top width of retaining wall in metres, and
b = bottom width of retaining wall metres.

For the structure to be in equilibrium, the following conditions must be satisfied:

- The algebraic sum of all the vertical forces must be zero, i.e., $\sum V = 0$;
- The algebraic sum of all the horizontal forces must be zero, i.e., $\sum H = 0$; and
- The moment of all forces acting on the wall about any point must be zero (to prevent it overturning), i.e., $\sum M = 0$.

Let R_V and R_H be the vertical and horizontal reactions at the point of application of the resultant force R on the base of the wall.

For $\sum V = 0$, $W = R_V$.
For $\sum H = 0$, $P = R_H$.
For $\sum M = 0$, taking the moment about B,
$P \times H/3 + W \times X = R_H (X + Z)$,

where
Z = the shift, i.e., EF.
Since $R_H = W$,
$P \times H/3 + W \times X = W(X + Z)$.

On simplification,

$$Z = \frac{P \times H}{3 \times W}.$$

If O is the middle point of base AB, then

eccentricity $(e) = OF = BF - BO = X + EF - b/2$

$= X + Z - b/2$.

After calculating the lateral pressure acting on the wall (P), self weight of the wall (W), point of application of lateral pressure force, centre of gravity of the wall, and eccentricity, the section can be checked for stability.

of a gravity retaining wall can be reduced if a small amount of reinforcement is provided near the back face (Figure 33b).

Cantilever retaining wall. A cantilever retaining wall has a relatively thin stem, usually made of concrete reinforced with steel to resist the tensile force (Figure 33c). The width of the footing is very important as it is designed to resist the sliding forces which the earth exerts upon the wall. The wall requires significant steel reinforcing in both the footer and the wall structures. The steel should extend from within the footer up into the wall so that the two pieces become one integral unit. This type of wall is generally economical up to a height of 6–8 m.

Counterfort retaining wall. A counterfort retaining wall is similar to a cantilever retaining wall, but further supported by additional thin triangular shaped walls, or counterforts, built at right angles to the main trend of the wall. The counterforts are spaced at regular intervals along the wall and connect the back of the wall to the top of the footing (Figure 33d). The footing, retaining wall, and support walls must be tied to each other with reinforcing steel. The counterforts reduce the shear force and bending moments in the stem and the base slab and add strength to the retaining wall. They are hidden within the earthen or gravel backfill of the wall. Counterfort retaining walls are economical at heights of more than 6–8 m.

Buttressed retaining wall. Buttressed and counterfort retaining walls are similar, with the main difference that in buttressed walls the vertical brackets are provided in front of the wall (Figure 33e). The buttresses add strength and help to stabilize the overall wall system. Depending upon the overall length of the main wall, several buttresses can be constructed at regular intervals.

Types based on construction material

Dry stone masonry. Dry stone masonry walls are usually the cheapest wall structures and are suitable for heights up to 3–4 m. A skilled mason, suitable stones, and bonding of stones with keystones are required to make a good quality wall. In general, the width to height ratio varies from 1:1–0.6:1 for walls with heights of 1–4 m.

Gabion wall. A gabion is a heavy duty basket-like structure made in the shape of a box from welded or twisted galvanized iron wire mesh, divided by wire diaphragms into cells, and filled with heavy material (typically rocks or broken concrete) that cannot escape through the mesh openings. Gabions are generally used as construction blocks, and are tied together with galvanized iron binding wire to form larger structures. Gabion walls are constructed using gabion boxes of various sizes stacked next to and on top of each other before tying. Good quality stone should be used to fill the boxes, with dimensions preferably not less than 10 cm, or at least greater than the mesh size. Stones should be packed as tight as possible to increase the density of the gabion wall. The gabion structures are flexible and provide good drainage due to the dry stone packing.

Cement masonry wall. Cement masonry walls are constructed using good quality stones with cement sand mortar. These walls are rigid and designed as gravity structures with a base width varying from 0.5–0.75 times the wall height. The foundation must be on firm, risk-free ground. Weep holes of at least 75 mm diameter should be included every 2 x 2 m^2 in a staggered pattern for drainage. As these walls are rigid and impermeable, they are not appropriate for construction to hold wet colluvial slopes or where ground movement is expected.

Composite masonry wall. Composite masonry walls are similar to cement masonry walls except that they have panels of dry stone masonry of about 0.6–1 m square forming a grid on the face and separated by 0.5 m strips of cement masonry. They are stronger than dry masonry walls but retain the advantage of having relatively good water drainage.

Cement concrete wall. Cantilever, counterfort, and buttressed retaining walls are constructed with reinforced cement concrete. The reinforced steel in the wall takes up the tensile stress that the wall is exposed to. The amount of steel required is calculated by analysing the load on the wall.

Crib wall. A crib wall is a box-type structure built from interlocking struts of timber, precast reinforced concrete, steel, or other material, and is usually infilled with soil or stone. The whole unit acts as a gravity wall. Due to its construction without fixed joints, and the segmented nature of the elements, crib walls are flexible and thus to some extent resist differential settlement and deformation.

Safety of a retaining wall

Retaining structures can fail for a variety of reasons. The major types of failure are shown graphically in Figure 35. The measures used to protect a wall against these different types of failure are summarized in the following sections.

Safety against sliding. Retaining walls should be able to resist the sliding force exerted by the lateral pressure (*P*) which tends to cause slide along the plane below the bottom slab, which is resisted by the shear force developed between the bottom slab and the ground (frictional resistance). If μ is the coefficient of friction between the base of the wall and the soil, the maximum frictional resistance is equal to μW. Thus for stability against sliding, *P* must never exceed μW. The factor of safety (*F*) is given by

$$F = \mu W/P.$$

A minimum factor of safety of 1.5 is generally recommended.

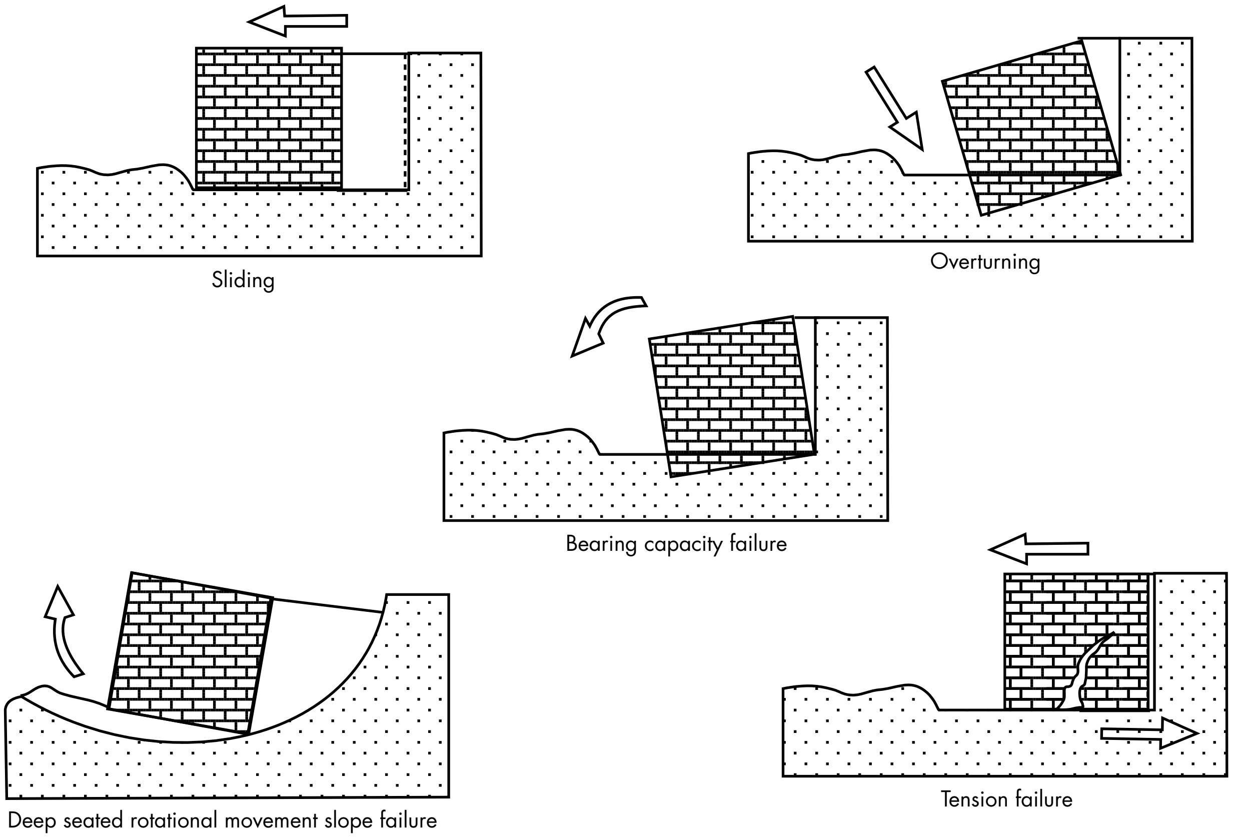
Safety against overturning. Retaining walls should be able to resist the overturning moment exerted by the horizontal component of the lateral earth pressure. The resisting moment is composed of the vertical component of the lateral earth pressure and the self weight.

The section is in equilibrium under the action of four forces (Figure 34):

- the horizontal pressure of the earth (*P*) acting at *H*/3 from the base of the wall;
- the weight of the wall (*W*) acting at a distance *X* from the wall face *BC*;
- the vertical component (R_V) equal to *W* and acting at *E*; and
- the horizontal component (R_H) equal to P and resulting from the frictional resistance between the wall body and the ground.

The section can overturn about the point *A*. As long as the resultant R touches the base, the section cannot overturn. If *R* touches the base at *A*, the section is on the point of overturning, and if it falls outside the base, the section will

Figure 35: Modes of failure of retaining structures



overturn. Hence, the limiting value is when F coincides with A, i.e., $EF = EA$, when the balancing moment will have a value equal to $W \times EA$.

$$\text{Factor of safety} = \frac{\text{Limiting balancing moment}}{\text{Overturning moment}} = \frac{W \times EA}{P \times H/3}.$$

The recommended factor of safety against overturning is usually 1.5–2.0.

Safety against bearing capacity failure. The supporting strength of soil or rock is referred to as its bearing capacity. The maximum pressure which soil can carry safely without risk of shear failure is the safe bearing capacity. In order to avoid bearing capacity failure of the soil at the base, the maximum comprehensive stress acting normal to the base must be less than the allowable bearing capacity of the soil. The maximum comprehensive stress normal to the base must also be less than the maximum comprehensive stress for the masonry to avoid crushing the masonry at the base.

$$\text{Factor of safety} = \frac{\text{Allowable bearing pressure or permissible comprehensive stress for the masonry}}{\text{Maximum comprehensive stress at the base of wall}}.$$

A factor of safety of 3 is recommended for safety against bearing capacity failure.

Safety against tension failure. There should be no tension at the base of the wall. To avoid tension within the structure, the eccentricity (*e*) should be not more than *b*/6 on either side of middle of the base, i.e., at the point O. Under such conditions, the resultant, *R* must be within the middle third of the base width.

In designing a gravity type retaining wall, a trial section is chosen and checked for all the stability conditions mentioned above. If the stability checks yield unsatisfactory results, the section is changed and rechecked. Table 7 shows the design dimensions for a typical retaining wall structure.

Table 7: Typical retaining wall design specifications

Type	Dry stone masonry	Composite masonry	Cement masonry	Gabion	
				Low	High
Top width	0.6–1.0 m	0.6–1.0 m	0.5–1.0 m	1.0 m	1–2 m
Base width	0.5–0.7 *H*	0.6–0.65 *H*	0.5–0.65 *H*	0.6–0.75 *H*	0.55–0.65 *H*
Front batter	vertical	varies	10:1	6:1	6:1
Back batter	varies	vertical	varies	varies	varies
Inward dip of foundation	1:3	1:3	horizontal or 1:6	1:6	1:6
Foundation depth below drain	0.5 m	0.5–1 m	0.5–1 m	0.5 m	1 m
Height range (*H*)	1–6 m	6–8 m	1–10 m	1–6 m	6–10 m
Hill slope	<35°	20°	35–60°	35–60°	35–60°
Toe protection in case of soft rock/soil	Boulder pitching				
General	Set stones along foundation bed. Use long bond stones.	Cement 50 cm thick, masonry bands at 3 m centre to centre	Make weep holes of 75 mm diameter at 1–2 m c/c. Provide 50 cm rubble backing for drainage.	Hand pack stones. Select block shapes in preference to flat. Specify maximum/minimum stone size. Do not use weathered stone. Compact granular backfill in a layer (<15 cm).	
	Foundation to be stepped up if rock encountered All walls require durable rock filling of small to medium size. Drainage of wall bases not shown				
Application	Least durable		Most durable	Can adjust to settlement and slope movement	
	Non-ductile structures, susceptible to earthquake damage			Very flexible structures	

Drop Structures

Drop structures, also known as grade control structures, are structures placed at intervals along a channel reach to change a continuous steep slope into a series of gentle slopes and vertical (or steep and roughened) drops, like a series of steps. They control erosion and river channel degradation by reducing the slope of the channel and preventing the development of high erosive flow velocities, and allow water to drop safely from one level to another without gouging out gullies. They can also help to control flooding and trap the sediment moving with runoff water.

Drop structures include sills, weirs, chute spillways, drop pipes, and check dams. A weir allows water to run over the edge like a miniature waterfall, dropping down onto a concrete apron. The apron absorbs the impact of the falling water and then the water streams to an outlet. When the drop in grade is more dramatic, a chute can be used to prevent severe erosion. As the name implies, water moves down a chute made of concrete or lined with rocks or concrete blocks. Like chutes, pipes are effective in handling water when the drop in grade is dramatic. They are designed to carry water through or under an earth embankment to a lower elevation. With a drop inlet, water drops down into the inlet and then flows through the pipe. Because of the high energies that must be dissipated, pre-formed scour holes or plunge pools may be required below these structures.

In steep hill and mountain areas, the most common drop structures are check dams, which are used to control gully erosion. Check dams are described in more detail in the following section. Drop structures are also used to reduce the effective slope below the upper limit for a grassed waterway. Weirs and sills are more common downstream as river training measures.

Drop structures can be made of concrete, timber, sloping riprap sills, and soil-cement or gabions. Drop structures made from timber or logs are more appropriate in small streams and gullies.

EC (1997) contains more details on the implementation of some of these structures.

Figure 36: Gully erosion (top) and check dam treatment (bottom) in Dahachowk, Kathmandu, Nepal

Source: DWIDP

Check dams

Check dams are small low drop structures built across a gully or channel to prevent it from deepening further. These small dams decrease the slope gradient and reduce the velocity of water flow and the erosive power of the runoff. They also promote the deposition of eroded materials to further stabilize the gully or channel.

Gully plugging using check dams, accompanied by planting between the dams to stabilize the channel, can be one of the most effective ways to conserve soil and water and rehabilitate land degraded by gullies (Guedel 2008). The effectiveness of different check dams depends upon the design, location, and construction materials. Figure 36 shows an example of check dams constructed to reduce gully erosion.

Check dams can be constructed from a wide range of materials including rock, wood, bamboo, gravel bags, sand bags, concrete, masonry, and fibre rolls. The characteristics, advantages, and disadvantages of some major different types of check dams are summarized in Table 8. Two different types are shown in Figure 37.

Details on check dam design are given in Box 12, and considerations for their construction are given in Box 13.

Figure 37: Gabion check dam (left) and masonry check dam (right)

Source: DWIDP

Source: Peng Huang

Table 8: Characteristics of some common types of check dam

Type of check dam	General characteristics	Advantages	Disadvantages
Brushwood	Made of wooden poles and brush Suitable for small gullies 1–2 m deep Low cost where materials are locally available	Simple Uses local materials Low cost If roots and shoots develop, they can form a long-term barrier	Least permanent of all types if not rooted Takes a long time for the dams to develop roots and become established
Loose stone	Made of loose stone or rock Stability and strength depends on the size of rocks and quality of the construction Commonly used in gully control where boulders or rocks are abundant	Uses local materials Simple Low cost (where stones are abundantly available)	If not made properly or stones are too small, they can be washed away
Boulder	Made of big boulders or rocks Stability and strength depends on the size of the boulders or rocks and quality of construction Commonly used in gully control where boulders or rocks are abundant	Uses local materials Simple Low cost If properly made, are almost permanent and durable	Transportation of big boulders is difficult (if not available upslope of the site) If large voids are not properly filled they, may create water jets, which can be destructive if directed towards the bank
Gabion	Made with wire gabions of different sizes filled with stones Flexible Preferred where big boulders are not available	Flexible and permeable Suitable where the land mass is unstable Economical compared to other solid structures	More expensive than loose stone or boulder structures The gabions have to be brought from outside which increases the cost Need skilled labour for construction
Masonry	Made of cement masonry or concrete Generally only used to protect important infrastructure such as roads and buildings	Permanent solid structure Good appearance	High cost Materials not locally available (cement, rods) Need more engineering design, and skilled labour for construction

Source: DSCWM 2004

Box 12: **Designing a check dam**

The discharge rate through the channel must be calculated first. The hydraulic element of the design, especially the spillway section, is also very important as any fault in the hydraulic design can reduce the life of the structure.

Spacing

The spacing between dams is an important factor in the design (Figure 38). The space between consecutive check dams is selected to obtain the desired gradient between the bottom of the upper dam and the top of the lower dam – known as the compensation gradient. The spacing depends on the slope of the original waterway, the compensation gradient, and the effective height of the dams (DSCWM 2005). It is given by

$$d = h \times \frac{100}{S_0 - S_e}$$

where
d = spacing between two successive check dams (horizontal distance),
h = height of the check dams up to the notch,
S_0 = existing slope of bed in per cent, and
S_e = stabilizing slope of bed in per cent (usually 3–5%).

The number of check dams (N) is calculated as follows (DSCWM 2005):

$$N = \frac{a - b}{H}$$

where
a = total vertical distance between the first and the last check dam in that portion of the gully or torrent,
b = total vertical distance calculated according to the compensation gradient for that portion of the gully, and
H = average height of the dams.

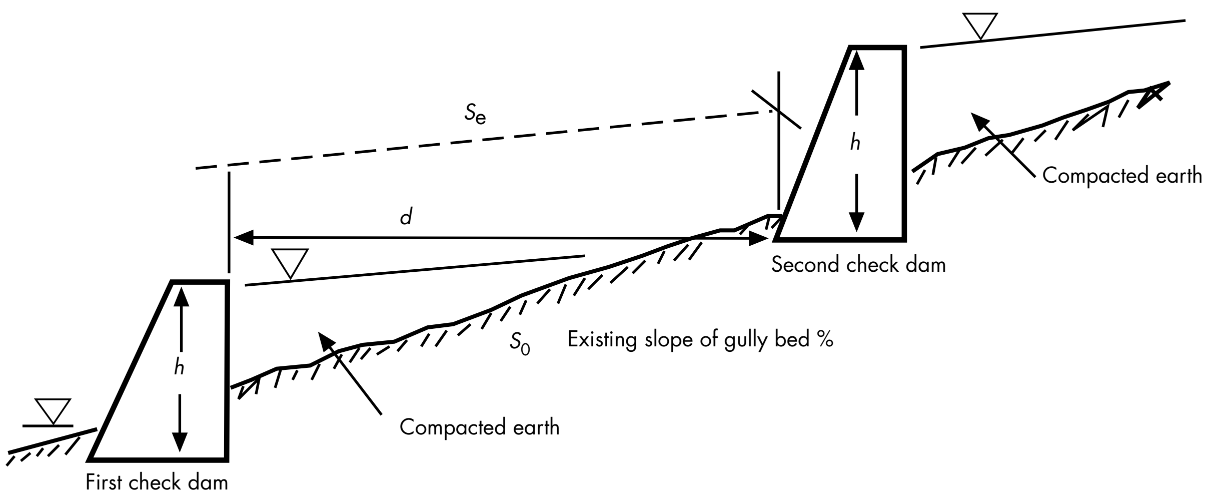
Runoff estimation

Various methods are used to estimate the runoff rate. The rational formula is the simplest method for determining peak discharge from drainage basin runoff, but the calculation is only possible if the rainfall intensity, area of watershed, and runoff coefficient are known (DSCWM 2004).

$$Q = \frac{C \times I_{tc} \times A}{360}$$

where
Q = rate of runoff in m^3/s,
I_{tc} = rainfall intensity in mm/hr for a designed frequency and a duration equal to the time of concentration (tc),
A = area of watershed in ha, and
C = dimensionless runoff coefficient.

Figure 38: Check dam spacing



The time of concentration (gathering time) is calculated from

$$tc = \frac{L^{1.15}}{15 \times H^{0.38}}$$

where
tc = time of concentration (gathering time) in hours,
L = length of the watershed along the main stream from the outlet to the most distant ridge in km, and
H = difference in elevation between the watershed outlet and the most distant ridge in km.

Note: The rational formula can only be used when a rainfall intensity (I_{tc}) map of the given area is available with frequencies of 5, 10, 25, 50, and 100 years. If no is map available, the following discharge formulae must be used instead (Kresnik's run-off equation and Manning's velocity or runoff rate formula).

The Kresnik run-off equation is

Q max = $C \times A$½,

where
Q max = maximum permissible discharge in m^3/s,
A = catchment area of the gully above the proposed check dam in km^2, and
C = coefficient ranging from 0.6–2.0 (depending on land use type).

Note: the Kresnik equation gives the best results for gullies with catchment areas of less than 20 ha. It can also be used in torrent control for catchments up to 300 ha.

The Manning formula estimates the runoff rate from the river bed characteristics:

$$V = \frac{1}{n} \times R^{\frac{2}{3}} \times S^{\frac{1}{2}}$$

where
V = velocity of flowing water (m/s),
n = roughness coefficient of the channel (for gully channels, n can be set at 0.025),
S = gradient of the gulley channel (%),
R = hydraulic radius (wetted area divided by wetted perimeter) (m) or $R = A/P$,
A = cross-sectional area of the river (m^2), and
P = wet surface of the river (m).

Note, however, that this formula is not accurate for rivers with a high bed load or with mudflow, because this changes the specific weight of the water.

The notch of the check dam, i.e., the spillway section, is designed to allow the spillway to accommodate peak runoff. The dimensions are calculated from

$Q = C \times L \times D^{2/3}$,

where
Q = maximum discharge of the gully catchment at the proposed check dam point (m^3/s),
C = coefficient, 3.0 for loose rock, boulder, log, and brushwood dams; 1.8 for gabion and cement masonry dams,
L = length of spillway (m), and
D = depth of spillway (m).

Foundation depth

The check dams are built on a foundation which anchors them into the ground to increase stability and ensure that they do not collapse or overturn when the peak flow or run off occurs or the dams are silted up. The following should be taken into account in the design and construction of the foundation:

- The bottom of the foundation should lie below the scour level.
- In erodible strata, if D is the anticipated maximum depth of scour below the designed highest flood level, including possible concentration of flow, the minimum depth of foundation below the highest flood level should be 1.33D.
- The scour depth should be taken from the expected bed level after siltation of the lower check dam and establishment of the new bed gradient, due to the reduced bed load after the erosion control.
- As a rule of thumb, take the foundation to be 1 m.

Scour depth

The safety of the check dams is mostly endangered by scouring. Scour occurs when the bed velocity of the stream reaches the velocity that can move the particles of the bed material. The scouring action of the current is not uniform; it is deeper at the obstruction and at bends.

The scour depth is calculated from Schocklitch's formula (DSCWM 2004):

Scour depth (D_S) = $(4.75 \times h^{0.2} \times q^{0.57})/dm^{0.35}$

where
D_S = scour depth in m below water level,
dm = grain diameter in mm, determined on the basis that 90% of the bed material is smaller than dm,
h = water level difference in m above and below the check dam, and
q = runoff in m^3/m width of spillway.

The breadth of the scour hole is calculated as 1.5 × length of the notch.

The length of the scour hole or apron is calculated as $4 \times (0.467 \times q^{2/3})^{1.5} \times h^{0.5}$.

General design considerations

Check dams are designed for safety against overturning, safety against sliding, and safety against the bearing pressure on the foundation soil. Table 9 summarizes the suggested general design specifications for different types of check dam.

Table 9: General specifications for check dams

Dam type	Maximum effective height	Minimum foundation depth	Thickness of dam at spillway level	Slope of the downstream face of the dam	Slope of the upstream face of the dam	Thickness of the base of the dam
Brushwood	1 m from ground level	0.75–1 m	–	–	–	–
Loose stone	1.0 m	0.5 m	0.5–0.7 m	20% (1:1/5)	vertical	calculated accordingly
Boulder	2.0 m	half of effective height	preferably 1.0	30% (1:3)	vertical	calculated accordingly
Gabion	may vary (recommended not more than 5.0 m)	half of effective height	>1 m	20% sloped, stepped, or vertical	stepped or vertical	calculated accordingly

Note: Use of these dimensions means no stability test is needed against overturning, collapsing, or sliding. However, the size of the spillway needs to be calculated according to the maximum discharge of the gully watershed area.

Source: DSCWM 2004 (based on Geyik 1986)

Box 13: **Basic considerations for check dam construction**

The function of check dams is to reduce the gradient and minimize the hydraulic energy of the flowing water. The flow velocity, and thus the erosion capacity, is controlled by the size of the dams and spillways. The following should be considered when constructing check dams.

- Construction should normally start at the downstream end of the active section of a gully.
- The top of the check dam should be below the level of the adjacent land to prevent spillover of flood to either side of the gully.
- The height of the outflow should be no more than 1 m. The lower the check dam, the smaller the risk of collapse and overflow to the side and of the need for repair. The ideal height of the spillway is often 0.5–0.6 m. It is better to build two low dams in a cascade than one high dam.
- The check dam should be made lower at the centre to form a spillway. The spillway will draw the stream to the middle, thus hindering erosion of the gully sides.
- The check dam should extend into the gully floor and the sides of the gully. This 'keying in' will help prevent erosion scouring and tunnelling under or around the check dam. The depth of the keying in depends on the local soil conditions, but should usually be between 0.3 and 1.0 m, more when the sides of the gully are unstable.
- An apron should be constructed in the gully area immediately downstream of the check dam to protect it from the erosive forces of the falling water. Without an apron, the check dam will be undercut and will eventually collapse. The apron should be 1.5–2 times longer than the height of the check dam depending on the slope of the gully. The greater the slope, the greater should be the length of the apron. Both the floor and the sides, from the top of the spillway to the downstream end of the apron, should be protected by piling stones.

Sabo Dams

(adapted from Ikeda 2004)

Figure 39: Debris flow controlled by a sabo dam

Source: Sundar Kumar Rai

Sabo dams are a common measure to limit debris flows. They are in some ways similar to check dams, but they are intended to limit debris flow rather than runoff velocity. The word sabo comes from Japanese and means soil conservation (sa means soil and bo means conservation); sabo dams are a Japanese technology that is now becoming popular beyond Japan. Sabo dams are relatively small structures built across the river bed in upstream areas in the form of a cross dike. They look like a normal small dam, except that they have a lower 'open' section at the centre which allows debris to pass through during normal conditions but prevents large-scale debris flow during flash floods. Sabo dams built in the upstream areas of mountain streams accumulate sediment and suppress the production and flow of sediment. Those built at the exits of valleys work as a direct barrier to a debris flow which has occurred. A sabo dam with slits is particularly effective in capturing a debris flow because it has a larger capacity of sand pool under normal conditions.

Sabo dams are usually constructed using masonry, concrete, reinforced concrete, or steel cribs according to the conditions in the planned area (Figure 39). The main functions of a sabo dam are to

- reduce erosion of the river bed and bank;
- trap sediment discharge;
- control sediment discharge;
- grade the effect of sediment; and
- reduce the energy of debris flows.

Based on their purpose and the way they function, sabo dams are classified into four types:

- check consolidation dam;
- river bed erosion control dam;
- river bed sediment runoff control dam; and
- debris flow control dam.

Sabo dam design is described in Box 14.

Gully Control

Gullies are a highly visible form of soil erosion created by running water. They are deep-sided water courses, metres to tens of metres in depth and width, gouged out by surface water flow. Gully formation can start with the formation of rills by surface water flowing down a slope, especially where soil is exposed (Figure 41). Water flow is concentrated and accelerated down the rills, leading to increased erosion and eventually formation of a full gully. Gullies channel and accelerate runoff, and thus contribute to flood and flash flood development, as well as causing damage to the surrounding area and infrastructure, reducing the productivity of farmland, and contributing to sediment flow and sedimentation of downstream lands, streams, channels, and reservoirs (DSCWM 2004).

The major causes of gully erosion are:

- erosion in the catchment,
- channel erosion by unmanaged runoff resulting in downward or sidewards scoring,
- steep unprotected slopes and drainage channels,
- gully head expansion, and
- side slope failure due to toe cutting of the gully channel embankment (DSCWM 2004).

Box 14: **Designing a sabo dam**

Sabo structures must be designed according to the intended function and purpose and should be stable enough to withstand all the expected design forces. The main steps in designing a sabo dam are as follows:

- determination of general design considerations,
- determination of design parameters of debris flow,
- design of open section,
- design of dam body,
- design of dam foundation, and
- design of other appurtenances.

The basic principles of design are summarized in the following. More details can be found in Ikeda (2004).

General considerations

The location and height of the dam are chosen according to the dam's purpose. The height may also be restricted by the geological and topographical conditions at the proposed location. The dam should be located on stable ground, if possible on firm bedrock, as dams are easily destroyed by slope failure if constructed in an unstable location. Ideally the dam should be located in a stable narrow section of the riverbed to give the highest stability and most cost effective construction. The height of the dam is usually reduced if it has to be built on a gravel base.

Design parameters of the debris flow

Before designing the dam, it is important to determine the design parameters of the debris flow. The fluid dynamic force of the debris flow, peak debris flow discharge, velocity of the debris flow and maximum water stage, height of the debris flow, and density of the debris flow should all be calculated or estimated.

Designing the open section

The topography and geological features upstream and downstream of the sabo dam should be taken into consideration when designing the open section. The axis of the sabo dam is placed at right angles to the direction of the river with the open section at the centre of the river course. The open section should be at least 3 m wide, and the final width also depends on the width of the stream bed. The height of the open section is determined from the design depth of the opening, the freeboard, and the maximum diameter of boulders expected in the debris flow.

A 50% sediment discharge is added to the actual flood discharge to obtain the design discharge.

$Q = (1+0.5)\ Q_1$,

where
Q = design discharge, and
Q_1 = actual flood discharge.

Design of the dam body and foundation

The design of the body of the dam is based mainly on a stability analysis. The main forces acting on the dam body are overturning, sliding, and bearing resistance of the foundation. The debris flow hydraulic forces are calculated by assuming a unit weight of debris-laden water of 11.8 kN/m^3.

The dam foundation is determined by considering the bearing capacity and the nature of the underlying foundation material (soil or rock). Foundation treatment such as construction of a cut-off wall or slurry wall is recommended when the material is poor. A cut-off wall should be constructed at the toe of the dam to prevent damage by scouring.

The design loads that must be considered for a gravity type sabo dam are:

- hydraulic static pressure,
- sedimentation pressure,
- uplift pressure,
- seismic inertia force, and
- hydrodynamic pressure during an earthquake.

Sub-sabo dam

A sub-sabo dam can be constructed when the main dam height is high or the overflow depth is deep (Figure 40). The main function of a sub-sabo dam is to reduce the overflow energy of the mass overflowing the dam. Selection of the position of the sabo dam and sub-sabo dam should be based on the extent of sedimentation and designed to prevent sediment-related disaster.

The desirable distance between the main dam and sub dam can be calculated using the following empirical formula.

$L = \beta \times (H_1 + h_3)$,

where
L = distance between the main dam and sub dam,
β = 1.5~2.0 (value depends on height of sabo dam at overflow section and width of crest),
H_1 = height of the main dam (front apron) above the bedrock (m), and
h_3 = overflow depth of the main dam (m).

Figure 40: Main sabo dam and sub-sabo dam

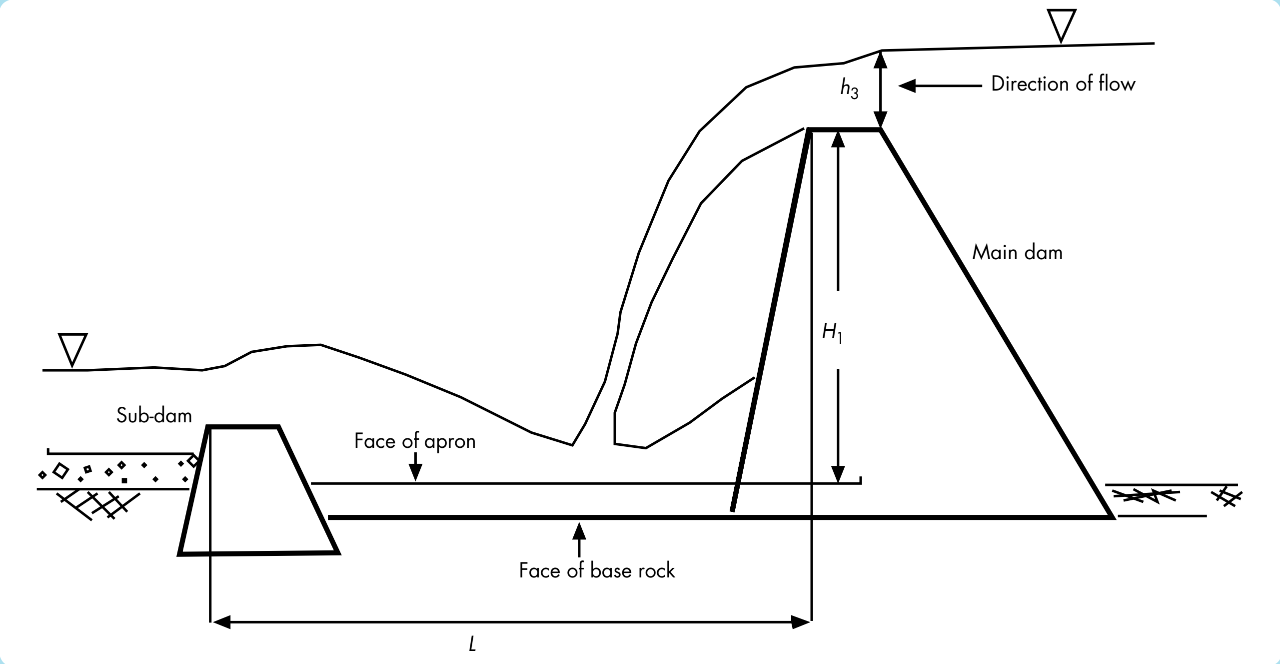


Figure 41: Gully formation

Source: ICIMOD 2008

Gully expansion mainly results from headward erosion by concentrated surface water flow. As a result, the gullies often expand upslope.

Ideally, land protection measures should be implemented across a catchment to help prevent gully formation. Once a gully is formed, however, remediation treatment should be undertaken to prevent further expansion of the gully and to slow the flow of runoff downstream. The main approaches are summarized as follows.

Improvement of the catchment above the gully

The techniques for improvement of the catchment above a gully are the same as those recommended to prevent gully formation. Essentially, they include all the methods recommended for controlling surface runoff by increasing infiltration and trapping moisture, as well as soil protection measures and slope stabilization. Measures include bioengineering approaches such as contour farming, strip farming, mulching, and afforestation, as well as physical measures such as bunding, terracing, levelling, and trenching, and building structures for diversion of surface runoff such as grassed waterways and weirs. Details of some of these are given in earlier sections.

Stabilization of the gully head

It is important to stabilize the gully head and prevent it from advancing. This can be done by diverting the runoff to stop it from entering the gully, or by allowing the runoff from upstream to enter the gully safely by installing drop structures.

Diversion of surface water above the gully head

In some cases, diverting excess runoff away from the gully head can control gully erosion. For this, diversion drains are constructed above the gully head to divert the excess runoff away from the gully.

Check dams

The major approach used to treat a gully is to build check dams to reduce the flow velocity down the gully. This method is described in detail in earlier sections.

Integrated measures for gully stabilization and treatment

Gullies are treated using a range of the bioengineering and construction measures outlined above in the watershed above the gully head, around the gully head, and down the gully. The aim is to prevent further deepening and widening of the gully and to control the flow velocity. Table 10 summarizes the different remediation techniques recommended for different depth classes of gully. Table 11 summarizes the criteria for the selection of different control measures along different parts of a gully (Geyik 1986).

Table 10: Remediation techniques for different sizes of gully

Type	Depth (m)	Recommended remediation techniques	
		Waterway	Gully area
Rill	<0.30	Fascines (community land), conservation tillage (agricultural land)	Planting
Small gully	0.3–1	Palisades, brushwood, check dams	Planting/brush layering/wattling
Medium gully	1–5	Brushwood and loose stone check dams	Planting/brush layering/wattling
Large gully	5–10	Loose stone and gabion check dams	Planting/brush layering/wattling/retaining walls
Ravine	>10	Loose stone and gabion check dams	Planting/brush layering/wattling/retaining walls

Source: DSCWM 2004

Table 11: Control measures for different parts of a gully

Length of main gully channel	Gradient of main gully channel (%)	Catchment area of gully	Required structural measures for each portion of main gully channel
–	–	≥ 2 ha	Above gully head: Diversion ditches or channels
100 m or less (from gully head)	Various	≥ 2 ha	Up to 100 m from gully head: Brush fills, earth plugs, woven-wire, brushwood, log, and loose stone check dams.
≥ 900 m	70 or less	2–20 ha	Between 100 and 1,000 m: Boulder check dams, retaining walls between check dams if necessary; first check dam is usually gabion or cement-masonry

Note: All structural measures should be accompanied by vegetative measures (planting of tree seedlings and shrub and grass cuttings; sowing of tree, shrub, and grass seeds).

Source: Geyik 1986

Trail Improvement

(adapted from DSCWM 2004)

Notwithstanding the advantages of road and trail construction in hill areas, it also poses considerable problems. The combination of slope instability, lack of understanding of slope dynamics, and poor planning and construction, means that roads and trails are a major source of landsides, slips, and flows in many parts of the Himalayan region, and thus contribute to the development of flash floods. Operations such as blasting and chipping create geological disturbances in the rock and soil masses of the mountain slopes. Blasting operations exert a tremendous dynamic force causing the movement of slip zones, cracks, fissures, and weak planes. In addition, poor stabilization of bared slopes and trail edges combined with heavy rainfall may lead directly to slips of different types originating along the line of the trail itself.

Trail improvement refers to the vegetative and structural measures used to protect trails from erosion and to improve them for people and livestock traffic, both during construction and in the form of remedial measures. General guidelines should be followed to ensure slope safety when designing and constructing trails and roads along steep slopes. Detailed discussion of the construction of roads and trails is beyond the scope of this manual but there are many publications available that the engineer can refer to, including the Mountain Risk Engineering Handbook published by ICIMOD in 1991 (ICIMOD 1991a,b) and various publications by the Swiss and German development agencies on 'green road' construction (GTZ and SDC 1999; SDC 2008).

Box 15 provides some basic guidelines for ensuring that trails (not roads) avoid negative impacts on slopes and runoff, together with some suggestions for remediation of specific problems.

Existing trails may start to show signs of erosion damage and instability which need to be addressed through remediation measures. Table 13 summarizes some of the improvements recommended for slopes of different steepness and condition.

Table 13: Trail improvement on different slope

Slope	Condition/problem	Suggested improvements
Flat	Earthen, no problem seen	Protection of the surrounding vegetation
<8°	Earthen, with rills	Rill plugging with fascines, palisades, sowing grass, construction of cross drains, levelling of the trail
<12°	Earthen, with gullying	Stone paving, construction of cross drains, planting at water disposal sites
<12°	Trail turns into a waterway	Stone paving with a concave profile and drop structures (e.g., checkdams, stepped falls), protection at water disposal sites
>12°	Earthen, with gullying	Stone steps, sowing grass, drainage management

Source: DSCWM 2004

Box 15: **Responsible trail design**

Basic design considerations

- Ideally, trails should follow a contour.
- All conservation measures required for the trail and slide slopes should be designed and implemented as a package.
- Drainage ditches should be provided at appropriate locations to guide surface runoff.
- The trail should slope outwards. A maximum cross slope of 1:20 (vertical height to horizontal length) is recommended to avoid cross ruts.
- Trails should be wider than 1.2 m.
- An average gradient of 10% is generally considered to be the maximum for comfortable walking; 15% is considered to be the maximum permissible gradient.
- Trails with gradients of less than 8° (≈14%) should be cut and levelled and sown with grass.
- Trails with gradients of 8° to 12° (≈20%) should be paved with stone.
- Stone steps should be constructed on trails with gradients above 12° (≈20%). The recommended step size is given in Table 12.
- The length of the landing (step) can be 1 m.

Table 12: Recommended step size for different slopes

Slope (θ) (degrees)	Riser height (*R*) (m)	Tread length (*T*) (m)
12–16	0.12	0.35
17–20	0.15	0.35
21–23	0.15	0.30
24–26	0.17	0.30
27–30	0.20	0.30
>30	0.20	0.25

Source: DSCWM 2004

DSCWM (2004) gives detailed instructions for designing steps.

Practical recommendations

- Safe disposal of trail runoff is one of the keys to the control of erosion associated with the trail.
- Trail runoff can be stored in conservation ponds for later use.
- Line the trail with stones wherever possible to reduce erosion.
- Trails can be used as waterway channels during the monsoon, make the stone pavement concave, and ensure the speed of the runoff does not exceed the resistive force of the lining material.
- On sloping sections where water may run down the line of the trail, install open, stone-lined cross drains at intervals of 10–15 m. These should lead off to a soak away area, into a well-vegetated line of natural drainage, or into a collection pond.
- Plant double lines of thorny shrubs along the side of the footpath to discourage people and animals from straying off the trail and eroding the sides.
- Plant trees, shrubs, or grass in nearby areas, improve drainage, and treat rills and gullies wherever necessary.