The purpose of this section is to illustrate some of the stabilizing techniques that are available. The emphasis is on simple methods that can be used safely without detailed soil analysis in low-risk situations.

3.3.1 Excavation

Excavation is the removal of soil from the head of a slide to reduce the driving force and thereby improve stability. **This method is only suitable for cuts into deep soil where rotational failures may occur.** It is ineffective on planar failures on "infinite" slopes, or on flow type landslides.

Excavation techniques that can be used to increase slope stability are:

REMOVING the entire slide mass
REDUCING the height of the slope
BACKFILLING with lightweight material
CONSTRUCTING benches
FLATTENING the slope angle

Excavation of slide mass

In some situations, removing the entire slide mass is an effective and economic solution. Generally, however, it is only practical on small slumps or small rotational failures. Large-scale excavation of larger landslide areas is usually not recommended for several reasons:

IT CAN BE INEFFECTIVE on large planar failures
IT MAY TRIGGER A LARGER LANDSLIDE by removing toe support
IT MAY DESTABILIZE the slide further upslope by undercutting
IN DEEPER SOILS, especially soft clays, where there are two potential failure surfaces, one deep and one shallow, excavation down to the first failure surface could trigger a sudden slippage on the deeper failure surface. A stability analysis using soil strength data is necessary for any major excavation project in deep clay.

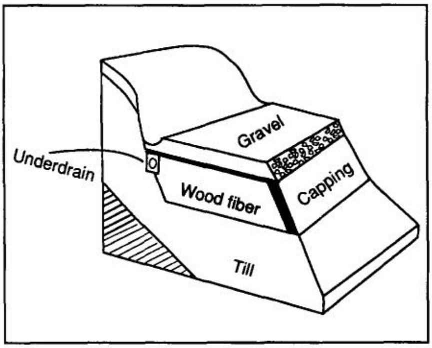
Reducing the height of the slope

Height reduction in a cutbank reduces the driving force on the failure plane by reducing the weight of the soil mass. It usually involves the construction of an access road above the main road and creation of a lower slope by excavation. It is also possible to excavate deeply and lower the main road surface if the right-of-way crosses the upper part of a landslide (see section on Cuts and Fills).

This method is only moderately efficient in increasing stability; it usually increases the Factor of Safety by only 10 or 15%.

Lightweight backfills

A related technique to height reduction is to excavate the upper soil and replace it with a lightweight backfill material such as woodchips, hog fuel, or logging slash. Once blanketed with a thin layer of coarse aggregate, the backfilled material can form a foundation for limited-use traffic.



Lightweight backfills

Benches

Benches are "steps" cut into a deep soil or rock face in an attempt to reduce the driving forces. They can reduce the incidence of shallow failures, but are generally not very efficient in improving the overall slope stability, for which other methods are recommended.

Benches are most useful in providing protection structures beneath rockfall-prone cliffs, controlling surface drainage, or providing a work area for installing drainpipe.

3.3.2 Slope Drainage

Groundwater is probably the most important single contributor to landslide initiation. Not surprisingly, therefore, adequate drainage of water is the most important element of a slope stabilization scheme, for both existing and potential landslides. Drainage is effective because it increases the strength of the soil and reduces the weight of the sliding mass.

Drainage can be either surface or subsurface. Surface drainage measures require minimal design and costs, and have large stability benefits. They are recommended on any potential or existing slide.

The two objectives of surface drainage are to prevent erosion of the face, reducing the potential for surface slumping, and to prevent infiltration of water into the soil, thereby reducing groundwater pressures.

Subsurface drainage is also effective, but can be relatively expensive. It is therefore essential that groundwater be identified as a cause of the slide before subsurface methods are used.

The various methods of drainage include:

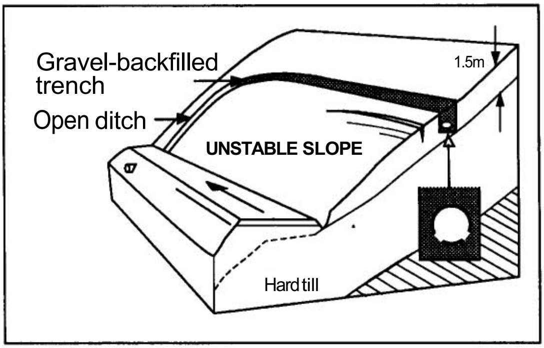
Site leveling

Smoothing the microtopography of the slide surface can prevent surface water from ponding or connecting with the groundwater. Any depressions on the slope that will contain standing water must be removed. Infilling and sealing large cracks in the soil surface by grading the soil mass is beneficial, as it prevents surface water from reaching the failure plane.

Ditches and drains

Surface drainage can be through either surface ditches or shallow subsurface drains. Surface drainage is especially important at the top of the slide, where a system of cutoff ditches across the headwall of the slide, and lateral drains to lead runoff around the edge of the slide, are desirable. Ditch gradient should be at least 2%, to ensure rapid flow away from the unstable area.

The simplest type of subsurface drain is the lateral trench constructed above an unstable slope. Drainage trenches are only economical for shallow soils overlying bedrock or hard impermeable till. The trenches should be excavated to the base of the shallow soil to intercept any groundwater flow along the failure plane. They are backfilled with coarse gravel to prevent sloughing of the ditch sidewalls. An improvement is to use drain pipe, backfilled with coarse gravel.



Drain trenches

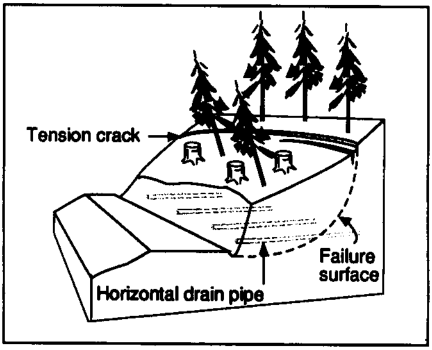
Drainpipe

Horizontal drainpipe is a widely used technique for landslide prevention in highway construction. It is most effective when installed during initial excavation. Because of the long lag-times to lower groundwater tables, the drains are effective only if the pipe is carefully installed, the failure surface is intersected, and the pipe actually drains the soil.

As most slopes have different soil, hydraulic and geometric conditions, drainage systems must be individually designed. The advice of a geotechnical engineer is recommended for any large projects.

The basic approach is to drill holes 5° upward from the horizontal into the slope, using standard drill equipment or continuous flight augers. The holes are drilled near the toe of the cut bank and must be deep enough to intersect the failure surface. A conservative "rule of thumb" in fine-grained soils is to make the length of the drain hole half the height of the slope needing drainage. Spacing and depth of holes depend on individual site conditions and can be determined by trial and error from flow observations. As a rough guide, 5 cm pipe, spaced at 5- to 10-m intervals in clays, or 10- to 15-m intervals in sandy soils, placed in a row as low as possible on the slope, can be effective.

After drilling has been carried out to the desired depth and the casing installed, the latter is cleared of soil and sections of slotted PVC drain pipe are covered with filter cloth, then pushed into the casing and coupled together. The casing is then withdrawn and screen is installed over the end of the drain. Drain holes must be thoroughly cleaned of drill cuttings and mud. Uncleaned holes may be only 25% effective.



Drain pipes

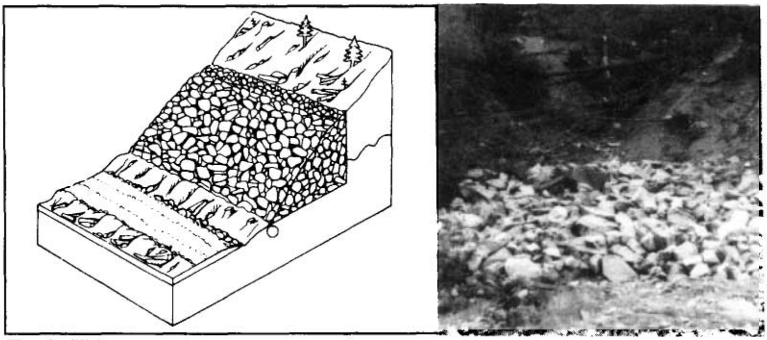
In clay soils, the full change in groundwater tables can take up to 5 years, with 50% of the improvement taking place in the first year. Once water tables are lowered in clay soils, the change is permanent: rainfall events will not alter the groundwater level in the slope provided the drains do not clog. In sandier soils, the groundwater table will lower within a few months but will also fluctuate with rain events.

3.3.3 Rock-fill Buttresses

A simple method to increase slope stability is to increase the weight of the material at the toe, creating a counterforce that resists failure. A berm or buttress of earth fill can simply be dumped onto the toe of the slope. Broken rock or riprap instead of soil is preferable, however, because it has a greater frictional resistance to shear and is also free draining, reducing problems with the plugging of groundwater flow.

Rock-filled buttresses are most effective when the natural soil is excavated below the potential failure surface and the excavation backfilled with the rock. This forces the failure circle to occur either through the stronger rock fill or along a deeper failure surface that is more resistant to failure.

This method requires considerable volumes of fill. The volume of rock-filled berms or buttresses should equal one-quarter to one-third of the unstable soil mass. If earth fills are used, then the volume should be increased to between one-third and one-half of the potential landslide volume.



Rock-fill buttresses

3.3.4 Retaining Walls

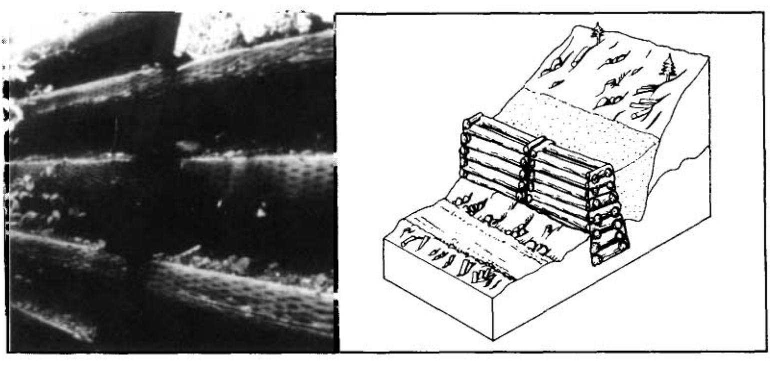
Retaining walls are structures built to support a soil mass permanently. They are used whenever space requirements make it impractical to slope the side of the excavation, or to prevent sloughing of loose hillslope soils onto the road. They are also used to prevent toe erosion by river scour. They **cannot,** however, be used to stop landslides.

There are several basic types of wall: timber crib, steel bin, pile, cantilever, sheet pile, plastic mesh, and reinforced earth. Each has advantages in certain situations, but cost is usually what determines which is used.

For all types of retaining walls, adequate drainage through the structure is essential because very high groundwater pressure can build up behind any retaining wall, leading to its failure. Drainage can be provided simply with a coarse backfill and foundation material.

Timber crib

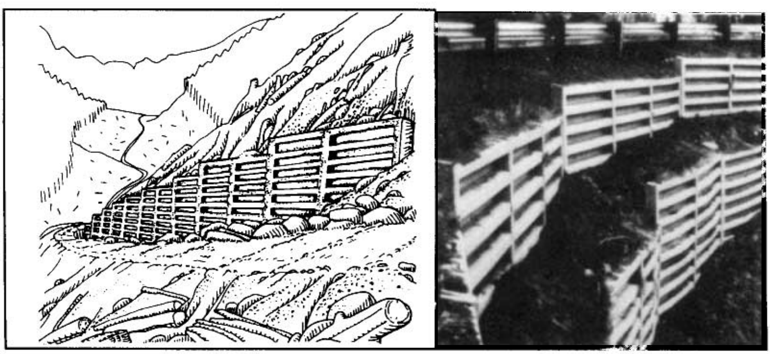
Timber crib walls are box structures built of interlocking logs and backfilled with coarse aggregate. They work by intersecting the critical sliding surface, thus forcing the potential failure surface to a deeper, less critical depth. The structure must be able to withstand: 1) shearing, 2) overturning, and 3) sliding at the base. It must, therefore, be strongly built and buried to sufficient depth, and extend deep enough to intersect the critical failure plane. Crib walls are only effective where the volume of soil to be stabilized is relatively small. They are most efficient where a thin layer of unstable soil overlies a deeper, more stable layer of soil. Crib wall structures should have a volume equal to 10-15% of the volume of the soil to be stabilized. This relatively small volume provides little counterweight support at the toe and, therefore, virtually the entire resistance to failure comes from the strength of the crib.



Timber crib

Steel bin wall

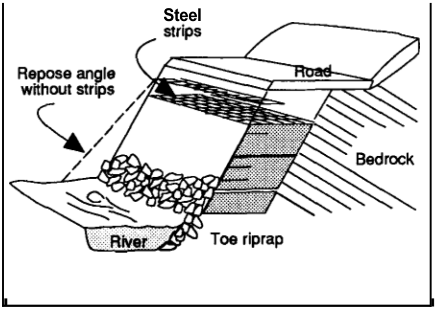
A steel bin wall is formed from corrugated galvanized steel components bolted together to form a box, and then filled with earth. The stability of a gravity wall is due to the weight of the wall itself, perhaps aided by the weight of soil in front of the wall. The bulk of the weight is from the contained soil, not the steel, and this should be kept in mind when the foundation is prepared. Large walls must be individually engineered, with load and foundation requirements calculated. Design charts have been prepared, which provide stringer specifications and height-to-width ratios for typical loading conditions. The widths of walls generally vary from 2-5 m and are one-half to three-fifths the height of the wall. To provide additional sliding resistance, the foot of the wall is usually 0.5-1.0 m below grade, although the design should not rely on the additional toe support, as it can erode or inadvertently be removed. The Factor of Safety is improved if the wall is at a 1:6 slope. Fill material must be well drained and compacted (preferably in 20 cm lifts). Material behind the wall should also be well drained and moderately compacted.



Steel bin wall

Reinforced earth walls

Reinforced Earth is a patented system for constructing fills at very steep to vertical angles without the use of supporting structures at the face of the fill. The system uses horizontal layers of flexible metal strips within the fill to form a composite earth-metal system with high strength.



Reinforced earth walls

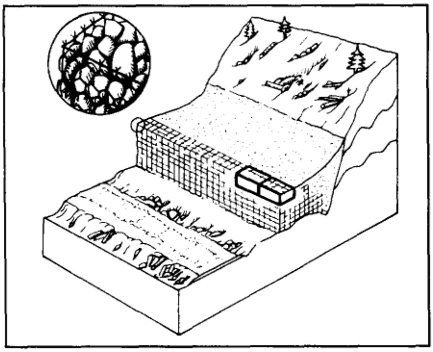
The reinforcing strips are made of galvanized steel. The number and dimensions of the strips are determined by the height of the structure. For routine applications, the length is 80% of the wall height. The strips are attached only to the facing material, which is usually elliptical galvanized steel, concrete panels, or gabions. The backfill material must be granular and well drained, ideally ranging from sand to gravel, 8 cm in size.

Gabion walls

Gabions are wire mesh boxes filled with cobble- sized rock (10-20 cm in size). A gabion retaining wall can be constructed from stacked gabions.

Gabion walls are relatively inexpensive and are easy and quick to construct. Because they are very flexible and can withstand foundation movement, they do not require elaborate foundation preparation; and because of their coarse fill, they are very permeable, providing excellent drainage.

Gabion walls work because the friction between the individual gabion rows is very high, as is the friction between the basal row and the underlying soil. If failure occurs, it is almost always in the foundation soil itself. Three-tiered walls up to 2.5 m high can usually be constructed without the need for any detailed engineering. Higher walls are very heavy and need larger basal foundations and possibly counterforts to brace the wall. Gabion walls built on clay soils require counterforts, which can be constructed as gabion headers extending from the front of the wall to beyond the slip circle. The counterforts serve as both structural members and as drains.



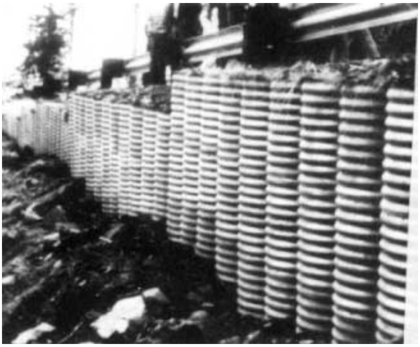
Gabion wall

Design charts are available for various combinations of hillslope angle and retaining wall height. The advice of a civil engineer is needed on any walls higher than 3 m, or those in difficult foundation soils.

3.3.5 Piles

Large diameter piles can be driven into the toe of a slope to form a closely spaced vertical pile wall. Pile walls are normally used as a pre-excavation restraint system, in front of which cut slope excavation takes place.

While large diameter concrete pile and culvert pile walls have been used successfully on highways, small diameter wood or steel piles have not. For most earth or rock movement, wood piles are incapable of providing adequate shearing resistance. They are only recommended where the volume of soil to be stabilized is small. Roughly, one wood pile is necessary for every 50 m^3 of soil, which is inefficient for large stabilization projects. Fewer piles can result in toppling or breakage by the moving soil mass, as well as soil movement between the piles.



Concrete-filled culvert pile wall

A major limitation with log piles is depth, as many failure surfaces occur below the length of the piles. Wood piles are best suited for shallow soil failures over deeper stable soils. The piles must extend below the potential failure surface and be driven into firm subsoil. If the depth of placement is not sufficient to allow the piles to act as a cantilever system, then the piles must be tied back with an anchor system.

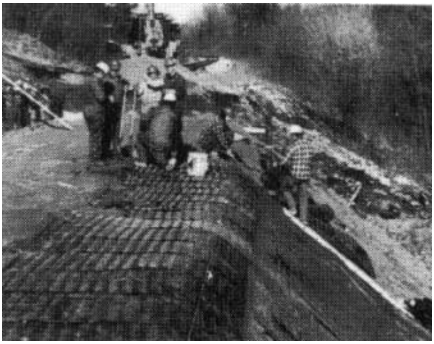
3.3.6 Plastic Mesh Reinforcement (Geogrid)

Geogrid is a synthetic soil reinforcement material, manufactured out of a stretched sheet of polymer plastic to form a lightweight, high tensile strength grid. The grid acts similarly to reinforcing mesh in concrete, adding strength to the shear strength of the soil.

The traditional use of geogrids has been to reduce the amount of ballast needed over soft ground by increasing the bearing capacity of the subsoil. Geogrids also have a number of possible applications in slope stabilization, including:

SOIL STRENGTH reinforcement
SOIL DRAINAGE improvement
RETAINING WALL construction

A fill slope can be constructed at a much steeper angle with geogrid because it increases the overall soil strength. Construction of a reinforced slope requires placing horizontal layers of geogrid on a compacted soil layer, followed by the next layer of fill. The number and spacing of geogrid layers depend on the steepness of the slope and the type of soil. Design charts and emplacement procedures are available from the manufacturers. On average, a layer is used about every 0.5-0.75 m, with short intermediate layers used in certain situations.



Geogrid mesh reinforcement

Geogrid emplacement is difficult in normal cut and fill road construction on steep ground. Apart from the construction difficulties, geogrids may not always work because the failure plane for sidecast slides is often in the intact soil beneath the fill. A "three bench construction" method (Section 3.2.1), backed up by geogrid reinforcement, will work under exceptional circumstances.

A more useful application may be for valley bottom roads pinched between a stream and a rock bluff. The geogrid allows a very steep fill slope to be constructed, preventing sidecast ravelling into the stream. The cost of the geogrid and the specialized construction will be partly offset by reduced end haul costs.

3.3.7 Check Dams

Check dams are small sediment storage dams built in the channels of steep gullies to stabilize the channel bed. They are commonly used in Europe and Japan to control channelized debris flow frequency and volume. A less common use of check dams is to control ravelling and shallow slides in the source area of debris slides. Check dams are expensive to construct and therefore are usually only built where important installations, such as a camp or unique spawning area, lie downslope.

Channelized debris flows are associated with channel gradients over 25 degrees and obtain most of their volume by scouring the channel bed. Check dams serve three purposes when installed in the channels. They:

REDUCE THE INCIDENCE OF FAILURE by reducing the channel gradient in the upper channel.
REDUCE THE VOLUME of channel-stored material by preventing downcutting of the channel with subsequent gully sidewall destabilization, and by providing toe support to the gully slopes.
STORE debris flow sediment, when installed in the lower part of the channel.

When installed on debris slides, the dams store ravelled material which eventually creates small terraces on the slide, reducing the surface slope. Check dams can be constructed of reinforced concrete or log cribs. Concrete mortared rock dams do not usually exceed 8 m in height, while log crib and mortared stone dams must not exceed 2 m. The spacing of dams depends on channel gradient and dam height according to the formula:

$$\text{Spacing} = \frac{\text{dam height}}{\text{tangent (original channel gradient } \phi \text{ - back filled channel gradient } \alpha}$$

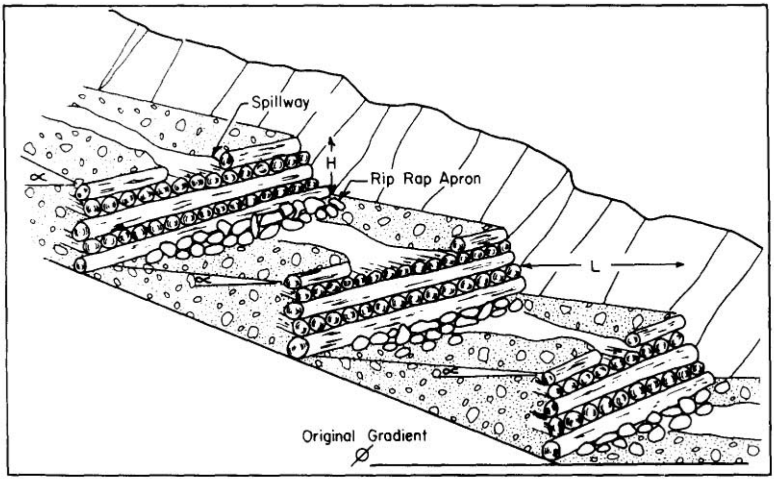
For example, a 2- m high dam in a 20 degree channel with 10 degree sloping channel infill will be spaced every 12 m.

Lateral stream erosion and scour by spillway water are the main causes of check dam failure. During construction, the concrete wing walls and log crib ends must be tied securely into the canyon wall and stream bed to withstand backfill pressures and lateral scour. Wingwalls should slope at about 70% and extend a minimum of 1-2 meters into the banks. The foundation of the dam should have a minimum width of one-third the total height of the dam and be deeper than any scour holes likely to develop.

Concrete check dam in steep stream

Rock and mortar check dams on ravelling debris slide

Every check dam must have a spillway large enough to handle peak flows and robust enough to withstand bed load scour. A spillway width of at least 1.0 m is recommended for most small streams. A riprap layer at the base of the dam prevents scour.



Crib wall check dam

Backfilling the dam, rather than allowing it to fill naturally, reduces the dynamic loading on the structure and results in a more robust design. The slope of the backfill should be less than one-half the channel gradient. Provided the dams have been back-filled, they will survive a debris torrent. The backfill material will not be scoured either during or after a torrent.

3.3.8 Creek Channel Linings

Channel linings are another means of stabilizing the creek channel and sides. The lining is usually slush grouted by high quality concrete, preferably a reinforced steel fiber mat, to resist abrasion. Protruding boulders are set in the concrete to dissipate the energy of water flow.

Channel linings reduce the incidence and volume of debris flows. They are also effective in maintaining channel alignment upstream of a bridge and protecting the abutments. They are most effective if applied over the entire reach of an unstable channel. Linings are usually much less costly than check dams, especially if a long reach is to be stabilized. Check dams are preferable, however, if the banks are very unstable, because they can be keyed into the bank, providing toe support.

Creek channel linings

3.4 PROTECTION

Protection measures are used whenever there is something valuable downstream (such as a camp, mainline road, or important spawning river) and it is either impossible or too expensive to stabilize the slopes above.

The protection measures described are for rockfall and channelized debris flows. Open-slope failures are very difficult to protect against, necessitating an enormous structure if containment is the goal. Also, since the volume of open-slope landslides is unpredictable, the building of protection structures has to assume the worst case–an expensive proposition.

3.4.1 Channelized Debris Flows

Logging camps or mainline roads may inadvertently be located in the runout zone of channelized debris flows.

The options available are to move the facility to a safer location, or to design protection measures. This decision should be based on the anticipated size and frequency of debris flows, as well as the level of development planned in the watershed. Terrain specialists can advise on these considerations.

Before any protection works are built, the upper slopes should be stabilized as much as is practical, thereby reducing the risk of a flow occurring. A sound option is to postpone logging the watershed until the last year of camp use.

The methods available for debris flow protection are debris racks, berms, dykes, and channel excavations and catch basins.

All of these methods require geotechnical expertise to determine size, location, and spacing of the structures. Design should be entrusted to a geotechnical engineer who has modeling facilities.

Runout zone prediction

Channelized debris flows have enormous amounts of energy. It is nearly impossible to try to stop them in the channel. Virtually all debris flows begin to stop flowing naturally when two conditions are met:

1. Flow becomes non-channelized on at least one side.

2. The stream channel gradient is less than 10-15 degrees.

The destructive scouring phase of the flow will not usually extend more than 200 m past this point. Deposition can occur well beyond this point, however, depending on the volume and water content of the flow.

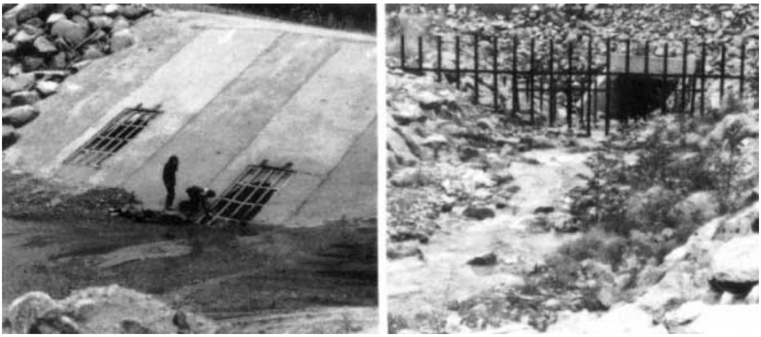
Another method of predicting runout is to look at fan deposits from old debris flows. Debris flows out of the same valley tend to have similar volumes and runout distances. Future debris flows usually will not extend far beyond the old fans.

Debris racks

Debris racks are steel fences built into the bed of steep mountain channels. They are installed immediately upstream of the road and are cemented into the bed and sides of the channel. The racks typically are constructed of welded steel railway rail. Their main function is to catch large pieces of wood that flow down the channel during storms and plug culverts, at the same time allowing the passage of water. When located on the lower part of hillslopes, they can also be surprisingly effective in sieving a lot of woody material out of a debris flow, reducing the magnitude of the flow.

Debris racks should be 1.5-2.0 m high, depending on the size of the channel. They should be grouted into the bed and sides of the channel at an equal depth, and a minimum of 1 m. Debris racks are normally installed 20-50 m upstream of the road; a pair is considerably more effective than one.

Another type of debris rack is a large-mesh steel grate installed over the mouth of the culvert. This is normally used only in conjunction with an upstream rack.



Debris racks require equipment access for cleaning

Berms and dykes

Earthfill berms are used to reduce the flow velocity and momentum of a channelized debris flow. A berm is a large deposit of gravel placed below the mouth of a gully. As it is virtually impossible to stop or redirect a channelized flow, the berm should

Earthfill dyke and excavated channel directing flows away from a highway

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