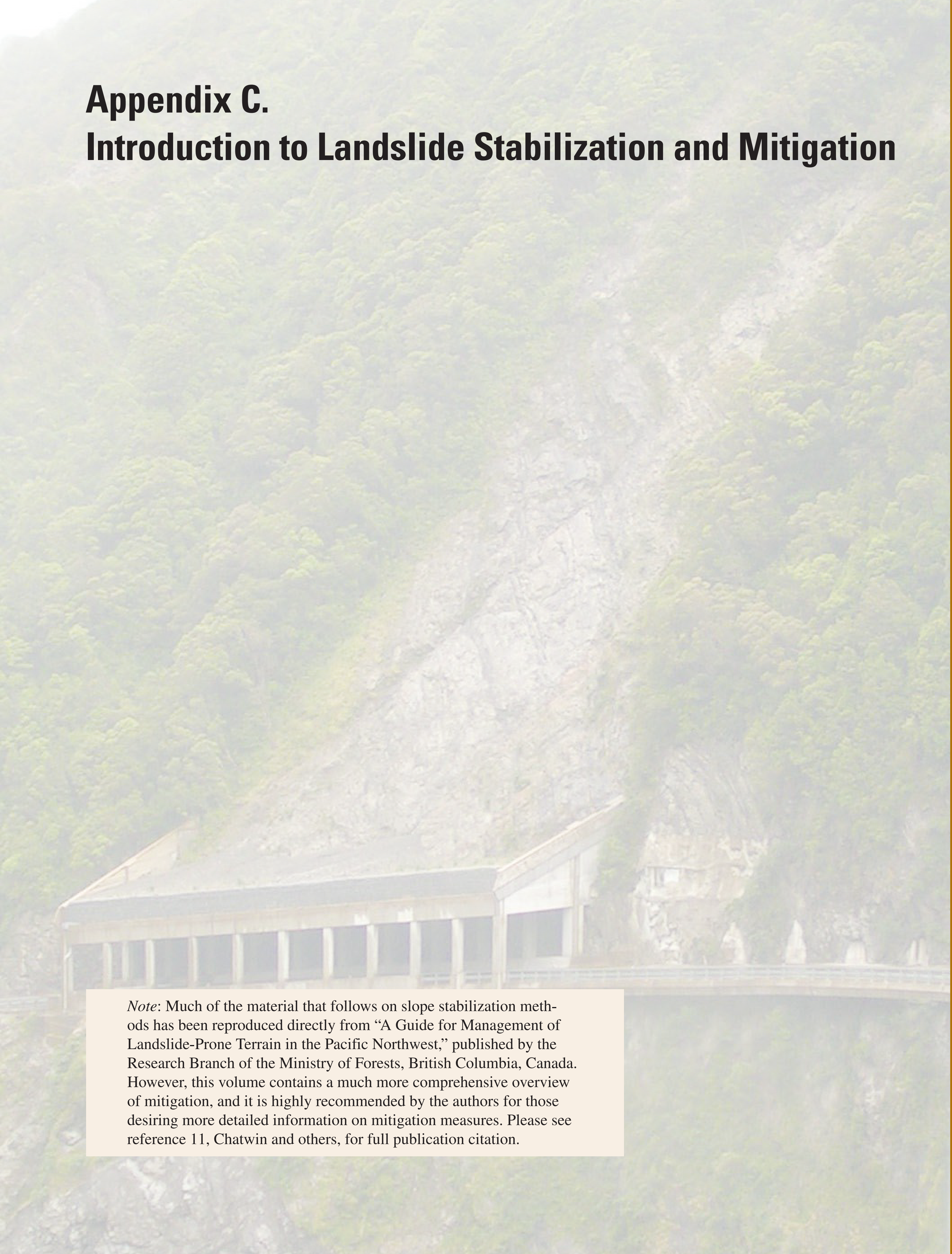
Appendix C.
Introduction to Landslide Stabilization and Mitigation



Note: Much of the material that follows on slope stabilization methods has been reproduced directly from “A Guide for Management of Landslide-Prone Terrain in the Pacific Northwest,” published by the Research Branch of the Ministry of Forests, British Columbia, Canada. However, this volume contains a much more comprehensive overview of mitigation, and it is highly recommended by the authors for those desiring more detailed information on mitigation measures. Please see reference 11, Chatwin and others, for full publication citation.

Part 1. Earth Slope Stabilization/Mitigation

Some of the stabilization techniques that are currently available in North America are illustrated in this discussion. We highlight simple methods that can be used safely in the absence of detailed soil or bedrock analysis or in low-risk situations. Some stabilization methods are very expensive and require significant time to implement. This is an overview of stabilization methods; many other methods are in use around the world. Professional advice is essential before, during, and after implementation (where possible), as is further literature consultation.

The stability of any slope will be improved if certain actions are carried out. To be effective, first one must identify the most important controlling process that is affecting the stability of the slope; second, one must determine the appropriate technique to be sufficiently applied to reduce the influence of that process. The mitigative prescription must be designed to fit the condition of the specific slope under study. For example, installation of drainage pipes into a slope that has very little ground water is pointless. Slope stabilization efforts take place during construction or when stability problems develop unexpectedly following construction. Most slope engineering techniques require a detailed analysis of soil properties and a sound knowledge of the underlying soil and rock mechanics.

> ***In any high-risk situation, where a landslide may endanger lives or adversely affect property, a professional landslide expert such as a geotechnical or civil engineer should always be consulted before any stabilizing work is undertaken.***

The following sections provide a general introduction to techniques that can be used to increase slope stability.

Excavation

Figures C1, C2, and C3 provide a cross-sectional view, in schematic form, of general principles for slope excavation, showing the effects and consequences of where on a slope the excavation takes place. These graphics are general in nature, and a geotechnical engineer or other professional should always be a consulted if possible.

Removal of soil from the head of a slide

This method reduces the driving force and thereby improves stability. This method is suitable only for cuts into deep soil where rotational landslides (see “Basic Landslide Types” in Section I) may occur. It is ineffective on translational failures on long, uniform or planar slopes or on flow-type landslides.

Reducing the height of the slope

Reducing the height of a cut bank reduces the driving force on the failure plane by reducing the weight of the soil mass and commonly involves the creation of an access road above the main road and the forming of a lower slope by excavation. Also, it is possible to excavate deeply and lower the main road surface if the right-of-way crosses the upper part of a landslide. This method is only moderately efficient in increasing stability, and a complete solution may involve additional modification of the land. According to Chatwin (Reference 11), it usually increases the Factor of Safety by only 10 or 15 percent. (“Factor of Safety” in its simple definition is the ratio of the maximum strength of a piece of material or a part to the probable maximum load to be applied to it.)

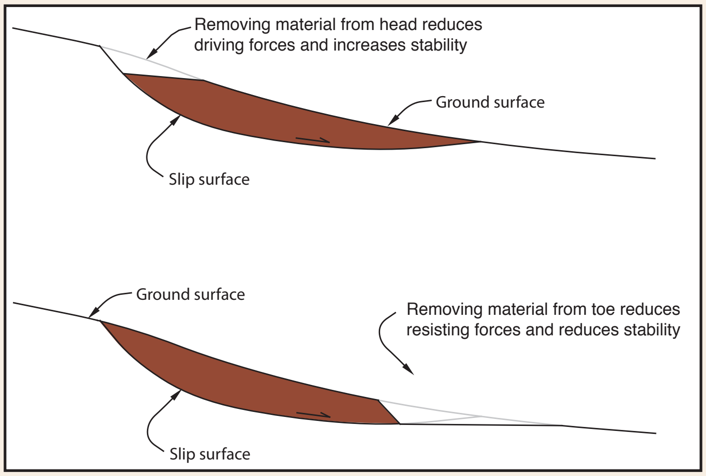


Figure C1. Illustration of the differences in stability resulting in excavation at the head and toe surfaces of a slope. (Graphic by Rex Baum, U.S. Geological Survey.)

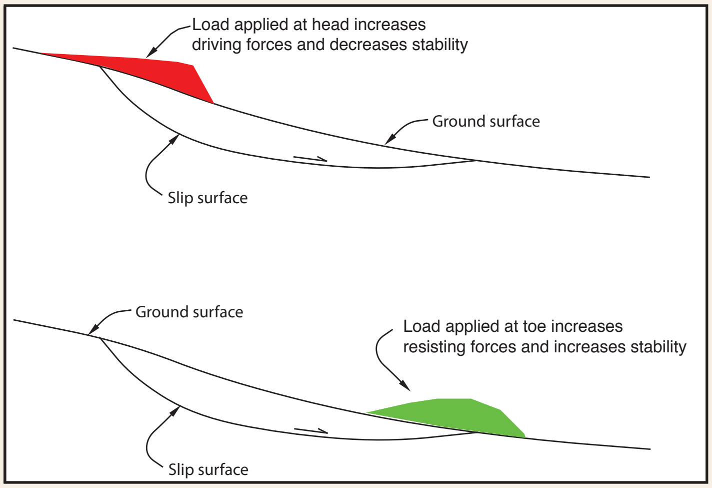


Figure C2. Illustration of the difference in stability of loading either the head or the toe of a slope. (Graphic by Rex Baum, U.S. Geological Survey.)

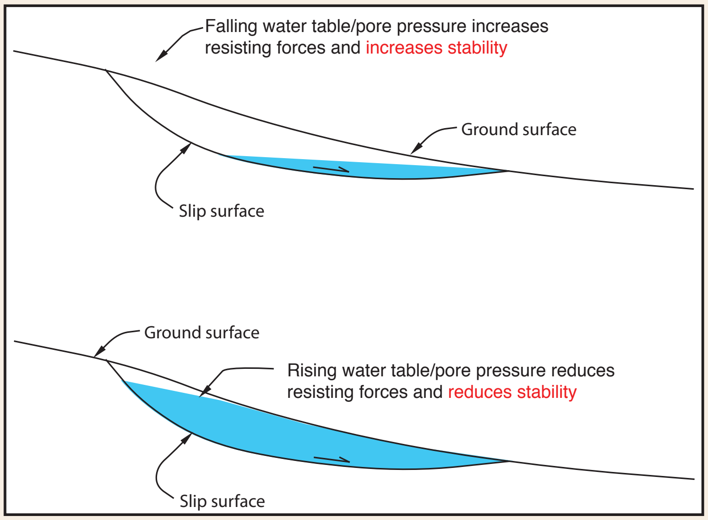


Figure C3. Illustration of the importance of water in the stability of a slope. (Graphic by Rex Baum, U.S. Geological Survey.)

Backfilling with lightweight material

A technique related to height reduction is to excavate the upper soil and replace it with a lightweight backfill material such as woodchips or logging slash. Then, covered with a thin layer of coarse aggregate, the backfilled material can form a foundation for limited-use traffic (fig. C4).

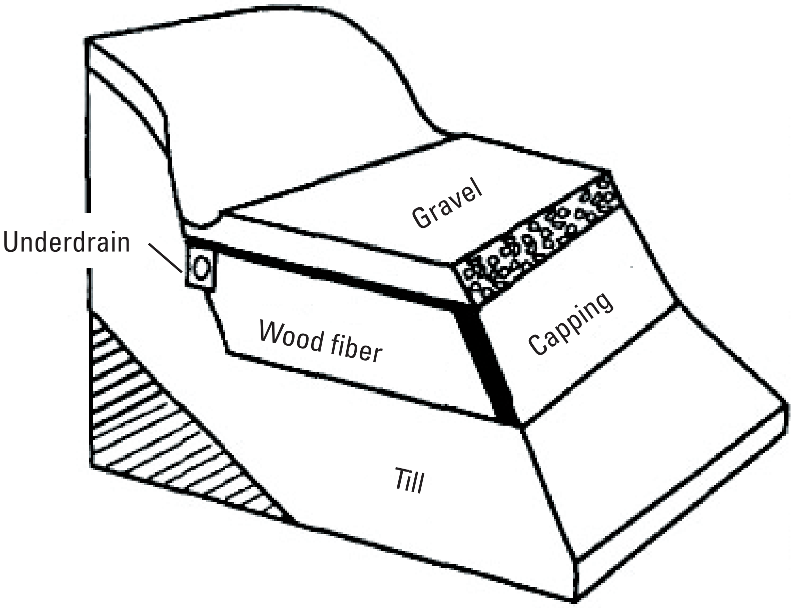


Figure C4. Schematic and photograph of a lightweight backfill. There has been an increased growth in the use of recycled tire shreds in civil engineering applications. Highway applications include using shredded tires as lightweight fill over weak soils in bridge embankments and retaining wall reinforcements or, in very cold climates, as insulation of the road base to resist frost heaves and as a high-permeability medium for edge drains. (Graphic from reference 11, photograph from U.S. Department of Transportation, Federal Highway Administration.)

Benches

Benches are a series of “steps” cut into a deep soil or rock face for the purpose of reducing the driving forces. They are mainly effective in reducing the incidence of shallow failures but generally are not very efficient in improving the overall slope stability for which other methods are recommended. Benches are useful in providing protection structures beneath rockfall-prone cliffs, for controlling surface drainage, or for providing a work area for installing drainpipe or other structures.

Please see figure C12 for a photo of benches cut into a slope.

Flattening or reducing slope angle, or other slope modification

This reduces the weight of material and reduces the possibility of stream/river undercutting or construction loading.

When not to excavate a 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:

- Excavation is not always effective—for large planar failures, excavation may not cause movement to stop and may allow the landslide to expand.
- Excavation may ***trigger a larger landslide*** by removing the support provided by the toe of the landslide.
- Excavation may actually ***destabilize*** the ground farther upslope by undercutting, which weakens the slope.
- ***In deeper soils***, especially soft clays, where there are two potential failure surfaces, one deep and one shallow, excavating down to the first failure surface might trigger a sudden slippage on the deeper failure surface. A stability analysis using soil strength data is advised and most always necessary for any major excavation project in deep clay soils.

Strengthening Slopes

Plastic mesh reinforcement

There are numerous synthetic soil reinforcement materials on the market, and one example is a reinforcement material of plastic polymer stretched 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.

These types of materials have been used to reduce the amount of ballast needed over soft ground by increasing the bearing capacity of the subsoil. These types of grids also have a number of possible applications in slope stabilization, including soil strength reinforcement, soil drainage improvement, and retaining-wall construction.

Rock-fill buttresses

A simple method to increase slope stability is to increase the weight of the material at the toe, which creates a counterforce that resists failure (fig. C5). A berm or buttress of earthfill can be easily dumped onto the toe of a slope. Broken rock or riprap instead of soil is preferable, however, because it has a greater frictional resistance to shear forces and is also free draining, which reduces the problem of impeding ground-water flow.

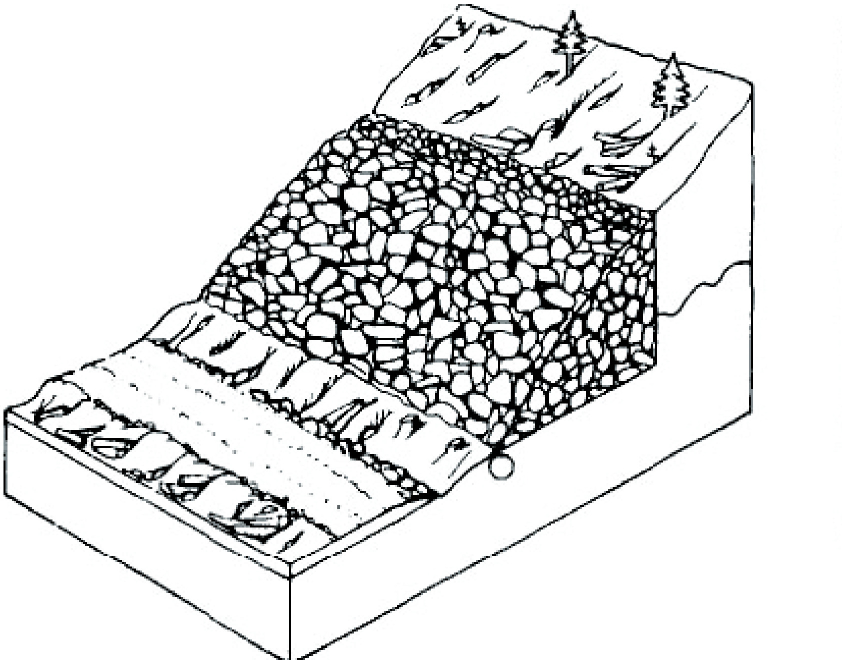


Figure C5. Schematic and photograph of a rockfill buttress in Canada. (Graphic is from Reference 11.)

Stream channel linings

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

Channel linings can reduce the incidence and volume of debris flows (fig. C6). They are also effective in maintaining channel alignment upstream from a bridge and for protecting the abutments. Channel linings are most effective if applied over the entire reach of an unstable channel. Linings are usually much less costly than, for example, check dams, especially if a long reach is to be stabilized. Check dams are preferable, however, if the banks are very unstable because a dam can be keyed into the bank, providing toe support and thereby enhancing stability.

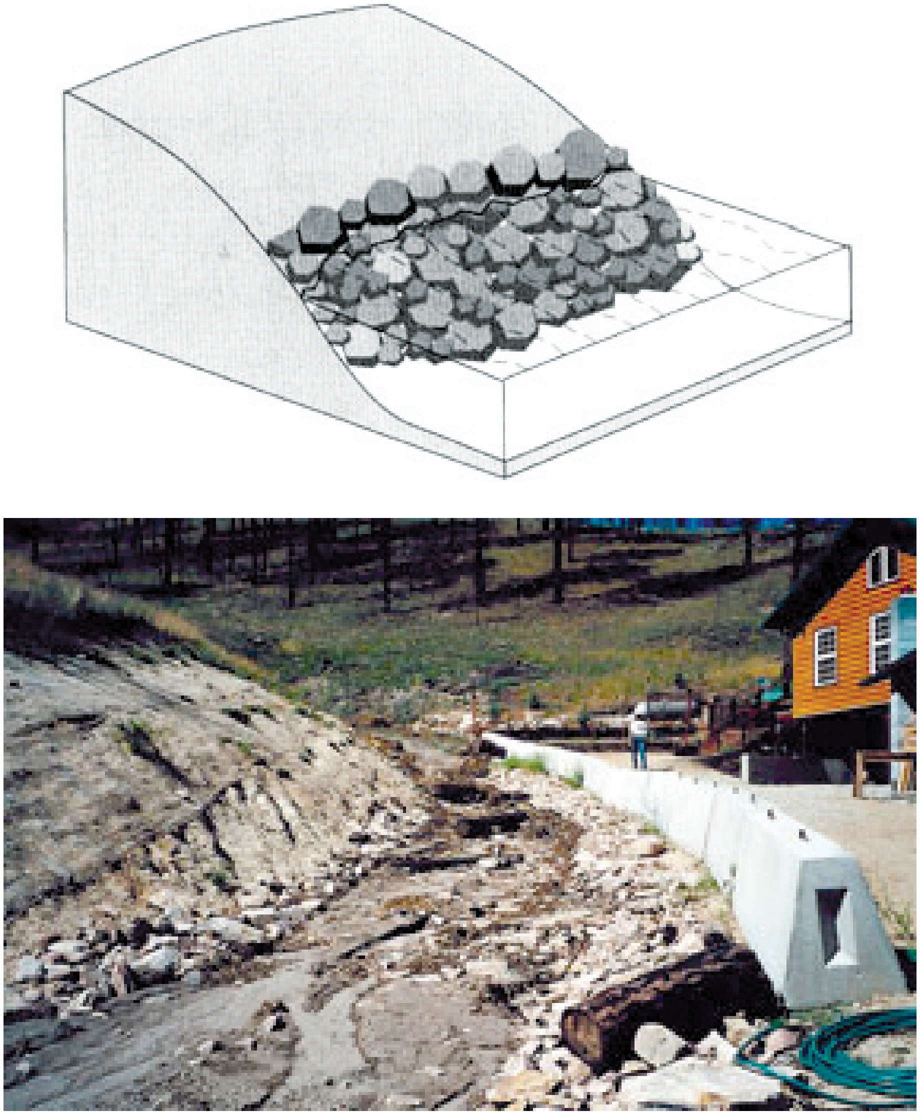


Figure C6. Example of creek channel lining using rock, Dickson Creek, Montana, USA. (Photograph and graphic, U.S. Department of Agriculture.)

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 raveling and shallow slides in the source area of debris slides. Check dams are expensive to construct and therefore are usually built only where important installations or wildlife habitat, 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 (following information quoted from Reference 11):

1. To mitigate the incidence of failure by reducing the channel gradient in the upper channel.
2. To reduce the volume of channel-stored material by preventing down cutting of the channel with subsequent gully sidewall destabilization and by providing toe support to the gully slopes.
3. To store debris-flow sediment, when installed in the lower part of the channel.

When installed on debris slides, the dams store raveled material, which eventually creates small terraces on the slide, reducing the surface slope. Check dams can be constructed of reinforced concrete or log cribs (figs. C7 and C8). Concrete mortared rock dams do not usually exceed 8 m in height, whereas log crib dams must not exceed 2 m (6 feet). The spacing of dams depends on channel gradient and dam height. For example, a 2-m-(6 foot) high dam in a 20-degree channel with 10-degree sloping channel infill will be spaced every 12 m (36 feet). Lateral stream erosion and scour by spillway water are the main drawbacks.

To prevent check dam failure

During construction, the concrete wingwalls and log crib ends must be tied securely into the canyon wall and streambed to withstand backfill pressures and lateral scour. Wingwalls should slope at about 70 percent and extend a minimum of 1–2 meters (3 to 6 feet) 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.

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

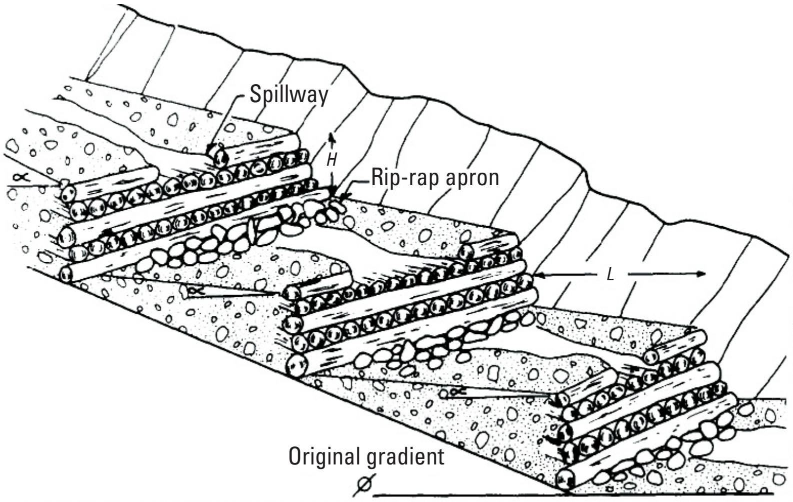


Figure C7. Schematic and photograph of a crib wall check dam, which is one kind of check dam. (Graphic from Reference 11, photograph taken in Trafoi, Italy, courtesy of "Erosion Control," Forester Communications, Santa Barbara, California, USA.)

Figure C8. Upstream view of concrete crib-type check dam with low-flow center section in southern California, USA. (Photograph by Los Angeles County Flood Control District.)

Drainage Techniques

Ground water probably is 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 stability 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 substantial 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 ground-water pressures. Subsurface drainage also is effective but can be relatively expensive. It is therefore essential that ground water be identified as a cause of the slide before subsurface methods are used. The various methods of drainage include the following:

Site leveling

Smoothing the topography of the slide surface can prevent surface water from ponding or connecting with the ground water. Any depressions on the slope that might retain standing water must be removed. Infilling and sealing large cracks in the soil surface by grading the soil mass are beneficial and prevent surface water from reaching the failure plane.

Ditches and drains

Surface drainage can be through either surface ditches or shallow subsurface drains (fig. C9). Surface drainage is especially important at the head of the slide, where a system of cutoff ditches that cross the headwall of the slide, and lateral drains to lead runoff around the edge of the slide are effective. Ditch gradient should be at least 2 percent, 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 economical only for shallow soils overlying bedrock or hard impermeable till. The trenches should be excavated to the base of the shallow soil to intercept any ground-water flow along the failure plane. They are backfilled with coarse gravel to prevent sloughing of the ditch sidewalls. An improvement is to use drainpipe and then backfill the area with coarse gravel.

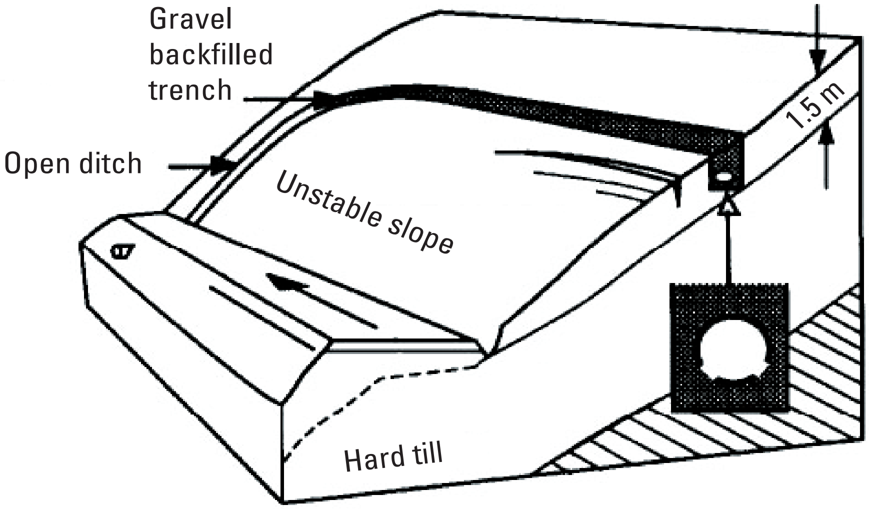


Figure C9. Schematic and photograph of a drain trench. (Graphic from Reference 11, photograph by Department of Transport, Energy and Infrastructure, South Australia.)

Drainpipes

Horizontal drainpipe is a widely used device for landslide prevention in highway construction (fig. C10). It is most effective when installed during initial excavation. Because of the long lag times to lower ground-water 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 varying soil and hydraulic and geometric conditions, drainage systems must be individually designed. 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 drainpipe 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 percent effective.

In clay soils, the full change in ground-water tables can take up to 5 years, with 50 percent of the improvement taking place in the first year. Once water tables are lowered in clay soils, the change is fairly permanent; however, seasonal fluctuations can occur: rainfall will not alter the ground-water level in the slope provided the drains do not clog. In sandy soils, the ground-water table will lower within a few months but will also fluctuate with rainfall.

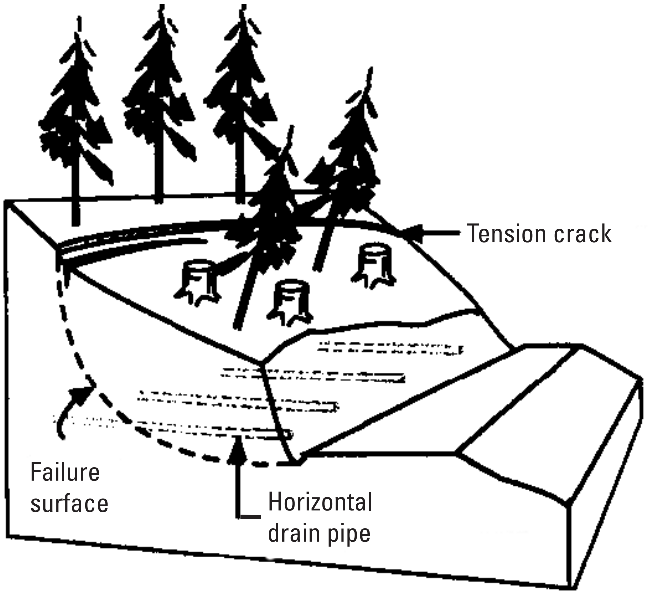


Figure C10. Schematic of drainpipes. (Schematic from Reference 11.) Photograph of drainpipes in a landslide in California, USA, by Andrew Alden.

Straw wattles and straw bales

Straw wattles, also known as straw worms, bio-logs, straw noodles, or straw tubes, are manufactured cylinders of compressed, weed-free straw (wheat or rice), 20 to 30 centimeters (8 to 12 inches) in diameter and 7 to 9 meters (20 to 25 feet) long (fig. C11). They are encased in jute, nylon, or other photodegradable materials and have an average weight of 16 kilograms (35 pounds). They are installed in a shallow trench forming a continuous barrier along the contour (across the slope) to intercept water running down a slope. Straw wattles should be effective for a period of 1 to 2 years if they can be installed on slopes up to 70 percent; however, their effect diminishes greatly on slopes steeper than 50 percent. Soils can be shallow but not less than about 8 inches. Straw wattles increase infiltration, add roughness, reduce erosion, and add short-term protection on slopes where permanent vegetation will be established to provide long-term erosion control. Straw bales are easily obtainable in most areas of the world, are very portable, and have a modular-type application for slope erosion and drainage control (fig. C12).

Figure C11. Straw wattles on the side of a road capture sediment and hold it onsite, enabling seeds to settle and germinate, aiding the revegetation process. (Photograph by Lynn Highland, U.S. Geological Survey.)

Figure C12. Straw bales have a similar application and are widely available. Individual bale size can be seen in the pile of bales, right center of photograph. (Photograph of slope in New Mexico, USA, New Mexico Department of Mining, Minerals, and Natural Resources.)

Retaining Walls

For all types of retaining walls, adequate drainage through the structure is essential because very high ground-water 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 (fig. C13). 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 by burying to sufficient depth and extending beyond 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 to 15 percent of the volume of the soil to be stabilized. This relatively small volume provides little counterweight support at the toe; therefore, virtually the entire resistance to failure comes from the strength of the crib.

Note: The advice of a civil engineer is needed for any walls higher than 3 meters (9 feet), or for those in complex foundation soils.

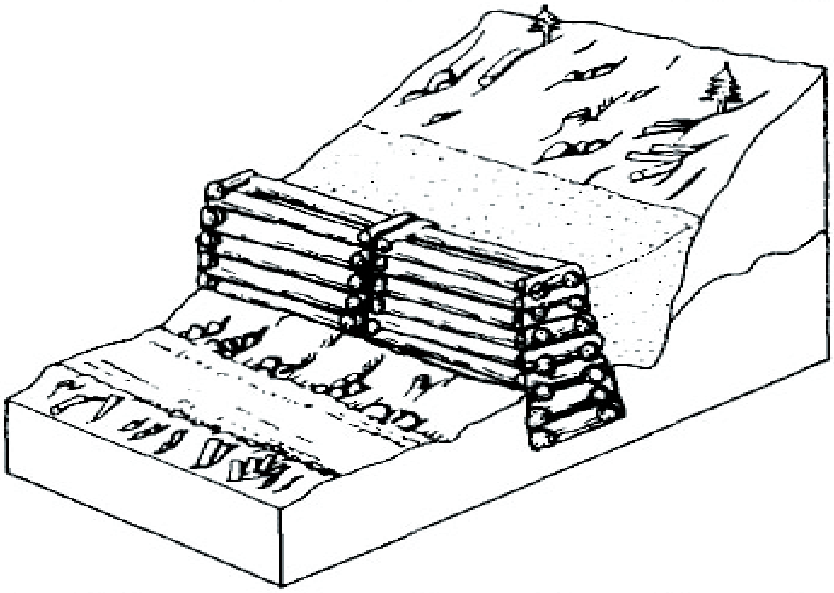


Figure C13. Schematic and photograph of a timber crib. (Schematic from Reference 11, photograph is courtesy of PHI Group, United Kingdom.)

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 (fig. C14). 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. Structural and civil engineering design charts provide stringer (horizontal member) specifications and height-to-width ratios for typical loading conditions. The widths of walls vary from 2 to 5 meters (6 to 15 feet) 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 to 1.0 meter (1.5 foot to 3 feet) below grade, although the design should not rely on the additional toe support, as it can erode or be removed inadvertently. 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-centimeter (7.8 inches) lifts. Material behind the wall also should be well drained and moderately compacted.

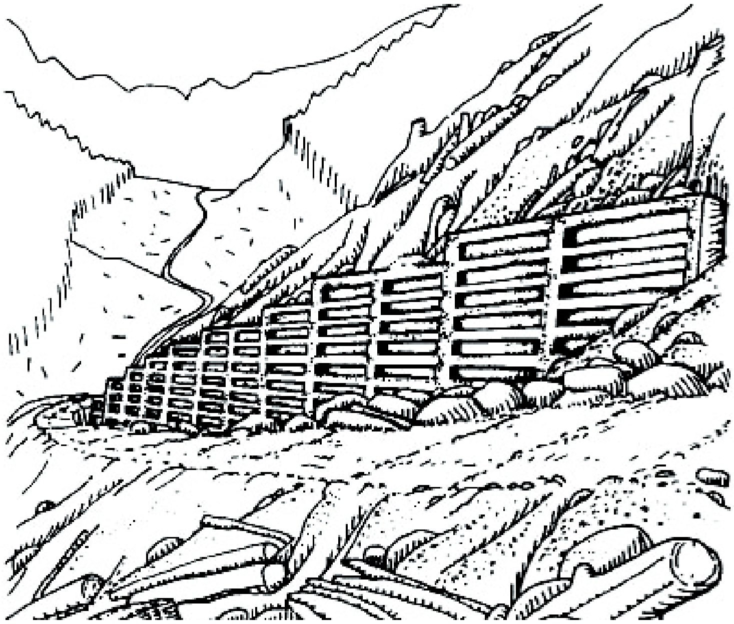


Figure C14. Schematic and photograph of a steel bin wall. (Schematic from Reference 11.)

Reinforced earth wall

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 (fig. C15). The system uses horizontal layers of flexible metal strips within the fill to form a composite earth-metal system with high strength.

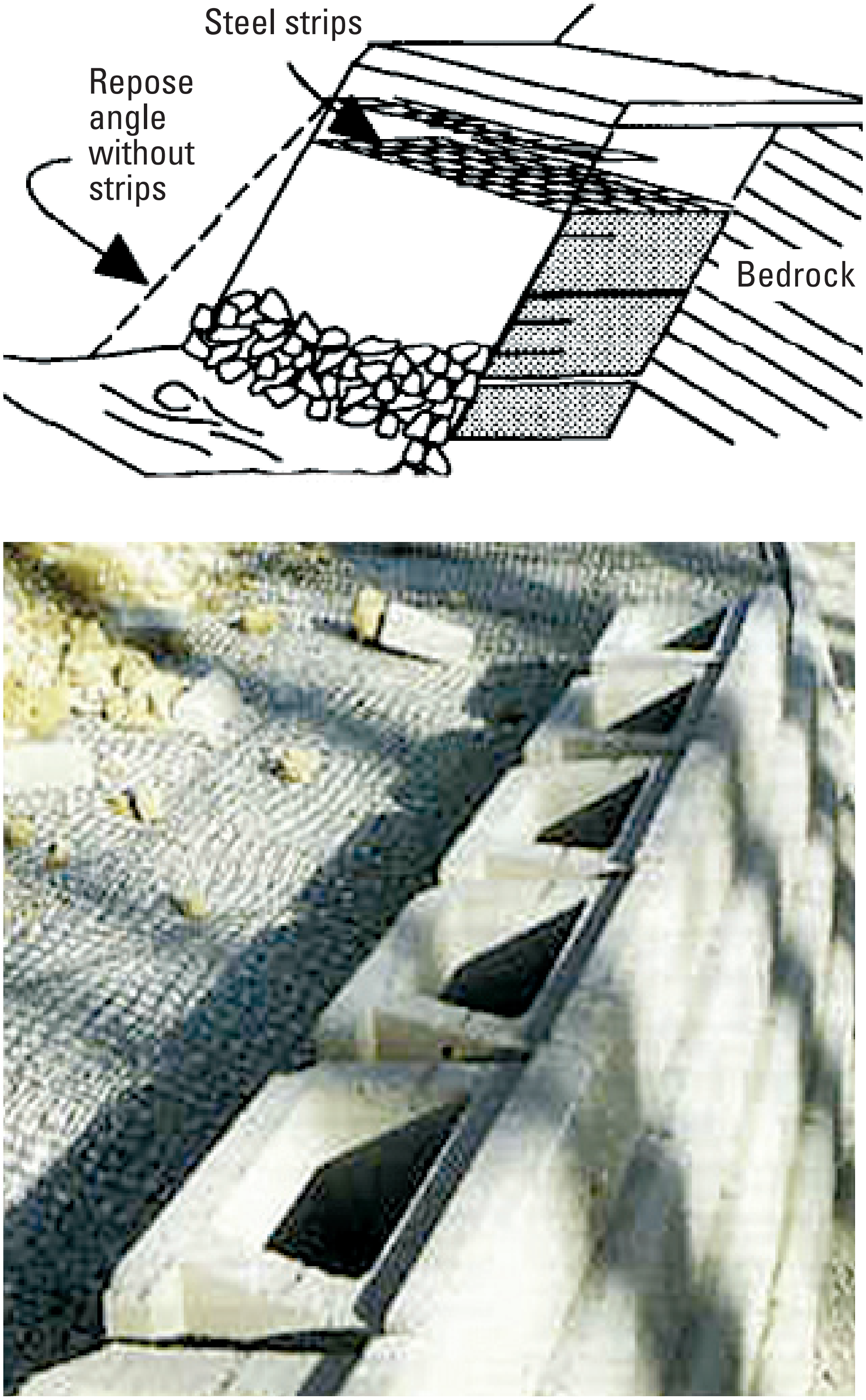


Figure C15. Schematic and photograph of a reinforced earth wall. (Schematic from Reference 11.)

Gabion walls

Gabions are wire mesh, boxlike containers filled with cobble-sized rock that are 10 to 20 centimeters (4 to 8 inches) size (fig. C16). A gabion retaining wall can also be constructed from stacked gabions. Gabion walls usually are inexpensive and are simple and quick to construct. Due to their flexibility, they can withstand foundation movement, and they do not require elaborate foundation preparation. Because of their coarse fill, they are very permeable and thus provide 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 soil underneath. When failure occurs, it is almost always in the foundation soil itself. Three-tiered walls up to 2.5 meters (8 feet) high can usually be constructed without consulting any detailed engineering analysis. Higher walls are very heavy by nature of their added bulk and need larger base foundations and possibly counterforts for bracing of the wall. (A counterfort is a buttress bonded to the rear of walls, designed to improve stability.) 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 components and as drains.

Design charts are available for various combinations of hillslope angle and retaining-wall height.

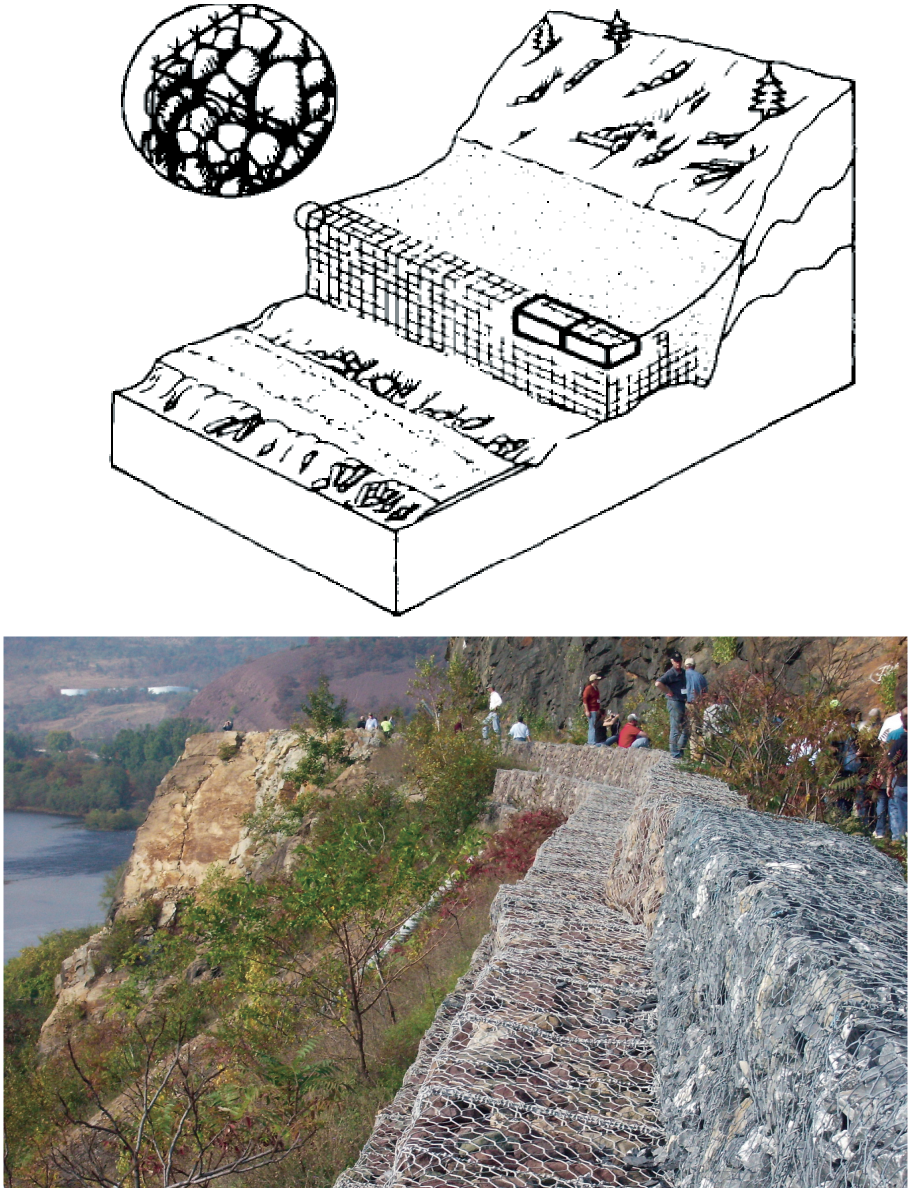


Figure C16. Schematic and photograph of a gabion wall along a highway. (Schematic from Reference 11.) (Photograph of gabions located in the Pocono Mountains, Pennsylvania, USA, by Lynn Highland, U.S. Geological Survey.)

Piles

Large-diameter piles can be placed into the toe of a slope to form a closely spaced vertical pile wall (fig. C17). Pile walls are normally used as a preexcavation restraint system—the cut slope excavation takes place in front. Whereas large-diameter concrete pile and culvert pile walls have been used successfully on highways, wood or steel piles that are small in diameter have not. For most earth or rock movement, wood piles are not adequate to provide enough shearing resistance. They are suitable only where the volume of soil to be stabilized is small. On average, one wood pile is necessary for every 50 cubic meters (65.3 cubic yards) of soil, which is not sufficient for large stabilization projects. Too few piles can result in toppling and (or) breakage by the moving mass of soil, as well as by soil movement between the piles.

A major limitation when log piles are used is depth, as many failure surfaces lie below the height of the piles. Wood piles are the best for shallow soil failures over deeper stable soils. The piles should extend well below the potential failure surface and be firmly 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 additional anchor system.

Figure C17. A concrete-filled pile wall. Reinforcing mesh has been hung over face of piles, ready for shotcrete spraying. Location is Brighton, Melbourne, Australia. (Photograph courtesy of Basement Construction Services, Victoria, Australia.)

Slope Stabilization Using Vegetation

Seeding with grasses and legumes reduces surface erosion, which can under certain conditions lead to landslides. Planting with shrubs adds vegetative cover and stronger root systems, which in turn will enhance slope stability. If not controlled, surface erosion and small, shallow slope failures can lead to larger problems that cannot be controlled. Large-scale erosion requires applied engineering technology to correct and control. The terms "bioengineering" and "biotechnical slope protection" refer to the use of vegetation as slope protection to arrest and prevent slope failure and surface erosion. Bioengineering is discussed in detail in Section III of the handbook.

Planning is required for the successful implementation of a revegetation program. Before undertaking seeding, a person with local experience should be consulted for advice. Local knowledge based on successes and failures of projects is invaluable. Seed application should begin immediately following a disturbance, at a minimum of approximately 6 weeks before periods of drought or damaging frost.

A slope made as stable as possible before seeding will be of benefit in making the slope resistant to future erosion and failure. Controlling surface-water drainage, removing cut-bank overhangs, reducing slope angles, and benching all should be done before seeding begins.

There are two basic types of seeding: dry seeding and hydraulic, also known as hydroseeding:

> **Dry Seeding** Dry seeding is done with rotary disk and air-blown seeders. These methods are less costly than hydraulic seeding but are limited to rough soil surfaces and gentler slopes. Rotary disk seeders spread seed and fertilizer by centrifugal force. The simplest seeder is the cyclone-type, hand-held seeder. Air-blown seeders use air to blow or shoot seed and fertilizer a distance of 5 to 8 meters (15 to 24 feet). Equipment can be adapted for motorized vehicles.
>
> **Hydraulic Seeding, or Hydroseeding** This type of seeding is the application of seed in a water slurry that contains fertilizer, soil binder, and (or) mulch. The system requires a mixing tank with mechanical hydraulic agitation and volume pumping capacity. Hydraulic seeding is effective for seeding slopes 1:1 and steeper, where tacking of the seed to the slope is necessary.

Types of seeds

A combination of two to five species is the normal grass-legume mix used for erosion control. Suitability of seeds depends on soil type, climatic conditions, species compatibility, and species replacement. Local conditions will vary, and no universal type of grasses or legumes can be recommended. The types of vegetation can vary from locality to locality, and it is best to get advice from locals who are familiar with local growing conditions.

Mulching

Mulch is a nonliving material spread over the soil surface to provide protection from surface erosion by rain and retention of soil moisture. Various types of mulches will work—straw, grass fibers, wood fibers, seaweed, and paper products.

Biotechnical Slope Protection

This type of slope protection is used to reduce the environmental consequences of landslide-mitigation measures. When used for landslide remediation or mitigation, conventional earth-retaining structures made of steel or concrete usually are not visually pleasing or environmentally friendly. These traditional “hard” remedial measures are increasingly being supplanted by vegetated composite soil/structure bodies that are environmentally more friendly. This process has come to be known as biotechnical slope protection. Common biotechnical systems include geonets anchored by soil nails that hold in place soil seeded with grass and geocells with seeded soils in the interstices.

Research has been done on using plants to stabilize soil to prevent excessive erosion and also to mitigate the effect of landslides. One of the most promising types of plants is Vetiver, a type of grass that works very well in many different environments, to stabilize slopes against erosion. See Appendix C for more information on this plant, its uses, and its geographical suitability.

Biotechnical slope protection consists of two elements: ***biotechnical stabilization*** and ***soil bioengineering stabilization***, both of which entail the use of live materials—specifically, biotechnical *vegetation* stabilization uses mechanical elements (structures) in combination with biological elements (plants) to prevent and arrest slope failures and erosion. Mechanical and biological elements must function together in a complementary manner. Soil bioengineering stabilization, on the other hand, can be regarded as a specialized subset of biotechnical stabilization in which live plant parts, that is, roots, stems, and branches, serve as the main structural/mechanical elements in the slope protection system. Biotechnical slope-protection systems blend into the landscape. They emphasize the use of natural, locally available materials, such as soil, rock, timber, and vegetation, in contrast to manufactured materials such as steel and concrete. The structural or mechanical components do not visually intrude upon the environment as much as conventional earth-retaining structures. Examples of biotechnical vegetation structures, which commonly incorporate vegetation into the structure itself, include log and timber cribs, gabion and rock-breast walls, welded wire walls, and reinforced earth. Internal, tensile reinforcements using the principles of bioengineering permit construction of oversteepened fill slopes to as much as 70º. A general guide to different bioengineering stabilization methods and more detailed information can be found in reference 30.

As noted previously, soil bioengineering relies mainly on the use of native materials such as plant stems or branches, rocks, wood, or soil. Appropriate vegetation for bioengineering can be obtained from local sources of willow, alder, and other native, easily propagated varieties. In addition, soil bioengineering systems commonly are environmentally compatible during the construction process because they generally require minimal access for equipment and workers and cause relatively minor disturbance. With time, the bioengineering systems become visually nonintrusive and blend into the natural surroundings. This is a favorable attribute in environmentally sensitive areas such as parks, riparian areas, and scenic corridors where esthetic quality, wildlife habitat, and ecological restoration are important. As bioengineered structures that utilize tree species become older, they have the added benefit that they become more stable and eventually assist in the natural succession and long-term colonization of forest species. In most cases, native grasses, shrubs, and trees are used as the vegetation in bioengineering stabilization. Willow has been very successful in many parts of the world. In tropical and subtropical areas, Vetiver grass hedgerows (VGHR) for stabilization have become very popular because of the fast growth and deep root penetration of this grass. However, if exotic species of plants or trees are introduced, there is a real danger that they will conflict with native plant life.

It is suggested that potential users consult the Vetiver grass Web site at: *http://www.vetiver.org*

Figure C18. A Vetiver grass system is being used in the Democratic Republic of the Congo for gully control in urban areas and for highway stabilization. These gullies are a major problem in this area and other West African countries (*top*); the same slope now has improved drainage, and the slope has been planted in Vetiver grass (*middle*); this planting of Vetiver grass is about 3 months old (*bottom*).

While detailed slope-stability assessments normally have been carried out by geotechnical engineers and engineering geologists, the organic interactions between vegetation, soil, and structures that must be evaluated in applying the technique of bioengineering stabilization are perhaps better understood by soil scientists, agriculturists, foresters, and hydrologists. Thus, the bioengineering approach to slope stabilization requires cooperation of geotechnical and plant-science disciplines working in parallel and in unison.

Publications are available that tell how effective it is in different regions of the world. A good beginner overview on Vetiver grass is the book, "Vetiver Grass: A Thin Green Line Against Erosion." The full reference for the book is in Reference 22. (See also reference 47.)

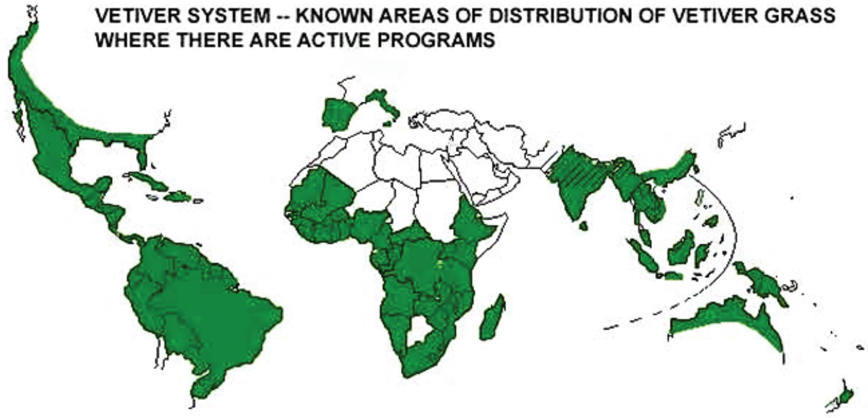


Figure C19. Worldwide distribution of active Vetiver grass programs. Graphic is from the Vetiver grass Web site (*http://www.vetiver.org*).

Additional Notes on Vetiver grass: For developing nations, soil erosion that encompasses, in its extreme form, landslides is one of the most damaging natural processes that must be dealt with. Little has been accomplished in dealing with erosion that can be widely applied, in inexpensive, long-lived, and appealing applications. Vetiver, a tropical grass, offers a practical and inexpensive way to prevent erosion. Planted in lines along the contours of sloping lands, Vetiver quickly forms narrow but very dense hedges. Its stiff foliage then blocks the passage soil and debris. This deeply rooted, persistent grass has restrained erodible soils for decades in Fiji, India, and some Caribbean nations. Figure C18 shows photographs of a Vetiver grass project in the Democratic Republic of the Congo and how it is used for stabilization for gullies and roads. The project is sponsored by various government agencies. These and additional photographs are on the Vetiver grass Web site, cited at the end of this section.

Part 2. Rock Slope Stabilization/Mitigation Techniques

Rockfall can range from a few fist-sized rocks to large cliff sections and boulders which, depending on size and shape, can roll, bounce, and careen down slopes, landing in areas at great distances from the fall lines. Recreation areas such as beaches near cliffs, parks, and open spaces are affected by rockfall, and people are frequently exposed to these hazards. People venturing too near the edges of cliffs and rocky slopes can add pressure to already weak overhangs and cause rockfalls to land on people below or sustain injuries themselves on these collapsing edges. Whether hiking, camping, walking, or working around cliffs or rock faces, people encounter the hazard many times without warning. A variety of engineering techniques can be implemented to help mitigate the effects of rockfalls, and some of these are discussed here. In some cases, more than one type of engineered solution is the best, and a combination of these remediation measures applied to one area of rockfall hazard is shown in figure C20.

Figure C20. This photograph shows rockfall countermeasures that include mass concrete retaining walls, gabion walls (both wall types are at top of photograph), check fences, boulder treatment, and buttressing. (Photograph is the Pen-y-Clip tunnel on a highway in North Wales, United Kingdom. Photograph by Dave Giles, Engineering Geology Consultancy Group, University of Portsmouth, United Kingdom.)

Safe Catching Techniques

Catch Ditches

Wide catch ditches are effective in containing rockfall, but the ditches must be designed with the cliff geometry taken into account, and it is best to consult a professional about specifications. The bottom of the catchment ditch should be covered with loose earth to prevent falling rock from bouncing or shattering into pieces or shards. If there is not enough space to construct as wide a ditch as is specified, then a combination of smaller ditches with a gabion or rock wall along their downhill edges can be used.

Cable, Mesh, Fencing, and Rock Curtains

Cable lashing and wire nets are simple, low-cost methods for protecting a road or path from rockfall. For large, unstable blocks, strands of metal cable are wrapped around the blocks and anchored to the slope. Where the rock is too fractured to be restrained by individual cables, cable nets are used. Wire mesh (closely spaced interwoven wires) can be used to prevent smaller rocks, less than 0.75 meter (2.4 feet) in size, from falling. (See figure C21 for a photograph of an example of wire mesh). The standard mesh is double-twisted gabion wire mesh or a heavy gage metal chain link. The mesh is either loosely draped over a uniform rock face or bolted or otherwise firmly secured where the cliff face is irregular and the mesh cannot make close contact with the rock. Bolting the mesh to the rock face can prevent rock from becoming dislodged and provides overall stability of the slope or rock face. Wire mesh also is useful on steep soil cuts, especially beneath talus slopes.

Catch nets made of cable and wire mesh can be constructed to catch falling rock at the bottom of gullies and slopes. When suspended from an anchored cable, the mesh forms a flexible barrier to dissipate the energy of the falling rock and will usually stop boulders up to 1 m in diameter, if properly secured. Additionally, catch nets can be used in conjunction with roadside catch ditches.

Rock fences such as the ones shown in figure C22 are fairly easy to install and can restrain small rocks from falling onto roads but do not stop rocks that bounce out over the top of the fence barrier. Rock curtains, such as the one shown in figure C23, are more effective in directing rocks down to a catch ditch or other catching structure, preventing them from bouncing outward onto the highway or structures below.

Figure C21. Example of wire mesh placed over a rocky slope to contain the rocks that may come down.

Figure C22. Protective rock barrier fencing along (*A*) a dirt trail in Pennsylvania, USA, and (*B*) a roadway in coastal California, USA. (Trail photograph, Lynn Highland, U.S. Geological Survey; roadway photograph from Federal Highway Administration, USA.)

Figure C23. Example of a “rock curtain” that controls rockfalls in problem areas. (Photograph by Doug Hansen, High Angle Technologies, Inc.)

Retaining Walls

Retaining walls can work much like those described for soil slope-stabilization techniques in keeping rockfall debris out of an area. They are similar to rockfall fences but are in most cases more substantial and stronger. Retaining walls can be made out of steel, concrete, timbers, or other materials and must be anchored properly so as not to tip over during rockfalls.

Rock Sheds/Shelters

These are built over roads, railways, and sometimes structures to shield the area from rockfall and rock avalanches. Shed structures are either open ended or completely envelope the rockfall area in a concrete or steel (or other material) structure that will deflect rockfall away from the road, railway, or structure. Figures C24 through C27 show examples of rock sheds/shelters.

Rock Ledge Reinforcement

These are not commonly used because they work only for unique situations and must be carefully engineered and structurally strong.

Figure C27 is an example.

Figure C24. Pitquah rock sheds, British Columbia, Canada. These sheds enclose sections of railroad, protecting it from rockfall and rock avalanches. (Photograph by John Carter, *www.trainet.org*.)

Figure C25. Example of an open rock shed in New Zealand (Photograph courtesy of Richard Wright, rock climber).

Figure C26. A rock avalanche shelter in the Montenyard area of France. The length of the shelter may be insufficient as a debris flow has damaged the road, shown to the right of the shelter. (Photograph by Dave Giles Engineering Geology Consultancy Group, University of Portsmouth, United Kingdom.)

Figure C27. Example of a reinforced rock ledge, Chapmans Peak Drive, Cape Town, South Africa. Photograph attribution: *http://commons.wikimedia.org/wiki/Image:Chapmans_peak_dr.jpg*.

Excavation of Rock

Benches

Horizontal benches excavated into a rock face are among the most effective kinds of protection from rockfall. In addition to intercepting rockfall, benches reduce tensional forces in the surface rock and reduce surface erosion rates. They also reduce the rate of occurrence of rockfall. However, they have little or no effect on potential deep-seated rock failure.

Bench faces can be constructed steeper than the overall slope angle, as rocks that fall will likely remain on the benches (fig. C28). Vertical bench-face angles should be avoided, however, as tension cracks, dangerous overhangs, and excessive rockfall can result. The placing of bench faces should be stopped at the base of weaker rock layers, fractured rock zones, or water-bearing zones. A minimum width of 4 m is recommended for the benches, and all benches should have drainage ditches to divert water away from the slope.

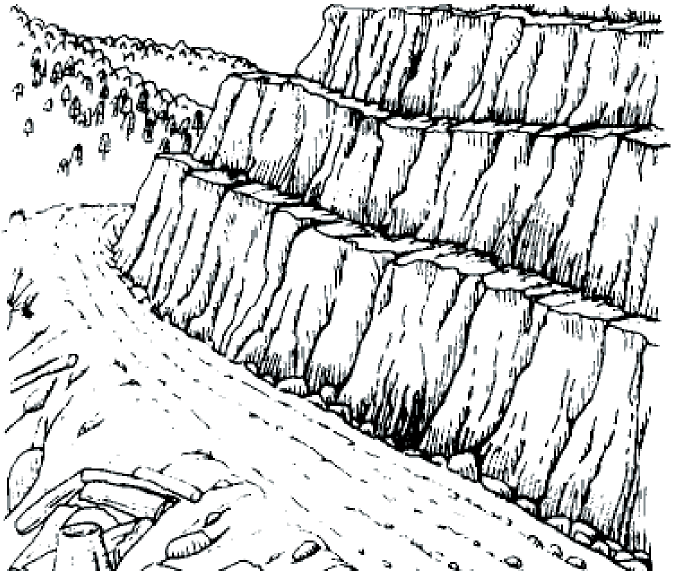


Figure C28. Schematic and photograph of rock benches. (Schematic from Reference 11, photograph of a mine in Tucson, Arizona, USA, by Steve Dutch, University of Wisconsin, USA.)

Scaling and Trimming

Loose, unstable, and (or) overhanging blocks of rock, which may pose a danger to passing traffic and (or) pedestrians, can be removed by scaling or trimming. Scaling is the removal of loose blocks by the use of hand-held pry bars and small explosive charges. Trimming involves some drilling and light blasting by explosives, followed by scaling, to remove larger areas of overhanging or potentially dangerous rock. The necessity of scaling and trimming can be reduced with the use of controlled blasting, but blasting is not always feasible. Overhanging rock is either removed or trimmed back to a stable part of the face. Scaling operations are usually carried out by workers suspended by ropes or other means, using pry bars, jacks, and explosives. These operations can be time-consuming and expensive (sometimes dangerous) and on active slopes may need to be repeated every few years, or as needed. Scaling is highly skilled work and can be dangerous; scaling crews should be trained and the work performed by professionals.

Photographs C29 and C30 show rock scaling and trimming operations.

Figure C29. Rocks dislodged by scaling and blasting. (Photograph by Washington Department of Transportation, USA.)

Figure C30. A hydraulic rock hammer in action, bringing down rock from the slope. This is an alternative to blasting rocks down. (Photograph by Washington Department of Transportation, USA.)

Reinforcing Potential Rockfall Areas

Shotcrete and Gunite

Shotcrete and gunite are types of concrete that are applied by air jet directly onto the surface of an unstable rock face. Shotcrete is an all-inclusive term to describe the spraying of concrete or mortar either by a dry- or a wet-mix process. Gunite refers only to the dry-mix process in which the dry cementitious mixture is blown through a hose to the nozzle, where the water is injected immediately before application. This is a rapid and relatively uncomplicated method commonly used to provide surface reinforcement between blocks of rock and also to reduce weathering and surface scaling. Shotcrete contains aggregate up to 2 cm in size and is more commonly used than gunite, which has smaller aggregate. Both materials can be applied rapidly by air jet so that large areas can be covered in a short time. Figure C31 shows a shotcrete operation on the side of a highway.

Figure C31. Shotcrete operation to stabilize rockfall area of Wolf Creek Pass in the Rocky Mountains of Colorado, USA. (Photograph by Colorado Department of Transportation.)

Anchors, Bolts, and Dowels

These are tools composed of steel rods or cables that reinforce and tie together a rock face to improve its stability. Anchors are post-tensioned members used to support large blocks of rock, whereas bolts are shorter and support surface rock. Dowels are similar to bolts but are not post-tensioned. Reinforcing a rock slope with steel requires a specialist's knowledge of rock stability analysis, of grouting techniques, and of testing procedures. The determination of the orientation of the potential failure surfaces is crucial to a successful anchor system and requires a considerable amount of engineering experience. Figures C32 and C33 show rock bolts and rock bolt installation along a highway.

Figure C32. Closeup photograph of a rock anchor on a rock face, with mesh over the surface for more protection. The anchor is set in the rock about 5 meters (15 feet) deep.

Figure C33. A rock bolting operation; notice broken-up (crumbling) nature of the rock. (Photograph by Washington Department of Transportation, USA.)

Part 3. Debris-Flow Mitigation

This section describes some simple mitigation methods for debris-flow hazards for homeowners, businesses, and others. A short section on erosion and fire control is included since erosion, fire, and subsequent debris flows and flooding are interrelated hazards.

Strengthening Slopes for Erosion/Debris Flows

Erosion may cause the steepening and lengthening of gullies and cause the loosening of soil, plant debris, rocks, and boulders, which can intensify the effects of debris flows. Keeping an area free of excess fuel for fires can also help in the mitigation of debris flows, as burned slopes become more vulnerable to the effects of debris-flow initiation and erosion (fig. C34). Loss of vegetation that holds soil in place and physical and chemical changes to the soil that result from intense heat and burning by fires make this soil more prone to debris flows.

Figure C34. Wildfire-burned slopes and debris flow that occurred shortly after the fire at Lytle Creek, California, USA. (Photograph by Sue Cannon, U.S. Geological Survey.)

erosion The processes where the materials of the Earth's crust are loosened, dissolved, or worn away and then are moved from one place to another. Process includes actions of wind, rain, freeze-thaw, weathering, and physical abrasion.

Strengthening the soil to resist erosion

Erosion is a process that must be taken into account when reinforcing an area, and some simple steps can be taken to lessen the effects of erosion. Erosion can sometimes lead to slope failures and drainage problems; trying to prevent it is something a homeowner can do, proactively, before bigger slope-failure problems are encountered. Straw or wood chips are effective in holding the soil in place. They have the further value of increasing the organic content of the soil. Place a covering of chips or straw about one-half centimeter (one-quarter inch) thick as slope and soil conditions indicate. Fertilizer may be added. Work the material into the top few centimeters (or inches) of the soil.

Woven burlap (a loosely woven, fibrous material of generally low cost) can be laid on the slope and tied down with stakes to prevent lifting by wind or water. Regular planting procedures can be followed before laying the burlap because the fabric will not interfere with establishing a growth on the slope. The burlap will decompose eventually but will remain long enough for vegetation to become well established.

Proper planting of vegetation on slopes can prevent erosion

Keep plants watered, but do not overwater. Replant barren areas or areas that have been burned. Make inspections during rains. Watch for gullying. Correct problems as soon as possible.

Keeping slopes free from fuel for wildfires

Burned slopes in debris-flow-prone areas can become hazardous as they increase the likelihood and intensity of debris flows when slopes become saturated by rainfall. Homeowners and businesses can act to keep properties free of excess fuel for wildfires, actions that may stop wildfires from spreading or burning large areas. Wildfires can denude slopes of vegetation and can change the soil chemistry, which may result in intensifying the hazard from debris flows. Piles of deadwood, dead vegetation, and other types of fuel that can accumulate on properties should be kept at a minimum to keep wildfires from starting or spreading. Many communities have local guidelines on controlling excess wildfire fuel and feature practical advice on the cleanup of property. Local municipalities can take community action to penalize unauthorized burning of trash, for example, through local ordinances. Lightning-caused wildfires are naturally occurring, but steps can be taken that preclude the spread of this type of wildfire through keeping available fuel at a minimum. For any necessary burning of farmland, for example, it is recommended that residents that live in areas of steep slopes be vigilant so a wildfire does not become uncontrolled and spread to other areas.

Note: It should be remembered that floods, earthflows, and debris flows (some of these known commonly as “mudslides”) have many of the same characteristics and generally can be dealt with in similar manners. Floods, “mudslides,” and debris flows sometimes accompany each other, but not always.

Structures for Mitigating Debris Flows

Debris-flow basins

These catchment basins are commonly built at the base of slopes where debris flows are frequent (fig. C35). They are used especially in areas where the debris must be contained so that soil and debris are stopped from flowing into sensitive ocean or river shorelines areas or where there are structures at the base of the slope that are vulnerable to debris-flow damage. These basins will eventually fill with the debris-flow deposits and must be emptied periodically or they will overflow. Commonly, large pieces of equipment such as dump trucks and power shovels are needed to empty the debris and carry it away. However, small basins can be emptied manually. They should be designed to be able to contain the maximum flow volumes of an area to prevent overtopping during a flow event.

Figure C35. Aerial photograph of a debris-flow basin, constructed at the bottom of a slope in San Bernardino, California, USA. (Photograph by Doug Morton, U.S. Geological Survey.)

Check dams

See Appendix C, "*Part 1*. Earth Soil Slope Stabilization/Mitigation," for an explanation of how check dams can also be used to reduce the hazards from debris flows.

Debris-flow retaining walls

These are structures that can be built of various kinds of materials. They are designed to stop the progress of the debris fall, either by blocking the flow or diverting it around a vulnerable area. These structures should be carefully designed as any deflection of material may be unintentionally redirected into additional vulnerable areas (figs. C36 and C37).

Figure C36. Caution is required in locating and constructing debris-flow retaining walls. This is a photograph of the partial failure of a retaining wall, caused by a landslide in Iztapalapa, a suburb of Mexico City, Mexico. The landslide slid onto a house at the toe of the slope, killing two people, and was triggered by heavy rains in the area. The house was below the 5-meter-high (15 yards) wall, but the wall could not withstand the mass of rocks and soil. (Photograph by Chinagate/Xinhua.)

Figure C37. A debris-flow retaining wall in Kamikochi Basin, Japan. (Photograph courtesy of Goncalo Vieira.)

Debris-Flow Mitigation for the Homeowner

This section provides some simple steps that a homeowner can take, or an emergency manager can recommend, to help individuals mitigate the effects of erosion, which in many cases may lead to debris flows and some landslides.

The following figures C38 through C52 show schematics of debris-flow mitigation techniques that may be helpful for protecting structures. The figures are modified from those found in Reference 20, a booklet published for Los Angeles, California, USA, homeowners by the Los Angeles County Department of Public Works, showing simple methodology for reducing hazards from floods, erosion, and debris flows.

Figure C38. Schematic of an ***unprotected home,*** in the path of a debris flow and (or) "mudslide." Suggested methods to reduce the hazards from debris flows are shown in figure C39.

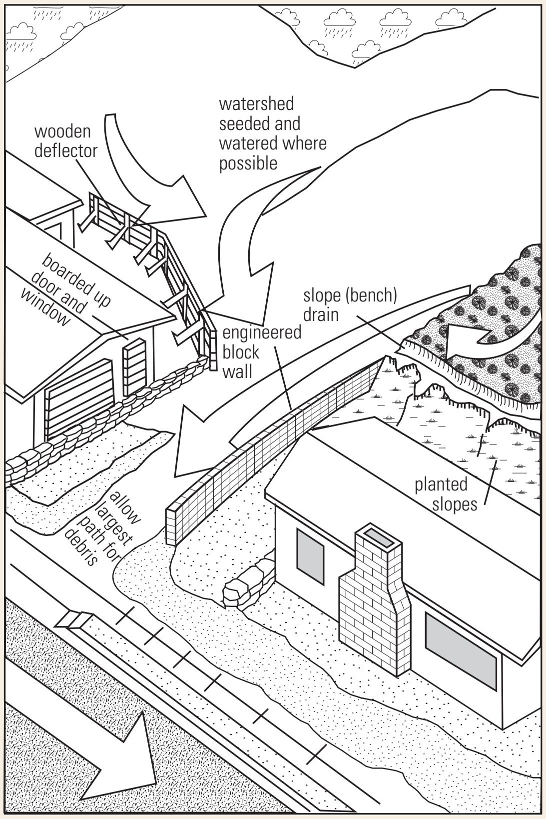


Figure C39. Schematic example of a house with protective structures in place. Shows construction of deflection walls and debris fences. Because of extreme force of impact associated with some debris flows, these and similar structures should be carefully engineered and constructed.

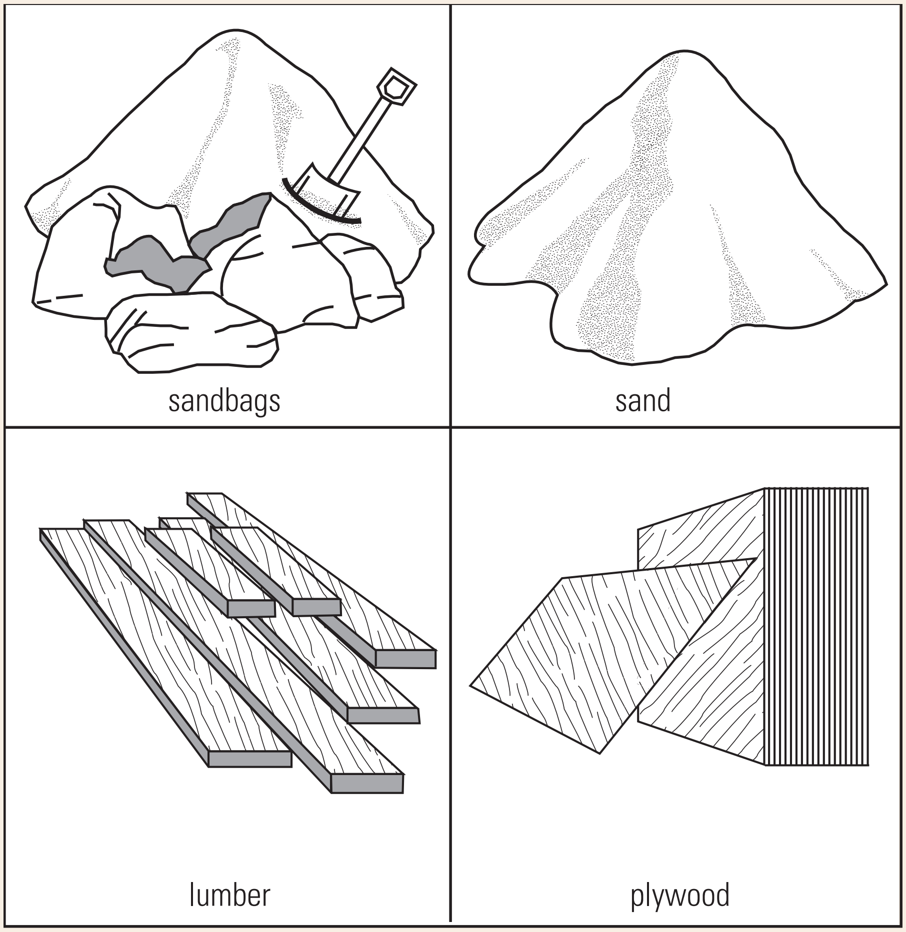


Figure C40. Schematic of typical materials, usually available in many regions of the world, for helping to reduce damage from flood/debris-flow events.

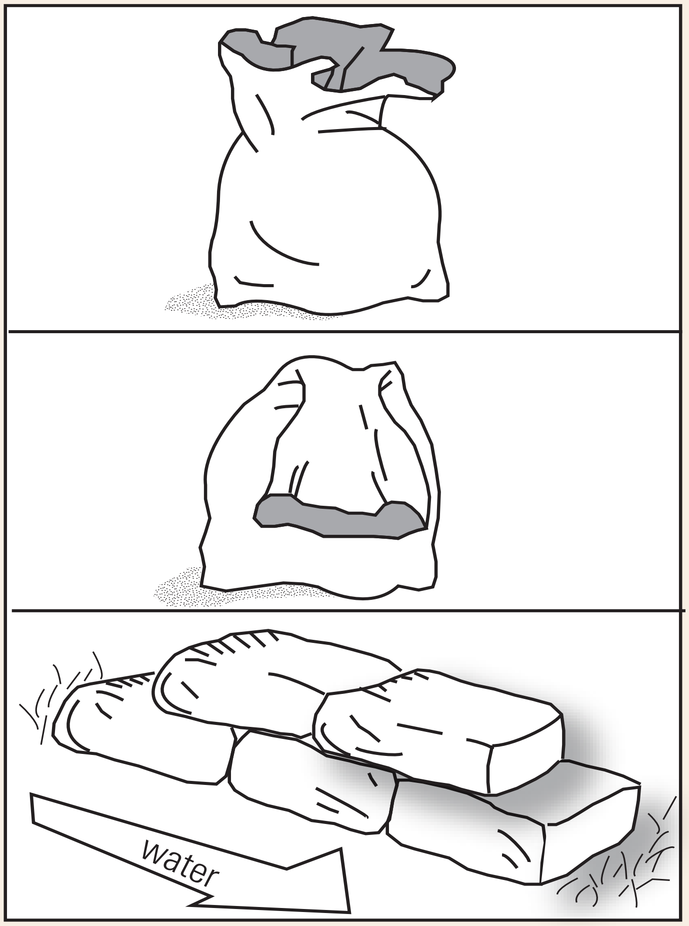


Figure C41. Sandbags are basically for low-flow protection of up to 0 .6 meter (2 feet). Protection from higher flows requires a more *permanent* type of structure. It should be noted that sandbags will not seal out water.

Note: The ideal material for sandbags is sand, and bags should not be filled with wood chips, paper, trash, or other materials. Sand- and soil-filled burlap sandbags deteriorate when exposed for several months to continued wetting and drying. If bags are placed too early, they may not be effective when needed.

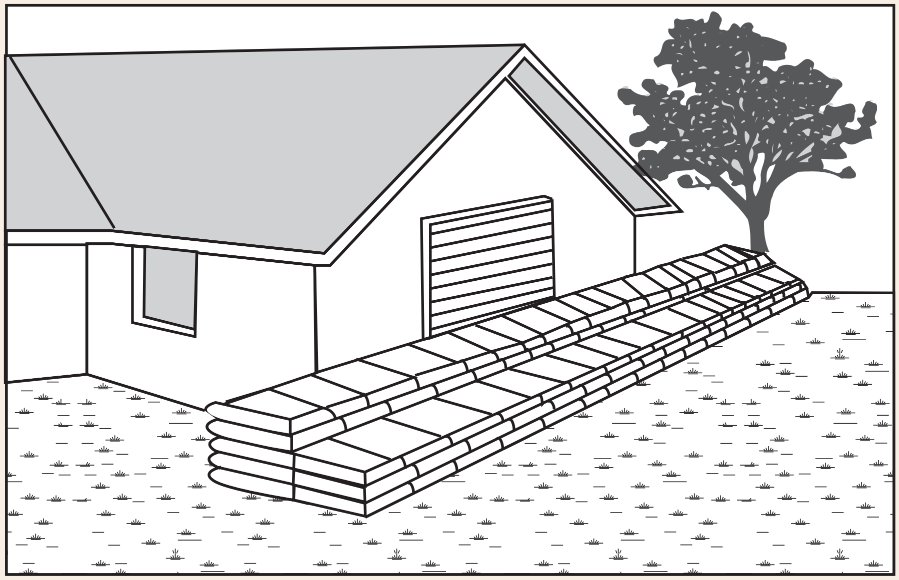


Figure C42. Schematic of a typical placement of sandbags for home protection (individual situations may vary in layout and orientation).

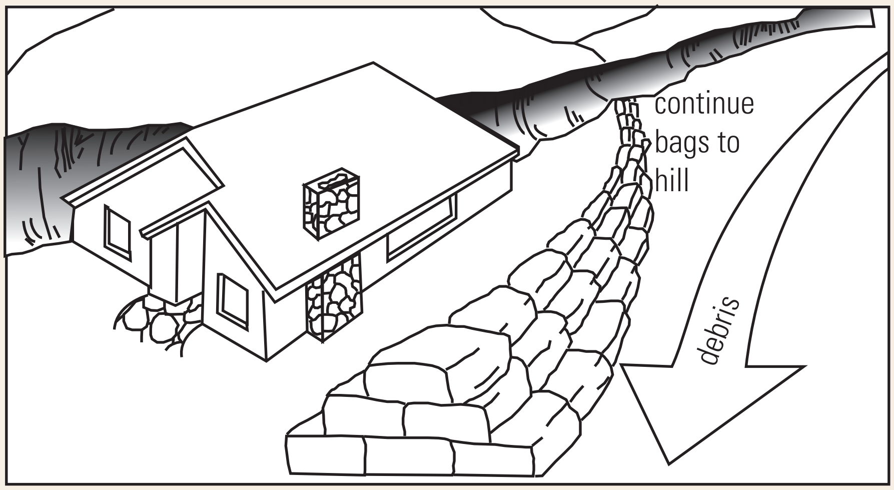


Figure C43. Sandbags help in directing debris away from buildings.

Caution: It is not advisable to use straw or bales of hay instead of sandbags. They do not perform as well as sandbags and may be washed away.

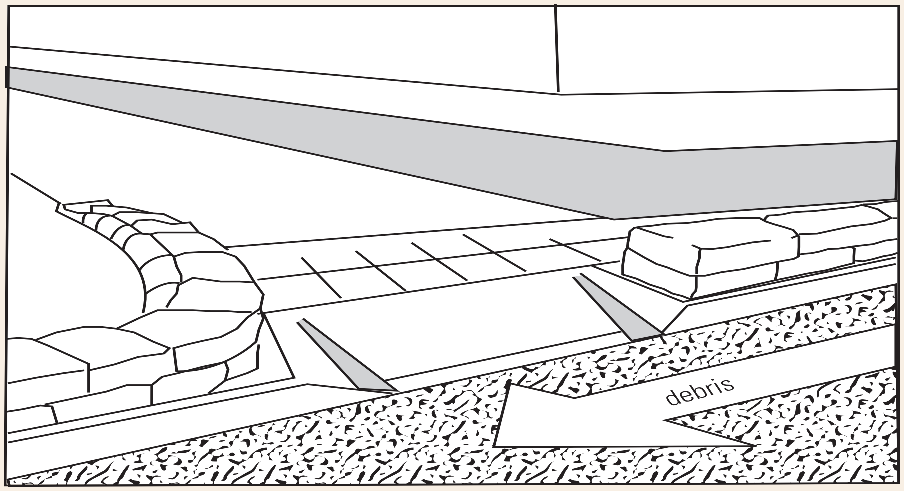


Figure C44. Controlling debris or stormflows in streets with sandbags.

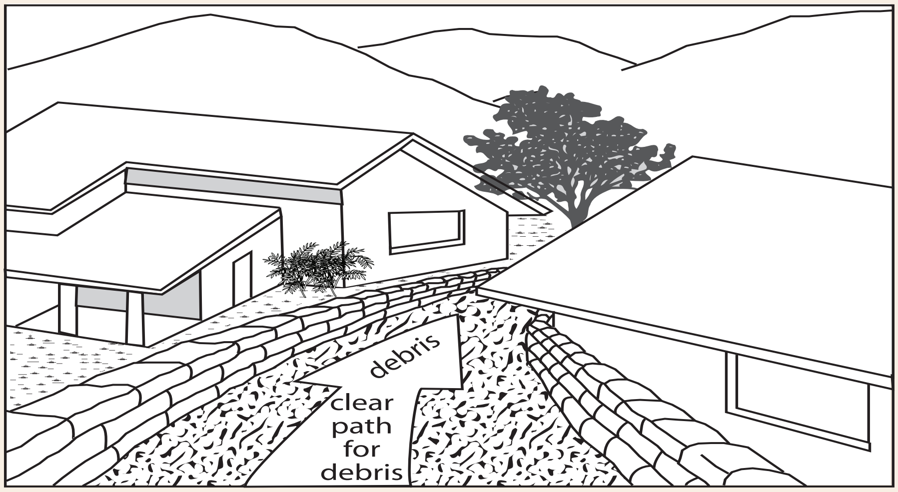


Figure C45. Directing flows between buildings by using sandbags.

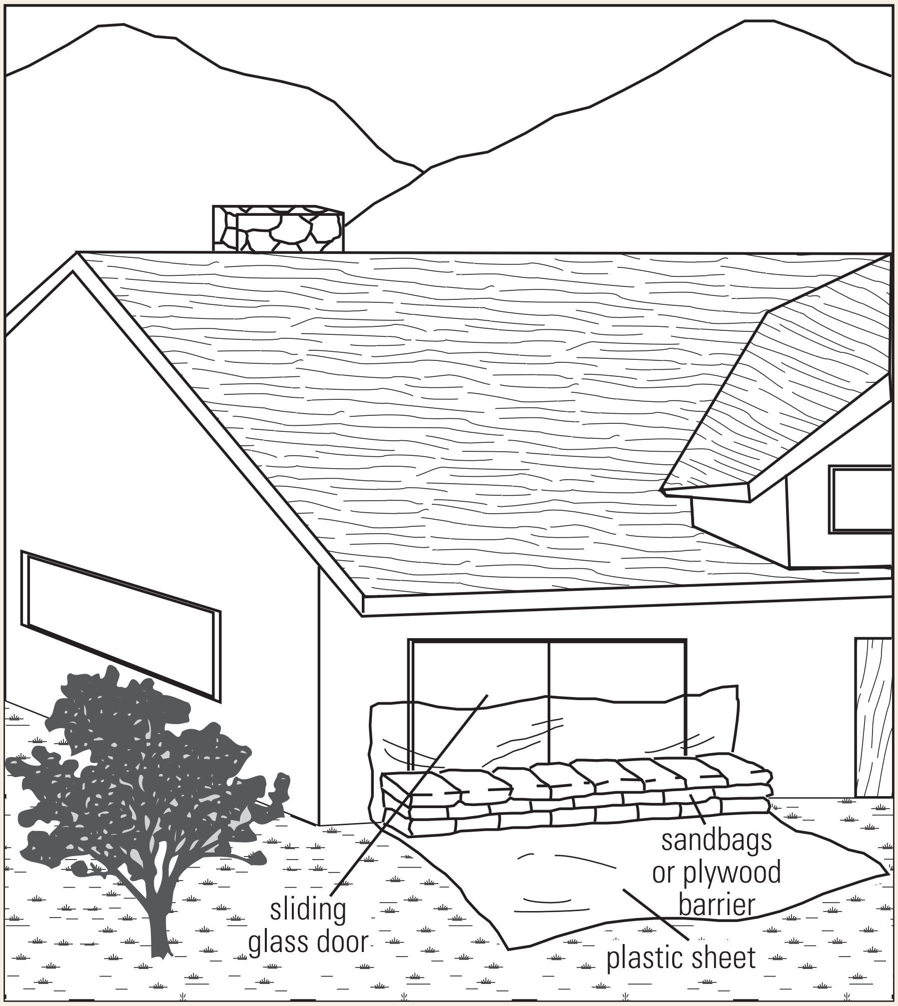


Figure C46. Sliding glass door sealing—Control of flows to prevent seeping into sliding glass door by using sandbags and plastic sheeting.

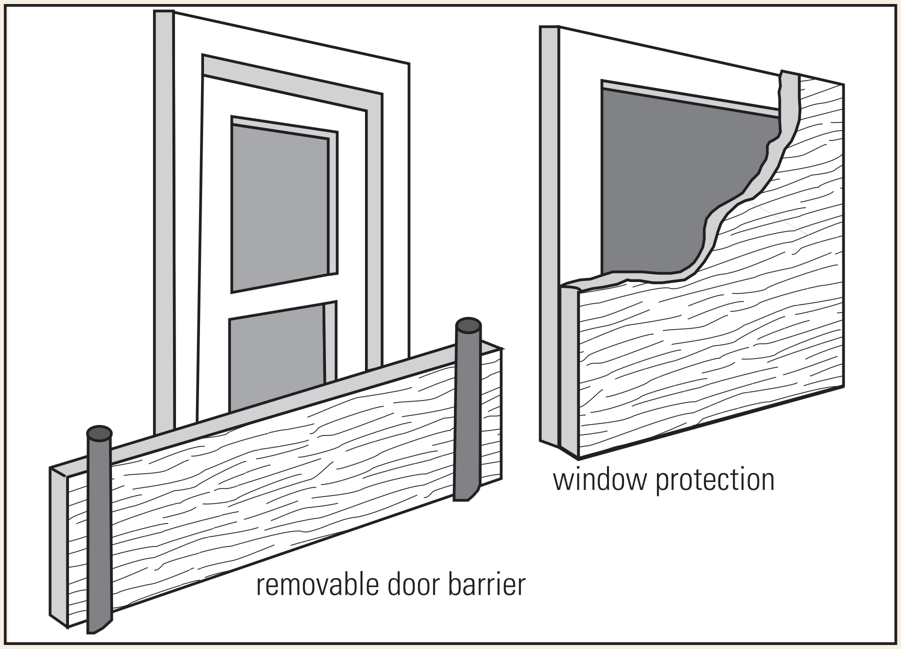


Figure C47. Typical window and door protection, using removable plywood.

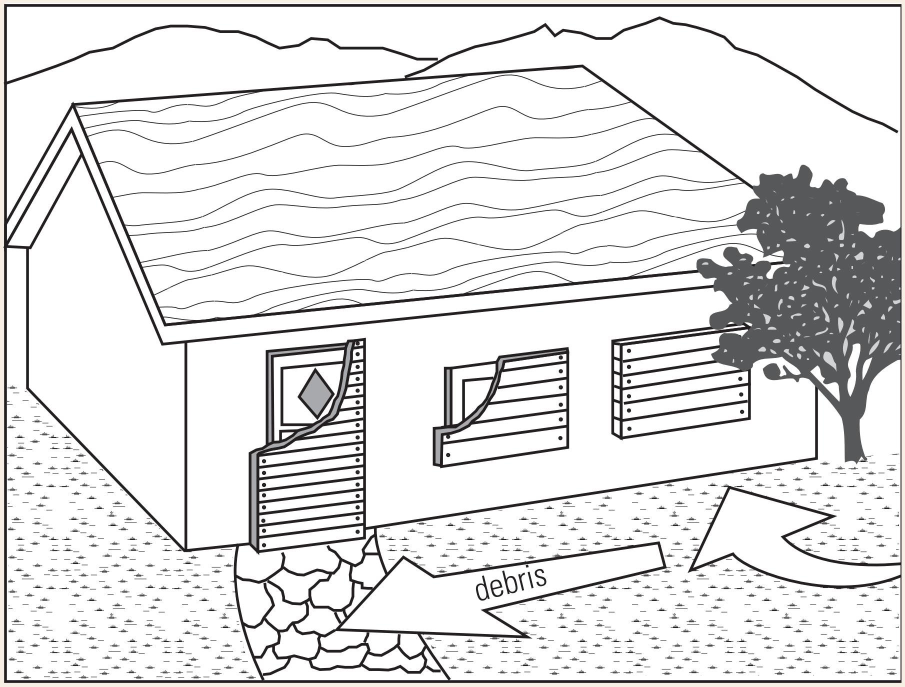


Figure C48. Nailing up plywood or lumber for window and door protection.

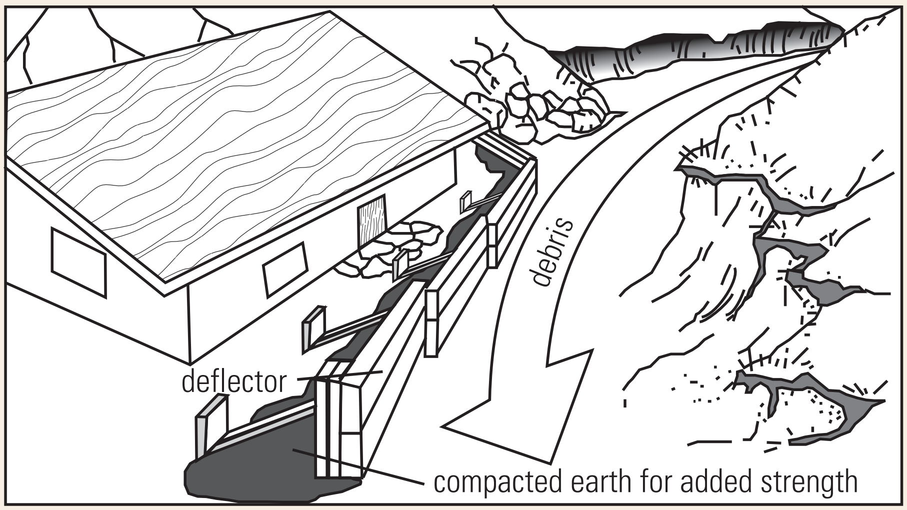


Figure C49. This is a timber deflector, which is more permanent than sandbags.

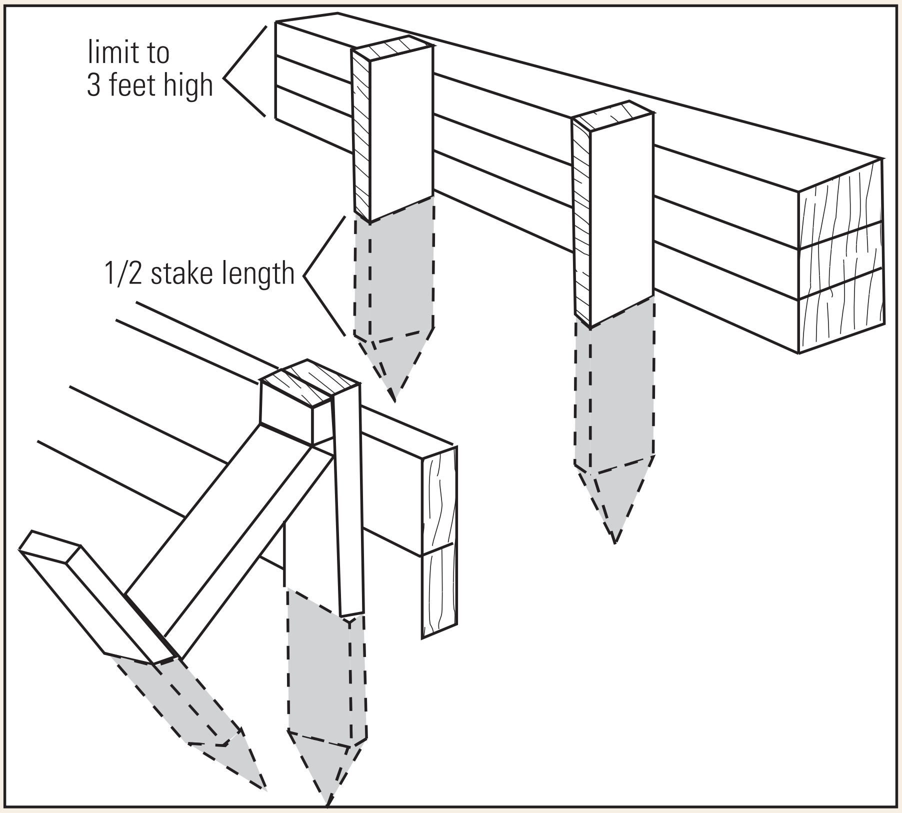


Figure C50. Closeup schematic of a timber deflector installation technique.

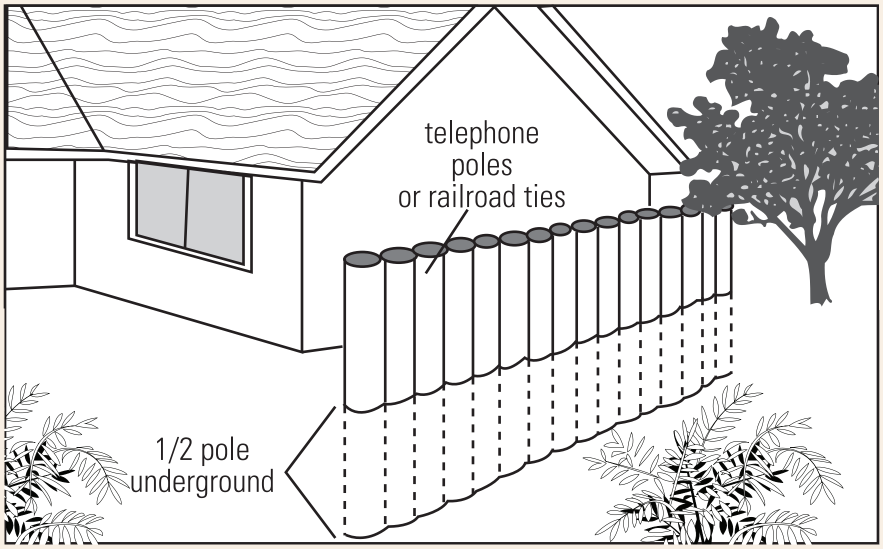


Figure C51. An alternative to timber deflectors—telephone pole sections or railroad tie barrier.

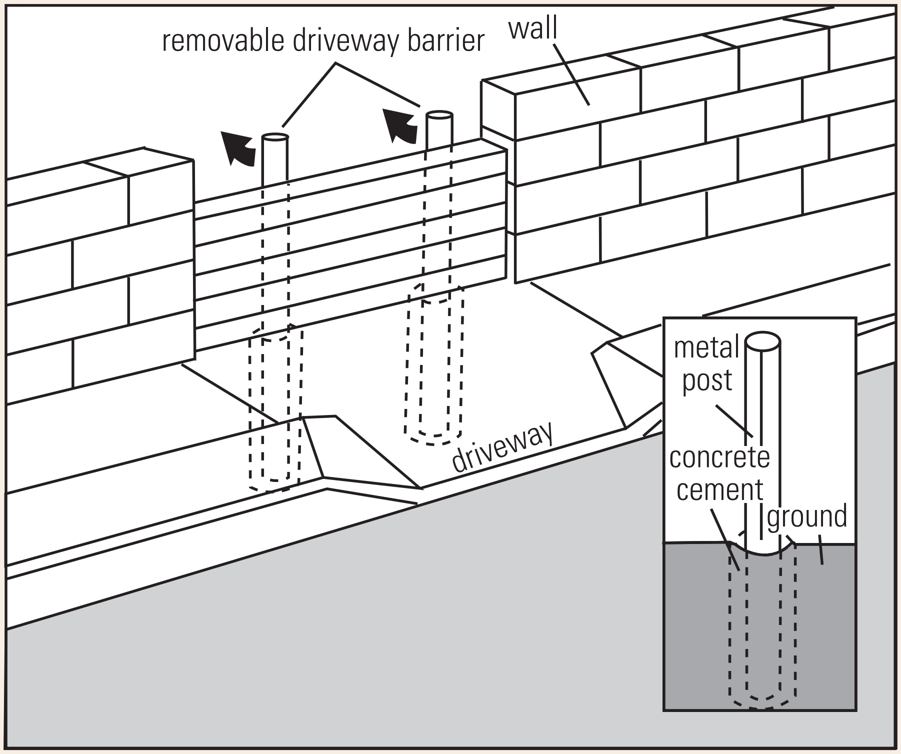


Figure C52. Removable driveway barrier. The metal posts can be removed and restored as needed, as they loosely fit into concrete casings in the ground

Basic Things to Remember Concerning Mitigation and Response to Debris-Flow and Other Landslide Hazards/Emergency Response

Sandbags, tools, and sheets of plastic may be useful during heavy rains (the plastic can be used to protect and waterproof some items). Keep them available, where possible. Help others in the community that may not be able to reinforce their dwellings, such as the disabled or elderly. Educate children in mitigation techniques. Mitigation techniques are the most effective when used by as many members of a community as possible.

- If unusual cracks, settling, or earth slippage starts, it is recommended that people consult a municipal agent (such as an emergency manager) and (or) a qualified civil engineer or geologist as soon as possible.
- It is suggested that slopes or drainage areas not be altered without expert advice. It is always best to consult a professional or someone with experience in this type of work.
- Normal property drainage usually flows to the street or an approved drainage device. When landscaping, homeowners or others should avoid disrupting flow patterns created when the property was originally graded. Obstructions such as patios, sidewalks, and decks should not be placed in side swales unless an alternate method of drainage is provided.
- Post illustrations in the form of simple schematics in public places, to help people implement mitigation techniques.
- It is advisable to have an emergency response plan for evacuation and relocation of populations that are threatened by landslide hazards. It is generally best to make sure everyone is aware of these procedures.

Landslide Dam Mitigation

As previously mentioned, the primary hazard from landslide dams is flooding that can occur when a landslide dam fails, or flooding that occurs when the dam is overtopped by the ongoing flow of water backing up behind the dam. The following measures can be implemented when communities are faced with potential hazards from landslide dams:

Diversion of inflow water before it reaches the lake formed by the landslide dam

This can be done by diverting water from the stream into upstream reservoirs or irrigation systems. Although usually only a temporary measure, diversion may slow the filling of the lake enough to allow the application of a more long-term solution.

Temporary drainage from the impoundment by pumps or siphons

The rising water level can be controlled temporarily by means of pumps or siphons, causing the water to flow over the low point of the dam. This is usually a short-term (less than 1 to 2 years) measure that provides time for more extensive, long-term solutions.

For more information and further reading:
References 11, 12, 13, 20, 25, 26, 39, 42, and 46

Construction of an erosion-resistant spillway

The most common method of stabilizing a landslide dam is to construct an erosion-resistant open-channel spillway either across the dam or across an adjacent abutment. When the overtopping by water occurs, flow is controlled by the spillway in much the same way that emergency spillways are constructed on engineered dams to control water level. An additional advantage of this type of spillway is that it allows for the lowering of the water level behind the dam, which helps lessen the upstream flooding that landslide dams may cause.

Spillways are not always successful in preventing dam breaching and downstream flooding; they sometimes fail due to retrogressive erosion (erosion from the spillway outlet to its intake) caused by high-velocity outlet flow. To prevent erosion by minimizing flow velocity, the spillway should be wide and shallow. If possible, it should be lined with erosion-resistant materials (commonly riprap), especially at the outlet. Often, check dams are installed along steeper grades of the spillway to prevent erosion. Spillways that fail due to erosion may have been partially successful because they limit the total volume of the water behind the dam, thus reducing total discharge even if the dam breaches entirely.

Open-channel spillways across the landslide dam commonly are excavated by bulldozers; however, draglines, backhoes, explosives, and hand labor all have been used. Excavation can be dangerous in rough terrain, so an access road has to be constructed.

Drainage tunnel through an abutment

A long-term method of preventing overtopping and breaching of a landslide dam is construction of a diversion tunnel through an adjacent dam abutment. Because large landslide dams commonly occur in mountain canyons, they usually have bedrock abutments; thus rock-tunneling methods commonly are used. Figure C53 shows the Thistle, Utah, landslide in the United States, triggered by the El Niño conditions of 1983. Heavy rains the previous autumn and rapid snowmelt caused the massive failure. For further reading please see Reference 31.

The Thistle landslide also destroyed sections of both a major highway and a main line of a railroad track. After a tunnel was excavated through the mountain trains could continue to travel the route. The motorway (highway) was rerouted over a saddle, away from the landslide deposit (fig. 54).

The landslide will be left as it is, as it is too massive to remove. The landslide is still being monitored with instrumentatino by the State of Utah, and it has recently reactivated. Reactivation is another peril from landslide dams such as Thistle (fig. C55).

Figure C53. The Thistle landslide in Utah, USA, 1983. This landslide dammed a river, which formed a lake (called "Thistle Lake") behind the dam, flooding the town of Thistle. (Photograph by Robert L. Schuster, U.S. Geological Survey.)

Figure C54. Closeup view of mitigation measures taken to reduce the impact of the Thistle landslide dam, showing the tunnel for the river, and the diversion overflow tunnel. (Photograph courtesy of the Utah Geological Survey).

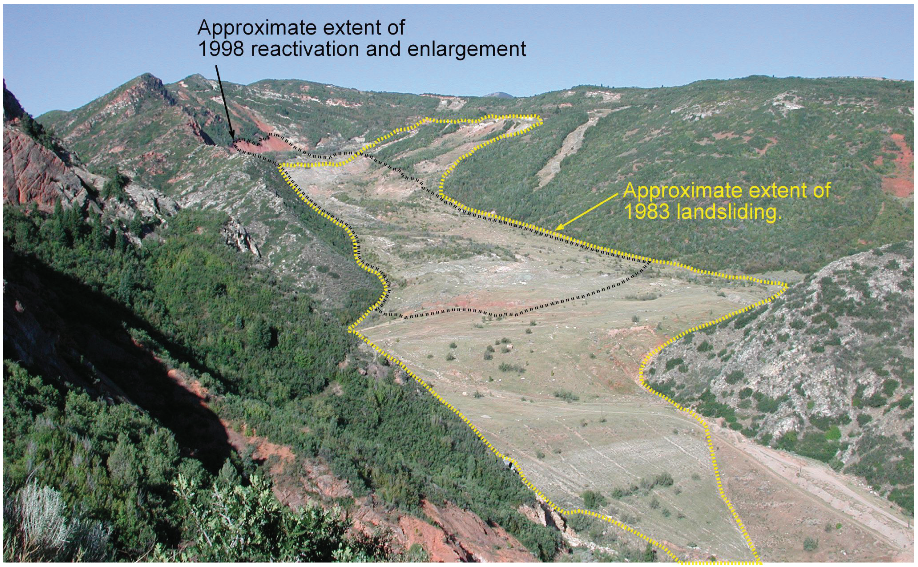


Figure C55. Photograph with annotations showing the reactivation and enlargement of the Thistle landslide dam. (Photograph courtesy of the Utah Geological Survey.)