Chapter 8

Design and Construction of Soil Slopes

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The design of stable slopes in soil has been extensively studied by engineers and geologists. In recent years, substantial advancements have been made in understanding the engineering characteristics of soils as they relate to stability. Chapters 6 and 7 describe the state of the art regarding the determination of pertinent soil parameters and the recommended approaches to engineering analysis. These techniques allow the design and construction of safe and economic slopes under varying conditions. This chapter applies the basic principles established in Chapters 6 and 7 to procedures for the design of stable slopes. The procedures can also be applied to preconstructed slopes and to correction of existing landslides.

PHILOSOPHY OF DESIGN

There are several basic considerations in the design of stable slopes. First, because of the nature of soils and the geologic environment in which they are found, each slope design is different. Second, the basic mechanics applied to estimate the stability of a cut slope in soil are the same as those used to estimate the stability of a fill slope. Third, finding the correct method of stability analysis solves only part of the design problem. Designing a stable slope includes field investigation, laboratory investigation, and construction control. The details involved in this work cannot be standardized because maximum flexibility is needed as each problem is assessed. Judgment, experience, and intuition, coupled with the best data-gathering and analytical techniques, all contribute to the solution.

SAFETY FACTOR

The specific analytical techniques used to predict the stability of slopes are explained in Chapter 7. In all cases, the geotechnical engineer determines the safety factor, which is defined several ways but most commonly as

1. The ratio of resisting forces to driving forces along a potential failure surface;
2. The ratio of resisting moments to driving moments about a point;
3. The ratio of available shear strength to the average shear stress in the soil along a potential failure surface; and
4. The factor by which the shear strength parameters may be reduced in order to bring the slope into a state of limiting equilibrium along a given slip surface.

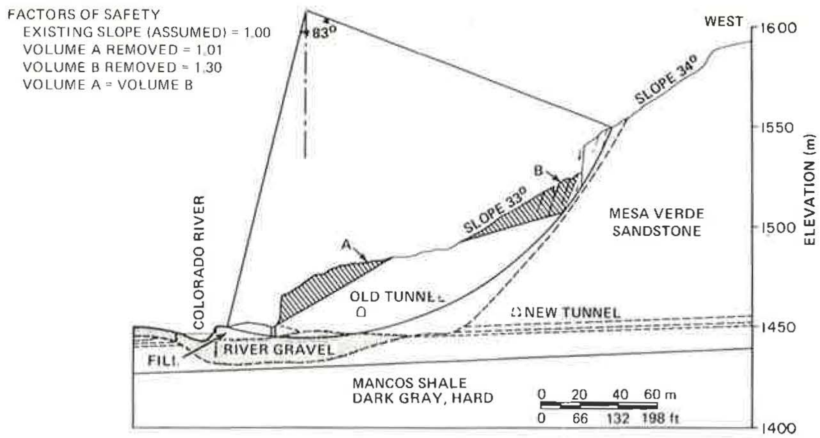
The last definition is used in Chapter 7, and, unless otherwise noted, effective stress parameters are implicit.

Ideally, failure is represented by factor of safety values less than one, and stability is represented by values greater than one. The geotechnical engineer must be aware that the safety factor for a given slope depends heavily on the quality of the data used in the analysis. In addition, the various methods used to compute safety factors give wide ranges of values, except when the ratio equals unity.

The problem of determining a meaningful safety factor is complicated by factors such as interpretation of field and laboratory data, uncertainty of construction control, and the designer's incomplete information about the design problem. In any case, using the best information attainable and the procedures outlined in Chapters 6 and 7 allows the engineer to compute a minimum factor of safety against failure as a basis for comparing design alternatives.

After consideration of the factors that influence design and the consequences of failure, the reasonableness of reducing the safety factor can be established. In highway engineering, slope designs generally require safety factors in the range of 1.25 to 1.50. Higher factors are required if there is a high risk for loss of human life or uncertainty regarding the pertinent design parameters. Likewise, lower safety factors can be used if the engineer is fairly confident of the accuracy of input data and if good construction control can be executed.

Figure 8.1. Stabilization of the Cameo slide above a railroad in the Colorado River Valley by partial removal of the head (*8.1, 8.22*). Stability analysis determined that removal of volume B was more effective than removal of volume A.



DESIGN PROCEDURES

The slope-stability design procedures outlined in Chapter 7 clearly involve a relation between available shear strength and applied shear stress within a soil mass. The analytical techniques allow comparison of various design alternatives, including effects of those alternatives on the stability of the slope and the economy of the solutions. In addition, Chapter 7 discusses the various shapes of potential failure surfaces, including a circular arc, a planar surface, and the Morgenstern-Price variations (*8.18*).

The preliminary design process may begin by considering various published stability charts based on simplified assumptions. Such a study may be adequate in some cases to decide whether a standard slope angle can be used. In all cases, the design process must include consideration of the full life span of the slope being studied, because soil strength and groundwater conditions usually change with time. At the minimum, the analysis should study conditions expected immediately after construction (end-of-construction case) and at some longer time after construction.

As indicated in Chapter 7, there is little difference among the results obtained from various methods of stability analysis performed immediately after construction. Since design problems in cohesionless soils are relatively minor, except for instances of dynamic loading, reasonable assumptions regarding shear strength may be used with appropriate safety factors. In cohesive soils, the total stress analysis with appropriate laboratory-determined strengths can be used for simplicity.

One should thoroughly study the background presented in Chapters 6 and 7 before proceeding with any of the design procedures outlined in this chapter. These procedures for stable slope design are separated into three broad categories:

1. Avoid or eliminate the problem;
2. Reduce the forces tending to cause movement; and
3. Increase the forces resisting the movement.

A summary of these procedures is given in Table 8.1.

Avoid Problem

For most highway design studies, a geological reconnaissance is an important preliminary part of the project development. During reconnaissance, potential stability problems, such as poor surface drainage, seepage zones on existing natural slopes, hillside creep, and ancient landslides, should be carefully noted. Early recognition of known troublesome areas encourages alternative studies for future highway location. If relocation is not possible, adjustments to the line and grade of the highway should be considered.

The most difficult landforms to detect, and the most costly to deal with in construction, are the geologically ancient landslides. Quite often, natural weathering processes or human changes to the environment all but obscure these landforms; however, a field examination by a trained geologist or geotechnical engineer and aerial photographs (Chapter 3) will reveal certain physical incongruities, such as hummocky terrain, blocked regional or local drainage patterns, ancient slide scarps, and vegetation differences.

Since old landslides and talus slopes continue to move downslope until driving and resisting forces are balanced, these slopes may have widely varying abilities to resist new loadings, either internal or external. For instance, such slopes may have perceptible movements during periods of heavy rainfall (high seepage force or increased elevation of groundwater or both). In any stability analysis in which the factor of safety against movement is at or near unity, the influence of even a slight increase in the seepage force or a slight reduction in the resisting forces due to raised groundwater levels is significant. Thus, the decision to construct transportation facilities through or over ancient landslides must be carefully studied and appropriate consideration given to remedial treatment and long-term stability.

Removal of Materials

If relocation or realignment of a proposed roadway is not practical, either complete or partial removal of the unstable materials should be among the alternative design considerations. Figure 8.1 shows an example of one such study. Economics, as well as the relative risk to slope stability, will quite naturally play an important role in the final course of action selected.

The removal of potentially unstable materials can vary from simple stripping of a near-surface layer a few meters thick before embankment construction to a more complicated and costly operation such as that encountered in a sidehill cut along the Willamette River in West Linn, Oregon,

Table 8.1. Summary of slope design procedures.

Category	Procedure	Best Application	Limitation	Remarks
Avoid problem	Relocate highway	As an alternative anywhere	Has none if studied during planning phase; has large cost if location is selected and design is complete; also has large cost if reconstruction is required	Detailed studies of proposed relocation should ensure improved conditions
	Completely or partially remove unstable materials	Where small volumes of excavation are involved and where poor soils are encountered at shallow depths	May be costly to control excavation; may not be best alternative for large slides; may not be feasible because of right-of-way requirements	Analytical studies must be performed; depth of excavation must be sufficient to ensure firm support
	Bridge	At sidehill locations with shallow-depth soil movements	May be costly and not provide adequate support capacity for lateral thrust	Analysis must be performed for anticipated loadings as well as structural capability to restrain landslide mass
Reduce driving forces	Change line or grade	During preliminary design phase of project	Will affect sections of roadway adjacent to slide area	
	Drain surface	In any design scheme; must also be part of any remedial design	Will only correct surface infiltration or seepage due to surface infiltration	Slope vegetation should be considered in all cases
	Drain subsurface	On any slope where lowering of groundwater table will effect or aid slope stability	Cannot be used effectively when sliding mass is impervious	Stability analysis should include consideration of seepage forces
	Reduce weight	At any existing or potential slide	Requires lightweight materials that are costly and may be unavailable; may have excavation waste that creates problems; requires consideration of availability of right-of-way	Stability analysis must be performed to ensure proper use and placement area of lightweight materials
Increase resisting forces	Drain subsurface	At any slide where water table is above shear plane	Requires experienced personnel to install and ensure effective operation	
	Use buttress and counterweight fills	At an existing slide, in combination with other methods	May not be effective on deep-seated slides; must be founded on a firm base	
	Install piles	To prevent movement or strain before excavation	Will not stand large strains; must penetrate well below sliding surface	Stability analysis is required to determine soil-pile force system for safe design
	Install anchors	Where rights-of-way adjacent to highway are limited	Involves depth control based on ability of foundation soils to resist shear forces from anchor tension	Study must be made of in situ soil shear strength; economics of method is function of anchor depth and frequency
	Treat chemically	Where sliding surface is well defined and soil reacts positively to treatment	May be reversible action; has not had long-term effectiveness evaluated	Laboratory study of soil-chemical treatment must precede field installation
	Use electroosmosis	To relieve excess pore pressures at desirable construction rate	Requires constant direct current power supply and maintenance	
	Treat thermally	To reduce sensitivity of clay soils to action of water	Requires expensive and carefully designed system to artificially dry out subsoils	Methods are experimental and costly

where a section of I-205 required extensive excavation to depths as great as 70 m (230 ft).

In the latter case, analytical studies predicted the need for flatter than the normal 2:1 slope because of weakened flat-lying deposits of clay shales just above the base of the proposed roadway ditch line. Right-of-way considerations for flatter slopes included an emergency water supply reservoir for the city of West Linn immediately adjacent to the present highway property lines. Various alternative design schemes for stability were studied, including grade and alignment changes, structural support walls, and complete relocation; all of these alternatives proved to be much more costly than purchasing additional highway right-of-way and replacing the municipal water supply system. In addition, adjacent projects were known to be deficient in borrow material for required embankment construction.

The final design used to complete the project included the excavation of a wide bench zone at or near the roadway level and the use of flat slope ratios to ensure a greater than required safety factor against potential failure. This example serves to underscore the need for accurate stability studies, not only to compare various design alternatives but to allow the design engineer to properly select the critical locations within a slope in need of treatment. Lack of such analysis could have substantially increased construction costs on the West Linn project.

Bridging

In some instances, removal of especially steep and long narrow unstable slopes is too costly. One alternative design is to span the unstable area with a land bridge or a structure whose support is founded on piles placed well below the unstable foundation materials (*8.1*). Stability studies must ascertain that the bridge is indeed founded at sufficient depth below the unstable materials and not just penetrating into a more stable stratum. If supports must penetrate through the moving soil, as shown in Figure 8.2, the foundation piling must be designed to withstand the predicted lateral forces. Bridging may also include limited excavation and the use of surface and subsurface drainage.

Reduce Driving Forces

Since the stability of soil slopes is a limiting equilibrium problem in which the external forces acting on a soil mass are at least balanced, the design of stable slopes must address ways to ensure proper safety from the forces tending to cause movements. Since the driving forces are essentially gravitational because of the weight of the soil and water, the simplest approach to reducing such forces is to reduce the mass that is involved. Flattened slopes, benched slopes, reduced cut depths, internal soil drainage, and lightweight fill all represent feasible treatments. The reduction of driving forces can be divided into three main categories:

1. Change of line or grade or both,
2. Drainage, and
3. Reduction of weight.

The stability of embankment slopes and natural slopes cannot necessarily be approached in the same way. Except in certain unique instances, the stability of embankment slopes increases with time because of consolidation and strength increases in the slope-forming materials. One noticeable exception could be embankments composed of degradable compacted shale, which will deteriorate with time and result in subsequent settlement and distortion or failure of the fills. In cut slopes, the long-term stability may be far less than that available at the time of construction. The ability of a cut slope to withstand the effects of time and stress change is discussed in Chapter 6.

Talus slopes often have marginal stability and deserve particular attention. Talus can be defined as rock fragments that have any size or shape and have been heterogeneously deposited by nature at the base of steep slopes. Runoff from normal rainfall may cause a sufficient increase in seepage forces to initiate movement within talus slopes. Recognition of talus slope forms is important in the predesign process; such slopes should be avoided during construction unless other alternatives are not available. If talus slopes must be disturbed by construction activity, careful analysis should consider the benefits of internal drainage to control potential slope movements that may be triggered by the buildup of large internal water pressures.

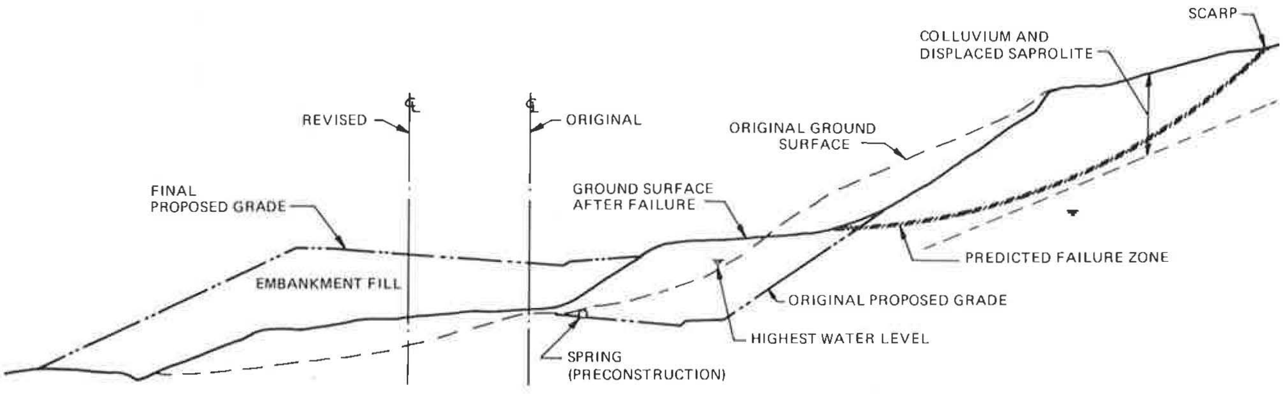
Figure 8.2. Landslide avoidance by bridging near Santa Cruz, California (*8.24*).

Change of Line or Grade

Early in the design stage, cut and fill slopes should be evaluated for potential stability. If conditions warrant, adjustments to the line and grade can be effected to minimize or completely eliminate the stability problem. This approach can also be applied to landslides during and after construction. The economics of various alternative solutions should ensure the feasibility of this approach. An example of a grade revision to prevent a cut slope movement is shown in Figure 8.3.

Line or grade changes are usually associated with a reduction of driving forces. Movement of the roadway alignment

Figure 8.3. Grade change effected during construction to preclude failure at cut slope.



away from the toe of a potential or existing slide area will prevent having to remove the toe support. When it is necessary to move the alignment away from an existing slide as a corrective measure, a buttress fill is usually placed to support the sliding mass. If a shift in alignment is not possible, the grade may have to be raised over the buttress fill. In this case, additional costs will accrue, since a transition zone on each side of the grade change will be required.

Changes to effect reduction in the driving forces during construction operations are not only difficult but expensive. To flatten construction slopes often requires additional right-of-way and could involve alignment shifts that affect the design on either side of the troubled area. The cost-effectiveness of geotechnical studies is greatest during the preliminary design stages of any project.

Surface Drainage

Of all possible design schemes considered for the correction of existing or potential landslides, proper drainage of water is probably the most important. Drainage will both reduce the weight of the mass tending to slide and increase the strength of the slope-forming material.

Adequate surface drainage is necessary in new cuts, as well as in completed slopes where movement has occurred. The design of cut slopes must always take into consideration the natural drainage patterns of the area and the effect that the constructed slope will have on these drainage patterns. Two items that should be evaluated are (a) surface water that will flow across the face of the cut slope and (b) surface water that will seep into the soil at the head of the cut. These conditions produce erosion and increase the tendency for potential surface slumps and localized failures on the slope face. As shown in Figure 8.4, diversion ditches and interceptor drains are widely used as erosion control measures in situations in which large volumes of runoff are anticipated. When trenches with a definite grade are constructed, the surface runoff and seepage are intercepted.

Good surface drainage is strongly recommended as part of the treatment for any slide or potential slide (*8.8*). Every effort should be made to ensure that surface waters are carried away from a slope. Such considerations become important when a failure has already occurred. Unless sealed, cracks behind the scarp face of a slide can carry large volumes of surface waters into the failure zone and result in serious consequences. Even the obvious activity of reshaping the surface of a landslide mass can be extremely beneficial, in that unnoticed cracks are sealed and water-collecting surface depressions are eliminated.

Figure 8.4. Surface drainage of slope by diversion ditch and interceptor drain.

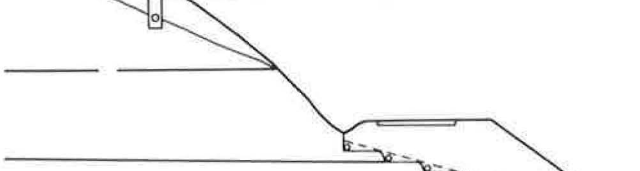
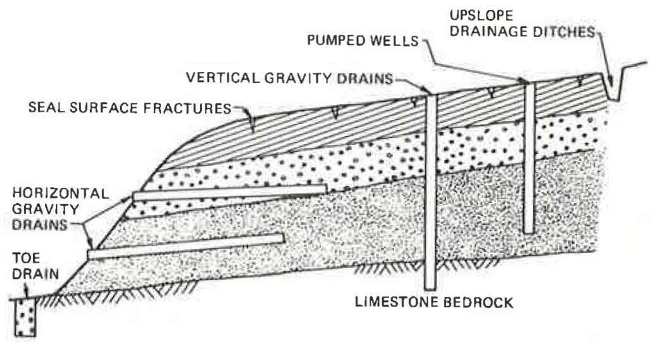


Figure 8.5. Slope protected by pneumatically applied mortar.

Figure 8.6. Horizontal and vertical drains to lower groundwater in natural slopes.



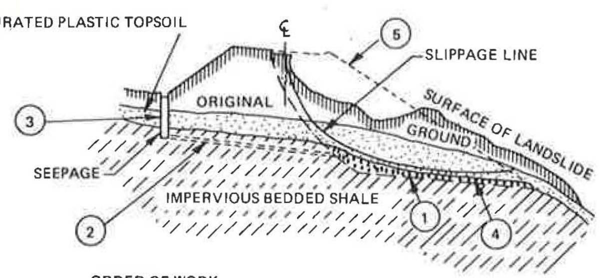
Slope treatment per se may involve a number of alternatives, all designed to promote rapid runoff and improve slope stability. Some of these measures are (a) seeding or sodding and (b) using gunite, riprap, thin masonry or concrete slope paving, and rock fills. Gunite and thin masonry or concrete slope paving have been used successfully to protect weak shales or claystones from rapid weathering (Figure 8.5). The use of asphalt paving to prevent infiltration of surface water is also common in some areas. These methods of controlling surface runoff are effective when used in conjunction with various subsurface drainage techniques. Surface drainage measures require minimal design and offer positive protection to slopes along transportation facilities.

Subsurface Drainage

The removal of water within a slope by subsurface drainage is usually costly and difficult. Methods frequently used to accomplish subsurface drainage are the installation of horizontal drains (Figure 8.6), vertical drainage wells (Figures 8.6 and 8.7), and drainage tunnels. The drainage-related

Figure 8.7. Vertical wells to lower groundwater in roadway slope.

Figure 8.8. Corrective measures for Castaic-Alamos Creek slides, California (*8.10*).



ORDER OF WORK

(1) Strip slide material.
(2) Place perforated pipe in horizontal boring.
(3) Construct intercepting trench.
(4) Construct gravel subdrain.
(5) Rebuild fill.

expense is generally less when these measures are incorporated into the preliminary design process than when they are included as remedial measures during or following construction. Occasionally, attempts are made to intercept subsurface flows above the sliding mass; however, the expense usually precludes treatment by this procedure for all but special cases. Since seepage forces act to increase the driving force on a landslide, the control of subsurface water is of major importance to the geotechnical engineer. If the preliminary investigation reveals the presence of groundwater, if design studies predict slide movement, and if positive subsurface drainage can preclude failure, a suitable design should be prepared for cost comparison with other alternatives.

Subsurface drainage is equally important in cut areas and under proposed embankments. The effectiveness and frequency of use of the various types of drainage treatment vary according to the geology and the climatic conditions. It is generally agreed, however, that groundwater constitutes the most important single contributory cause for the majority of landslides; thus, in many areas of the country the most generally used successful methods for both prevention and correction of landslides consist entirely or partially of groundwater control (*8.8, 8.29*). Figure 8.8 shows the use of both surface and subsurface drainage to satisfy stability requirements for finished slopes on a highway project. Although most types of subsurface-drainage treatment are applicable to the prevention and correction of landslides in both embankment and excavation areas, the differences in methods are considered of sufficient importance to justify separate discussion of the subsurface-drainage treatments applied to these two general types of landslides.

Embankment Areas

Landslides may occur when the imposed embankment load results in shear stresses that exceed the shear strength of the foundation soil or when the construction of the embankment interferes with the natural movement of groundwater. Therefore, two factors must be considered in the investigation of possible landslides: (a) weak zones in the foundation soil that may be overstressed by the proposed embankment load and (b) subsurface water that may result in the development of hydrostatic pressures so as to induce slide movement by a significant reduction in the shear strength of the soil. Because there often is no apparent surface indication of unstable slope conditions, a careful exploration must be made if these conditions are to be predicted before construction. Some of the methods of preventing landslides related to drainage are discussed below (*8.4*).

If a surface layer of weak soil is relatively shallow and underlain by stable rock or soil, the most economical treatment is usually to strip the unsuitable material, as shown in Figure 8.9. If seepage is evident after stripping or if there is a possibility that it may develop during wet cycles, a layer of pervious material should be placed before the embankment is constructed. This layer may consist of clean pit-run gravel, free-draining sand, or other suitable local materials. If springs or concentrated flows are encountered, drain pipes may also be required.

Where subsurface water or soil of questionable strength is found at such great depths that stripping is uneconomical, stabilization trenches have been used successfully to prevent landslides. Stabilization trenches (Figure 8.10) are usually excavated with the steepest side slopes that will be stable for the construction period.

The trench should extend below any water-bearing layers and into firm material. A layer of pervious material is used as a lining within the excavation, and an underdrain pipe is used as a collector. The trench is backfilled, and the embankment is constructed. If the unstable area is in a natural depression of limited areal extent, one trench normal to the centerline of the road may be sufficient. In

Figure 8.9. Stripping of unstable surface material as a slide-prevention measure on Redwood Highway, Humboldt County, California (*8.24*). Filter material ensures drainage at base of new embankment fill.

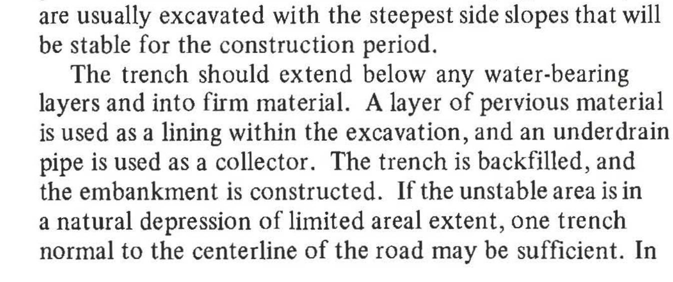


Figure 8.10. Stabilization trench with pervious material and perforated pipe for subsurface drainage (*8.24*).

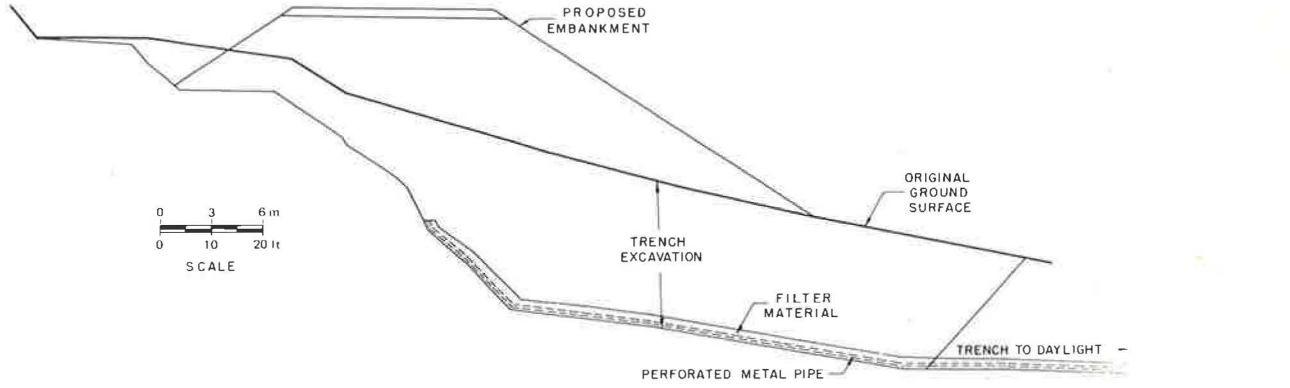
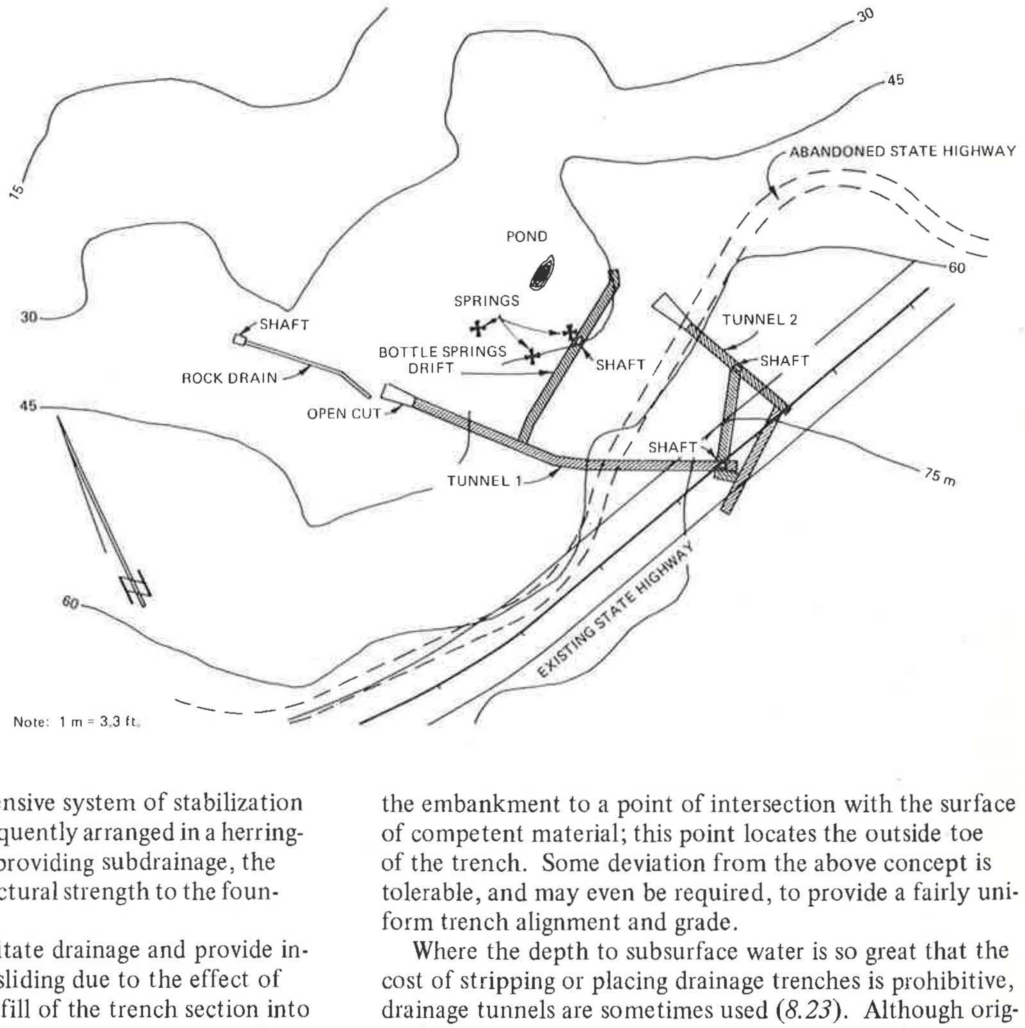


Figure 8.11. Drainage tunnels to prevent landslides near Crockett, California (*8.24*).



the case of large areas, an extensive system of stabilization trenches may be necessary, frequently arranged in a herringbone pattern. In addition to providing subdrainage, the trenches add considerable structural strength to the foundation.

Stabilization trenches facilitate drainage and provide increased resistance to possible sliding due to the effect of "keying" the compacted backfill of the trench section into the firm material beneath the trench. This procedure has generally been effective in preventing embankment landslides, but a few failures have occurred because the trenches were not carried down to firm material or they were too widely spaced.

Stabilization trench design requires a thorough subsurface investigation program, which must adequately define the subsurface soil layers and locate all water levels in the zone affected by the proposed embankment. One method of designing stabilization trenches is as follows: A line on a 1:1 slope is projected from the outside edge of the top of the embankment to a point of intersection with the surface of competent material; this point locates the outside toe of the trench. Some deviation from the above concept is tolerable, and may even be required, to provide a fairly uniform trench alignment and grade.

Where the depth to subsurface water is so great that the cost of stripping or placing drainage trenches is prohibitive, drainage tunnels are sometimes used (*8.23*). Although originally and more commonly used as a correctional treatment, drainage tunnels are sometimes constructed as a preventive measure. The use of drainage tunnels was fairly common at one time by both railroad companies and some highway departments, but at present this method is used rather infrequently largely because of the high construction cost.

An elaborate installation of drainage tunnels, together with an ingenious hot-air furnace for drying the soil, was used to control a large slide near Santa Monica, California (*8.15*). The use of drainage tunnels in Oregon has also been reported (*8.23*). These tunnels, usually about 1 m (3 ft) wide by 2 m (6 ft) high (in cross section), must be excavated manually; since skilled tunnel workers are not normally employed on such construction projects, other methods of treatment that permit the use of construction equipment are likely to cost less than the tunnels. Figure 8.11 shows an installation of drainage tunnels on a highway project.

Horizontal drains have supplanted drainage tunnels in most cases. Like drainage tunnels, they were first installed as corrective treatment. Although they are still used for this purpose, horizontal drain installations are now commonly used as a preventive measure for slope instability. A horizontal drain is a small-diameter well drilled into a slope on approximately a 5 to 10 percent grade and fitted with a perforated pipe. Pipes should be provided to carry the collected water to a safe point of disposal to prevent surface erosion.

Both vertical and horizontal drains were used in a slide that occurred in 1968 during construction on I-580 at Altamont Pass in California. Figure 8.12 shows such an installation. The slide extended along 310 m (1015 ft) of roadway with about 30 m (100 ft) of embankment. Remedial measures were (a) installation of a line of vertical drainage wells along the edge of the eastbound lanes; (b) construction of a berm between the eastbound and westbound lanes and a berm adjacent to the eastbound lanes; (c) installation of horizontal drains in five general areas to control groundwater, relieve excess hydrostatic pressure, and intercept and drain the vertical wells; and (d) completion of the construction of the embankment at a controlled rate of loading. The vertical wells were about 1 m (3 ft) in diameter, 12 m (40 ft) deep, and belled at the bottom so that they interconnected to form a somewhat continuous curtain. The drain had a 20-cm (8-in) perforated pipe in the center for the full depth of the vertical drain and was backfilled with pervious material. The horizontal drains were then drilled to intersect and drain the belled portion of the vertical well. The 20-cm perforated pipe was used to observe the water tables and to monitor the success of the system. Inspection of the system during September 1973 indicated that all water tables were successfully maintained at levels near the bottoms of the vertical drains.

A similar combination drainage system was used on a landslide on I-80 near Pinole, California. This roadway had been open to traffic for several years when a 23-m (75-ft) embankment failed abruptly and closed the freeway in both directions. A drainage gallery formed by a line of vertical wells with overlapping belled bases was placed on each side of the embankment, as shown in Figure 8.13. The lower line of vertical wells was drained with a 30-cm (12-in) pipe, and the uphill line of vertical wells was drained by means of horizontal drains. Berms were used to support the material placed in the failed area. A field and laboratory investigation of the Pinole slide included borings, installation of inclinometers, casings, and laboratory triaxial tests. The existence of water pressure in the layered subsoils was evidenced by a rise of water in the borings of 3 to 4.5 m (10 to 15 ft) when pervious strata were encountered.

Based on the observed excessive seepage at the upstream toe of the fill and the water level data, engineers from the California Division of Highways concluded that hydrostatic pressures had indeed triggered this failure. Two vertical wells were immediately installed upstream of the failed embankment and pumped to a depth of 10 m (33 ft); they produced water at the rate of 5400 L/d (1425 gal/d). Twelve horizontal drains were then installed, varying from 170 to 250 m (560 to 820 ft) in length, and these produced a total flow of 38 000 to 46 000 L/d (10 000 to 12 000 gal/d). In a 6-week period this subdrainage system lowered the groundwater 2 m (6.5 ft) at the upstream toe, 0.7 m (2.3 ft) beneath the sliding mass, and 0.3 m (1 ft) at the downstream toe. The triaxial tests indicated that the impervious soils forming the mass of the foundation material had cohesion values ranging from 25 to 145 kPa (3.5 to 20 lbf/in^2) with a negligible friction angle. The minimum factor of safety was calculated to be 1.01 when the failure oc-

Figure 8.12. Horizontal and vertical drains to prevent slides (*8.24*).

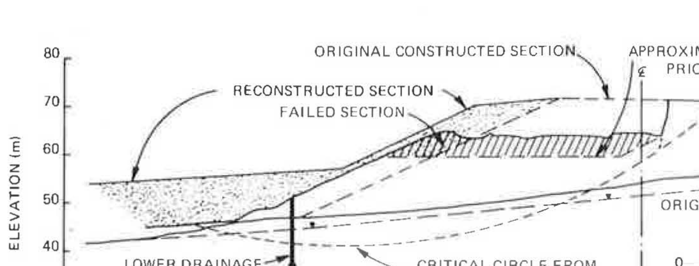
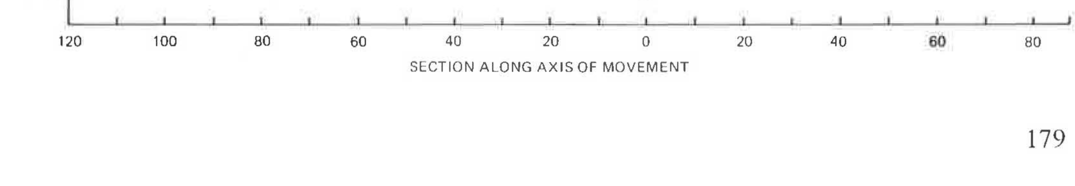


Figure 8.13. Cross section along axis of movement of landslide on I-80 near Pinole, California.



curred. The location of the critical circle was confirmed by movements observed from slope indicator readings. A factor of safety of 1.4 was obtained for the conditions after treatment and reconstruction (*8.31*).

Figure 8.14 shows a system of horizontal drains that was installed as a slide-correction measure; similar installations are frequently used as corrective treatments at other locations.

Vertical drain wells have also been installed under embankments to accelerate the consolidation of weak compressible foundation soils. Discussion of the various uses of vertical drains for this purpose is beyond the scope of this chapter, but many excellent references to vertical sand drain design and construction practices are available in the soil mechanics literature (e.g., *8.7, 8.16*).

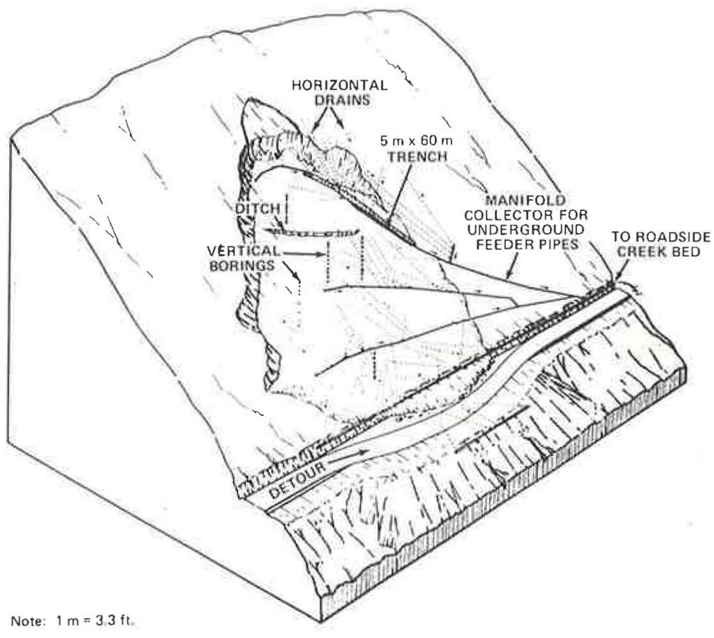
The continuous siphon is an excellent method devised by the Washington State Highway Commission for providing a drainage outlet for drainage wells or sumps (Figure 8.15). This siphon arrangement can be used to drain trenches, wells, or sumps and is less costly than tunnels, drilled-in pipes, or similar conventional outlet systems. In addition, it permits the installation of subdrainage systems in areas that do not have readily accessible outlets. A continuous siphon method has the usual limitation of depth, but is useful where applicable.

Excavation Areas

All of the subsurface drainage methods discussed in connection with prevention of landslides in embankments can also be applied to prevention of landslides in excavation areas. Drainage is sometimes installed to intercept subsurface water above the limits of the excavation, but there is seldom any assurance that such interceptor trenches will effectively cut off all groundwater that might contribute to slope failure. If deep trenches are required, the cost is frequently prohibitive, considering the probable effectiveness of the drainage trenches.

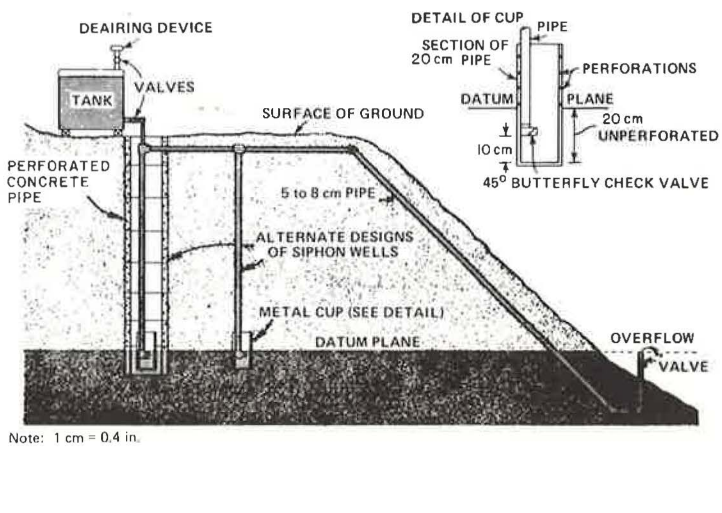
Deep trench drains (which, when finally extended deep enough, did work effectively to halt a large slope movement) were used during the construction of a portion of I-81 near Hollins, Virginia (Figure 8.16); this section of highway required a small cut about 10 m (33 ft) deep with 2:1 slopes. The removed material consisted primarily of

Figure 8.14. Horizontal drains used to control large land movements (*8.1, 8.14*).



Note: 1 m = 3.3 ft.

Figure 8.15. Washington siphon used by Washington Department of Transportation to lower water level and stabilize landslides (*8.24*).



Note: 1 cm = 0.4 in.

colluvium and residual soil weathered from a deeper shale bedrock. During construction a small landslide occurred, and the first attempts toward stabilization called for reducing the driving forces by flattening the slope to 3:1. Although stability analyses based on the assumption that the water table was at the ground surface predicted a safe condition, the regraded slope remained stable only until the following spring, when a second much larger slide occurred. It was obvious that a close relation existed between rainfall intensity and slope movement. Also, calculations in stability studies indicated that the average soil shear strength was much lower than originally assumed.

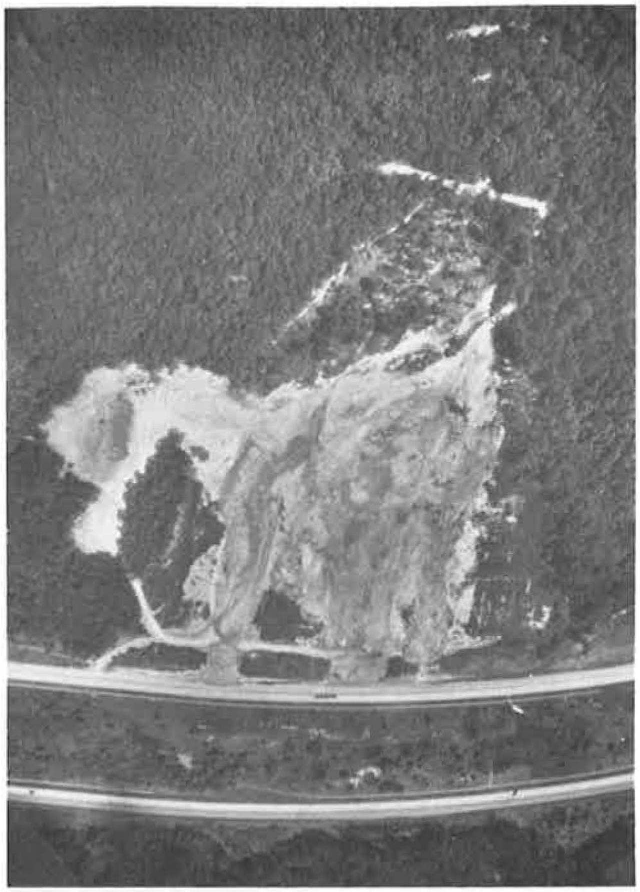
After consideration of many alternatives, including complete relocation of the roadway, construction of a drilled-pile restraint structure, and complete removal of the sliding mass, a remedial scheme was designed to further unload the slope and to ensure interception of subsurface waters. The design included (a) installing a trench drain around the slide scarp and up the face of the slide more or less at right angles to the roadway; (b) flattening the slope to 4:1; and (c) cutting an intermediate bench at approximately the midheight of the slope. Unfortunately, the trench around the scarp area did not totally halt the heavy subsurface water flow, and the movement continued during periods of heavy rainfall. Some 9 years of costly maintenance followed until the headward progression of the slide necessitated large increases in rights-of-way. The final remedial scheme consisted of (a) using a large rock buttress to restrain the slope above the existing scarp face and to effect deeper drainage interception; (b) placing large granular drainage trenches in two channels down the slope within the flow debris; and (c) regrading the final slope to attain full surface drainage and allow grass establishment. The final slope has remained stable for the past 3 years. The total cost for remedial construction was more than $1 million. However, this proved to be at least $1 million less than the closest alternative, which was to completely relocate the highway away from the slide area (*8.13*).

The most widely used method of subsurface drainage for cut slopes is probably the use of horizontal drains, which are described in the previous section. In excavation areas the drains are installed as the cut is excavated (Figure 8.17), often from one or more benches in the cut slope. Numerous cut slopes drained by this method have remained stable in spite of unfavorable soil formations and the presence of large amounts of subsurface water. If the treatment is delayed until after a landslide has developed, the cost of correcting the slide by subsurface drainage will be much greater and have much less chance of success.

Reduction of Weight

Another technique for reducing the driving forces is referred to as selective "unloading" of a slide. Unloading refers to removal or excavation of a sufficient quantity of slope-forming material at the head of the slide to ensure stability of the mass. This approach is ineffective for infinite slopes or for flow types of earth movement, as discussed in Chapter 6. The required quantity of material to be removed must be carefully predicted by stability analyses using high-quality laboratory and field data. In addition, economics and material usage may dictate whether unloading procedures are reasonable on any project. The design of removal procedures must always consider the stability of the slope behind the area to be removed. In some instances, either through project needs for borrow materials or through consideration of the size of total volumes of slide materials, simply to remove the total slide mass is feasible. This procedure is usually limited to slides in which material volumes are relatively small, and it is an effective means of reducing problems when used during the design stage. In addition, the use of variable or flattened slopes at the top of a cut will often aid in unloading a potential slide area.

Figure 8.16. Aerial view of Hollins slide on I-81 near Roanoke, Virginia.



Slope flattening was used effectively on a 98-m (320-ft) cut for a southern California freeway (Figure 8.18). A failure took place during construction on a 1:1 benched cut slope composed predominantly of sandstone and interbedded shales. After considerable study and analysis, the slope was modified to 3:1, and the final roadway grade was raised some 18 m (60 ft) above the original design elevation. Moreover, to provide additional stability, earth buttresses were placed from roadway levels to a height of 21 m (69 ft) along the final slopes.

In the past, benching has been used by some engineers to reduce the driving force on a potential or existing slide. However, both field experience and stability analyses indicate that this objective is not always achieved (*8.25*). Hence, a careful study and review of alternatives is recommended when benching is proposed. The use of benching to reduce the driving forces is not generally recommended, but

Figure 8.17. Combined benching and drainage for slope stabilization at Dyerville cut on US-101 in California (*8.29*).

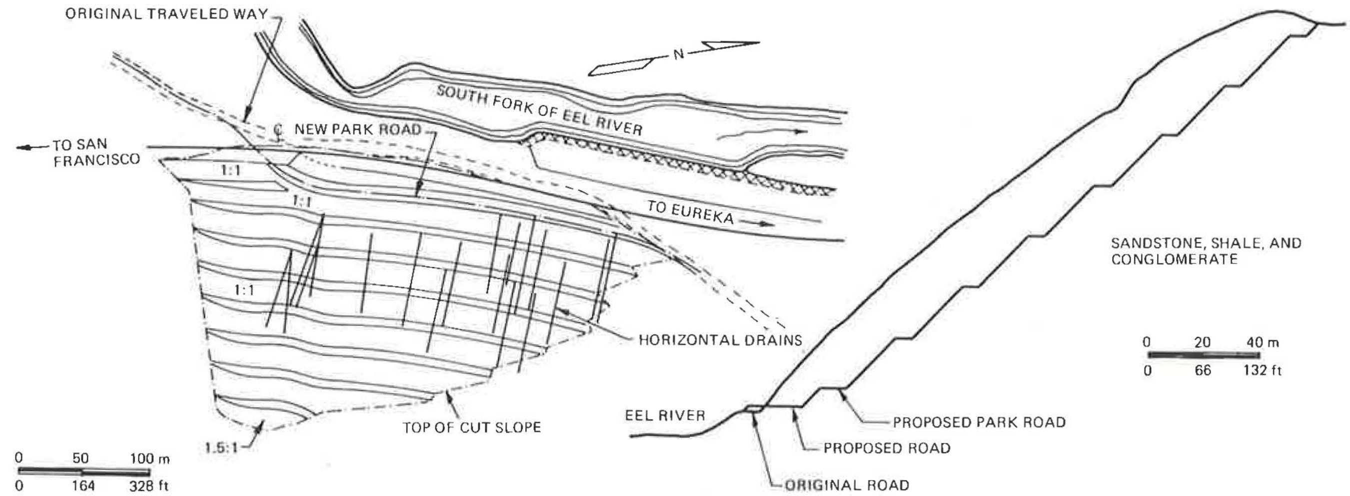


Figure 8.18. Slope flattening and grade change at Mulholland cut on San Diego Freeway (*8.29*).

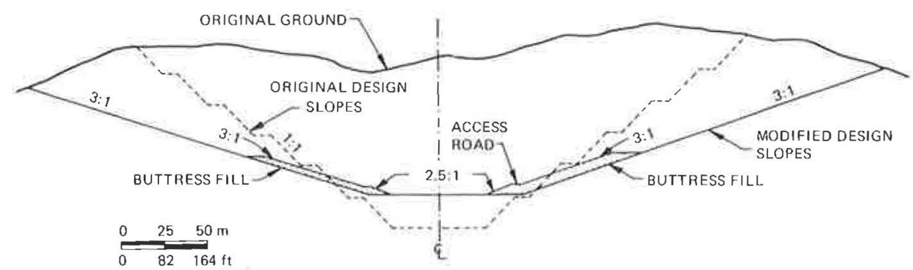


Figure 8.19. Use of lightweight fill and gravel counterweight.

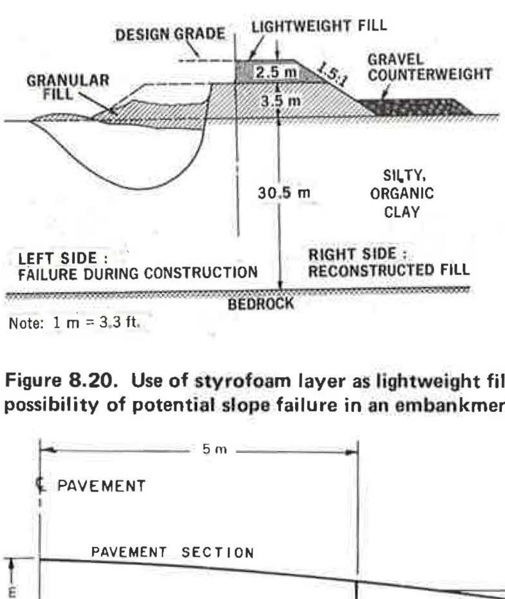
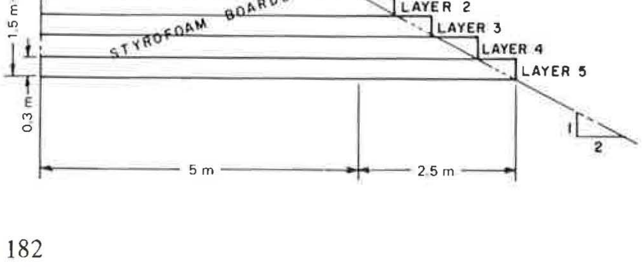


Figure 8.20. Use of styrofoam layer as lightweight fill to reduce possibility of potential slope failure in an embankment (*8.9*).

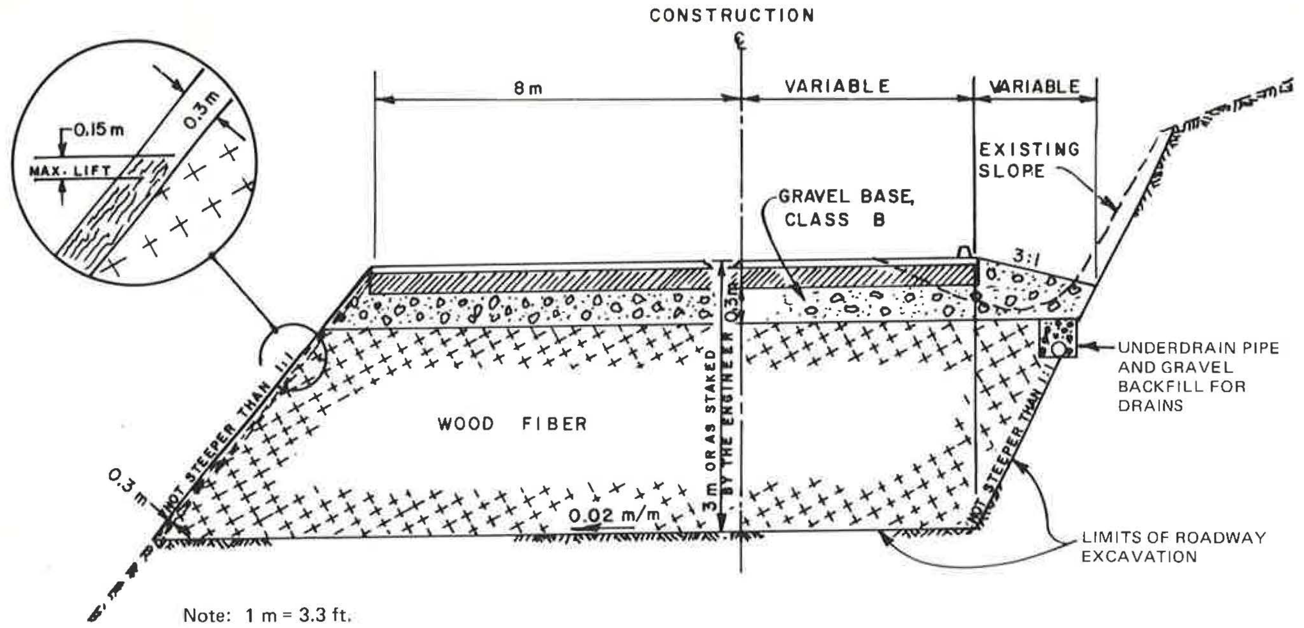


benches do serve a useful purpose in (a) controlling surface runoff if the bench is properly designed and has paved ditches and (b) providing work areas for the placing of horizontal drains.

In embankment construction, lightweight materials such as slag, encapsulated sawdust, expanded shale, cinders, and seashells, have been used successfully to reduce the driving force (Figure 8.19). Polystyrene foam has also been used recently as a lightweight fill material to reduce the stresses in a fill foundation. In an example in Michigan (*8.9*), a 1.5-m (5-ft) lift thickness of styrofoam in 0.3 by 0.6 by 2.4-m (1 by 2 by 8-ft) boards was placed with staggered joint patterns (Figure 8.20). The foam backfill was covered by 1-mm (4-mil) polyethylene sheeting to protect the foam from possible spills of petroleum-based liquids that might seep through a 1.5-m-thick pavement and granular fill cap. The roadway pavement structure was then placed on the granular cap material (Figure 8.20). Since the polystyrene foam had a density of 768 kg/m^3 (48 lb/ft^3) compared to 1928 kg/m^3 (120 lb/ft^3) for the normal sand backfill, a rather significant weight reduction was realized with the 1.5-m substitution.

In areas where wood product waste is available at reasonable cost, highway departments have used sawdust or wood chips as lightweight fill. Nelson and Allen (*8.19*) report such a case in which a landslide was stopped by removing earth from the landslide head and replacing it with encapsulated sawdust and wood fiber (Figure 8.21). Since exposed wood products above the groundwater table are known to decay with time, asphalt encapsulation commonly is applied as a retardant to the decay process.

Figure 8.21. Excavation and lightweight fill detail used by Washington Department of Transportation (*8.19*).



Seashells have been used as lightweight fill wherever the shells can be obtained in sufficient quantities. A layer about 1.5 to 2 m (5 to 7 ft) thick over surface swamp deposits forms a foundation that can support construction hauling equipment and effectively reduce the foundation stresses caused by the fill.

Expanded shale aggregates have found excellent, but somewhat expensive, use in embankment construction where fill slope movements suggest potential long-term instability. In one northeastern state, these lighter heat-expanded materials have been used extensively instead of normal fill soils to stabilize high fills on which bridge abutments are constructed. In most instances, the average weight of the shale material is about two-thirds that of a normal earth fill. However, because of the high cost of this material, other alternatives for reducing driving forces will probably provide better design alternatives.

Increase Resisting Forces

The third general method for stabilizing earth slopes is to increase the forces resisting the mass movement. As explained in Chapter 7, two approaches to improving stability are (a) to offset or counter the driving forces by an externally applied force system and (b) to increase the internal strength of the soil mass so that the slope remains stable without external assistance. Both techniques should be considered during design studies to ensure the best engineering and most economical solution. Similar techniques are used to correct landslides that occur during or after construction. The basic principles of soil shear strength (Chapter 6) and the importance of groundwater, excess hydrostatic pressure, and seepage pressure on soil strength should be reviewed.

A multitude of methods is available to the geotechnical engineer to increase the resisting forces on a potential or existing landslide. Although the techniques may vary widely, they may be reduced to two basic principles: (a) application of a resisting force at the toe of the slide and (b) increase in the strength of the material in the failure zone. Three systems presented (buttress or counterweight fills, pile systems, and anchor systems) basically apply a resisting force at the toe of the sliding mass; the remaining systems (subsurface drainage, chemical treatment, electroosmosis, and thermal treatment) are essentially methods for increasing the strength of the material in the failure zone.

Apply External Force

Buttress or Counterweight Fills

Buttress (Figure 8.22) or counterweight fill design for slope stability involves one basic principle: to provide sufficient dead weight or artificially reinforced restraint near the toe of the unstable mass to prevent movement. Stability analyses based on the unretained slope geometry and available soil shear strengths predict the forces tending to cause movement and those that exist within the soil mass to resist the movement. A buttress design provides an additional resistance component near the toe of the slope to ensure an adequate safety factor against failure.

The ability of any restraining structure to perform as a designed stabilizing mass is a function of resistance of the structure to (a) overturning, (b) sliding at or below its base, and (c) shearing internally. An overturning analysis is performed by treating the buttress as a gravity structure and resolving the force system to ensure the proper location of the resultant. Potential sliding at or below the base requires a similar analysis, and care must be taken in both the design and the construction phases to ensure adequate depth for founding the buttress and prescribed quality for the layer on which the buttress is placed. Internal shear requires that the designer check the cross-sectional area at

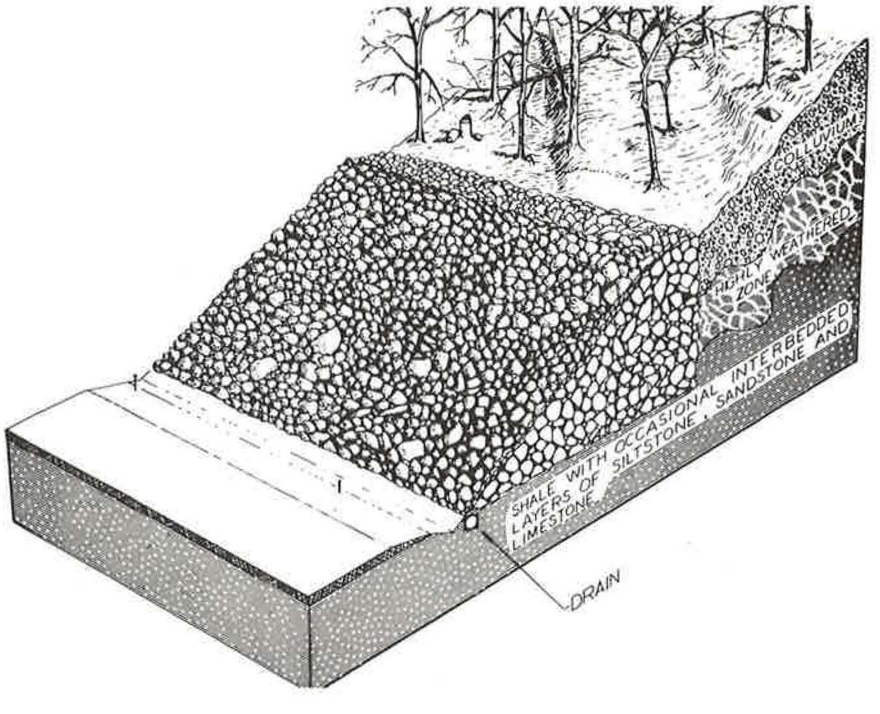


Figure 8.22. Rock buttress used to control unstable slope.

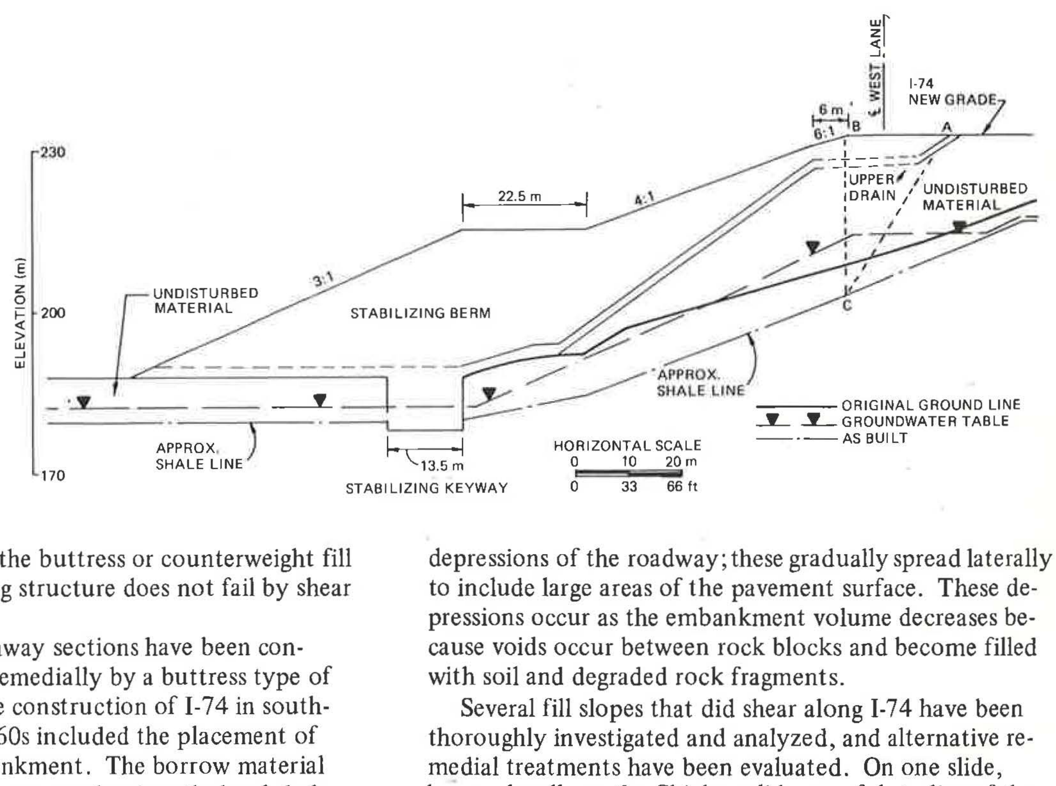


Figure 8.23. Stabilization berm used to correct landslide in shale on I-74 in Indiana.

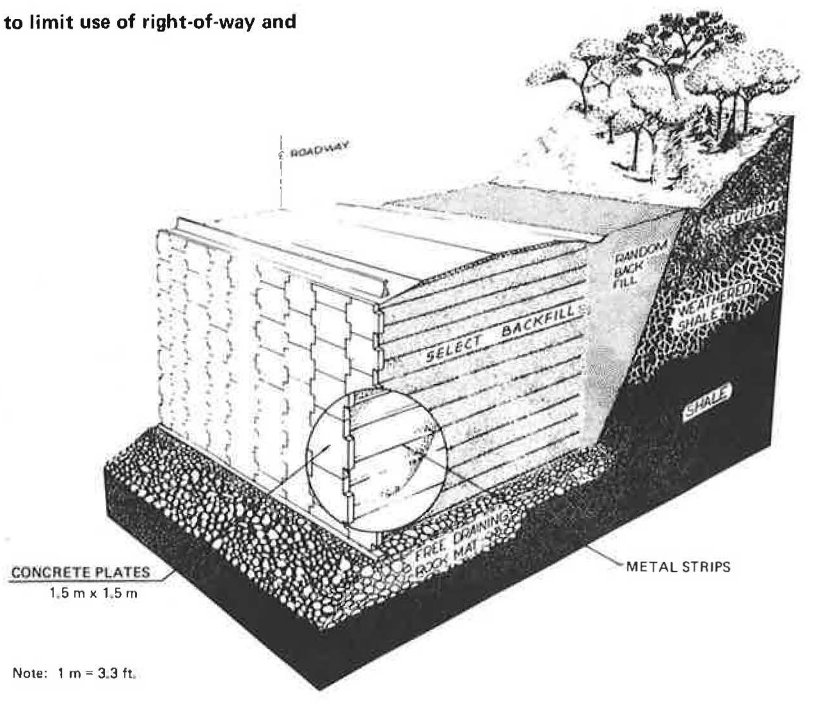
various elevations within the buttress or counterweight fill to ensure that the resisting structure does not fail by shear within itself.

Several important highway sections have been constructed with or treated remedially by a buttress type of restraining structure. The construction of I-74 in southeastern Indiana in the 1960s included the placement of many kilometers of embankment. The borrow material used in the embankments was predominantly local shale materials that were interbedded with limestone and sandstone. Unfortunately, shales deteriorate with time when exposed to the environment, and cut slopes in fresh shale steeper than 1:1 will deteriorate and slough on the surface until a final stable slope of about 2:1 is attained. These same shale materials, when placed and manipulated into an embankment by the use of accepted construction techniques, will similarly degrade with time. Ultimately, the embankment slopes may slough and eventually fail. The first indications of the degradation process are localized depressions of the roadway; these gradually spread laterally to include large areas of the pavement surface. These depressions occur as the embankment volume decreases because voids occur between rock blocks and become filled with soil and degraded rock fragments.

Several fill slopes that did shear along I-74 have been thoroughly investigated and analyzed, and alternative remedial treatments have been evaluated. On one slide, known locally as the Chicken slide, careful studies of the in situ shear strength of the shales (ϕ = 14° to 16°) versus the original strengths used in the preconstruction studies showed an approximate reduction of one-half from the as-built condition (*8.12*). The alternatives considered by the Indiana State Highway Commission were (a) relocate, (b) remove and replace, (c) buttress with earth and rock counterweight, and (d) buttress with reinforced earth wall.

Each alternative was thoroughly studied, and appropriate cost figures were determined. By far the least expensive and least disruptive to traffic were the two buttress

Figure 8.24. Reinforced earth wall used as a highway fill to limit use of right-of-way and ensure stability to sidehill.



alternatives. Since cost estimates for both solutions were close to $1 million, the highway commission advertised for bids. Based on contractor bid prices ($700 000 versus $1 000 000 for reinforced earth), the earth and rock counterweight design was finally selected. A cross section of the design, as finally constructed, is shown in Figure 8.23.

Reinforced earth, as the name implies, is a construction material that involves the designed use of backfill soil and thin metal strips to form a mass that is capable of supporting or restraining large imposed loads (Figure 8.24). The face of a reinforced earth wall is usually vertical, and the backfill material is confined behind either metal or unreinforced concrete facings. Reinforced earth is finding increased use in highway construction, particularly when it is used as a buttress type of retaining structure. As a buttress, reinforced earth acts as a gravity structure placed on a stable foundation, and it must be designed to resist the slope driving forces, i.e., overturning, shearing internally, and sliding at or below the base.

The Tennessee Department of Transportation selected a reinforced earth buttress wall to correct a large landslide on a section of I-40 near Rockwood (*8.26*). Alternative designs were prepared for a rock buttress and the reinforced earth structure. Cost estimates ($505 000 for reinforced earth versus $930 000 for a rock buttress), ease of construction, and time for construction were the principal reasons for selecting the reinforced earth wall. The slope-forming materials were essentially a thick surface deposit of colluvium underlain by residual clays and clay shales (Figure 8.25). The groundwater table was seasonally variable, but was generally found to be above the colluvium-residuum interface. This particular landslide occurred within an embankment placed as a sidehill fill directly on a colluvium-filled drainage ravine. Because of blocked subsurface drainage and weakened foundation soils, the fill failed some 4 years after construction. Instrumentation, including slope inclinometer casings, placed the failure surface at the contact zone between the colluvium-residuum materials.

Final design plans called for careful excavation of the failed portion of the fill to a firm unweathered shale base, installation of a highly permeable drainage course approximately 10 m (33 ft) wide below the wall area, placement of the reinforced earth wall, and final backfill operations behind the reinforced earth mass (Figure 8.26). The wall was designed for a minimum safety factor of 1.5 against failure. The 253-m long by 10-m high (830-ft by 3.3-ft) wall was completed in approximately 60 d (Figure 8.27).

Other types of buttress or restraining structures commonly used include timber bulkheads; timber, metal, and concrete cribbing; rubble and masonry retaining walls; reinforced concrete retaining walls; and various forms of anchor walls (Figures 8.28, 8.29, 8.30, and 8.31).

Pile Systems

In many urban locations, flattened slopes or counterweight fills are not feasible solutions to cut slope stability problems. Right-of-way limitations and the presence of existing private and commercial structures require much closer attention to the relative risk acceptable in a proposed stability solution. One positive approach is the use of large-diameter piles placed as a preexcavation restraining system. In this system, the forces tending to cause movement are carefully predicted, and the additional restraint necessary to offset soil movement is provided by a closely spaced vertical pile wall. The cast-in-place piles may be designed and placed as cantilevers or tied back with an anchor system. Either alternative requires the pile cross section to resist the full earth thrust imposed by the soil as excavation progresses.

Perhaps the best known application of this design is on a section of I-5 near Seattle, Washington (*8.21*). Cuts in a major interchange area in heavily overconsolidated marine clays were designed with slope ratios based on laboratory-determined undrained shear strength parameters from re-

Figure 8.25. Fill failure on I-40 near Rockwood, Tennessee (*8.26*).

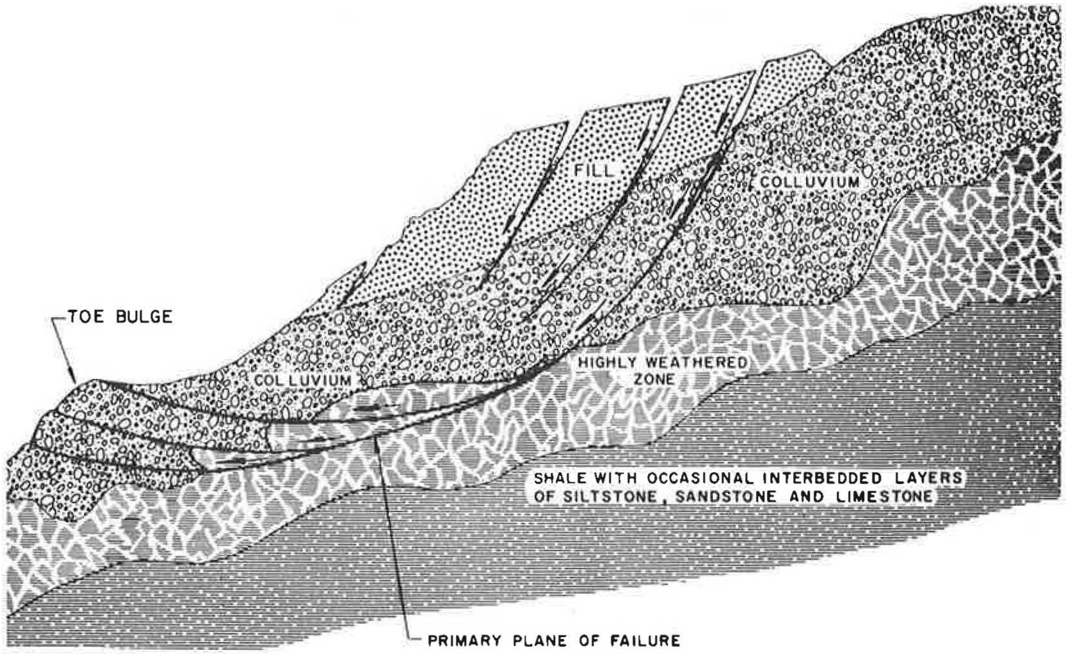


Figure 8.26. Cross section of reinforced earth wall to correct fill failure on I-40 near Rockwood, Tennessee (*8.26*).

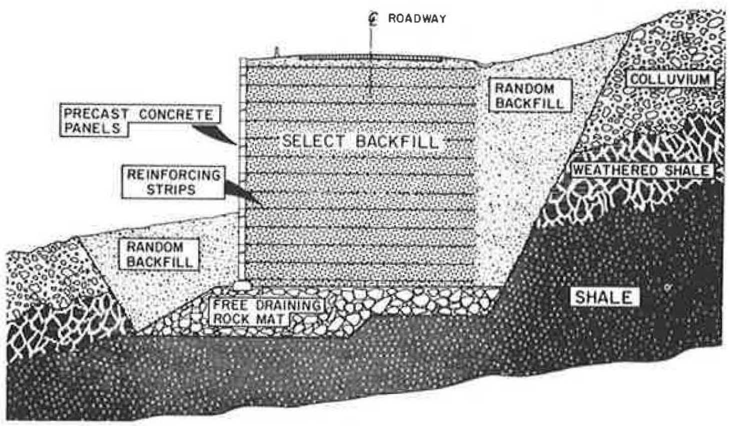


Figure 8.27. Aerial view of final correction to fill failure using reinforced earth, I-40 near Rockwood, Tennessee (*8.26*).

Figure 8.28. Concrete crib wall and gravel backfill installed to prevent movement in Arcata, California (*8.24*).

Figure 8.29. Uses of retaining walls for slope stabilization (*8.27*).

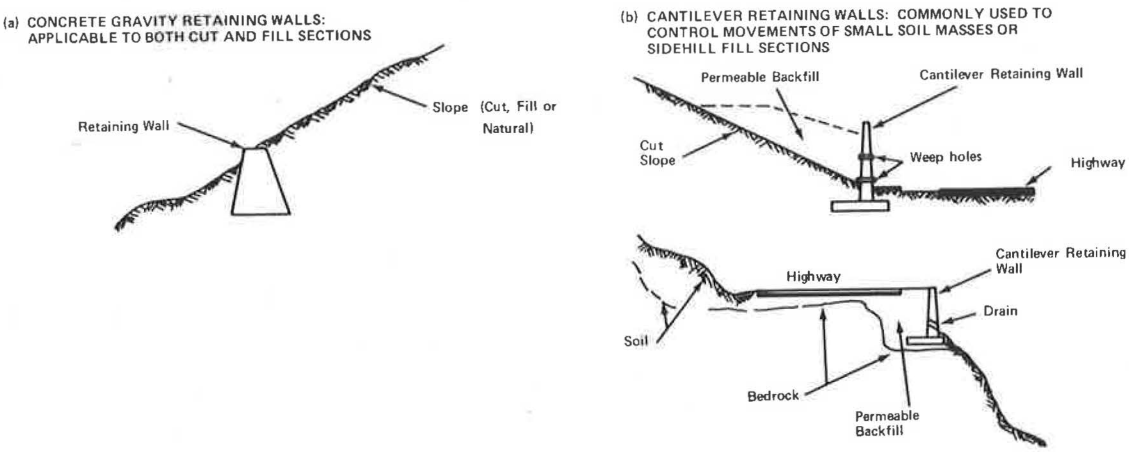


Figure 8.30. Gabion-wall retaining structure.

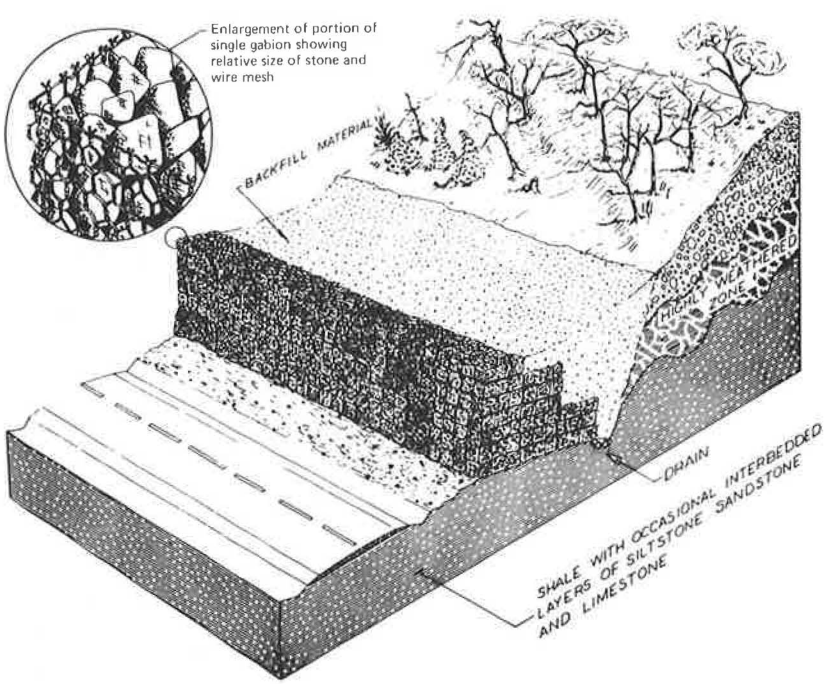


Figure 8.31. Design of strut to correct cut slope failure on I-94 in Minneapolis-St. Paul (*8.28*).

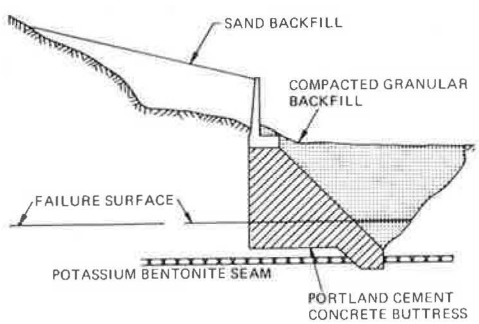
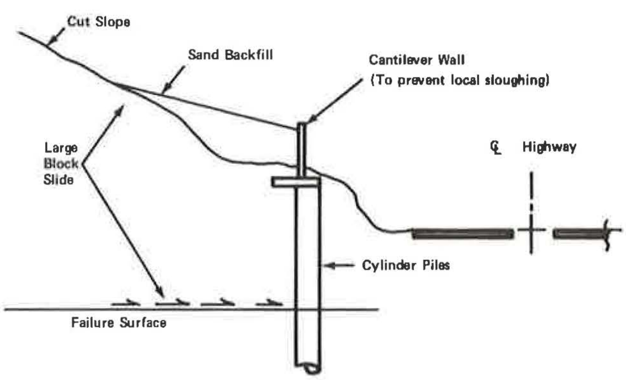


Figure 8.32. Cylinder pile wall system proposed to stabilize deep-seated slope failure on I-94 in Minneapolis-St. Paul (*8.28*).



covered soil samples. Some weeks after the cuts had been opened, movements in the form of bulges and sloughing began on several slope faces. Detailed analysis by geotechnical engineers laid the cause for these movements to the release of large "locked-in" soil stresses. The stresses were caused geologically by massive overburden pressures previously applied to the clays. The subsequent removal of these loads was not accompanied by equally large elastic rebounds by the soil; thus, the soil retained a large prestress history. During roadway excavations, substantial cuts were made through these prestressed soils, and the removal of the lateral support, together with the increased moisture content, permitted expansion and subsequent loss of soil strength.

Further slope flattening was not feasible on this project, and large-diameter (1 to 4 m, 3 to 13 ft) drilled, cast-in-place concrete shafts were spaced to form an almost continuous wall to minimize the potential for large soil strains as the excavations were made. Since the anticipated lateral soil forces were large, heavy steel H-pile sections formed the cores of the shafts, and high-strength concrete was placed around those sections. Only minor lateral expansion occurred during the excavation process, and the shafts were designed by using the fully mobilized shear strength of the clay. Drilled shafts were also used in remedial work for the slope of the Potrero Hill cut in San Francisco (*8.30*) and in the I-94 cuts (Figure 8.32) in and around Minneapolis-St. Paul (*8.33*).

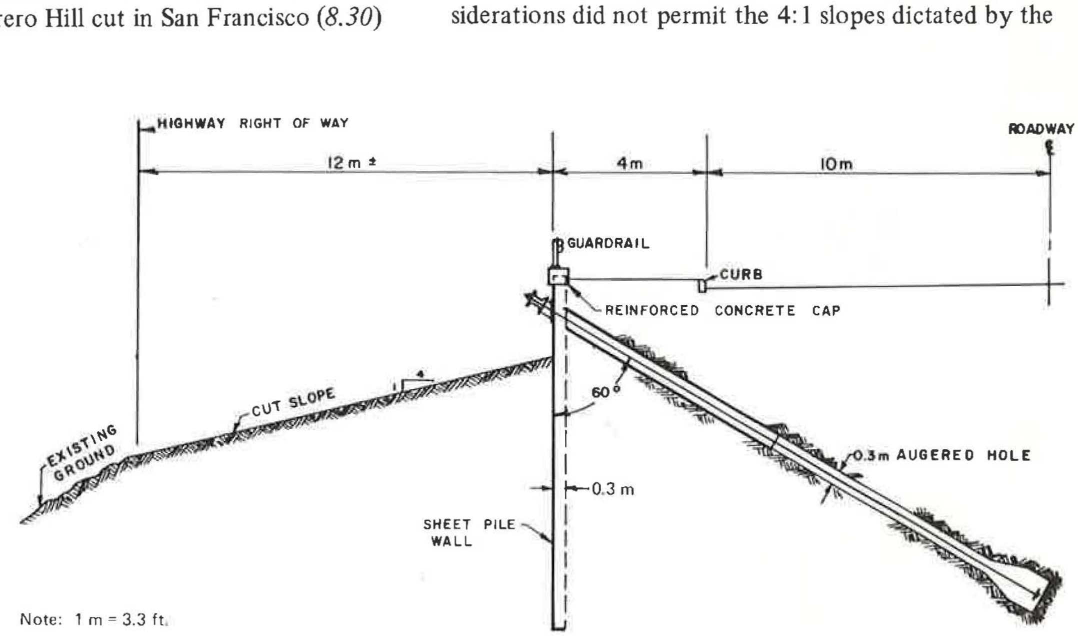
Recorded attempts to use driven steel piles or wood piles of nominal diameter to retard or prevent landslides have seldom been successful. For most earth or rock movements, such piles are incapable of providing adequate shearing resistance. In addition, when they are used in even small earth slides, movement of soil between and around the piles must be considered. Quite often, a major earth movement develops a rupture surface in the soil below the pile tips. All such pile schemes should be carefully designed by using realistic soil parameters (*8.2*). The forces involved in even the smallest landslide are large, and for the piles to be effective they must have sufficient cross section and depth to prevent movement.

Anchor Systems

One type of anchor system is tied-back walls, many variations of which are available to the design engineer. Most such wall designs use the basic principle of carrying the backfill forces on the wall by a "tie" system to transfer the imposed load to an area behind the slide mass where satisfactory resistance can be established. The ties may consist of pre- or post-tensioned cables, rods, or wires and some form of deadmen or other method to develop adequate passive earth pressure.

A good example of such a design was used to retain a large movement in Washington, D.C. (*8.20*). A section of New York Avenue, a major street in the District of Columbia, was to be widened sufficiently to provide an additional two lanes of roadway. The original street was built in a sidehill cut; the shoulder area was founded on an uncompacted fill of clay, rubble, and cinders. The natural soil below the miscellaneous fill was an overconsolidated clay with a residual shear strength of 31.6 kPa (660 lbf/ft²) (60 percent of laboratory-measured peak value) and a sensitivity of about 4. Since the new construction required an additional width for the roadway fill, the final design called for removal and replacement of the miscellaneous existing embankment as a first order of work. Right-of-way considerations did not permit the 4:1 slopes dictated by the

Figure 8.33. Section of tied-back wall to correct slide condition on New York Avenue in Washington, D.C. (*8.20*).



stability studies of the widened embankment section.

A comparison of the various design alternatives indicated the economic use of a tied-back sheet pile wall (Figure 8.33). The depth of embedment for the tie-back system varied from 12 to 21 m (40 to 69 ft) to ensure adequate anchorage in the stiff clays. A system of belled concrete anchors into which 3.2-cm (1.25-in) diameter high-strength steel rods were cast acted as the principal support against pullout. The rods were pretensioned against the sheet-pile wall system to the full design loads following installation. A maximum allowable long-term shear stress of 23.9 kPa (500 lbf/ft^2) for the clay was used in analysis; this stress provided a safety factor of about 2. Instruments left in place to facilitate the long-term recording of actual stress levels indicate that the tensile stresses in the steel were well within predicted values.

Increase Internal Strength

Subsurface Drainage

One of the most effective treatments of landslides is to increase the forces available to resist motion by increasing the shear strength of the soil through subsurface drainage (increase in the effective normal stress on the failure surface). This treatment is discussed earlier in this chapter.

Chemical Treatment

Various schemes have been tried by researchers and practitioners to treat unstable soil slopes with injected chemicals. One interesting application under research in California is a patented ion-exchange technique described by Smith and Forsyth (*8.30*). The ion-exchange technique consists of treating the clay minerals along the plane of potential movement with a concentrated chemical solution. The actual chemicals used in the ion exchange are determined by the clay mineralogy of the soil to be treated and by the prevailing groundwater conditions in the slide mass.

To chemically change a clay soil by ion exchange, some cations in the clay minerals are replaced with different cations that are introduced by chemical solution. In a saturated clay, the rate of migration through the soil structure appears to be much greater for cations than for water. Cation replacement can result in as much as a 200 to 300 percent increase in soil shear strength. Since the initial strength in the shear zone is low for most clays in which this method can be used, this relatively minor increase in strength may be sufficient to stabilize a landslide. Although the ion-exchange technique was successfully used in northern California to stabilize a slide (*8.17*), it may have little chance for success on other landslides.

Other chemical treatments used with varying degrees of success are lime or lime-soil mixtures, cement grout, and potassium injections. Perhaps the chemical treatment most used in attempts to increase soil shear strength is lime. High-pressure injections of lime slurry have been used in several states with limited success. One successful treatment was reported by Handy and Williams (*8.11*); approximately 45 000 kg (100 000 lb) of quicklime were placed in predrilled 0.2-m (0.5-ft) diameter holes on 1.5-m (5-ft) centers throughout an extensive slide area. The lime migrated a distance of 0.3 m (1 ft) from the drilled holes in 1 year. Slide movements subsequently ceased, and the area has remained stable to date.

An interesting application of cement grout occurred on a section of I-40 along the Pigeon River in North Carolina. A 90-m (300-ft) benched cut slope for the roadway began moving forward, threatening the road and a large water supply reservoir on the downhill side of the roadway. Subsequent investigations and analyses showed the roadway foundation area to consist of broken rubble and talus debris to great depths. Instruments placed movement along a definite plane where rock voids were large. Large volumes of cement grout were injected into the voids of this layer and surrounding areas in an attempt to increase the shearing resistance of the slope foundation. Although great volumes of grout were required at considerable expense, the slope did become stable, and the water supply for a major city was not lost.

Electroosmosis

One method that effectively increases soil shear strength in situ is electroosmosis (*8.5, 8.6*). This technique, although extremely expensive, causes migration of pore water between previously placed electrodes; the loss of pore water, in turn, causes consolidation of the soil and a subsequent increase in shear strength. Casagrande, Loughney, and Matich (*8.6*) describe a highway project that required an excavation approximately 4.5 m (15 ft) in depth and some 24 by 12 m (80 by 40 ft) in area to install a bridge foundation support system. The side slopes were predominantly a saturated, somewhat uniform silt material placed on a 2.5:1 slope. During excavation a slide occurred. After consideration of alternatives such as freezing, chemical injection, slope flattening, and restraining walls, the designers selected electroosmosis as the most economical solution. Some 3 months were required to lower the groundwater sufficiently to proceed with construction; however, the final slope excavation was steepened to 1:1 and the project was successfully completed. Long-term solutions using electroosmosis must give full consideration to the need for a constant supply of direct current and the need for maintenance personnel to periodically check the system for replacement of field-installed electrodes.

One interesting variation of the electroosmotic effect is that suggested by Veder (*8.32*). Where landslides occur at the contact zone between soil layers, Veder reports that differences in water content between the layers means a difference in electropotential. This difference in potential creates a gradient that forces water to move through the soil toward the region of lower potential. Veder suggests that the insertion of metallic conductors into the soil to create short-circuit electrodes will halt soil-water movement. Thus, the imposed short-circuit effectively acts in the reverse of electroosmosis where an external source of direct current is used to cause soil water migration. Veder reports several cases in which this procedure has successfully stabilized landslides.

Thermal Treatment

For several years the Russians have experimented and reported on the success of thermal treatment of plastic and loessial soils. The high temperature treatments cause a permanent drying of the embankment or cut slope. Hill (*8.15*) discusses the use of thermal treatment in the United States. Beles and Stanculescu (*8.3*) describe an interesting use of thermal methods to reduce the in situ water contents of heavy clay soils in Romania. Applications to highway landslides and to unstable railroad support fills are cited.

Combination of Treatments

In most applications, a combination of the various methods outlined above is used. A buttress fill may be combined with a subdrainage system to provide a resisting force that allows the drainage system to become effective, thus tending to increase the stability of the slope with time. Vertical wells may be pumped to stabilize a cut during construction; however, horizontal drains usually are installed as a long-term solution, and pumping the vertical wells is then discontinued. This procedure was used in California to stabilize the Pinole slide (Figure 8.13); two vertical wells were pumped immediately to relieve the water pressure while the horizontal drains were installed. Then, berms were placed as the embankment was reconstructed to ensure the integrity of the reconstruction while the horizontal drains continued to reduce the water pressure. The long-term stability of this treatment requires that the horizontal drains function properly for the life of the structure. On another project in California, several different approaches were also used to stabilize a slow moving landslide by chemical injection to effect a strength increase within the predetermined slide zone. Then, horizontal drains were installed a year later to effect positive drainage by gravity flow deep within the slide and thereby ensure long-term stability to the area.

Each case in which combinations of various methods have been used both in design and construction represents a study of carefully considered and applied engineering principles to reach a reasonably economic solution. Perhaps the relation between design and actual construction is somewhat unique in geotechnical engineering, because a failure of the slope may result if various combinations of soil strength, groundwater levels, and slope geometrics that occur during construction are not fully considered in design.

TOE EROSION

Toe erosion, as used in this chapter, is the removal of material from the base or toe of a slide or natural slope by natural forces. Although wind erosion can be appreciable, the most common type of toe erosion encountered by a geotechnical engineer is that caused by moving water in rivers, streams, or oceans eroding slope-forming materials. The general solution for this type of problem is to protect the toe of a slope by either a riprap surface layer or a free-draining durable rock layer placed at the base of the slope to an elevation of about 1 m (3.3 ft) above the expected mean high water level.

The erosion of natural or human-made slopes by rivers or streams is a major cause of land instability. Geologic studies refer to the erosion of stream valleys, cliff formations on oceanfronts, and loss of land due to moving waters. Engineers are faced with these problems in design and construction of transportation facilities. Careful attention must be given to the protection of earth slopes in any channel design. Protection may be in the form of (a) riprap or other suitable material or (b) a lining of reinforced concrete with designed hydraulic features to ensure dissipation of the destructive forces of the anticipated flow. One should never assume that a slope adjacent to natural water-courses is adequate until thorough hydraulic studies are made and corresponding protection of the slope provided for the anticipated long-term effects of the water.

Various buttress systems have been used successfully in situations in which the general lack of space precludes other treatments, particularly where a facility follows a river or ocean face. Pile systems have had little success where the ocean is eroding away the toe of a cliff. Various surface and subsurface drainage systems have been used in combination with buttress systems, and, if properly designed and constructed, these will be successful. In general, the solution to the toe erosion problem is to install a system that prevents further loss of support for the slope and to use other means for increasing the resisting forces. Thus, a combination of several methods will generally be required.

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