CHAPTER 10

Slope Stabilization

This chapter pertains to the design of earth slopes as it relates to road construction. It particularly concerns slope stability and which slopes should be used under average conditions in cuts and embankments. Some of the subjects covered are geologic features that affect slope stability, soil mechanics, indicators of unstable slopes, types of slope failures, and slope stabilization.

Road failures can exert a tremendous impact on mission success. It is vital that personnel engaged in road-building activities be aware of the basic principles of slope stability. They must understand how these principles are applied to construct stable roads through various geologic materials with specific conditions of slope and soil.

Basic slope stability is illustrated by a description of the balance of forces that exist in undisturbed slopes, how these forces change as loads are applied, and how groundwater affects slope stability and causes road failure.

GEOLOGIC FEATURES

There are certain geologic features that have a profound effect on slope stability and that can consequently affect road construction in an area. Many of these geologic features can be observed in the field and may also be identified on topographic maps and aerial photographs. In some cases, the presence of these features may be located by comparing geologic and topographic maps. The following paragraphs describe geologic features that have a significant effect on slope stability and the techniques that may be used to identify them:

Faults

The geologic uplift that accompanies mountain building is evident in the mountainous regions throughout the world. Stresses built up in layers of rock by the warping that accompanies uplift is usually relieved by fracturing. These fractures may extend for great distances both laterally and vertically and are known as faults. Often the material on one side of the fault is displaced vertically relative to the other side; sometimes igneous material or serpentine may be intruded into faults. Faults are the focal point for stress relief and for intrusions of igneous rock and serpentine; therefore, fault zones usually contain rock that is fractured, crushed, or partly metamorphosed. It is extremely important to recognize that fault zones are zones of geologic weakness and, as such, are critical in road location. Faults often leave topographic clues to their location. An effort should be made to identify any faults in the vicinity of a proposed road location.

The location of these fault zones is established by looking for—

- Saddles, or low sections in ridges, that are aligned in the same general direction from one drainage to another.
- Streams that appear to deviate from the general direction of the nearby streams.

Notice that the proposed locations of the fault zones on the topographic map follow saddles and drainages in reasonably straight lines.

Aerial photographs should be carefully examined for possible fault zones when neither geologic maps nor topographic maps offer any clues. An important feature of a fault zone slide that may be detected from aerial photography is the slick, shiny surface caused by the intense heat developed by friction on sliding surfaces within the fault zone.

Field personnel should be alert for on-the-ground evidence of faulting when neither geologic maps nor topographic maps provide definite clues to the location of faults.

Bedding Plane Slope

There are many locations where sedimentary or metamorphic rocks have been warped or tilted and the bedding planes may be steeply sloped. If a road is planned for such an area, it is important to determine the slope of the bedding planes relative to the ground slope. In areas where bedding planes are approximately parallel to the slope of the sidehill, road excavation may remove enough support to allow large chunks of rock and soil to slide into the road (see *Figure 10-1).* If preliminary surveys reveal that these conditions exist, then the route may need to be changed to the opposite side of the drainage area or ridge where the bedding planes slope into the hillside.

SOIL MECHANICS

The two factors that have the greatest effect on slope stability are-

- Slope gradient.
- Groundwater.

Generally, the greater the slope gradient and the more groundwater present, the less stable will be a given slope regardless of the geologic material or the soil type. It is absolutely essential that engineers engaged in locating, designing, constructing, and maintaining roads understand why slope gradient and groundwater are so important to slope stability.

Slope Gradient

The effects of slope gradient on slope stability can be understood by discussing the stability of pure, dry sand. Slope stability in

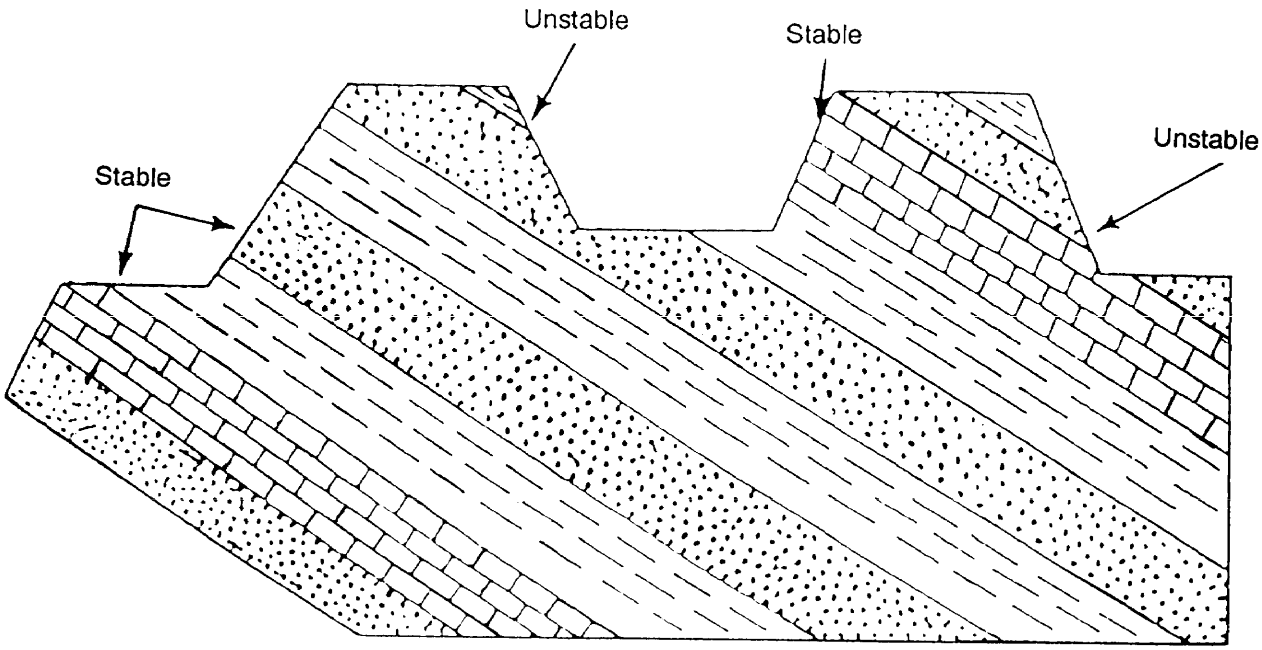


Figure 10-1. Slope of bedding planes.

sand depends entirely on frictional resistance to sliding. Frictional resistance to sliding, in turn, depends on—

- The slope gradient that affects the portion of the weight of an object that rests on the surface.
- The coefficient of friction.

Normal Force. The fraction of the weight of an object that rests on a surface is known as the normal force (N) because it acts normal to, or perpendicular to, the surface. The normal force changes as the slope of the surface changes.

The upper curve in *Figure 10-2, page 10-4,* shows how the gradient of a surface changes the normal force of a 100-pound block resting on the surface. When the slope gradient is zero, the entire weight of the 100-pound block rests on the surface and the normal force is 100 pounds. When the surface is vertical, there is no weight on the surface and the normal force is zero. The coefficient of friction converts the normal force to frictional resistance to sliding (F). An average value for the coefficient of friction for sand is about 0.7. This means that the force required to slide a block of sand along a surface is equal to 0.7 times the normal force.

The lower curve in *Figure 10-2, page 10-4* shows how the frictional resistance to sliding changes with slope gradient. The lower curve was developed by multiplying the values of points on the upper curve by 0.7. Therefore, when the slope gradient is zero, the normal force is 100 pounds, and 70 pounds of force is required to slide the block along the surface. When the slope gradient is 100 percent, the normal force is 71 pounds (from point 3 on the upper curve), and 50 pounds (or 71 pounds x 0.7) is required to slide the block along the surface (from point 3 on the lower curve).

Downslope Force. The portion of the weight that acts downslope provides some of the force to overcome frictional resistance to sliding. The downslope force, sometimes known as the driving force, also depends on the slope gradient and increases as the gradient increases (see *Figure 10-3, page 10-5).* Obviously, when the slope gradient becomes steep enough, the driving force exceeds the frictional resistance to sliding and the block slides.

Figure 10-4, page 10-6, shows the curve for frictional resistance to sliding (from *Figure 10-2, page 10-4)* superimposed on the curve of the driving force (from *Figure 10-3, page 10-5).* These two curves intersect at 70 percent (35 degree) slope gradient. In this example, this means that for slope gradients less than 70 percent, the frictional resistance to sliding is greater than the downslope component of the weight of the block and the block remains in place on the surface. For slope gradients greater than 70 percent, the block slides because the driving force is greater than the frictional resistance to sliding. This discussion has been confined to the case of pure, dry sand, a case which is seldom found in soils, but the principles of the effects of slope gradient and frictional resistance to sliding apply to any dry soil.

Shear Strength. A block of uniform soil fails, or slides, by shearing. That is, one portion of the block moves past another portion in a parallel direction. The surface along which this shearing action takes place is called the shear plane, or the plane of failure. The resistance to shearing is often referred to as shear strength. Pure sand develops shear strength by frictional resistance to sliding; however, pure clay is a sticky substance that develops shear strength because the individual particles are cohesive. The presence of clay in soils increases the shear strength of the soil over that of a pure sand because of the cohesive nature of the clay.

A dry clay has considerable shear strength as demonstrated by the great force required to crush a clod with the fingers. However, as a dry clay absorbs water, its shear strength decreases because water films separate the clay particles and reduce its cohesive strength. The structure of the clay particle determines how much water will be absorbed and, consequently, how much the shear strength will decrease upon saturation. There are some clays, such as illite and

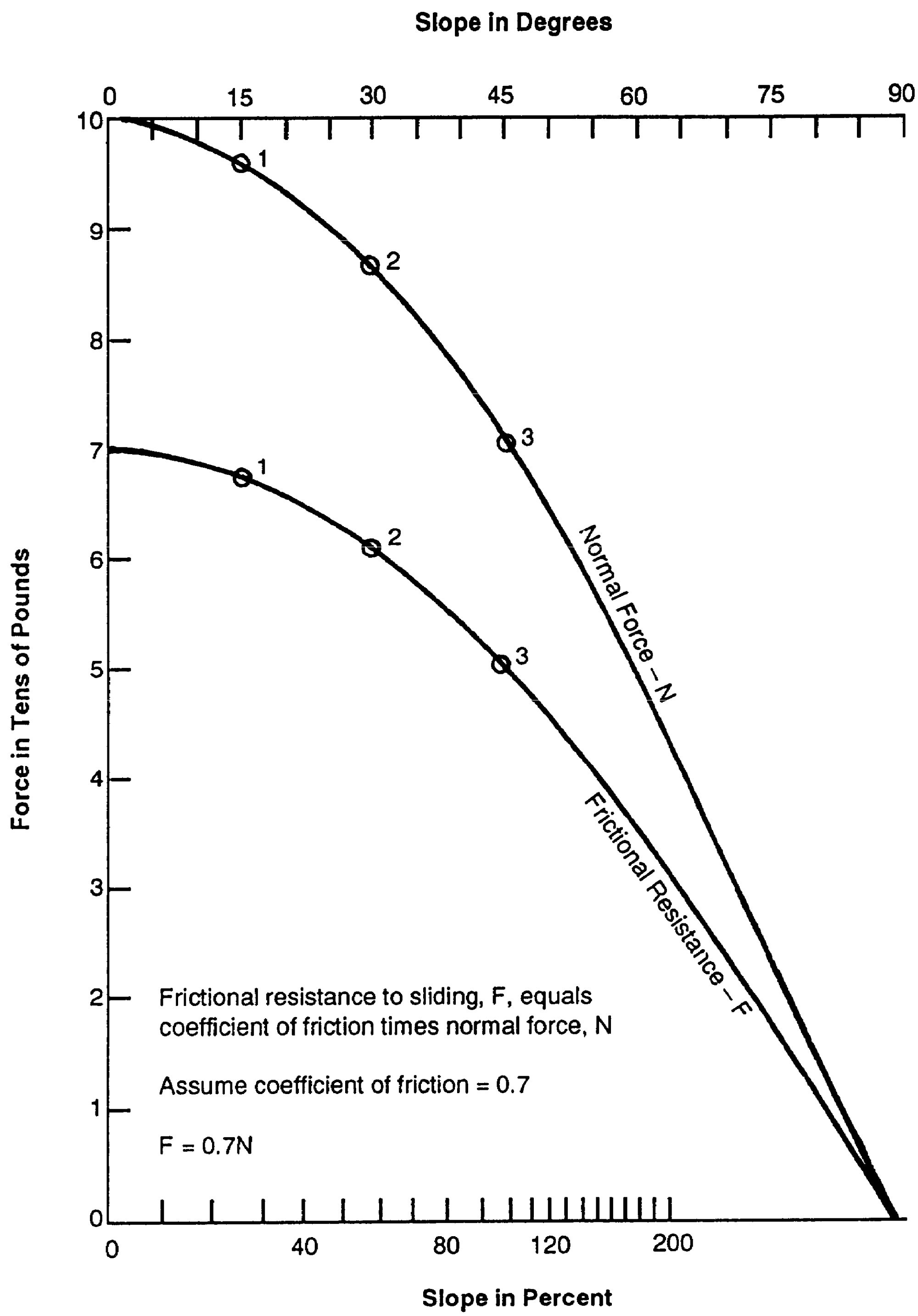


Figure 10-2. Normal force.

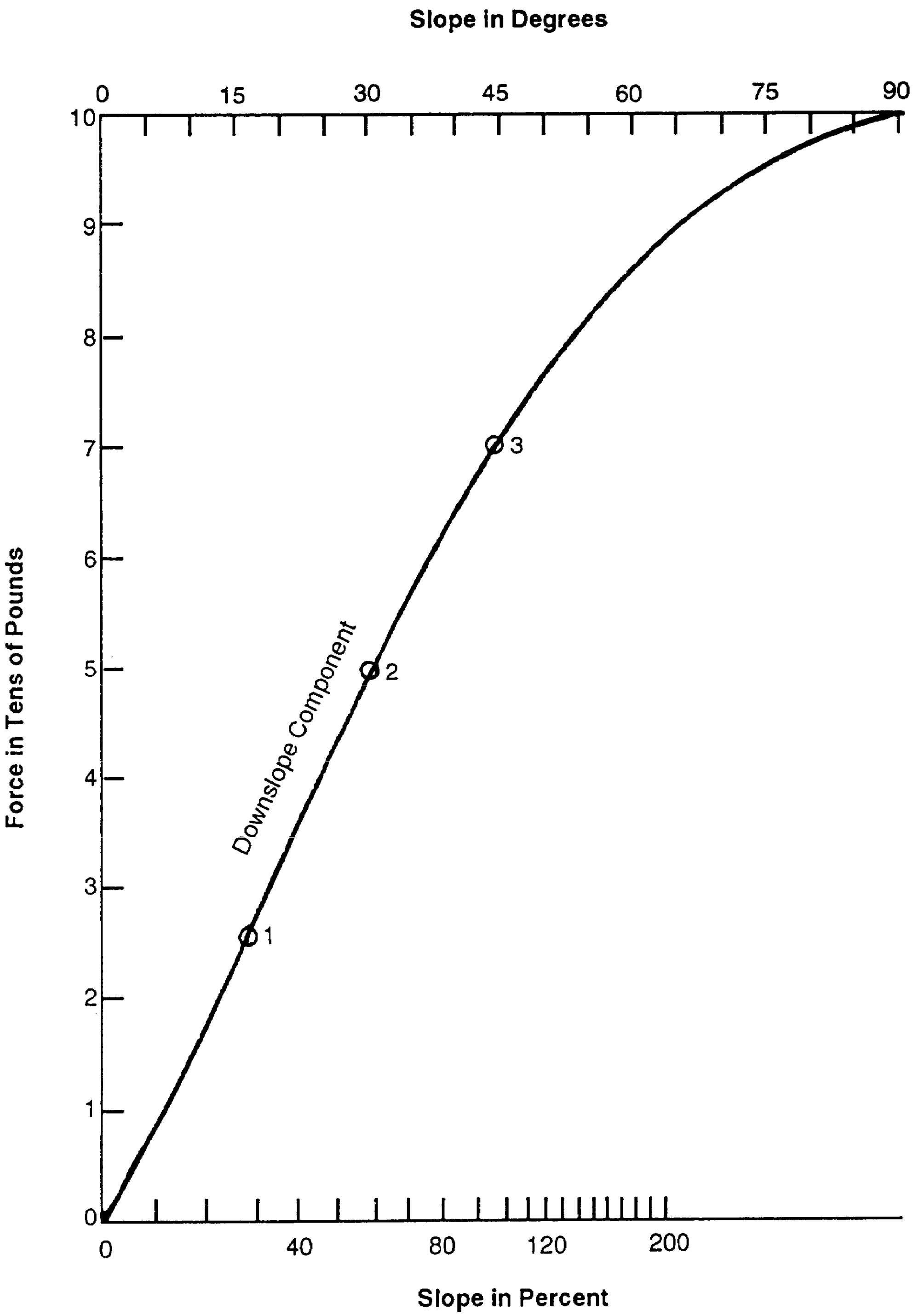


Figure 10-3. Downslope or driving force.

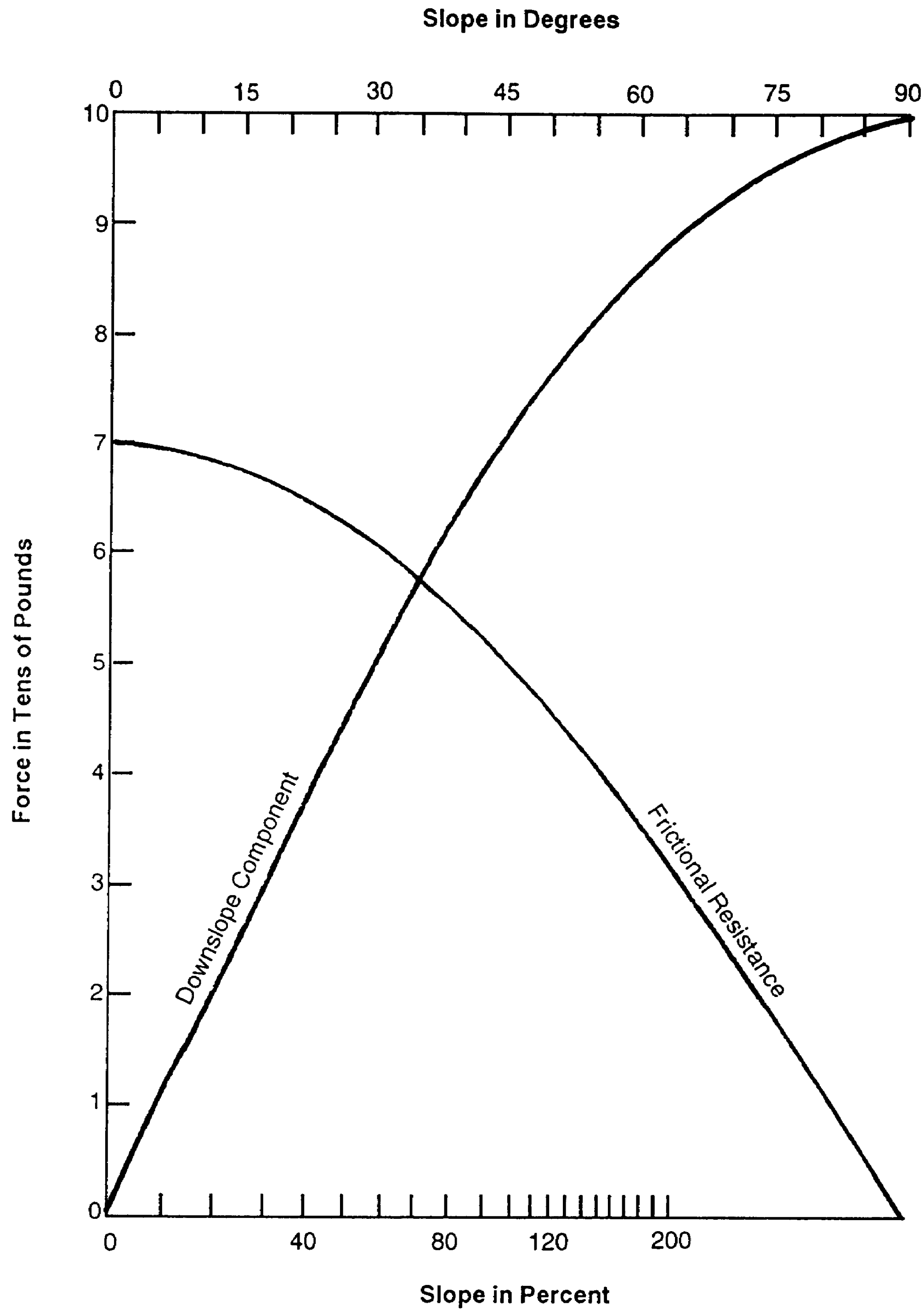


Figure 10-4. Frictional resistance to sliding.

kaolinite, that provide relative stability to soils even when saturated However, a saturated montmorillonite clay causes a significant decrease in slope stability. Saturated illite and kaolinite clays have about 44 percent of their total volume occupied by water compared to about 97 percent for a saturated montmorillonite clay. This explains why montrnorillonite clay has such a high shrink-swell potential (large change in volume from wet to dry) and saturated clays of this type have a low shear strength. Thus, the type of clay in a soil has a significant effect on slope stability.

Granitoid rocks tend to weather to sandy soils as the weathering process destroys the grain-to-grain contact that holds the mineral crystals together. If these soils remain in place long enough, they eventually develop a significant amount of clay. If erosion removes the weathered material at a rapid rate, the resulting soil is coarse-textured and behaves as a sand for purposes of slope stability analysis. Many soils with a significant clay content have developed from granitoid material. They have greater shear strength and support steeper cut faces than a granitoid-derived soil with little clay.

The relative stability among soils depends on a comparison of their shear strength and the downslope component of the weight of the soil. For two soils developed from the same geologic material, the soil with the higher percentage of illite or kaolinite clay has greater shear strength than a soil with a significant amount of montmorillonite clay.

Groundwater

A common observation is that a hillslope or the side slopes of a drainageway may be perfectly stable during the summer but may slide after the winter rains begin. This seasonal change in stability is due mainly to the change in the amount of water i n the pores of the soil. The effect of groundwater on slope stability can best be understood by again considering the block of pure sand. Frictional resistance to sliding in dry sand is developed as the product of the coefficient of friction and the normal force acting on the surface of the failure plane. A closeup view of this situation shows that the individual sand g-rains are interlocked, or jammed together, by the weight of the sand. The greater the force that causes this interlocking of sand grains, the greater is the ability to resist the shear force that is caused by the downslope component of the soil weight. As groundwater rises in the sand, the water reduces the normal force because of the buoyant force exerted on each sand grain as it becomes submerged.

Uplift Force

The uplift force of the groundwater reduces the interlocking force on the soil particles, which reduces the frictional resistance to sliding. The uplift force of groundwater is equal to 62.4 pounds per foot of water in the soil. The effective normal force is equal to the weight of the soil resting on the surface minus the uplift force of the groundwater.

The following example illustrates the calculation of the effective normal force.

- If 100 pounds of' sand rests on a horizontal surface and contains 3 inches (or 0.25 foot) of groundwater, then the effective normal force is 100 - (62.4 x 0.25) = 100 - 15.6 or 84.4 pounds. This shows how groundwater reduces frictional resistance to sliding.
- The frictional resistance to sliding with this groundwater condition is 84.4 x 0.7 (average coefficient of friction for sand), which equals 59.1 pounds.
- As a comparison, for 100 pounds of dry sand on a horizontal surface the frictional resistance to sliding is 100 x 0.7 or 70 pounds.

The following examples further emphasize how the presence of ground water can decrease slope stability by reducing the frictional resistance to sliding:

- First, a layer of dry sand 5 feet thick is assumed to weigh 100 pounds per foot of depth. The downslope component of the dry weight and the frictional resistance to sliding for dry sand was calculated for various slope gradients as in *Figure 10-2, page 10-4, and Figure 10-3, page 10-5.*

- Next, 6 inches of groundwater is assumed to be present and the frictional resistance to sliding is recalculated, taking into account the uplift force of the groundwater. The results of these calculations are shown in *Figure 10-5.*

Note: In a dry condition, sliding occurs when the slope gradient exceeds 70 percent. With 6 inches of groundwater, the soil slides when the slope gradient exceeds 65 percent.

- For a comparison, assume a dry sand layer only 2 feet thick that weighs 100 pounds per foot of depth. Again, assume 6 inches of groundwater and recalculate the downslope component of the soil weight and the frictional resistance to sliding with and without the groundwater (see *Figure 10-6).*

Note: With 6 inches of groundwater, this thin layer of soil slides when the slope gradient exceeds 58 percent.

These examples demonstrate that the thinner soil mantle has a greater potential for sliding under the same ground water conditions than a thicker soil mantle. The 6 inches of groundwater is a greater proportion of the total soil thickness for the 2-foot soil than for the 5-foot soil, and the ratio of uplift force to the frictional resistance to sliding is greater for the 2-foot soil. A pure sand was used in these examples for the sake of simplicity, but the principles still apply to soils that contain varying amounts of silt and clay together with sand.

Although adding soil may decrease the effect of uplift force on the frictional resistance to sliding, it is dangerous to conclude that slopes can be made stable solely through this approach. The added soil reduces uplift force, but it may increase another factor that in turn decreases frictional resistance, resulting in a slope failure. Decreasing the uplift force of water can be best achieved through a properly designed groundwater control system.

Seepage Force

There is still another way that groundwater contributes to slope instability, and that is the seepage force of groundwater as it moves downslope. The seepage force is the drag force that moving water exerts on each individual soil particle in its path. Therefore, the seepage force contributes to the driving force that tends to move masses of soil downslope. The concept of the seepage force may be visualized by noting how easily portions of a coarse-textured soil may be dislodged from a road cut bank when the soil is conducting a relatively high volume of groundwater.

SLOPE FAILURE

Slope failure includes all mass soil movements on—

- Man-made slopes (such as road cuts and fills).
- Natural slopes (in clear-cut areas or undisturbed forest).

A classification of slope failure is useful because it provides a common terminology, and it offers clues to the type of slope stability problem that is likely to be encountered. Types of slope and road failures are remarkably consistent with soils, geologic material, and topography. For example, fast-moving debris avalanches or slides develop in shallow, coarse-textured soils on steep hillsides; large, rotational slumps occur in deep, saturated soils on gentle to moderate slopes.

Rockfalls and Rockslides

Rockfalls and rockslides usually originate in bedded sediments, such as massive sandstone, where the beds are undercut by stream erosion or road excavation. Stability is maintained by the—

- Competence of the rock.
- Frictional resistance to sliding along the bedding planes.

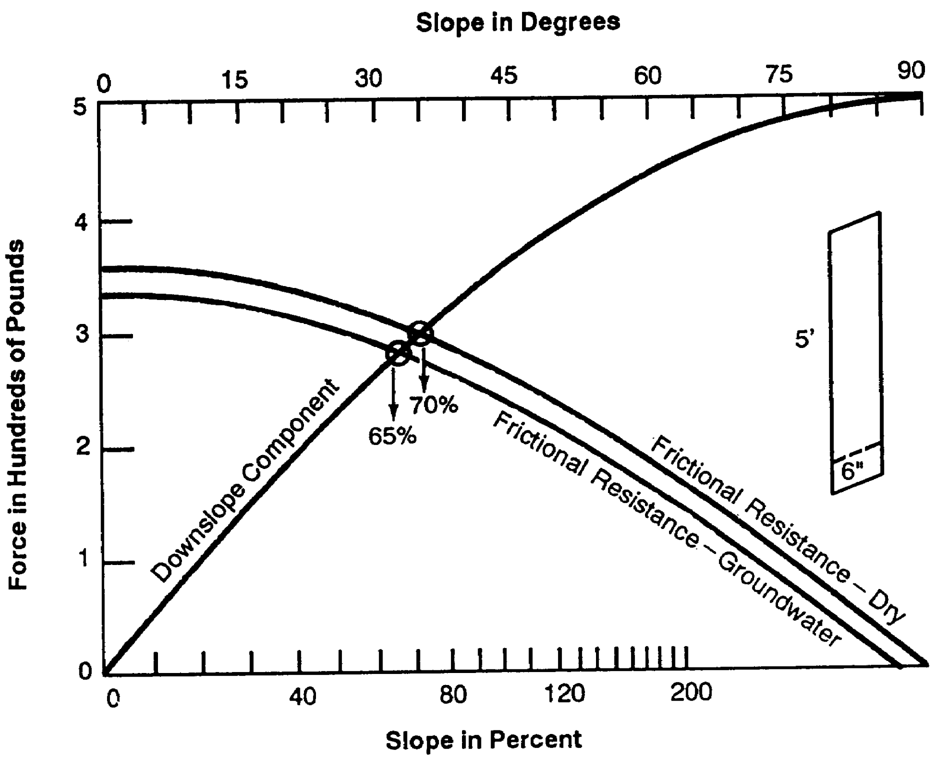


Figure 10-5. Frictional resistance to sliding with uplift force of groundwater.

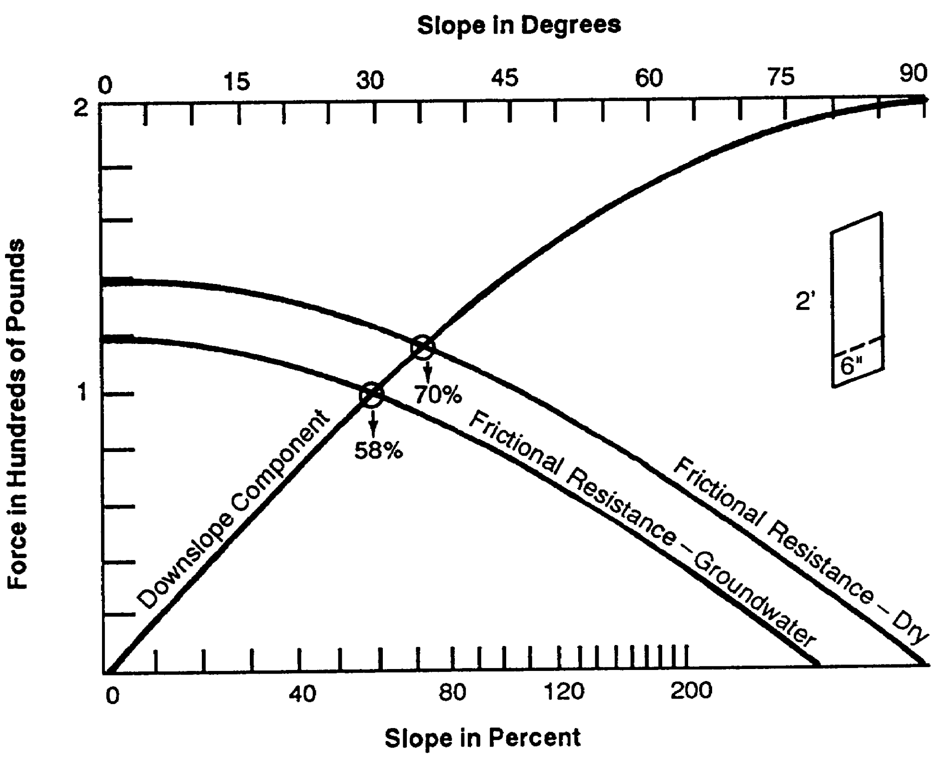


Figure 10-6. Frictional resistance to sliding with and without groundwater.

These factors are particularly important where the bedding planes dip downslope toward a road or stream. Rockslides occur suddenly, slide with great speed, and sometimes extend entirely across the valley bottom. Slide debris consists of fractured rock and may include some exceptionally large blocks. Road locations through areas with a potential for rockslides should be examined by specialists who can evaluate the competence of the rock and determine the dip of the bedding planes.

Debris Avalanches and Debris Flows

These two closely related types of slope failure usually originate on shallow soils that are relatively low in clay content on slopes over 65 percent. In southeast Alaska, the US Forest Service has found that debris avalanches develop on slopes greater than 65 percent on shallow, gravelly soils and that this type of slope failure is especially frequent on slopes over 75 percent.

Debris avalanches are the rapid downslope flowage of masses of loose soil, rock, and forest debris containing varying amounts of water. They are like shallow landslides resulting from frictional failure along a slip surface that is essentially parallel to the topographic surface, formed where the accumulated stresses exceed the resistance to shear. The detached soil mantle slides downslope above an impermeable boundary within the loose debris or at the unweathered bedrock surface and forms a disarranged deposit at the base. Downslope, a debris avalanche frequently becomes a debris flow because of substantial increases in water content. They are caused most frequently when a sudden influx of water reduces the shear strength of earth material on a steep slope, and they typically follow heavy rainfall.

There are two situations where these types of slope failure occur in areas with shallow soil, steep slopes, and heavy seasonal rainfall.

The first situation is an area where stream development and geologic erosion have formed high ridges with long slopes and steep, V-shaped drainages, usually in bedded sedimentary rock. The gradient of many of these streams increases sharply from the main stream to the ridge; erosion has created headwalls in the upper reaches. The bowl-shaped headwall region is often the junction for two or more intermittent stream channels that begin at the ridgetop. This leads to a quick rise in ground water levels during seasonal rains. Past debris avalanches may have scoured round-bottom chutes, or troughs, into the relatively hard bedrock. The headwall region may be covered with only a shallow soil mantle of precarious stability, and it may show exposed bedrock, which is often dark with ground water seepage.

The second situation with a high potential for debris avalanches and flows is where excavated material is sidecast onto slopes greater than 65 percent. The sidecast material next to the slope maintains stability by frictional resistance to sliding and by mechanical support from brush and stumps. As more material is sidecast, the brush and stumps are buried and stability is maintained solely by frictional resistance to sliding. Since there is very little bonding of this material to the underlying rock, the entire slope is said to be overloaded. It is quite common for new road fills on steep overloaded slopes to fail when the seasonal rains saturate this loose, unconsolidated material, causing debris avalanches and flows. Under these circumstances, the road fill, together with a portion of the underlying natural slope, may form the debris avalanche (see *Figure 10-7).*

Debris avalanches and debris flows occur suddenly, often with little advance warning. There is practically nothing that can be done to stabilize a slope that shows signs of an impending debris avalanche. The best possible technique to use to prevent these types of slope failures is to avoid—

- Areas with a high potential for debris avalanches.
- Overloading steep slopes with excessive sidecast.

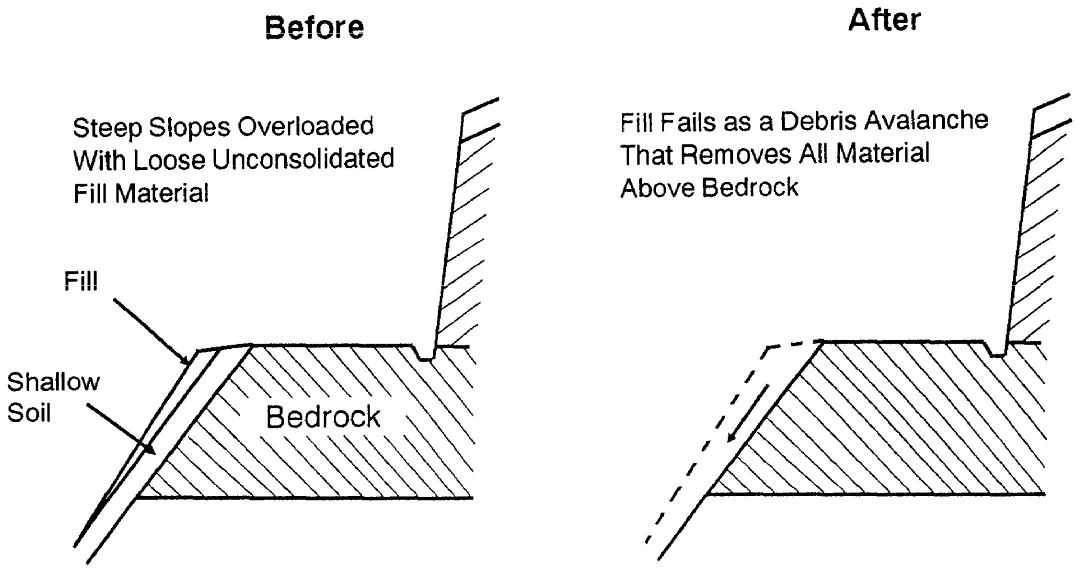


Figure 10-7. Debris avalanche.

Engineers should learn the vegetative and soil indicators of this type of unstable terrain, especially for those areas with high seasonal groundwater levels.

If unstable terrain must be crossed by roads, then radical changes in road grade and road width may be required to minimize site disturbance. Excavated material may need to be hauled away to keep overloading of unstable slopes to an absolute minimum. The location of safe disposal sites for this material may be a serious problem in steep terrain with sharp ridges. Site selection will require just as much attention to the principles of slope stability as to the location and construction of the remainder of the road.

Slumps and Earthflows

Slumps and earthflows usually occur in deep, moderately fine- or fine-textured soils that contain a significant amount of silt and/or clay. In this case, shear strength is a combination of cohesive shear strength and frictional resistance to sliding. As noted earlier, groundwater not only reduces frictional resistance to shear, but it also sharply reduces cohesive shear strength. Slumps are slope failures where one or more blocks of soil have failed on a hemispherical, or bowl-shaped, slip surface. They may show varying amounts of backward rotation into the hill in addition to downslope movement (see *Figure 10-8, page 10-12).* The lower part of a typical slump is displaced upward and outward like a bulbous toe. The rotation of the slump block usually leaves a depression at the base of the main scarp. If this depression fills with water during the rainy season, then this feature is known as sag pond. Another feature of large slumps is the "hummocky" terrain, composed of many depressions and uneven ground that is the result of continued earthflow after the original slump. Some areas that are underlain by particularly incompetent material, deeply weathered and subject to heavy winter rainfall, show a characteristically hummocky appearance over the entire landscape. This jumbled and rumpled appearance of the land is known as melange terrain.

Depressions and sag ponds allow winter rains to enter the ground water reservoir, reduce the stability of the toe of the slump, and promote further downslope movement of the entire mass. The mature timber that usually covers old slumps often contains "jackstrawed, " or "crazy," trees that lean at

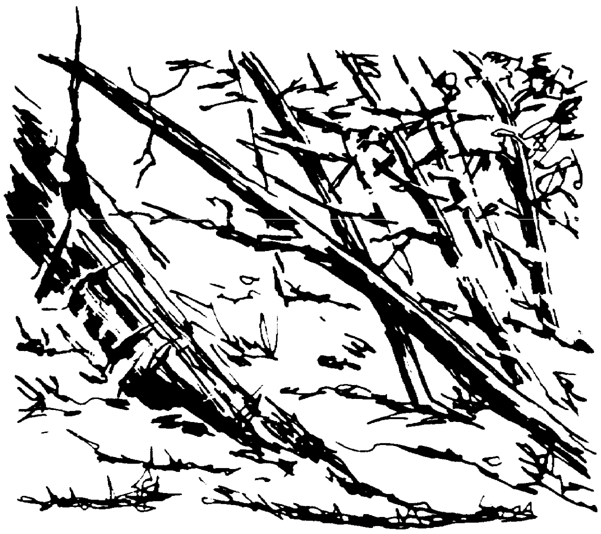


Figure 10-8. Backward rotation of a slump block.

many different angles within the stand. This indicates unstable soils and actively moving slopes (see *Figure 10-9).*

There are several factors affecting slumps that need to be examined in detail to understand how to prevent or remedy this type of slope failure. The block of soil that is subject to slumping can be considered to be resting on a potential failure surface of hemispherical shape (see *Figure 10-10).* The block is most stable when its center of gravity is at its lowest position on this failure surface. When the block fails, its center of gravity is shifted to a lower, more stable position as a result of the failure. Added weight, such as a road fill, at the head of a slump shifts the center of gravity of the block to a higher, more unstable position and tends to increase the potential for rotation. Similarly, removing weight from the toe of the slump, as in excavating for a road, also shifts the center of gravity of the block to a higher position on the failure surface. Therefore, loading the head of a slump and/or unloading the toe will increase the potential for further slumping on short slopes (see *Figure 10-11).* The chance of slumping can be reduced by shifting the center of gravity of a potential slump block to a lower position by following the rule: Unload the head and load the toe.

Figure 10-9. Jackstrawed trees.

If it is absolutely necessary to locate a road through terrain with a potential for slumping, there are several techniques that may be considered to help prevent slumps and earthflows. They are—

- Improve the surface drainage.
- Lower the groundwater level.
- Use rock riprap, or buttresses, to provide support.
- Install an interceptor drain.
- Compact fills.

Surface Drainage. Improving the surface drainage is one of the least expensive and most effective techniques, but it is often overlooked. Sag ponds and depressions can be connected to the nearest stream channel with ditches excavated by a bulldozer or a grader. *Figure 10-12, page 10-14,* shows the theoretical effect on the groundwater reservoir of a surface drainage project. Improved drainage removes surface water quickly, lowers the groundwater level, and helps stabilize the slump.

Groundwater Level. Lower the groundwater level by means of a perforated pipe that is augered into the slope at a slight upward

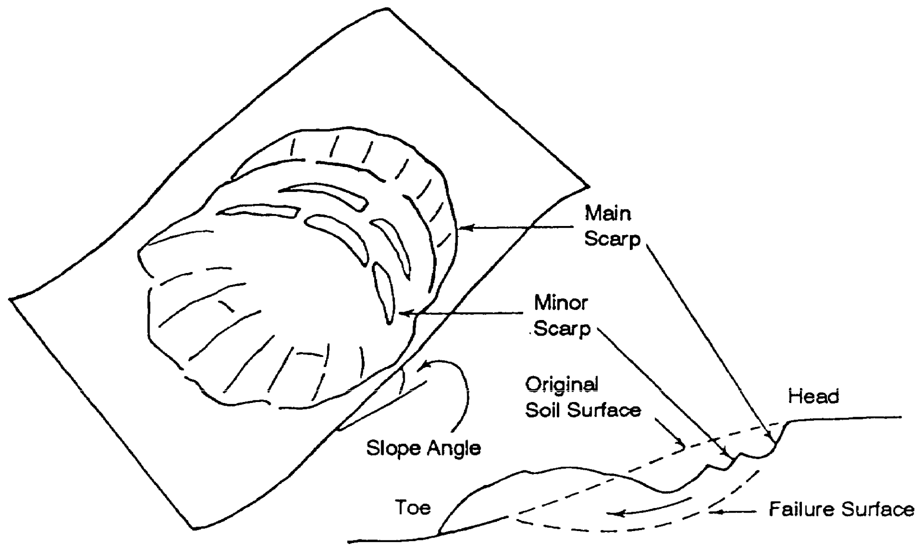


Figure 10-10. Structural features of a slump.

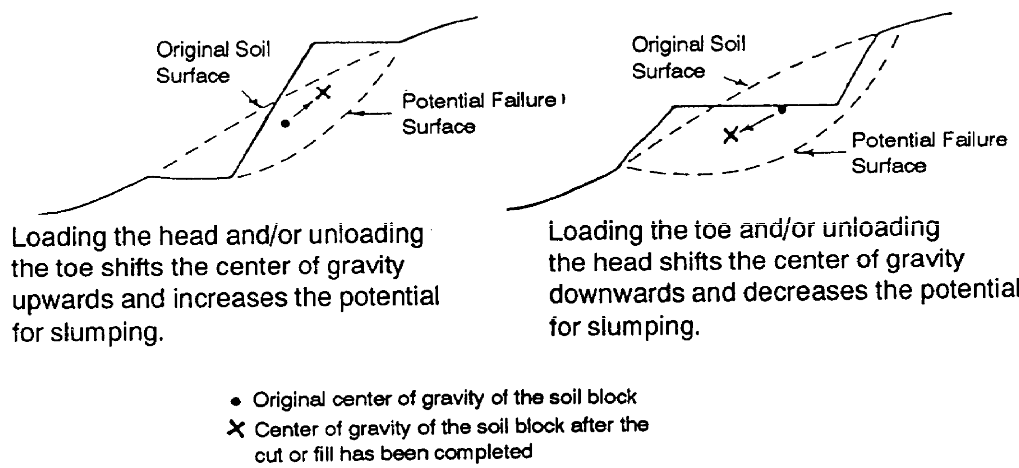
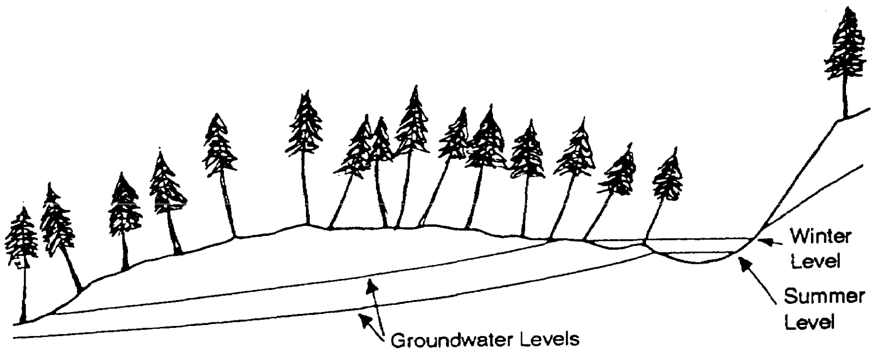


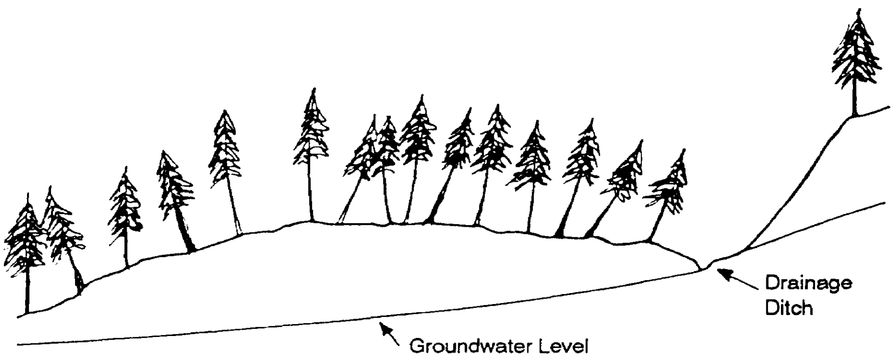
Figure 10-11. Road construction across short slopes.

angle. These drains are usually installed in road cutbanks to stabilize areas above an existing road or below roads to stabilize fills. Installing perforated pipe is relatively expensive, and there is a risk that slight shifts in the slump mass may render the pipe ineffective. In addition, periodic cleaning of these pipes is necessary to prevent blockage by algae, soil, or iron deposits.

Rock Riprap, or Buttresses. Stabilize existing slumps and prevent potential slumps by using rock riprap, or buttresses, to provide support for road cuts or fills (see *Figure 10-13, page 10-15).* Heavy rock riprap replaces the stabilizing weight that is by excavation during road construction (see *Figure 10-11).* Another feature of riprap is that it is porous and allows groundwater to drain out of the



Sag ponds add water to the groundwater reservoir and increase the potential for further slumping.



Ditches drain sag ponds, lower groundwater levels, and increase slope stability.

Figure 10-12. Increasing slope stability with surface drainage.

slump material while providing support for the cut slope.

Interceptor Drain. Install an interceptor drain to collect groundwater that is moving laterally downslope and under the road, saturating the road fill. A backhoe can be used to install interceptor drains in the ditch along an existing road. *Figure 10-14* shows a sample installation.

Fills. Compact fills to reduce the risk of road failure when crossing small drainages. Compaction increases the density of the material, reduces the pore space, and thereby reduces the adverse effect of ground water. The foundation material under the proposed fill should be evaluated as part of the design process to determine if this material will support a compacted fill without failure. Roads may often be built across gentle slopes of incompetent material with a high groundwater table by overexcavating the material, placing a thick blanket of coarse material, then building the road on the blanket (see *Figure 10-15, page 10-16)*. The coarse rock blanket distributes the weight of the roadway over a larger area and provides better drainage for groundwater under the road.

Soil Creep

Many of these slope failures may be preceded and followed by soil creep, a relatively slow-moving type of slope failure. Soil

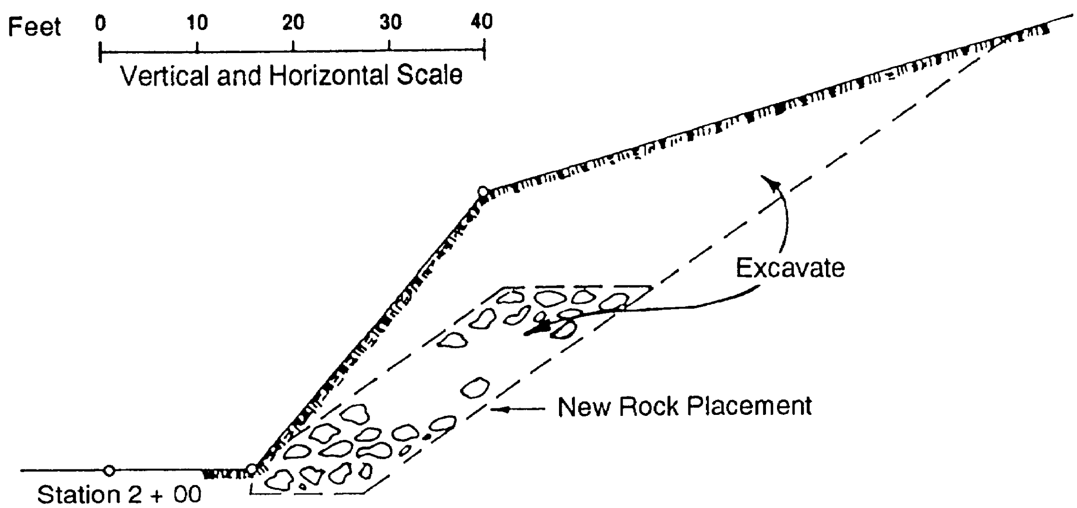


Figure 10-13. Using rock riprap to provide support for road cuts or fills.

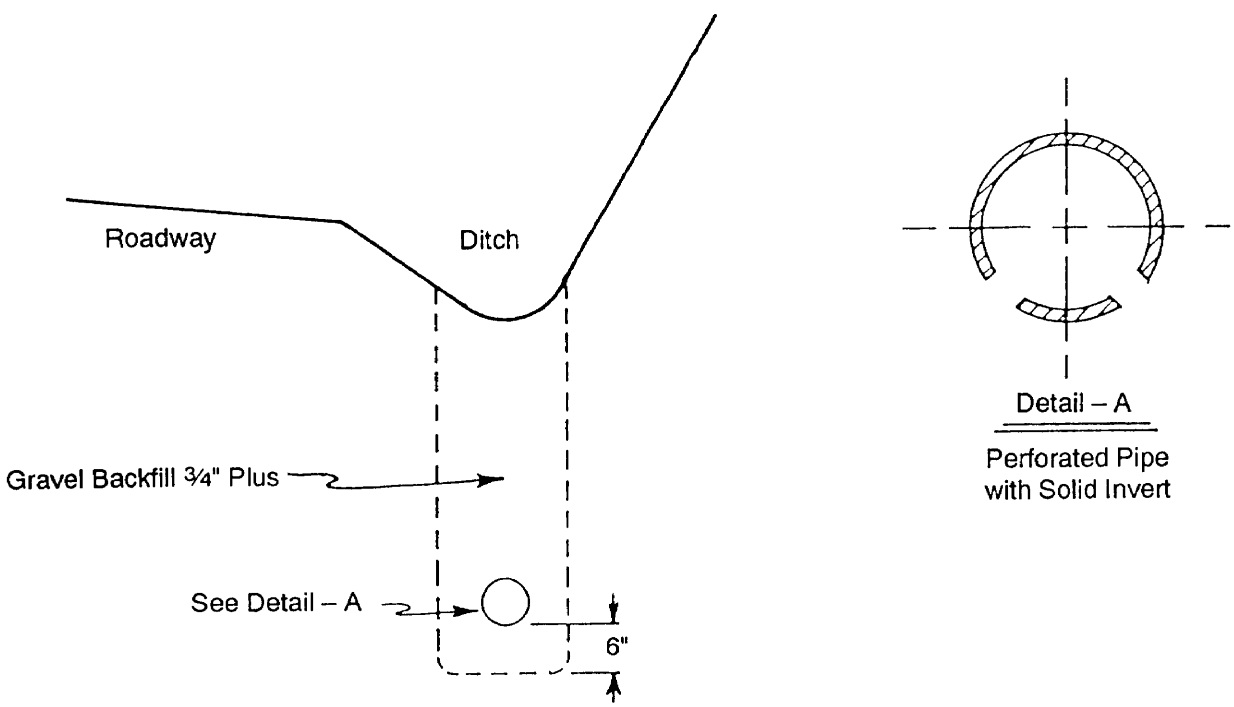


Figure 10-14. Installing interceptor drains along an existing road.

creep may be a continuous movement on the order of less than 1 foot per decade. The indicators of soil creep may be subtle, but you must be aware of the significance of this type of slope failure. Soil creep, at any moment, may be immeasurable; however, when the effect is cumulated over many years, it can create stresses within the soil mantle that may approach the limit of frictional resistance to sliding and/or the cohesive shear strength along a potential shear failure surface.

Soil creep is particularly treacherous in conjunction with debris avalanches. The balance between stability and failure may be approached gradually over a number of years until only a heavy seasonal rain or a minor disturbance is necessary to trigger a catastrophic slope failure. Soil creep also builds up stresses in potential slumps so that even moderate rainfall may start a slow earthflow on a portion of the slope. Depending on the particular conditions, minor movement may temporarily relieve these stresses and create sags or bulges in the slope; or it may slightly steepen the slope and increase the potential for a major slump during the next heavy rain. The point to remember is that soil creep is the process that slowly changes the balance of forces on slopes. Even though an area may be stable enough to withstand high seasonal groundwater levels this year, it may not be able to 5 years from now.

STABLE SLOPE CONSTRUCTION IN BEDDED SEDIMENTS

Construction of stable roads requires not only a basic understanding of regional geology and soil mechanics but also specific, detailed information on the characteristics of soils, groundwater, and geology where the road is to be built. This following paragraphs present techniques on road location and the soil and vegetative indicators of slope instability and high groundwater levels.

Bedded sediments vary from soft siltstone to hard, massive sandstone. These different geologic materials, together with geologic processes and the effect of climate acting over long periods of time, determine slope gradient, soil, and the rate of erosion. These factors also determine the particular type of slope stability problem that is likely to be encountered. There are four slope stability problems associated with distinctive sites within the bedded sediments. They are—

- Sandstone - Type I.
- Sandstone - Type II.
- Deeply weathered siltstone.
- Sandstone adjoining ridges of igneous rock.

Sandstone - Type I

Type I sites are characterized by sharp ridges with steep slopes that may show a uniform gradient from near the ridgetop to the valley bottom. The landscape is sharply dissected by numerous stream channels that may become extremely steep as they approach the ridgetop. Headwalls (bowl-shaped areas with slope gradients often 100 percent or greater) may be present in the upper reaches of the drainage. The headwall is usually the junction for several intermittent streams that can cause sharp rises in the groundwater levels in the soil mantle during winter storms. It is quite common to note groundwater seepage on exposed bedrock in the headwall even during the summer. *Figure 10-16* shows a block diagram that

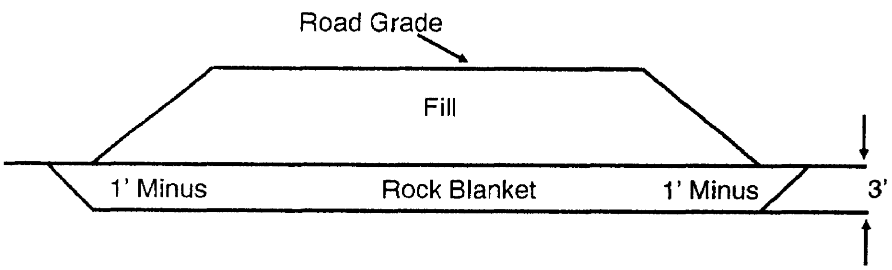
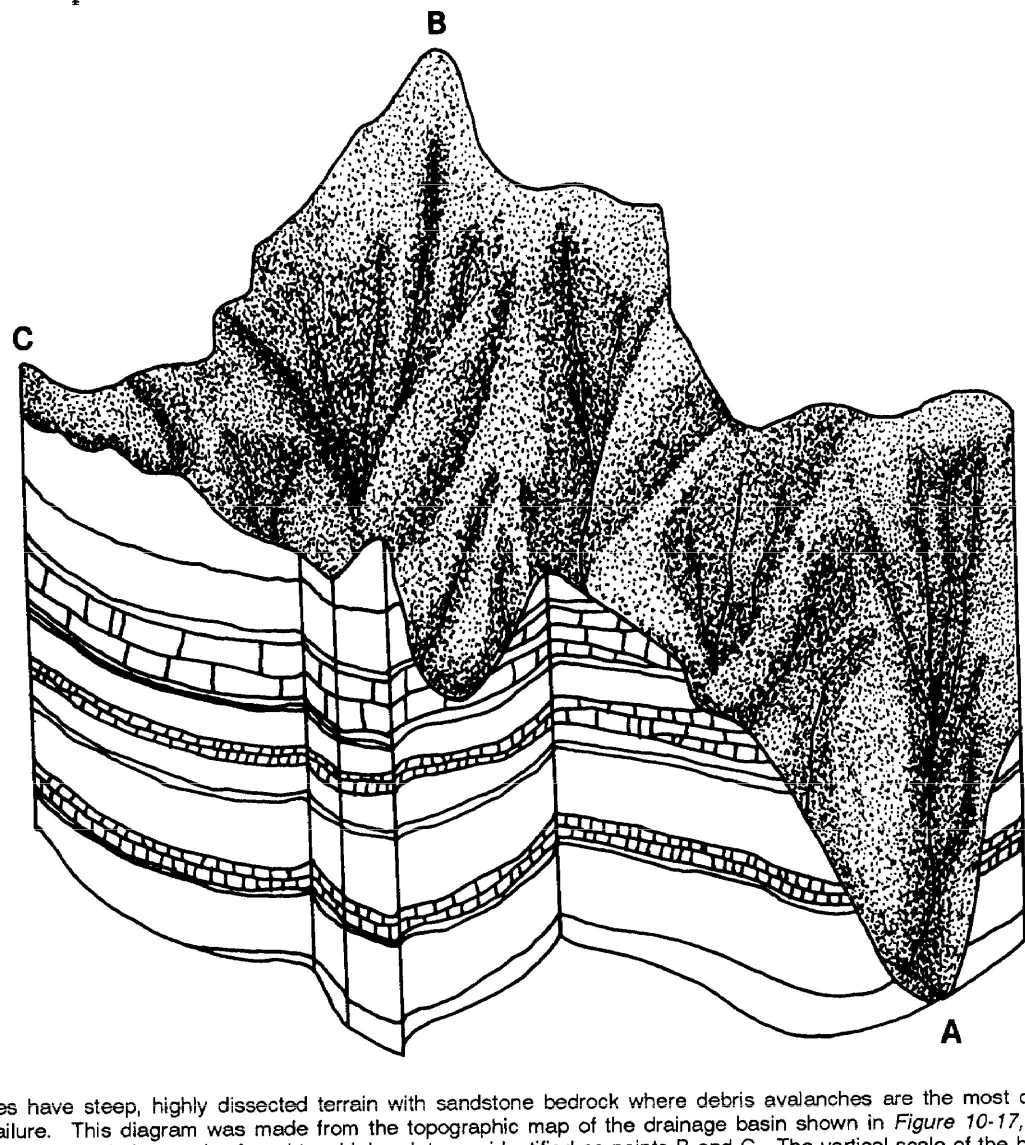


Figure 10-15. Building a road on a blanket.

illustrates the features of Type I sites. This area was taken from the topographic map of the upper Smith River in Oregon *(Figure 10-17, page 10-18).*

The soils on the most critical portions of Type I sites are coarse-textured and shallow (less than 20 inches to bedrock). These soils are considered to be unstable on slopes greater than 80 percent. In areas where groundwater is present, these soils are considered to be unstable on slopes considerably less than 80 percent.

Debris avalanches and debris flows are the most common slope failure on Type I sites, and the headwall region is the most likely point of origin for these failures. Road construction through headwalls causes unavoidable sidecast. The probability is high for even minimum amounts of sidecast to overload slopes with marginal stability and to cause these slopes to fail. Observers often comment on the stability of full bench roads built through headwalls without realizing that debris avalanches may have occurred during construction before any traffic moved over the road.



Type I sites have steep, highly dissected terrain with sandstone bedrock where debris avalanches are the most common kind of slope failure. This diagram was made from the topographic map of the drainage basin shown in *Figure 10-17, page 10-18.* The mouth of the basis is at point A and two high points are identified as points B and C. The vertical scale of the block diagram is greatly exaggerated. Note the steep headwall areas below point B and above point A.

Figure 10-16. Block diagram of Type I site.

Unstable-Slope Indicators. There are certain indicators of unstable slopes in Type I sites that may be used during road location. They are—

- Pistol-butted trees (see *.Figure 10-18).* Sliding soil or debris or active soil creep caused these trees to tip downslope while they were small. As the tree grew, the top regained a vertical posture. Pistol-butted trees are a good indicator of slope instability for areas where rain is the major component of winter precipitation; however, deep, heavy snow packs at high elevations may also cause this same deformation.
- Tipped trees (see *Figure 10-19).* These trees have a sharp angle in the stem. This indicates that the tree grew straight for a number of years until a small shift in the soil mantle tipped the tree. The angled stem is the result of the recovery of vertical growth.
- Tension cracks (see *Figure 10-20).* Soil creep builds up stresses in the soil mantle that are sometimes relieved by tension cracks. These features may be hidden by vegetation, but they definitely indicate active soil movement.

Road-Location Techniques. Techniques for proper road location on Type I sites include the following:

- Avoid headwall regions. Ridgetop locations are preferred rather than crossing through headwall regions.
- Roll the road grade. Avoid headwalls or other unstable areas by rolling the road grade. Short, steep pitches of adverse and favorable grade may be included,

Construction Techniques. Consider the following techniques when roads must be constructed across long, steep slopes or above headwall regions where sidecast must beheld to a minimum:

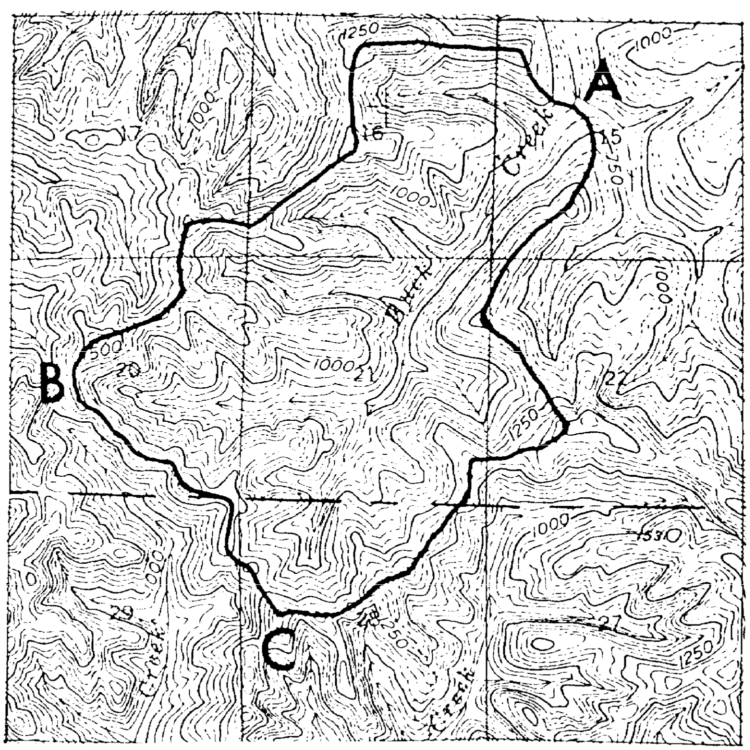


Figure 10-17. Topographic map of Type I site.

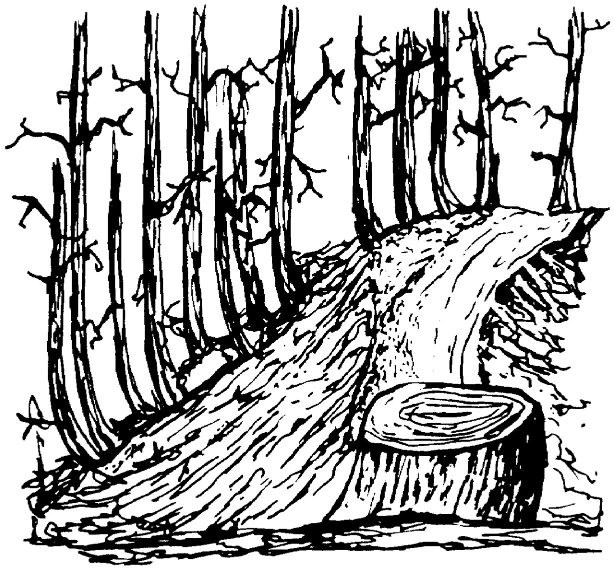


Figure 10-18. Pistol-butted trees.

Figure 10-19. Tipped trees.

- Reduce the road width. This may require a small tractor with a more narrow blade (for example, a D6) for construction. A U-shaped blade results in less sidecast than a straight blade, possibly because of better control of loose material.
- Control blasting techniques. These techniques may be used to reduce overbreakage of rock and reduce the amount of fractured material that is thrown out of the road right-of-way and into stream channels.
- Remove material. Hauling excavated material away from the steepest slopes may be necessary to avoid overloading the lower slopes.
- Select safe disposal sites. Disposal sites for excavated material should be chosen with care to avoid overloading a natural bench or spur ridge, causing slope failure (see *Figure 10-21, page 10-20).* The closest safe disposal site may be a long distance from the construction site but the additional hauling costs must be weighed against the damage caused by failure of a closer disposal site with a higher probability of failure.
- Fill saddles. Narrow saddles may be used to hold excess material by first excavating bench roads below and on each side of the saddle. The saddle may then be flattened and the loose

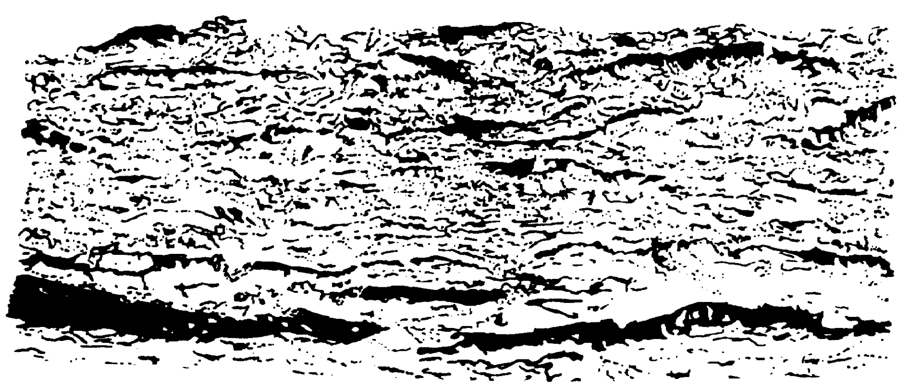


Figure 10-20. Tension cracks.

Figure 10-21. Safe disposal site.

material that rolls downslope will be caught by the benches. Excavated material may be compacted on the flattened ridge to buildup the grade.

- Choose the correct culvert size. A culvert should carry the maximum estimated flow volume for the design storm.
- Protect slopes. Culverts must not discharge drainage water onto the base of a fill slope. Culverts should either be designed to carry water on the natural grade at the bottom of the fill or downspouts or half-round culverts should be used to conduct water from the end of shorter culverts down the fill slope to the natural channel.

Sandstone - Type II

Type II sites have slopes with gradients that range from less than 10 percent up to 70 or 80 percent. The longer slopes may be broken by benches and have rounder ridges, fewer drainages, and gentler slope gradients than those on Type I sites. Headwalls are rare, and small patches of exposed bedrock are only occasionally found on the steeper slopes.

The soils on the gentle slopes developed over many centuries and are deep (often greater than 40 inches), with a clay content as high as 50 to 70 percent. The soils on the steeper slopes may be as deep as 40 inches, but the bedrock is fractured and weathered so there is a gradual transition from the soil into the massive bedrock. It is these factors of deeper soils, higher clay content, gentler slopes, and a gradual transition to bedrock that makes this terrain more stable than the terrain on Type I sites.

The factors that characterize Type II sites also cause this terrain to have more slope failures due to slumps and earthflows. The most unstable portions of Type II sites are the steep, concave slopes at the heads of drainages, the edge of benches, or the locations where ground water tends to accumulate. Road failures frequently involve poorly consolidated or poorly drained road fills and embankments greater than 12 to 15 feet on any of the red clayey soils. Soil creep also creates tension within the clayey soils at the convex ridge nose where slope gradients may be onfy 50 percent. Excavation for roads at these points of sharp slope convexity sometimes causes failure of the embankment.

Unstable-Slope Indicators. Vegetative indicators of unstable portions of the landscape include mature trees that tip or lean as a result of minor earthflow or soil creep on the steeper slopes. Tipped or leaning trees may also be found on poorly drained soils adjacent to the stream channels. Actively moving slopes may show tension cracks, particularly on the steeper slopes.

There are several good indicators that may be used to determine the height that groundwater may rise in the soil and roughly how long during the year that the soil remains saturated. Iron compounds within the soil profile oxidize and turn rusty red or bright orange and give the soil a mottled appearance when the groundwater rises and falls intermittently during the winter. The depth below the soil surface where these mottles first occur indicates the average maximum height that this fluctuating water table rises in the soil. At locations where the water table remains for long periods during the year, the iron compounds are chemically reduced and give the soil profile a gray or bluish-gray appearance. The occurrence of these gleyed soils indicates a soil that is saturated for much of the year. Occasionally, mottles may appear above a gleyed subsoil, which indicates a seasonally fluctuating water table above a subsoil that is subject to prolonged saturation. Engineers should be aware of the significance of mottled and gleyed soils that are exposed during road construction. These indicators give clues to the need for drainage or extra attention concerning the suitability of a subsoil for foundation material.

Road-Location Techniques. Techniques for locating stable roads on Type II sites include the following

- Avoid steep concave basins. Do not locate roads through these areas where stability is questionable, as indicated by vegetation and topography. Ridgetop locations are preferred.
- Choose stable benches. Benches may offer an opportunity for location of roads and landings, but these benches should be examined carefully to see that they are supported by rock and are not ancient, weathered slumps with marginal stability.
- Avoid cracked soil. Avoid locating a road around convex ridge noses or below the edge of benches where tension cracks or catsteps indicate a high probability for embankment failure.

Construction Techniques. Certain design and construction practices should be considered when building roads in this terrain.

- Avoid overconstruction. If it is necessary to build a road across steep drainages, avoid overconstruction and haul excess material away to avoid overloading the slopes.
- Avoid high cut embankments. An engineer or soil scientist may be able to suggest a maximum height at the ditch line for the particular soil and situation. A rule-of-thumb estimate for maximum height for a cut bank in deep, clayey soils is 12 to 15 feet.
- Pay special attention to fills. Fills of clayey material over steep stream crossings may fail if the material is not compacted and if groundwater saturates the base of the fill. Fill failures in this wet, clayey material on steep slopes tend to move initially as a slump, then may change to a mudflow down the drainage. To avoid this, compact the fill to accepted engineering standards, paying special attention to proper lift thicknesses, moisture content, and foundation conditions. Also, design drainage features, where necessary, to control groundwater in the base of a fill. For example, consider either a perforated pipe encased in a crushed rock filter or a blanket of crushed rock under the entire fill.

Deeply Weathered Siltstone

This stability problem originates in siltstone that is basically incompetent and easily weathered. Slumps and earthflows, both large and small, are very common when this material is subjected to heavy winter rainfall. The landscape may exhibit a benchy or hummocky appearance. Slopes with gradients as low as 24 percent may be considered unstable in deeply weathered siltstone with abundant water.

Unstable-Slope Indicators. Vegetative and topographic indicators of slope instability are numerous. Large patches of plants associated with set soils indicate high groundwater levels and impeded drainage. Conifers may tip or lean due to earthflow or soil creep. Slumps cause numerous benches, some of which show sag ponds. Blocks of soil may sag and leave large cracks, which gradually fill in with debris and living vegetation. The sharp contours of these features soften in time until the cracks appear as “blind drainages” or sections of stream channel that are blocked at both ends. The cracks collect water, keep the groundwater reservoir charged, and contribute to active soil movement.

Road-Location Techniques. Techniques for locating stable roads through terrain that has been derived from deeply weathered silt-stone include the following

- Check for indicators of groundwater. Avoid locating roads through areas where groundwater levels are high and where slope stability is likely to be at its worst. Such locations may be indicated by hydrophytes, tipped *or* leaning trees, and mottled or gleyed soils.
- Consider ridges. Ridgetop locations may be best because groundwater drainage is better there. Also, the underlying rock may be harder and may provide more stable roadbuilding material than weathered siltstone.
- Ensure adequate reconnaissance. Take pains to scout the terrain away from the proposed road location, using aerial photos and ground reconnaissance to be sure that the line does not run through or under an ancient slump that may become unstable due to the road construction.

Construction Techniques. Special road design and construction techniques for this type of terrain may include the following

- Drainage ditches. Every effort should be made to improve drainage, both surface and subsurface, since groundwater is the major factor contributing to slope instability for this material. Sag ponds and bogs may be drained with ditches excavated by tractor or with ditching dynamite.
- Culverts. Extra culverts should be used to prevent water from pending above the road and saturating the road prism and adjacent slopes.
- Road ditches. They should be carefully graded to provide plenty of fall to keep water moving. A special effort should be made to keep ditches and culverts clean following construction.

Sandsone Adjoining Ridges of Igneous Rock

This slope stability problem in bedded sediments is caused by remnants of sandstone adjoining ridges of igneous rock. As a general rule, any contact zone between sedimentary material and igneous material is likely to have slope stability problems.

Unstable-Slope Indicators. The igneous rock may have caused fracturing and partial metamorphosis of the sedimentary rock at the time of intrusion. Also, water is usually abundant at the contact zone because the igneous material is relatively impermeable compared to the sediments; therefore, the sedimentary rock may be deeply weathered.

Road-Location Techniques. Special road location techniques for this type of slope stability problem include the following

- Pay attention to the contact zone. Examine the terrain carefully on the ground and on aerial photos to determine if the mass of sandstone is large or small relative to the igneous rock mass. If the sandstone is in the form of a relatively large spur ridge, then the contact zone deserves special attention. The contact zone should be crossed as high as possible where groundwater accumulation is at a minimum. Elsewhere on the ridge of sandstone, the stabilty problems are the same as for Type I or Type II sandstone.
- Consider an alternative location. If the remnant of sandstone is relatively small, such as a ridge nose, then the entire mass of sandstone may be creeping rapidly enough to be considered unstable and the road should be located above this material in the more stable igneous rock.

Construction Techniques. Design and construction techniques to be considered are as follows:

- Avoid high embankments. The sedimentary rock in the contact zone is likely to be fractured and may be somewhat metamorphosed as a result of the intrusion of igneous rock. In addition, the accumulation of groundwater is likely to have caused extensive weathering of this material. The road cut height at the ditch line should be kept as low as possible through this zone. Support by rock riprap may be necessary if the cut embankment must be high.

- Ensure good drainage. It is good a practice to put a culvert at the contact zone with good gradient on the ditches to keep the contact zone well drained. Other drainage measures, such as drain tile or perforated pipe, may be necessary.