Chapter 23

JERRY D. HIGGINS AND
VICTOR A. MODEER, JR.

LOESS

1. INTRODUCTION

The purpose of this chapter is to review the engineering character of loess and typical cut-slope stability problems that have been observed and to suggest design approaches with special consideration for cut slopes related to transportation facilities. The discussion relies heavily on the experience of state transportation departments in Missouri, Tennessee, Illinois, and Washington.

Loess is an eolian deposit composed primarily of silt-sized particles. Loess deposits constitute approximately 11 percent of the land surface of the earth and 17 percent of the soil deposits of the United States (Turnbull 1965). Extensive areas of Europe, Asia, New Zealand, the Arctic, and the Antarctic are covered by loess deposits with thicknesses commonly between 20 and 30 m. However, the most extensive loess deposits are in China (Hobbs 1943; Schultz and Frye 1965; Eden and Fulkert 1988). The most extensive deposits in the United States cover parts of the Midwest as well as portions of Washington, Oregon, Idaho (Figure 23-1), and Alaska.

Loess is characterized by a loose structure that consists of silt and fine sand particles coated by a clay binder. Because of the clay coating on the silt and sand particles, there is little true intergranular contact, particularly at low confining pressures. Thus, most of the strength is attributable to the clay binder. At low water contents, high negative pore pressures develop in the binder, producing relatively high shear strengths. As a result, as long as it remains unsaturated, loess has the ability to stand in vertical cut slopes and to support relatively large loads as a foundation material. However, upon wetting, the negative pore pressures are eliminated, reducing effective stresses, and thus the strength, as water content within the clay fraction increases to near saturation.

Sudden settlement from wetting (*hydroconsolidation*) is also a result of the loose structure. Upon wetting, the reduction in shear strength allows the granular material to reorient, producing a denser soil with a substantially lower void ratio, which can result in large settlements. It was this tendency to consolidate, particularly with respect to earth-dam

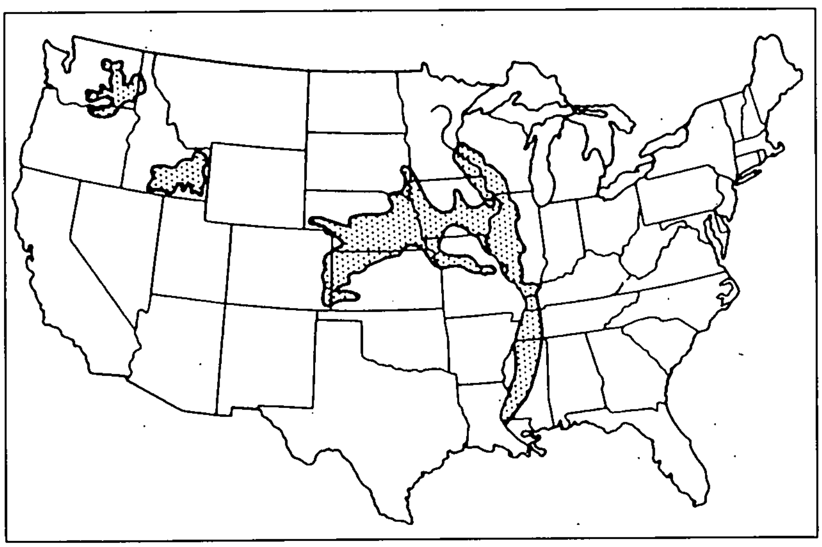


FIGURE 23-1
Loess deposits in the conterminous United States (modified from Turnbull 1965).

foundations, that led to much of the original research on the physical properties of loessial soils performed by the U.S. Bureau of Reclamation in the early 1950s and 1960s (Leighton and Willman 1950; Hansen et al. 1959).

Slope stability problems in loess deposits appear to be common and range in scale from massive landslides to small slides and flows or erosion problems. A number of very large landslides in loessial materials have been documented in the literature, only a few examples of which are noted here.

One of the most infamous landslides in loess deposits occurred in 1920 in Gansu Province, China, as a result of the Richter magnitude (**M**) 8.5 Haiyuan earthquake. Approximately 650 loess collapses (slides and flows) killed about 100,000 people (see Chapter 2) (Close and McCormick 1922; Tungsheng 1988). In the Tadzhik Republic of the former USSR, the 1949 **M** 7.5 Khait earthquake triggered numerous massive debris avalanches and flows (many of which were in loess deposits) that buried 33 villages (Leonov 1960; R. L. Schuster, personal communication, 1993, U.S. Geological Survey, Denver, Colorado). In March 1983, 45 million m^3 of loess collapsed from the crest of a hill in Gansu Province. The debris, consisting of a 100-m-thick slab of rain-saturated loess, dropped 270 m and traveled laterally 1.7 km at speeds of 7 to 12 m/sec. The slide buried four villages, dammed a river, and killed 220 people (Adams 1988).

A rare type of landslide in loess occurred in 1989 in a suburb of Dushanbe in the Tadzhik Republic. The terrain was hilly and the highly porous silt (loess) had been wetted by irrigation. An **M** 5.5 earthquake caused liquefaction of the collapsible loess deposits, which triggered a chain of landslides. The landslides turned into a very large mud flow, which buried more than 100 houses 5 m deep (Ishihara et al. 1990).

Although such large and catastrophic loessial landslide problems have not occurred in the United States, a number of slope stability problems related to loess have been of concern to engineering geologists and civil engineers for many years. Many of the problems recorded in the literature are related to transportation issues. The slope problems range from moderate to small slides and flows to erosion. The impact of these problems ranges from concern for safety of the public to environmental damage (soil erosion and stream sedimentation) or, in some cases, to aesthetics.

2. LITERATURE REVIEW

2.1 Formation of Loess

As shown in Figure 23-1, the distribution of loess deposits in the United States centers around major waterways, which during the Late Pleistocene were points of egress for meltwater from continental glaciers. Glacial erosion of the land surface produced soil and rock debris that was transported by the meltwater. Rivers did not have the capacity to transport the large volume of sediment, causing formation of braided streams and outwash plains. Thermal effects of rising temperatures during the glacial retreat created winds that induced eolian transport of materials from the outwash plains. It is generally accepted that these winds eroded and transported silt- and clay-sized materials and deposited them in a loose loessial structure. The eolian source of deposition has been substantiated by the sorting of loess with distance from the source; that is, loess deposits characteristically become more fine grained with distance from the source (Smith 1942; Schultz and Frye 1965).

2.2 Fundamental Properties

Comprehensive studies of the engineering and index properties of loess were made by Holtz and Gibbs (1951), followed by Royster (1963), Royster and Rowan (1968), the Missouri State Highway Department (1978), and Higgins et al. (1985, 1987). Holtz and Gibbs were primarily interested in consolidation. Basic laboratory tests, including gradation, specific gravity, plasticity, and shear strength, were performed on a large number of samples. Grain size characteristics revealed that the majority of samples (71 percent) fell within gradation limits arbitrarily defined as silty loess. Samples found to be finer than the boundaries established for silty loess were termed clayey loess (21 percent), and coarser samples were categorized as sandy loess (8 percent). A grain-size distribution chart delineating these subdivisions is presented in Figure 23-2.

Holtz and Gibbs (1951) also conducted Atterberg-limit tests and plotted the results on a plasticity chart. The plot exhibited a concentration of points representing soils with plasticity indexes ranging from 5 to 12 percent and liquid limits between 28 and 34 percent. Examination of these data in conjunction with the gradation analysis re-

vealed that the concentration was indicative of silty loess. Furthermore, a more poorly defined grouping of higher plasticity index and liquid limits was found to coincide with gradation curves in the clayey loess range. Thus, a useful relationship between gradation and plasticity was established.

Holtz and Gibbs found that shear strength, as determined by triaxial testing, varied considerably with water content and to a lesser extent with dry density. As would be expected, strength increased with decreasing water content and increasing density. The angle of internal friction remained fairly constant, ranging from 30 to 34 degrees, whereas the cohesion intercept increased rapidly as water content decreased.

Although Holtz and Gibbs believed that strength was not affected substantially by the gradational subdivisions (sandy, silty, and clayey loess), it is evident that this is not true at low water contents when a total stress analysis is employed. Undrained cohesion increases with increasing clay content for a given water content below saturation, resulting in higher strength. However, this effect is at least partially offset by the tendency of clayey loess to maintain a higher natural water content than that of silty or sandy loess (Missouri State Highway Department 1978).

Gibbs and Holland (1960) expanded the data base of the original work by Holtz and Gibbs. The results of additional laboratory tests and of plate-load and pile-driving tests were incorporated into their report. Conclusions pertinent to strength properties remained essentially unchanged.

The relationship between water content and shear strength was more thoroughly examined by Kane (1968), who presented what he termed the "critical water content" concept. Unconsolidated-undrained (UU) triaxial shear tests were conducted at various water contents on undisturbed samples obtained from a site near Iowa City, Iowa. In addition, tests to measure negative pore-water pressures and volumetric variation with water content were performed. It was found that above a given water content (the critical water content) the clay binder was volumetrically stable. Below the critical water content, the clay fraction shrinks as a result of desiccation. The critical water content can also be described as the water content at which the clay binder becomes saturated. This mechanism provides a reasonable explanation of the variation in strength with water content. Because the clay binder is nearly saturated once the critical water content is reached, any additional water fills voids between particles and has little effect on effective stress levels until complete saturation is achieved. As water content decreases below critical, desiccation occurs and negative pore-water pressures are developed in the clay binder. As the water content decreases, the negative pore pressure increases, which increases effective confining pressure and thus increases strength. The applicability of the concept of critical water content to slope stability problems in loess has been noted by several investigators (Missouri State Highway Department 1978; Higgins et al. 1985, 1989; Higgins and Fragaszy 1988). They found the critical water content for Missouri and Washington loess to be in the range of 17 to 20 percent.

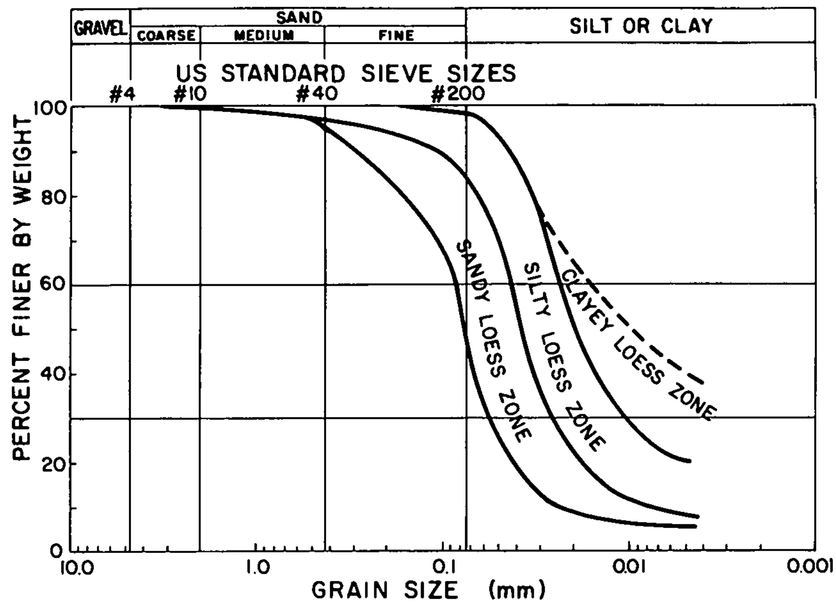


FIGURE 23-2 Range in grain-size distribution for loess from Missouri River Valley (modified from Holtz and Gibbs 1951).

2.3 Index Properties and Shear Strength

General trends in index and shear strength properties of loess have been determined for many locations in the central United States, eastern Washington, and Alaska.

2.3.1 Clay Composition

Montmorillonite, or a combination of montmorillonite and illite, is the dominant clay mineral for loess deposits in the central United States (Handy et al. 1955; Gibbs and Holland 1960; Crumpton

and Badgley 1965; Krinitzsky and Turnbull 1965; Bandyopodyopadhyay 1983). The clay fraction of Alaskan loess is predominantly chlorite with minor amounts of illite and possibly kaolinite (Davidson and Roy 1959).

2.3.2 Calcium Carbonate

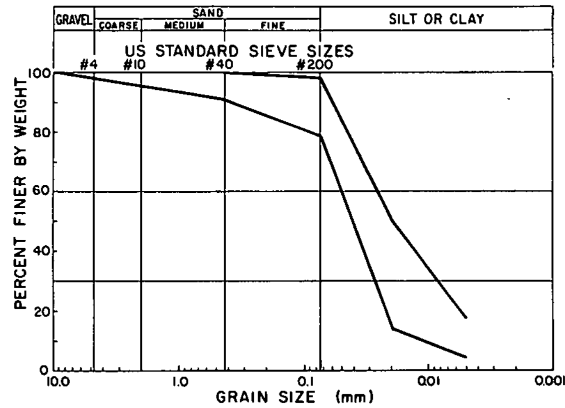
Calcite deposits in loess are generally found as discrete grains, root fillings, or nodules (Holtz and Gibbs 1951; Gibbs and Holland 1960). In some cases a continuous layer or crust of calcite may form at shallow depths below the ground surface. This crust generally forms as the result of ground-surface evaporation and has been observed on cut slopes in Mississippi (Krinitzsky and Turnbull 1965) and eastern Washington (Higgins et al. 1989).

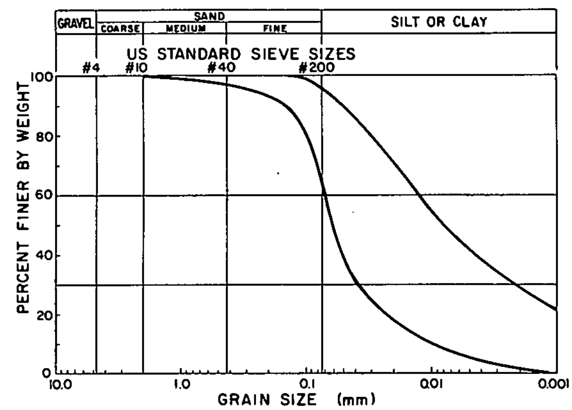
In eastern Washington, it appears that the presence or absence of calcium carbonate is at least partially related to mean annual precipitation or evaporation. In areas averaging greater than 51 cm of precipitation per year, no samples containing calcium carbonate were encountered. Conversely, a large majority of samples collected in areas where mean precipitation was less than 38 cm contained a significant quantity of calcite.

Where present in sufficient quantities, calcite increases the dry strength of loess. However, because of the discontinuous nature of calcite accumulation, care must be taken when strength properties are determined for a specific site. If test samples are obtained from a location containing a higher-than-average percentage of calcite, the tests may indicate a strength higher than the actual strength for the site as a whole.

2.3.3 Gradation

Gradation characteristics of loess from different locations in the United States are presented in Figures 23-3 through 23-9. In general, the range in grain-size distribution falls within the bounds established by Holtz and Gibbs (1951), with the exception of Alaskan loess, which tends to be slightly coarser. The maximum grain size in loess deposits examined within the conterminous United States is 2.00 mm (No. 10 sieve), whereas analyses on Alaskan loess exhibit an upper limit of 9.53 mm (3/8-in. sieve). It is thought that the particles larger than 2.00 mm in Alaskan loess may be carbonate concretions formed after deposition of the loess (Sheller 1968).





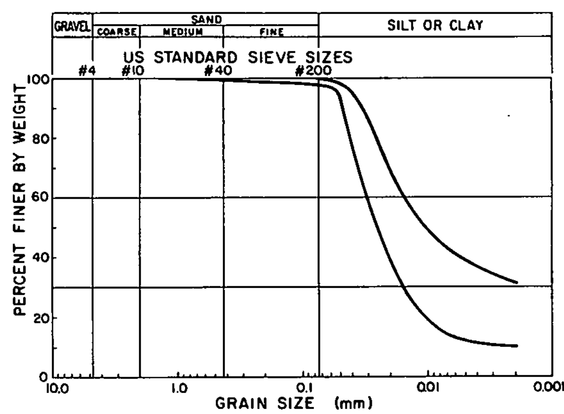


FIGURE 23-3 *(top)*
Range in grain-size distribution for loess from Alaska (modified from Morrison 1968).

FIGURE 23-4 *(center)*
Range in grain-size distribution for loess from Kansas (modified from Bandyopodyopadhyay 1983).

FIGURE 23-5 *(bottom)*
Range in grain-size distribution for loess from southwestern Iowa (modified from Davidson and Handy 1952).

2.3.4 Plasticity

The results of Atterberg-limit tests from various investigations are presented in Figure 23-10. Although substantial variability can be observed in the range of plasticity from location to location, the approximately linear relationship between liquid limit and plasticity index appears to be similar for all locations.

2.3.5 Shear Strength

Shear strength is the most important engineering property of any soil when slope stability is considered. Unfortunately, shear strength is difficult to quantify for loessial soils when saturation is less than 100 percent. The angle of internal friction reported in early studies remains relatively constant, between 28 and 36 degrees, whereas the cohesion intercept varies inversely with water content. Higgins et al. (1987) found shear strength values for UU tests on eastern Washington silty and clayey loess. Cohesion ranged from 21 to 69 kPa and the angle of internal friction ranged between 9 and 21 degrees. Consolidated-undrained tests showed a range for cohesion of 0.5 to 31 kPa and for internal friction of 27 to 29 degrees.

The highest values of cohesion were reported for loess samples with high density, high clay content, and low moisture content. Cohesion values as high as 448 kPa have been observed (Holtz and Gibbs 1951). Conversely, low-density silty loess samples tested at high water contents produced Mohr envelopes with cohesion intercepts equal to zero.

Although the variability of the angle of internal friction appears to be confined to a narrow range (with some exceptions), some controversy exists regarding the strength of low-density silty loess at high water contents. Some authors observed a complete loss of strength below a minimum consolidation pressure of approximately 69 kPa (Holtz and Gibbs 1951; Clevenger 1956; Gibbs and Holland 1960; Royster and Rowan 1968), whereas other authors did not (Olson 1958; Akiyama 1964; Kane 1968). Some investigators explained the lack of shear strength at low consolidation pressures by stating that a minimum degree of consolidation is required to produce grain-to-grain contact and thus shearing resistance (Holtz and Gibbs 1951; Clevenger 1956; Gibbs and Holland 1960).

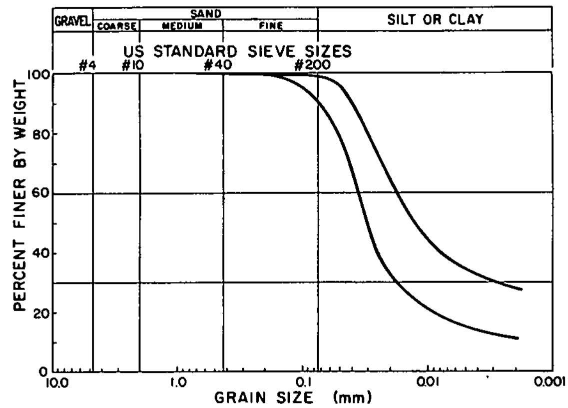


FIGURE 23-6
Range in grain-size distribution for loess from east-central Iowa (modified from Handy et al. 1955).

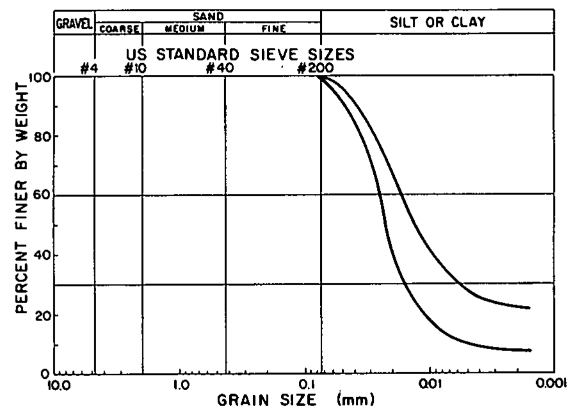


FIGURE 23-7
Range in grain-size distribution for loess from Mississippi (modified from Krinitzsky and Turnbull 1965).

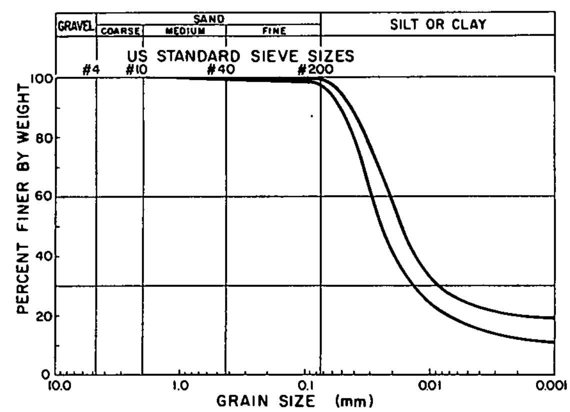


FIGURE 23-8
Range in grain-size distribution for loess from northeast Iowa (modified from Handy et al. 1955).

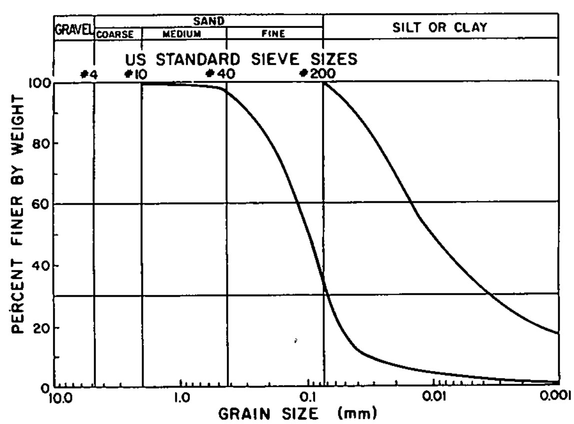


FIGURE 23-9
Range in grain-size distribution for loess from eastern Washington (Higgins et al. 1985).

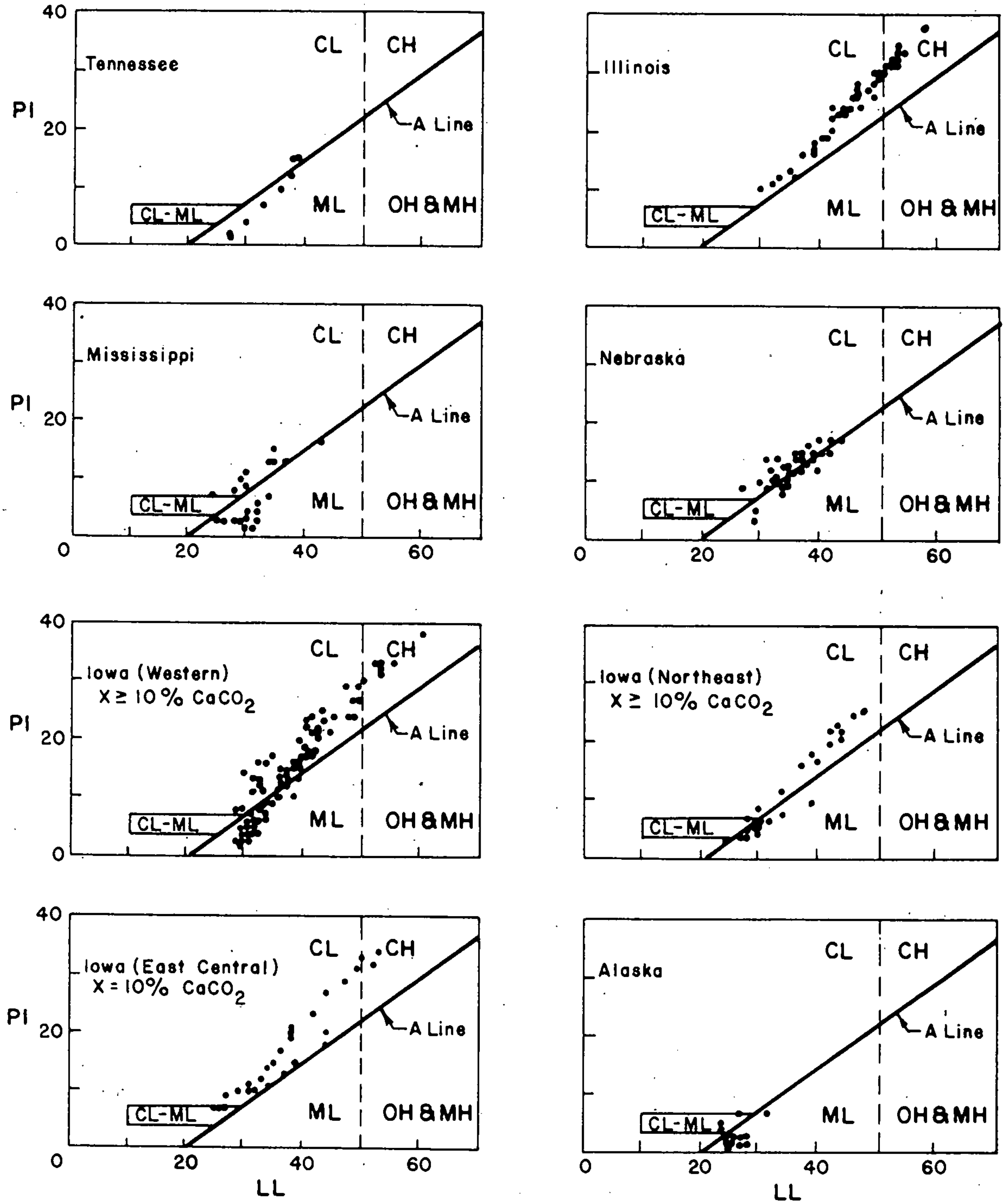


FIGURE 23-10
Plasticity data for loessial deposits throughout the United States (modified from Sheller 1968).

2.3.6 Variability of Index Properties with Distance from Source

Although index properties within a given deposit of loess tend to vary within narrow bounds, some trends have been noted with respect to the distance from the source of the loess. Investigations in the Midwest, the South, and the state of Washington (Dahl et al. 1952; Krinitzsky and Turnbull 1965; Handy 1976; Higgins et al. 1985, 1989) indicated an increase in clay content and decrease in total thickness with distance from the source. Studies in Iowa (Dahl et al. 1952), Mississippi (Krinitzsky and Turnbull 1965), and Washington (Higgins et al. 1985, 1989) noted that as clay content increases, silt content decreases, with sand content being a uniform, minor constituent.

Variation in clay content tends to affect engineering and other properties. As clay content increases, natural water content and density also increase (Davidson and Handy 1952; Higgins et al. 1985, 1989). Thus, natural water content and density can be expected to increase with distance from the source.

A linear relationship between thickness and the logarithm of distance from the source has been established (Handy 1976) for midwestern loess deposits. Although this relationship is undoubtedly true for some deposits, in many cases thickness is highly variable on a local scale with no clear trends discernible. When a high degree of variability is encountered, it is usually due to hummocky terrain with maximum thicknesses near the crests of hills and thin deposits in intervening depressions (Kolb 1965).

2.3.7 Density

Typical densities for eastern Washington loess were reported by Higgins and others (1987). Dry densities for 12 samples of silty loess ranged from 1.13 to 1.57 Mg/m^3, and for three samples of clayey loess the range was 1.36 to 1.44 Mg/m^3.

2.3.8 Depth Effects

It is not possible to generalize about the variation in textural composition with depth other than to say that changes in the relative percentage of the sand, silt, and clay constituents with depth are usually minor. In some areas sand content was found to increase slightly with depth, whereas clay content remained constant or showed a minor decrease (Lyon et al. 1954; Higgins et al. 1985). Conversely, some vertical sections exhibited a uniform percentage of sand with depth, whereas clay content remained constant but increased slightly at the base of the unit (Hansen et al. 1959). Except for isolated cases, constituent percentages did not vary more than 7 to 8 percent.

In-place density and natural water content demonstrate a more consistent trend with depth than does textural composition. Ignoring fluctuations in the upper 2 m, both density and water content tend to increase with depth.

3. REVIEW OF CUT-SLOPE DESIGN PRACTICE

In the United States, comprehensive design criteria that specifically address the unique engineering properties of loessial soils are applied by a limited number of state transportation departments. A summary of design procedures employed by various states is presented in Table 23-1.

The results of three comprehensive studies (Royster and Rowan 1968; Missouri State Highway Department 1978; Higgins et al. 1985) in three states (Tennessee, Missouri, and Washington) on the design of cut slopes in loess have been published. The findings of all three concerning loess properties and slope behavior showed only minor differences, usually because of different climatic conditions.

In general, the design specifications recommended by these studies are based on four main criteria: (a) gradation boundaries similar to those established by Holtz and Gibbs (1951) for silty and clayey loess, (*b*) the critical-water-content concept developed by Kane (1968), (*c*) experience from studying the relationship between slope performance and physical properties of loess soils, and (*d*) surface-water drainage.

It was concluded that vertical slopes perform well in silty loess when water contents are maintained below about 17 percent (the critical water content). Slightly higher water contents (less than 20 percent) could be tolerated with a favorable exposure (between southeast and southwest). Flattened slopes should be used for silty loess with high water contents and for all cuts in clayey loess. Although 2H:1V slopes are generally flat enough

Table 23-1
Design Procedures Used by Various State Departments of Transportation for Cuts in Loess

State	Design Procedure
Arkansas	No set design procedure indicated; vertical cuts often utilized with benches added for cuts exceeding 8 m in height; bench widths approximately 3 to 5 m wide and slope gently toward backslope Drainage ditches usually constructed near top of cut and at toe, with ditch paving utilized on benches to channel drainage; collection pipes used to convey runoff from top of cut and benches to road level
Indiana	Experience with cut slopes in loess limited; vertical cuts employed with 3-m-wide benches for cuts over 5 m high; paved interceptor ditches installed above cut to prevent runoff flow over face
Iowa	No special design techniques used for loess; normal backslope design 5 m wide with benches every 8 m of vertical height; benches sloped to back of cut; drains used when loess overlies relatively impermeable layer to drain contact
Kansas	Slopes of 3H:1V or flatter usually employed, although some 2H:1V benched slopes have been constructed; slope performance generally good; however, some erosional problems experienced when runoff flowed over slope face
Missouri	Both vertical cuts and flattened slopes (<2.5H:1V) based on grain-size distribution and water content; slope-stability analysis used for saturated deposits; drainage design specified above and below cut slope
Nebraska	Although vertical cuts constructed for some minor roadways, slopes flattened to 3H:1V typically constructed; flattened slopes perform well once vegetative cover established; use of dikes to ditches preferred when runoff must be restricted on cut face
Ohio	No special considerations; 2H:1V slopes used
Tennessee	Slopes cut to 2H:1V or flatter with 5- to 8-m benches at 6- to 8-m intervals; drainage design specified above and below cut slope
Washington	Both vertical cuts and flattened slopes (<2.5H:1V) constructed on basis of grain-size distribution and water content; slope-stability analysis used for saturated deposits or cuts >15 m high; drainage design specified for slopes above and below cut slope

from a stability point of view, slopes flattened to 2.5H:1V undergo much less degradation from erosion and allow better establishment of a vegetative cover. Where water tables are truncated, much flatter slopes may be required because of seepage forces.

When a vertical cut is employed, it is typically benched when the total height exceeds 10 m. Benches are placed approximately every 6 m vertically with a width of 5 to 8 m. The benches serve the dual purpose of limiting erosion and providing increased stability for the overall slope.

The Missouri and Washington investigations suggested some problems with the drilling and sampling methods most commonly used to obtain "undisturbed" samples, particularly at high water contents. Undisturbed samples were obtained by both Shelby tubes and Denison double-tube samplers, and their densities were compared with those for hand-cut samples. In all cases downhole samples were found to be denser, indicating compression during sampling. The largest discrepancies between hand-cut and downhole samples were found when water contents were in excess of 18 percent (Missouri State Highway Department 1978). The Washington study found that all Shelby-tube samples had a higher density than hand-cut samples; however, no specific correlations were noted (Higgins et al. 1987). A similar investigation on the sampling effect on Bulgarian loess (Milovic 1971) obtained similar results.

The general conclusion of the Missouri and Washington reports regarding near-vertical versus flattened slopes is that the use of near-vertical cuts should be restricted but not eliminated. Provided that the deposit meets the gradation and moisture criteria outlined, a near-vertical cut is the preferable choice, particularly since silty loess tends to erode severely on flattened slopes. However, efficient drainage of surface water away from the slope face is essential.

Although Royster (1963) and Royster and Rowan (1968) generally agreed with these conclu-

sions, the Tennessee Department of Transportation (TDOT) design criteria do not include near-vertical cut slopes. Conventional flattened slopes are commonly constructed, probably for aesthetics and maximum stability. However, TDOT has developed useful guidelines for surface drainage of loess slopes, many of which were adopted or modified by the Washington Department of Transportation.

4. FAILURE MECHANISMS

Studies in Missouri and Washington (Missouri State Highway Department 1978; Higgins and Fragaszy 1985, 1988; Beard et al. 1986; Higgins et al. 1989) on slope design in loess recorded numerous observations of slope-failure modes. Additional examples are included here from Illinois and other portions of the midwestern United States. These observations define the typical types of slope failures and the causative failure conditions that can be expected in loess slopes. An understanding of these failure modes will aid the engineer and engineering geologist in identifying potentially unstable conditions and in the design of stable cut slopes in loess.

4.1 Erosion

Erosion damage (including piping) is a common form of slope degradation, primarily in silty loess, although clayey loess is susceptible also in both dry and moist climates. In eastern Washington many large erosion gullies have been initiated by small piping failures originating 2 to 3 m behind the top of the cut face. As the pipe enlarges, the surface caves, forming a gully. These gullies are sometimes initiated by animal burrows that are intersected by the slope cut. The piping phenomenon often occurs in moist climates when the slope cut truncates a water table.

The loess piping mechanism normally results in relatively small volumes (1 to 5 m^3) of displaced material. However, in Illinois, piping in saturated loess has displaced volumes of 200 to 300 m^3. The piping manifests itself by an accumulation of redeposited loess at the piping outfall. The displaced mass can result in creation of either an erosion channel or a horizontal pipe coupled with a vertical sink. Erosion channels may be as much as 6 m deep, and vertical sinks may be up to 3 m in diameter. The larger vertical sinks either occur in areas of ponding water or are created by material removed through the horizontal pipe.

Major erosional features are found to be the result of improper drainage or channel protection. In eastern Washington, serious erosion problems were observed in long cuts transecting small drainage basins that had no provisions for conveying excess runoff away from the cut. The highly erosive nature of silty loess requires the diversion of runoff from what normally would be considered insignificant drainage areas. Figure 23-11 illustrates the result of truncating a small drainage area without providing a means of conveying excess runoff from the slope or providing erosion protection.

Figure 23-12, which shows gully erosion along US-12 near Walla Walla, Washington, demon-

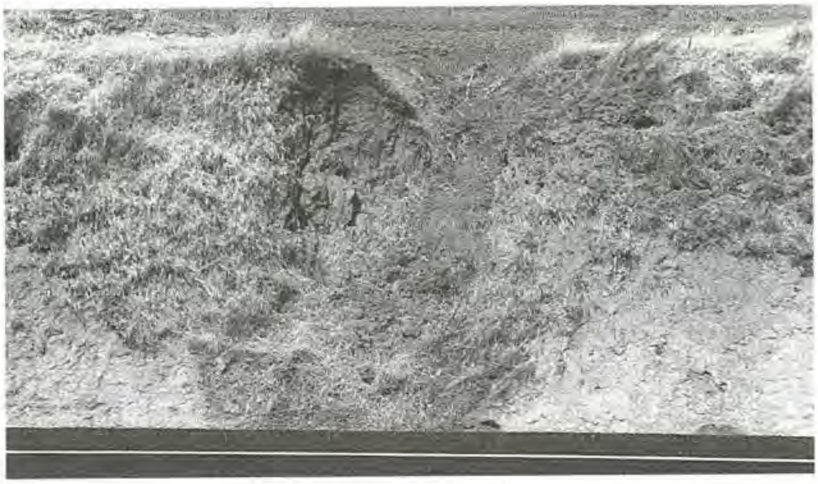


FIGURE 23-11
Gully erosion resulting from truncation of a small drainage basin near Dusty, Washington.

FIGURE 23-12
Gully erosion where small side drainage was truncated by highway cut to right of photograph, US-12 near Walla Walla, Washington.

strates the progressive nature of erosion in loessial soils. Erosion was initiated where a small side drainage was truncated by the highway cut (to the right in the photograph) and has progressed rapidly up gradient. Erosion will continue until the overall gradient is decreased below that causing channel scour.

Figures 23-13 and 23-14 illustrate two important points. In Figure 23-13 the majority of the erosion in the left portion of the photograph is due to piping. To the right of the small pipes, gully erosion is beginning to develop. Vegetation in the base of the depression, as well as the shape of the developing gully, indicates that the gully originated as a pipe. When the pipe enlarged to the point where the overlying material could no longer be supported, caving occurred and the overlying vegetation was deposited in the depression. This mechanism is very common in the formation of erosion gullies in silty loess.

FIGURE 23-13
Piping erosion developing into gully erosion (US-12 near Walla Walla, Washington).

FIGURE 23-14
Runoff source causing erosion in Figure 23-13 (small depression at center of photograph).

The second point is that extensive erosion problems may develop caused by runoff from extremely small drainage basins. Figure 23-14 shows the drainage area above the erosion shown in Figure 23-13. When the area was first examined in June, before the harvest of winter wheat in late July and August, there was no indication that drainage was concentrating flow toward the problem area. Figure 23-14, taken following harvest in the early autumn, shows a minor basin draining into the existing erosion zone.

Figure 23-15 demonstrates the extent of damage when proper drainage is not provided. The majority of the damage appears to be due to a single summer storm event; a combination of piping and surface erosion is taking place. Piping inlets originated a substantial distance behind the cut, which exemplifies the need for construction of drainage ditches an adequate distance behind the cut slope.

Figures 23-16 and 23-17 show erosion damage to near-vertical cuts in Mississippi and Louisiana where water ponded near the crest of the slope. If natural drainage is directed away from a loess slope, erosion is usually minimal (Figure 23-18).

The Missouri study (Missouri State Highway Department 1978) reported extensive erosion damage on sodded V-shaped benches in silty loess. The slopes were cut nearly vertical and benched. However, drainage channels on the benches eroded severely, which can lead to failure of the entire bench. Paved ditches have been used in Missouri and Illinois to mitigate this effect.

Another serious erosional problem in loessial soils in any climate, particularly on flattened slopes, is surface erosion during construction and up to the time of establishment of a good vegetative cover. Even with adequate drainage, extensive damage may result from raindrop impact and rill erosion. This problem is most critical in silty loess, but clayey loess is also susceptible.

The ability of a slope to hold a vegetative cover appears to be related to the steepness of the slope. The relationship is complicated by factors such as

exposure, type of vegetative cover, soil type, and climatic conditions. There is no quantitative method that accurately predicts the maximum angle at which a slope can be cut and still retain a continuous vegetative cover. However, experience from transportation departments in Washington, Missouri, Illinois, and other states indicates that slopes of 2.5H:1V or flatter are reasonable for establishment and maintenance of vegetation.

4.2 Shallow Slope Movements

Higgins et al. (1985, 1989) found shallow downslope movements to be common in the eastern part of the Washington loess deposit where precipitation is nearly 500 mm annually, but these failures are not common in the midwestern United States. This type of failure is largely due to late-winter and early-spring climatic conditions. Precipitation and snowmelt are common at this time of year, resulting in a thin layer of thawed, saturated soil overlying either frozen or unsaturated soil. The layer of thawed, saturated soil, along with any overlying vegetation, tends to slide or flow downhill.

This form of failure appears to be primarily related to the amount of precipitation, the clay content, and the slope angle. In the western two-thirds of the Washington loessial deposit where precipitation is less than 38 cm annually, downward movements of shallow slopes were rarely observed. Clay content increases from west to east, as does precipitation. Increases in clay content, resulting in lower permeability combined with increased precipitation, raise the likelihood of obtaining the near-surface saturated conditions required for failure.

Two different forms of shallow slope failure have been observed in eastern Washington and appear to be related to soil type. In silty loess it is not uncommon to see sheets of vegetative cover 5 to 15 cm thick with an arcuate upper boundary move downslope (Figure 23-19). In this form, only minor damage was observed. However, over the years these small failures can expose large areas of soil to erosion, and damage increases considerably over time.

In clayey loess, shallow slides and flows are common and result in major slope degradation. Movement appears to be a mud-flow phenomenon with both large- and small-scale failures. Higgins

FIGURE 23-15
Area of large-scale piping near Endicott, Washington; flattened vegetation indicates flow over slope as well as piping.

FIGURE 23-16
Erosion damage to near-vertical cut slope in Mississippi.

FIGURE 23-17
Erosion damage to near-vertical cut in Louisiana.

FIGURE 23-18
Minimal erosion damage where natural surface drainage is away from slope face (east of Walla Walla, Washington).

FIGURE 23-20
(below) Small-scale mud flow in highway cut on US-195 near Pullman, Washington; flow approximately 3 m long.

et al. (1985, 1989) observed at least minor damage in many of the clayey loess slopes over 3 m high and steeper than 2.5H:1V.

Small-scale slides, flows, or both, such as that in Figure 23-20, were found to be the most common form of failure in eastern Washington. Failures were typically 0.3 to 3 m wide with the depth of failure ranging between several centimeters and about a meter. The initial failure was normally followed by increased erosion due to the loss of vegetative cover, with severe gully erosion a common result. In some cases, failure is due to saturation of the soil under the snowpack as well as to weight of the snowpack on the underlying saturated slope (Figure 23-21).

FIGURE 23-19
Fairly common shallow failures with arcuate scarps in silty loess near Colfax, Washington.

Although not as common, large-scale slides and flows have been observed in Washington. The failure mechanism is thought to be the same as that for small-scale failures with a low depth-to-width ratio for the failure surface. Figure 23-22 shows a relatively large failure. The effect of steepness on stability of slopes cannot be emphasized strongly enough. In all cases where extensive damage was observed in eastern Washington, slopes were approximately 2H:1V or steeper. No instances of failure were observed for slopes flatter than 2.5H:1V. These observations agree with experience in the midwestern United States, where slopes greater than 2.5H:1V have proven to be too steep to maintain good vegetative cover in loessial soils (Royster and Rowan 1968; Missouri State Highway Department 1978).

Exposure has an influence on these shallow slides and flows. It is not uncommon to find that

two opposing cuts with similar slopes and drainage, one facing north and the other south, are affected very differently. The north-facing slope will invariably demonstrate a greater degree of degradation because of shallow slides and flows than the south-facing slope, because slopes facing north typically have higher average water contents than do slopes with any other orientation. Figures 23-23 and 23-24 show south- and north-facing slopes, respectively, cut in clayey loess at approximately 2H:1V. Note that in Figure 23-23 erosion has occurred where small patches of vegetation and soil have slipped away. However, the north-facing slope (Figure 23-24) has experienced numerous shallow failures that have stripped the vegetation. Near the slope crest are scarps from larger failures that have occurred over the past several years and have significantly steepened the slope. The result of the shallow slides is exposure of bare soil and rapid formation of erosion gullies, some of which range up to 0.6 m in depth.

The practice of constructing drainage ditches immediately adjacent to the toes of slopes appears to contribute to this type of failure. Periodic highway maintenance requires removal of sediment from ditches, which may result in undercutting of the toe. In addition, drainage ditches directly adjacent to the toe may raise the water content of the toe materials, further encouraging failure.

4.3 Volume Change

Failure of slopes as a result of shrinkage cracks that develop in clayey loess is common in the humid midwestern United States. Blocks and slabs of soil fall from near-vertical faces of loess along shrinkage cracks that have developed from drying of the slope face (Figure 23-25). Shrinkage potential of a soil is a function of soil density, moisture content, and clay content. This type of failure often occurs shortly after slope faces of wet, clayey loess are exposed to drying. In Missouri this phenomenon occurs most often in clayey loess with liquid limits near 35 percent (Missouri State Highway Department 1978).

4.4 Undercutting

Undercutting is common in the midwestern United States in both silty and clayey loess with liquid limits ranging from 31 to 34 percent. The failure is progressive, originating as local sloughing near the base of a near-vertical slope; the shallow failure then oversteepens or undercuts the original slope, which eventually causes material upslope to fail. Undercutting is most frequently found where a vertical rise truncates a water table or a stratum with very low cohesive strength (such as sand) or high water content (Missouri State Highway Department 1978).

FIGURE 23-21
Failure of slope under melting snowdrifts on US-195 near Pullman, Washington.

FIGURE 23-22
Relatively large-scale mud flow located near Pullman, Washington; undisturbed soil at right indicates depth of failure at approximately 1 m.

4.5 Freezing Damage

Frost damage was found to be a serious problem on near-vertical slopes in silty loess in Missouri

FIGURE 23-23
South-facing slope on US-195 near Pullman, Washington, showing little degradation.

FIGURE 23-24
North-facing slope, opposite cut in Figure 23-23, exhibiting severe gully erosion.

FIGURE 23-25
Slabbing of near-vertical cut along Mississippi State Highway 220.

(Missouri State Highway Department 1978). Failure is initiated by formation of an ice lens at a shallow depth within a slope, thawing of the ice lens raises pore-water pressures, and failure occurs by slump along the resulting surface of weakness. The resultant damage leaves soil exposed to erosion and further damage.

Four conditions are required for this type of failure:

1. The soil must transmit sufficient water during freezing periods to enable ice lenses to form, for example, in silt with high frost-heave susceptibility;
2. Water must be available, for example, at the intersection of a cut slope by the water table;
3. Freezing must occur over relatively long periods, for example, on north-facing slopes; and
4. The slope must be steep enough to allow failure after the ice lens melts.

4.6 Rotational Slides

Rotational slides on loess slopes have occurred in both moist and dry climates; however, they appear to be more common in the moist climate of the midwestern United States than in eastern Washington. Generally, this type of failure is associated with saturated (or nearly saturated) conditions on steep slopes. Occasionally, rotational failures occur in clayey loess in the Washington loess deposit. Water-table depths tend to be great throughout the loess deposit area. However, in the eastern section of the deposit where seasonal precipitation is relatively high and the loess has at least 20 percent clay content, some failures do occur (even on undisturbed slopes). Figure 23-26 shows an example of a rotational failure (a slump

and earth flow) on a natural slope. The slope was inclined approximately 2H:1V, the head scarp was approximately 5 m high, and the failed material flowed about 15 m from the base of the scarp. As is common in this area, the failure occurred in a region where runoff and groundwater seepage from the surrounding field could be expected to collect and saturate the soils. Geotechnical investigations for slopes should be designed to detect such groundwater conditions.

4.7 Summary

The foregoing discussion indicates that the majority of experience with cut slopes in loess involves those that are less than 15 m high. This experience shows that the most significant influences on stability are surface drainage, soil water content, and grain-size distribution. Silty loess soils should perform well in near-vertical cuts (¼H:1V) if they are protected by surface-drainage structures and if natural moisture contents remain less than 17 to 20 percent. Cuts in clayey loess should perform well if they do not exceed approximately 2.5H:1V and are protected by a cover of vegetation, and if concentrated runoff flow is not directed across the slope face. The examples presented illustrate that major performance problems are due to (*a*) poor or inadequate surface drainage systems for cuts in silty loess (and in a few cases for cuts in clayey loess) and (*b*) oversteepened slopes for cuts in clayey loess. The experience with cut slopes in sandy loess is inadequate to suggest any design criteria other than conventional soil-cut designs.

The designer of slopes in loess should be fully aware of the following soil properties and should design cut slopes to avoid the resulting problems:

1. Loess is highly erodible, and the flow of water, even at low to moderate volumes and gradients (less than 5 percent and 5 to 10 percent, respectively), can cause severe erosion;
2. Disturbance of the natural soil structure by grading, operation of heavy equipment, farming activities, and so forth, makes the soil more susceptible to erosion;
3. Saturation of the soil softens the clay binder and greatly decreases the strength, leading to slope failure or accelerated erosion; and
4. Silty loess soils are highly susceptible to failure by piping.

FIGURE 23-26 Rotational failure and earthflow in loess near Pullman, Washington.

5. SITE CHARACTERIZATION

5.1 Office Study

Before a site visit, published information on the project area should be reviewed. Much generally can be learned about the geotechnical properties of the soils in an area before a site visit, which will then help the slope designer plan the field investigation program.

Typical sources of information on soil conditions can be found in the research reports listed in the reference section to this chapter, U.S. Department of Agriculture county soil surveys, or geologic maps published by the U.S. Geological Survey or the appropriate state geological survey. The county soil conservation agent can also be a good source of information. This information will help the designer determine whether significant thicknesses of loessial soils are present and provide general knowledge of soil properties at the proposed site (grain-size distribution, percentage of clay-sized material, soil stratigraphy, permeability, drainage character, depth to bedrock, agricultural use, and irrigation potential). The general knowledge gained from these data should be used to plan an efficient field investigation to define the specific site conditions.

5.2 Field Reconnaissance

After the office study, the site should be visited to verify information gained in that study and to determine soil type and stratigraphy, natural drainage conditions, land use and potential for its change, and presence of structures or activities near the top of the backslope. Observations of

geologic processes at or near the site that could affect the project are important. These may include erosion problems on nearby slopes, seeps, and condition of existing cut slopes in the general area. These observed conditions should be considered in the cut-slope design.

5.3 Field Exploration Program

Sampling should be done in the most efficient manner, which is dependent on the size and type of cut slope that is proposed. Soil samples are required for determination of the natural water content, grain-size distribution, and Atterberg limits for standard cut-slope projects. Cuts in excess of 15 m high or with nonuniform stratigraphy may require stability analysis, and therefore undisturbed samples may be needed for shear-strength tests. Sampling methods in loess are summarized in Table 23-2.

Sampling for shallow cuts can be accomplished by hand augering and for the face of an existing cut by means of horizontal test holes. These holes must extend a minimum of 1 m into the face and should be spaced so that the deposit is characterized both vertically and laterally. Major cuts should be sampled by means of test holes to a minimum of 3 m below grade. Sampling should be continuous in the top 2 m of the hole and every 1.5 m thereafter. There should be a minimum of two holes per cut, normally spaced 60 to 100 m apart (150 m maximum). Samples for shear-strength analysis should be hand cut to avoid densification of the sample by sample-tube collection methods.

6. LABORATORY TESTING

Laboratory tests are used to evaluate soil index and engineering properties that are related to the ultimate engineering behavior of a cut slope and the recommended design. For cut slopes higher than 15 m or for nonuniform stratigraphy, strength tests may be required.

Routine laboratory tests required for cut-slope design include Atterberg limits, sieve analysis, and hydrometer analysis for classification of the soil as silty, clayey, or sandy loess. Determination of natural moisture content is also required. These soil properties determine the appropriate slope design for cuts no higher than 15 m and supply useful information for the stability analysis and design of higher cuts.

Table 23-2
Sampling Methods in Loess

Parameter and Sampling Method	Reliability	Cost
Density		
Type 1: dry hollow-stem auger boring, tube sampling (Higgins et al. 1987)	Very poor	Low
Type 2: dry hollow-stem auger boring, <5-in. pitcher-type sampling with lined tube (Casias 1987)	Fair	Moderate
Type 3: dry hollow-stem auger boring, > 5-in. pitcher-type sampling with lined tube (Casias 1987)	Good	Moderate to high
Type 4: block samples (Higgins et al. 1987; Gibbs and Holland 1960)	Excellent	High (requires excavation)
Gradation, index parameters		
Type 1	Excellent	Low
Types 2, 3, 4	Excellent	Moderate to high
Strength, consolidation		
Type 1	Very poor to unacceptable	Low
Type 2	Poor	Moderate
Type 3	Fair to good	Moderate to high
Type 4	Excellent	High

Loessial soils require slightly different testing procedures than more conventional soils. These differences arise in testing for strength and consolidation properties. Standard procedures are used for gradation determination and index-property testing.

The sensitive, collapsible nature of loess requires extreme care in handling samples. Some disturbance will occur in the preparation of samples for density determinations and triaxial and consolidation testing; such disturbance can be minimized only by care in handling.

The collapse sensitivity of loess adds another parameter that should be evaluated. Collapse sensitivity can be formally evaluated by parallel triaxial tests in which one sample is tested dry and another is saturated at some point in the test. Double oedometer tests (Holtz and Gibbs 1951) can be performed to evaluate the effects of water in causing collapse.

Natural moisture content is an indicator of the degree of disturbance. A moisture content between the shrinkage limit and the plastic limit indicates a high likelihood that the deposit is undisturbed. Moisture contents midway between the plastic and liquid limit (liquidity index of 0.5) indicate an extremely metastable condition. A higher moisture content (liquidity index of 0.8 or higher) generally initiates collapse.

If deep cuts are planned (greater than 15 m) or if water contents are expected to be greater than critical (17 percent), it may be necessary to run strength tests on undisturbed samples. Undisturbed strength testing should ideally model the state of stress and groundwater regime. Triaxial testing should be performed using compression or extension loading as the stress state in the slope dictates. The residual shear strength should be determined by extending the triaxial-test strain beyond the peak value to capture the residual strength value.

Groundwater conditions will indicate whether drained or undrained conditions are required if saturated or high-moisture loess is tested. The relatively dry nature of undisturbed loess requires triaxial testing without saturation and disallows pore-pressure measurements. When groundwater conditions are such that achieving a moisture content above 17 percent is considered unlikely, a total stress analysis is the preferable approach. Conversely, where water contents in excess of 17 percent are anticipated, an effective-stress analysis should be performed on saturated samples.

Triaxial testing with K_o-consolidation has not been reported in the literature, likely because of difficulty in determining the appropriate K_o-value for the porous-structured loess. The negative pore pressure in the undisturbed loess clay binder normally far exceeds the overburden pressure, and the strength is derived from this high negative pore pressure. Practically, it suffices to consolidate dry, undisturbed loess under isotropic conditions for triaxial testing.

The unconfined compression test is used frequently in loessial soil testing. This test provides an indication of the available strength to enable loess to stand vertically. Drawbacks of this test include lack of residual strength data and a failure to indicate strength anisotropy (Matalucci et al. 1970).

7. FIELD TESTING

The Iowa borehole shear-testing device and the cone penetrometer test have been used to determine shear-strength parameters in loess (Higgins et al. 1987; Modeer et al. 1991). The results obtained by these methods have been compared favorably with the results of triaxial testing of block samples from the same soils.

8. LOESS SLOPE DESIGN

The most common procedures for designing slopes to account for the unique properties of loess incorporate soil mechanics with a significant amount of empiricism. This heuristic approach has served many transportation departments and engineering organizations very well, considering the time and expense of an alternative extensive field and laboratory endeavor. Each agency or organization has either modified existing loess slope design procedures or expended significant effort to develop original design procedures. All of these procedures are remarkably similar, and those recommended below are based on a combination of experience and established procedures from the Missouri, Illinois, and Washington transportation departments.

If the soil at the site of the proposed cut is a silty loess with water content below critical ($\leq$ 17 percent can be used as an approximation on the basis of experience in the Midwest), near-vertical cuts (¼H:1V) may be considered. If utilized, near-

vertical cuts should be benched on approximately 6-m vertical intervals (or at the approximate midpoint) when the total height of the cut exceeds 9 m. Benches should be 3 to 5 m wide and gently sloped (10H:1V) toward the back of the cut (Figure 23-27). In cases where benched cuts are required, the benches should be seeded or sodded. Benches should maintain a longitudinal gradient for drainage that should not exceed 3 to 5 percent. If the drainage system above the slope crest is properly constructed (as discussed in the next section), it should not be necessary to employ erosion-control methods in excess of vegetative cover unless extremely long cuts are made. The selection of near-vertical cuts for silty loess is an attempt to avoid potentially severe erosion problems if the slope is flattened. However, it should be noted that maintenance of the near-vertical slope is difficult.

If water content exceeds critical (17 percent) or if the soil is a clayey loess, flattened slopes should be utilized. Generally, 2.5H:1V slopes would perform adequately, but if a water table is intercepted, flatter slopes may be required because of seepage forces (Figure 23-27). A flattened cut should be seeded immediately following construction. In addition, a protective cover such as a straw mulch or a synthetic material should be placed over the slope. These covers serve the dual purpose of preventing raindrop impact, a major cause of erosion on newly opened cuts, and helping to retain moisture required to initiate a vegetative cover.

The design of cuts (near-vertical or flattened) deeper than about 15 m or cuts that intersect a water table or high-moisture-content zones should be based on a detailed stability analysis. When groundwater conditions are such that achieving a saturated condition is unlikely, a total-stress analysis is the recommended approach. Conversely, when groundwater conditions make saturation possible, an effective-stress analysis should be used.

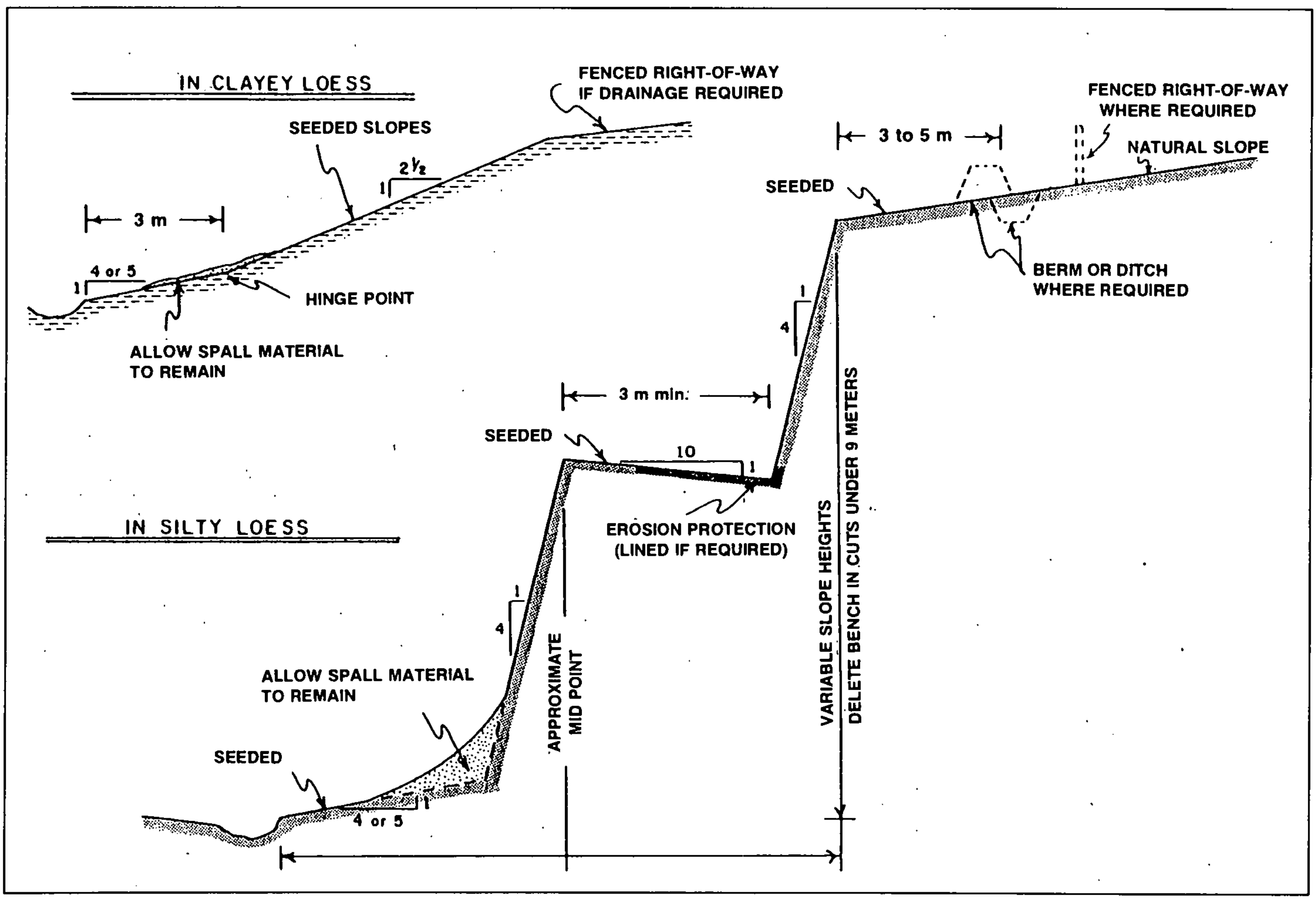


FIGURE 23-27 Typical sections for cut slopes in silty and clayey loess (modified from Higgins and Fragaszy 1988).

If a slope stability analysis is to be performed on a silty loess that maintains a water content below critical (< 17 percent), a wedge-type failure is perhaps the most likely geometry. When saturation at depth is encountered for either silty or clayey loess, a rotational failure may occur; however, because of possible anisotropy of the soils, the geometry of the failure surface may deviate from circular. Subsurface data from the borehole should aid in evaluating whether a circular or planar surface should be used in the stability analysis.

A near-vertical slope design based on strength-test results on undisturbed loess must take into account the potential for factors that will reduce the available strength. Increasing the design factor of safety or limiting the height of individual cuts (benching) is a common method to account for these intangibles. For example, the designer may use normal global factors of safety for all slopes but limit the heights of vertical faces rather than designing the height on the basis of strength testing. Reduced strength parameters may be used for design in addition to an increased design factor of safety. For example, Illinois uses a limiting factor of safety of 2 for vertical slopes.

These design recommendations are for homogenous materials and do not account for sandy layers or sandy loess. Under these conditions, a conventional soil mechanics approach should be applied.

9. DRAINAGE DESIGN

Designers of surface-water drainage systems for cut slopes in loess should use the following recommendations as a basis for design:

1. Prevent water (sheet wash) from flowing over the face of a cut in silty loess. Prevent concentrated flows from washing over a cut face in silty or clayey loess.
2. Do not allow water to collect in or saturate the soil within 3 to 5 m of the top of the cut face in silty loess. Water has been observed to contribute to piping.
3. Do not allow water to collect against the toe of the cut in silty or clayey loess. Saturation of the soils in the toe can cause sloughing of the slope.
4. Do not direct flow into unprotected channels in silty or clayey loess but line them with vegetation or synthetic or natural material, or deep gullies may appear within a short period of time (i.e., 1 to 4 years).
5. Avoid disturbance of soil structure and natural vegetation at the crest of the slope cut as much as possible during and after construction to maintain soil strength and erosion resistance.

On the basis of observations of the erosion problems around cut slopes discussed above, the following design criteria are suggested with respect to the drainage required for cut slopes in loess:

1. Damage from sheet wash over the face of flattened slopes (2.5H:1V) in clayey loess is minor if a vegetation cover is maintained. Therefore, surface-water diversion above the cut is not necessary unless gullies, swales, channels, and so on, will concentrate flow onto the slope face.
2. For cuts in silty loess (¼H:1V), placement of drainage ditches or berms 3 to 5 m behind the top of the cut slope is recommended if the drainage area above the cut is inclined toward the cut. The drain should be U-shaped or flat-bottomed and lined to protect it from erosion (Figure 23-28). Also, a gradient must be maintained so that water does not stand and saturate the slope.
3. Drains that convey surface water around the sides of cut slopes often have moderate (5 to 10 percent) to steep (> 10 percent) gradients. In many cases the erosion protection required in these channels will be more substantial than for those at the heads of cuts. These steep drains may require paving with asphalt or concrete or lining with filter fabric, crushed rock, and so forth.
4. If natural drainage channels are truncated by a cut, the drainage system should be adequate to transmit the flow around the cut face (which may require considerable right-of-way) or across the cut face in lined channels or structures. Direct flow across the cut face must be avoided. All drainage structures should be located in a fenced right-of-way for protection, and the area should be seeded or have the natural vegetation preserved to maintain the soil structure and strength and to prevent traffic from farm equipment or other vehicles from damaging or destroying the drainage system and protective cover.
5. Toe drainage can be accomplished with ditches (U-shaped or flat-bottomed) located approximately 3 m from the toe of the slope. The ground slope between the toe of the slope and

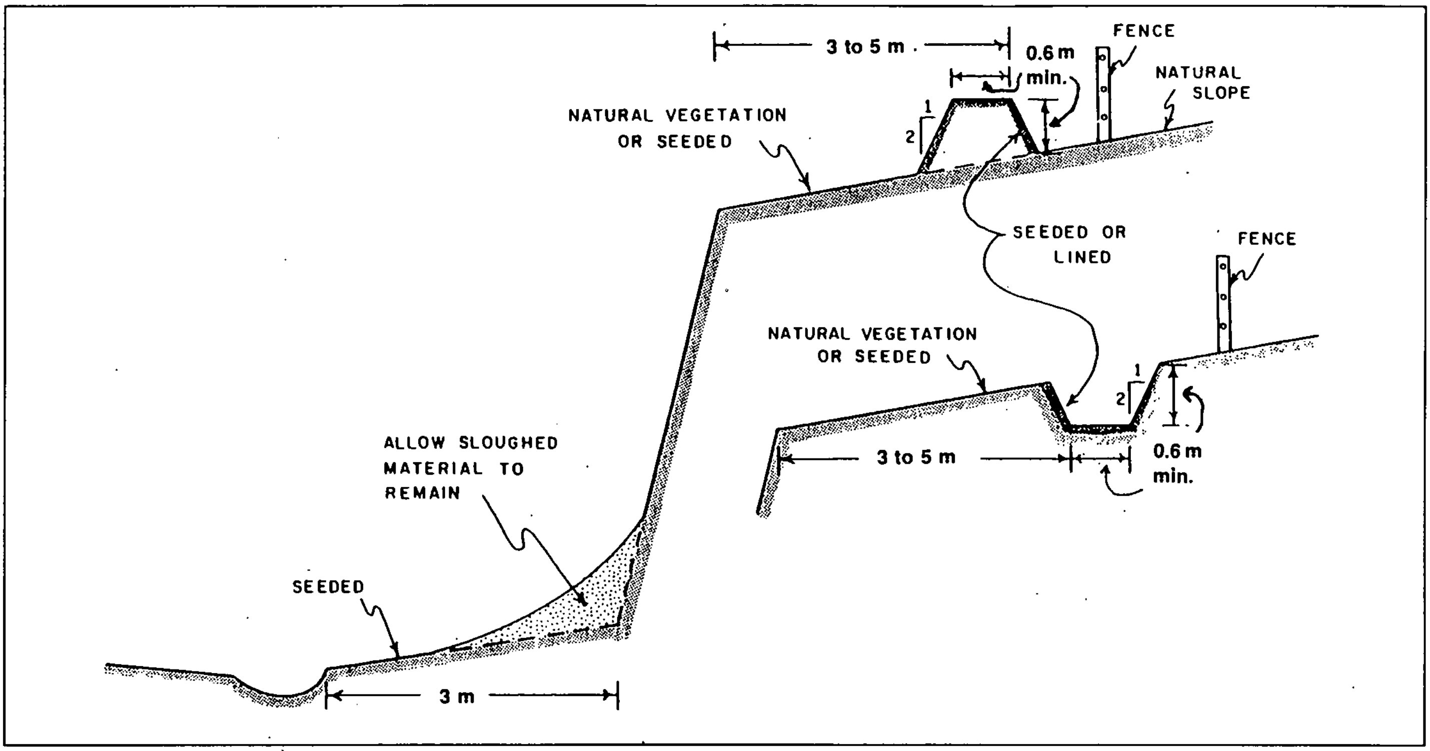


FIGURE 23-28 Drainage design for cut slopes in loess; fence is to protect drainage structures from traffic (modified from Higgins and Fragaszy 1988).

the ditch should be gently inclined toward the ditch (between 4H:1V and 5H:1V is recommended). Any material that spalls downslope between the toe and the ditch should be left in place to protect the toe.

10. CONSTRUCTION-CONTROL CONSIDERATIONS

Considering the adverse effects of water on the stability of loess, cut slopes are best constructed during the dry season. The drainage structure above the crest of the cut should be constructed before the opening of the cut and with as little disturbance to the surrounding vegetation as possible. Once the cut is made, construction equipment should be kept away from the crest.

A flattened cut should be seeded immediately following construction. In addition, a protective cover such as a straw mulch or a geosynthetic material should be placed over the slope. Any area stripped of vegetation, such as a ditch or berm, should be covered with the appropriate material as soon as possible to avoid excessive erosion.

Slopes should be cut uniformly (there should be no compound slopes) to avoid concentration of erosion and undercutting. Also, if animal holes intersected by the cut daylight above the crest where water may easily enter (such as in the drainage structure), they should be backfilled with low-permeability fines to avoid development of erosion pipes.

11. MAINTENANCE AND REPAIR

Because of their highly erosive nature, loess slopes deteriorate very rapidly once erosion has been initiated. Thus, it is very important to repair any erosion damage as soon as it is discovered. Maintenance may require repairs to, enlargement of, and removal of deposited silt from existing ditches. Increased erosion protection, such as installation of liners in ditches or in some cases construction of drainage facilities where they were previously believed to be unnecessary, may be required.

Vegetative cover requires periodic attention. In order to maintain a heavy ground cover, fertilizer must be applied every 3 to 5 years (on the basis of experience in the midwestern United States). In addition, some areas will not seed well the first time and may require a second and possibly a third seeding.

Sediment should be removed carefully from toe ditches on existing slopes to avoid undercutting the toe of the slope. Even minor undercutting will cause at least some sloughing, and therefore the grader blade should not contact the slope cut.

Repair of loess piping failures as well as erosion damage on all loess slopes should disturb the soil structure as little as possible and should reduce areas of concentrated surface water flow. Attempts to regrade loess slopes have had only marginal success. It is impossible to regrade damaged near-vertical slopes. These slopes require redirection of surface water from the damaged slope and removal of failed material. The vertical face may be reestablished in the undisturbed portions of the loess.

Large vertical sink areas (developed from piping) can be repaired by placing a geosynthetic liner (with an appropriately designed infiltration rate), backfilling with graded aggregate, placing an impervious cover, and redirecting drainage. Repair measures have failed only when surface drainage was not adequately diverted or the drainage system was not maintained, allowing infiltration.

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