Physical Properties of Southeastern Washington Loess Related to Cut Slope Design

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Loess is an aeolian soil consisting primarily of silt. The silt particles along with a lesser percentage of sand are coated by a clay binder, giving loess its unique structure. Because of the lack of development in the loessial soils of southeastern Washington, little is known about their engineering characteristics. However, recent highway construction requiring large cut slopes has prompted interest. The results of a literature review of engineering characteristics of loess and an evaluation of the physical properties of southeastern Washington loess related to design of cut slopes are presented. A map shows the general distribution of clayey, silty, and sandy loess. Results to date indicate that the basic physical properties of southeastern Washington loess are quite similar to those from deposits in the central United States. Water content tends to increase from west to east because of increasing clay content and precipitation to the east. Washington loess has a slightly lower plasticity than midwestern deposits, possibly because of greater illite and lower montmorillinite content. Based on experience in the midwestern United States and observations of existing cut slopes in southeastern Washington, design recommendations are presented. Near-vertical cuts are recommended in silty loess with low water content, and flatter cuts (approximately 2.5:1 H:V) are recommended in clayey loess and silty loess with high water content. Adequate surface drainage is a key factor of slope design.

Loess is an aeolian soil consisting primarily of silt-sized particles. The word "loess" is derived from the German word *lösen*, which means "to loosen or dissolve" and is descriptive of the structure associated with loessial soils. Major deposits of loess are located in China, Europe, and the United States. Although the most extensive deposits in the United States are located in the Midwest, a substantial portion of southeastern Washington is covered by loess. Loess is characterized by its loose structure of silt and fine sand particles coated by a clay binder. This structure allows vertical or near-vertical cuts exceeding 50 ft in height to perform exceptionally well, provided the water content remains low. Conversely, upon wetting, loess becomes relatively unstable and slope failures can occur in slopes as flat as 2:1 (H:V) *(1)*. In addition to slope failures, excessive settlement of foundations upon wetting (termed hydroconsolidation) is a well-known phenomenon associated with loessial soils.

When the structure of loess is considered, its adverse reaction to increased water content is easily understood. Because of the clay coating on the silt and sand particles, there is little intergranular contact, particularly at low confining pressures. Thus, most of the strength is attributable to the clay binder. At low water content high negative pore pressures develop in the binder, which increases shear strength. However, upon wetting, the negative pore pressures are reduced as water content within the clay fraction increases to near saturation. This leads to lower effective stress in the soil and therefore lower shear strength.

Hydroconsolidation is also a result of loess structure. As previously stated, loess exhibits a loose structure, that is, a high void ratio. Upon wetting, the reduction in shear strength allows the granular fraction to reorient, which may produce a denser soil (with a substantially lower void ratio) and large settlements.

The first comprehensive investigation of the physical properties that control the engineering behavior of loessial soils was performed by the Bureau of Reclamation on Missouri River Valley loess (*2*,pp.9–26). Following this work, research on other loess deposits was conducted primarily within Missouri, Iowa, Kansas, Tennessee, and Mississippi (*1,3–9*, pp.13–38; *10;11*, pp.01–020;*12*,pp.C1–C45). These works examined the variation of physical properties (gradation, plasticity, specific gravity, etc.) within deposits related to distance from the source and the influence of these properties on the engineering behavior of loess.

Because of the relative lack of development within southeastern Washington, very little research had been directed toward determination of the physical properties of the loess in that area. However, recent highway construction and realignment in southeastern Washington has produced many slope cuts that have suffered from erosion and slope stability problems related to the unique properties of loess. These problems have prompted the Washington State Department of Transportation (WSDOT) to begin research on the physical properties of southeastern Washington loess to determine how these properties relate to cut slope performance *(13)*.

Some of the principal components of the investigation are presented here: a review of previous research on the physical properties of loess related to cut slope design and a description of the physical properties of southeastern Washington loess. The literature review establishes the important physical properties that control (or help predict) engineering behavior of

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loessial soils. Also, it includes a general description of physical properties of loessial deposits in the United States, which provides a basis for defining the similarities and differences between southeastern Washington loess and deposits from other locales. Samples collected throughout southeastern Washington were tested to establish the physical properties of the deposits. The laboratory tests included grain size distribution, Atterberg limits, and specific gravity. The test results define the basic characteristics of the deposit and reveal variations in physical properties with areal extent. Recommendations for improved cut slope design are developed on the basis of experience in similar soils in the central United States.

PHYSICAL PROPERTIES OF LOESSIAL SOILS

Characterization of Properties

One of the earliest comprehensive studies of the physical properties of loess was conducted by Holtz and Gibbs *(2)*. Although they were primarily interested in consolidation, basic laboratory tests including gradation, specific gravity, Atterberg limits, and shear strength were performed on a large number of samples. Grain size analyses revealed that the majority of samples fell within gradation limits defined as silty loess. Samples found to be finer than the boundaries established for silty loess were termed clayey loess, whereas coarser samples were categorized as sandy loess. A grain size distribution chart delineating these subdivisions is given in Figure 1.

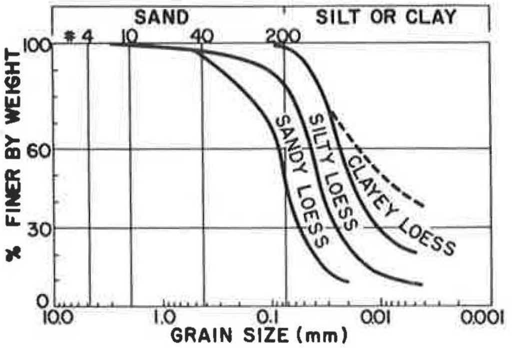

FIGURE 1 Range in grain size distribution for Missouri River Valley loess [after Holtz and Gibbs *(2)*].

Holtz and Gibbs *(2)* plotted the results of the Atterberg limits tests on a plasticity chart. A concentration of points with plasticity indexes ranging from 5 to 12 and liquid limits between 28 and 34 was found. Examination of these data in conjunction with the gradation analysis reveals that the concentration is 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.

The investigators report that drained shear strength, as determined by triaxial testing, varies considerably with water content and to a lesser extent with dry density. Strength increased with decreasing water content and increasing density. The angle of internal friction remained fairly constant, ranging from 30 to 34 degrees, and the cohesion intercept increased rapidly as water content decreased. It is unclear to the authors whether these parameters reflect effective or total stress conditions. Gibbs and Holland *(14)* expanded the data base of the original work by Holtz and Gibbs. Additional laboratory tests as well as plate load and pile-driving tests were incorporated into the report. Results pertinent to strength properties remained essentially unchanged. The authors are currently conducting a comprehensive field and laboratory testing program including measurement of effective stress parameters for Washington loessial soils.

The relationship between water content and shear strength was more thoroughly explained by Kane *(15)*, 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 strain with increasing water content were performed.

It was found that a critical water content can be determined such that an increase in water content beyond critical fills voids between particles and has little effect on the clay binder. As water content decreases below critical, negative pore-water pressures develop in the clay binder, leading to increased strength in the soil matrix. This concept has been applied by the Missouri State Highway Department as discussed in the following.

Chemical Composition

Montmorillonite or a combination of montmorillonite and illite are the dominant clay minerals for loess deposits in the central United States *(6, 8, 12, 14, 16)*. The clay fraction of Alaskan loess is predominantly chlorite with minor amounts of illite and possibly kaolinite *(17*, p.67).

Calcite deposits in loess are generally found as discrete grains, root fillings, or nodules *(2, 14)*. In some cases a continuous layer or crust of calcite may form. This crust generally forms as the result of evaporation and has been observed on cut slopes in Mississippi *(12)*.

When 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 samples are obtained from a location containing a larger-than-average percentage of calcite, tests will indicate a strength higher than actually exists for the site as a whole.

Gradation and Plasticity

Figure 2 presents the combined grain size distribution for a number of locations in the United States. In general, the range in grain size distribution falls within the bounds established by Holtz and Gibbs *(2)* with the exception of Alaskan loess, which tends to be slightly coarser. The maximum grain size in loessial deposits examined within the continental United States is 2.00 mm, whereas analysis on Alaskan loess exhibits an upper limit

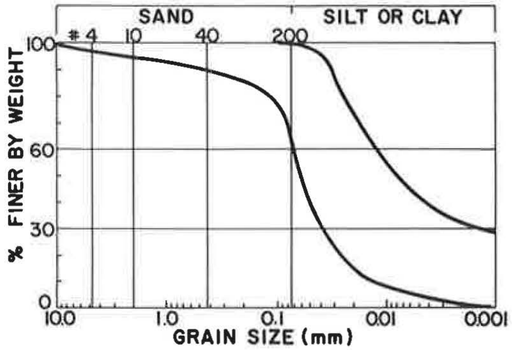

FIGURE 2 Range in grain size distribution of loess for Alaska *(18)*, Kansas *(16)*, Iowa *(17, 6)*, and Mississippi *(12)*.

of 9.53 mm. Present theory is that the particles in Alaskan loess larger than 2.00 mm may be carbonate concretions formed after deposition of the loessial unit, although testing has not been performed to substantiate this hypothesis *(19)*. The results of Atterberg limit tests from various investigations are shown in Figure 3.

Variability with Distance from Source

Although physical 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. Investigations in the Midwest and South *(3, 5, 12)* indicate an increase in clay content and decrease in total thickness with distance from the source. These same studies show that in Iowa and Mississippi as clay content increases, silt content decreases and sand is a uniform, minor constituent. Variation in clay content tends to affect the engineering properties. As clay content increases, natural water content and density also increase *(4)*. 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 *(5)* for midwestern loess deposits. Although this relationship is valid for some deposits, in many cases thickness is highly variable on a local scale and no clear trends are 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 minimal deposits in intervening depressions *(11)*.

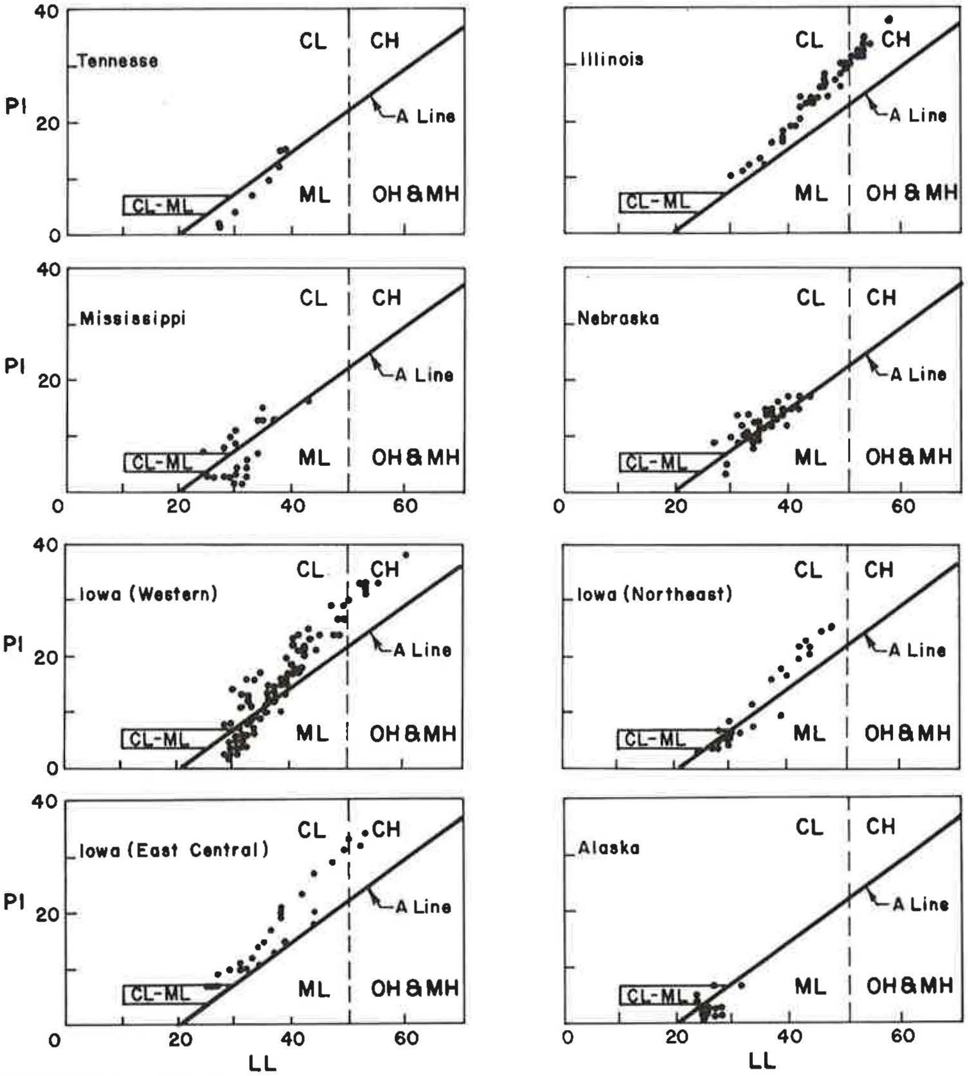

FIGURE 3 Plasticity data for loessial deposits throughout United States *(19)*.

Depth Effects

When the variation in textural composition with depth is discussed, it is not possible to generalize except to say that changes in the relative percentages of sand, silt, and clay constituents with depth are usually minor. In some areas sand content has been found to increase slightly with depth whereas clay size content remained constant or showed a minor decrease *(7)*. Conversely, some vertical sections exhibit a uniform percentage of sand with depth, whereas clay size content remains constant up to the base of the unit, where it increases slightly *(20)*. Except for isolated cases, constituent percentages do 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 6 to 7 ft, both density and water content tend to increase with depth.

INDEX PROPERTIES OF SOUTHEASTERN WASHINGTON LOESS

Origin

Loessial deposits blanket the majority of southeastern Washington and extend into northern Idaho and northeastern Oregon. Traditionally the deposit has been subdivided into four loess formations: Palouse, Nez Percé, Ritzville, and Walla Walla. The earliest engineering reference to these subdivisions was by Eske (*21*, p.75) (Figure 4). The formation boundaries evidently are based on pedological classification; therefore their value with respect to engineering properties is questionable.

The source material for the southeastern Washington loess deposit is still a matter of debate. Various investigators have proposed sources ranging from northwest to southwest of the deposit; the Ringold formation, centered in the Pasco Basin west of the deposit, is the most widely accepted origin *(22)*.

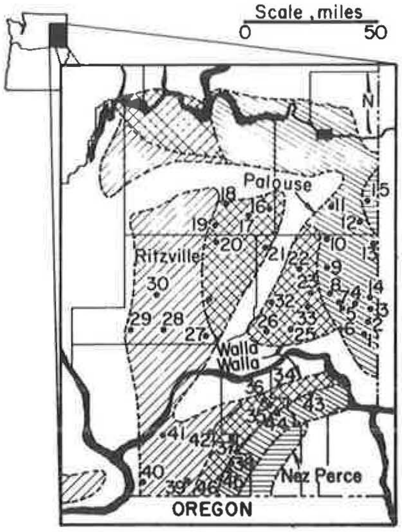

FIGURE 4 Southeastern Washington loess formations *(21)* and sample locations for field study.

Laboratory Testing Program

The primary goal of the sampling and testing program was to collect and evaluate a sufficient number of soil samples to delineate the variation in physical properties with location throughout the deposit. A total of 40 samples was collected from road cuts by hand augering. In general, samples were collected from the C horizon by augering horizontally into the road cut a minimum of 3 to 4 ft and sampling within the last foot. Samples were placed in plastic bags and immediately sealed to prevent moisture loss. An effort was made to pick sites evenly spaced throughout the study area. In this way trends in physical properties and the validity of the formation boundaries previously outlined could be evaluated. The sample locations are indicated in Figure 4.

Atterberg limits (liquid and plastic), grain size analysis, and water content were determined for 40 representative samples, and specific gravity was determined for 18 samples. All tests were performed in accordance with ASTM standards. These properties, particularly gradation and plasticity, have been found to influence engineering behavior strongly *(1, 2)* as well as to provide a basis for comparison with other deposits.

Specific Gravity

Specific gravity of southeastern Washington loess varies within narrow limits. Values range from 2.67 to 2.74 with a mean of 2.71 for the 18 samples tested. The consistency of the test results led to the decision not to conduct specific gravity tests on all samples. It was believed that the laboratory time could be better spent increasing the data base for grain size distribution and Atterberg limit tests.

Gradation

The range in grain size distribution of the 40 samples examined is shown in Figure 5 and corresponds closely with the boundaries established by Holtz and Gibbs. Of the samples tested 10 percent were classified as sandy loess, 68 percent as silty loess, and 22 percent as clayey loess.

The change in grain size distribution is a primary indicator of variation in physical properties with location for loessial soils.

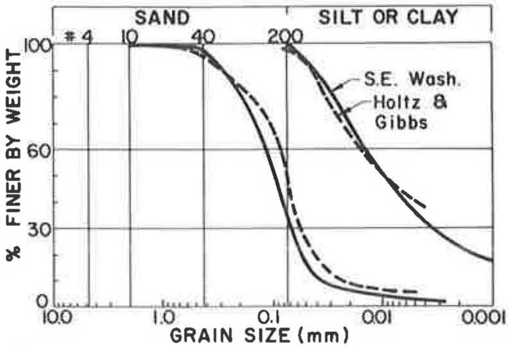

FIGURE 5 Range in grain size distribution for 40 samples of southeastern Washington loess.

As was established in the literature review, clay content, water content, and density all tend to increase with distance from the source. As the engineering behavior of loess varies with the aforementioned properties, definition of directional variation within the deposit becomes extremely important.

Although 40 samples do not constitute a large enough data base to provide a definitive answer with regard to source or distribution, they supply sufficient data to establish general trends within the deposit that should be very helpful to engineering geologists and geotechnical engineers. Figure 6 shows the locations of three cross sections constructed through the deposits, one trending east-west and the other two north-south. In Figure 7, the east-west cross section *A–A′*, a general increase in clay size content and a decrease in sand to the east are shown. In Figure 8, the westernmost north-south cross section *B–B′*, fairly constant clay-silt-sand ratios are revealed with only local fluctuations. The easternmost north-south cross section *C–C′* (Figure 9) is similar to that in Figure 8 in that the relative percentages of sand, silt, and clay size remain fairly constant. However, cross section *C–C′* has a higher clay size content and lower sand content than *B–B′*.

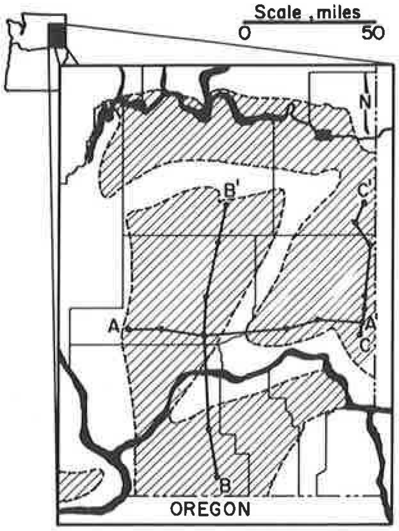

FIGURE 6 Location map for cross section *A–A′*, *B–B′*, and *C–C′*.

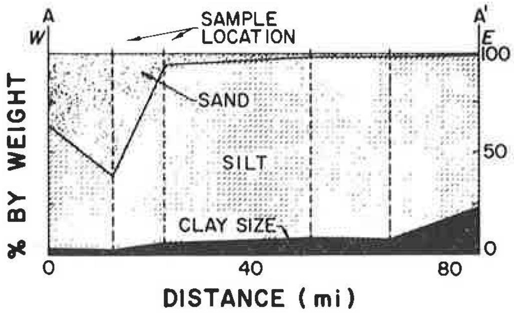

FIGURE 7 Cross section *A–A′*.

Clay size content (< 2 μm) was contoured for the study area and is shown in Figure 10. Although anomalies are present, a definite trend of increasing content of clay-size material to the east is apparent. As established earlier, sand content decreases from west to east. These facts in conjunction with the cross sections suggest that the source material was to the west of the deposit with no major north or south directional component.

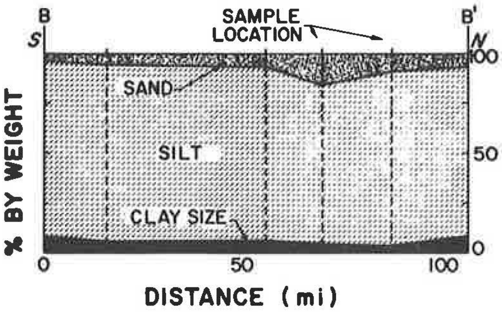

FIGURE 8 Cross section *B–B′*.

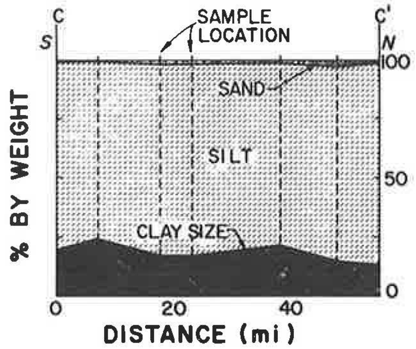

FIGURE 9 Cross section *C–C′*.

None of the data collected support the use as engineering units of formation boundaries shown in Figure 4. Although the subdivisions may be useful from an agricultural or pedological standpoint, the data clearly demonstrate that with regard to the

FIGURE 10 Generalized contour map of percentage content of clay-size particles for southeastern Washington loess.

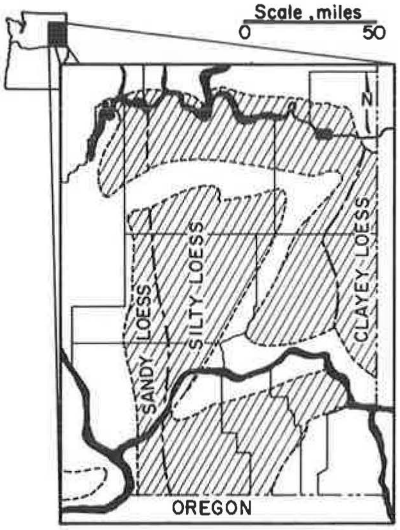

FIGURE 11 Approximate gradation boundaries for southeastern Washington loess.

properties mentioned earlier, variations can be expected to show east-west trends independent of formation boundaries. Figure 11 shows approximate gradation boundaries for southeastern Washington loess based on testing to date.

Figure 12 shows a typical vertical profile at sampling site B–25 determined from five discrete sampling points. Little variation in the relative percentages of the sand, silt, and clay fractions is shown. Although the percentage of sand-size particles varies by less than 1 percent, the clay-size material (< 2 μm) varies up to 5 percent, which is still relatively minor for a natural soil.

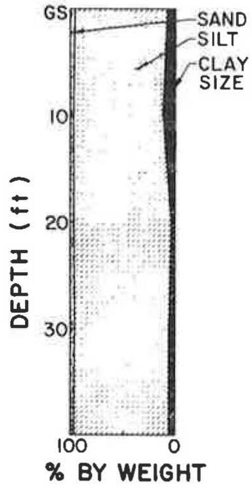

FIGURE 12 Typical variation in textural composition with depth.

Density

Although in situ densities were not measured, limited data are available from a previous investigation. Lobdell *(23)* reported dry densities ranging between 95 and 98 pcf in Palouse loess. These densities were determined from block samples in the form of 6-in. cubes from an excavation site at Washington State University. Thus, the values Lobdell reported should be an accurate indication of in situ dry density for the eastern extreme of the deposit. As discussed previously, density tends to increase with distance from the source. Because the source is to the west of the deposit, it is likely that in situ density increases from west to east. Thus, it is assumed that the density data reported by Lobdell provide an upper bound for the deposit.

Water Content

From the 40 samples tested, natural water content was obtained for 22 sites throughout the study area. From the samples tested, water content ranged from 4.5 to 27.7 percent. As might be expected, water content shows a high degree of variability from location to location. Even so, water content generally tends to increase from west to east. The directional variation in water content may be attributed to two factors. First, content of clay-size material increases from west to east as determined by the grain size analysis. As previously indicated, water content tends to increase with increasing clay size content. Second, mean annual precipitation tends to increase from west to east by as much as 100 percent.

Plasticity

Plasticity characteristics were evaluated by the Atterberg limit tests. Plastic and liquid limit tests were conducted on 40 samples and plotted on a plasticity chart (Figure 13). Examination of the plot and the grain size distributions reveals two groupings of the data. Silty loess tends to have liquid limits ranging from 14 to 32 and plasticity indexes of 0 (nonplastic) to 11. Clayey loess has liquid limits that vary between 33 and 49 with

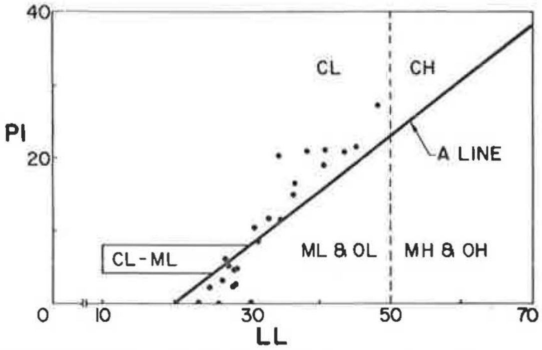

FIGURE 13 Plasticity data for southeastern Washington loess.

plasticity indexes ranging from 11 to 27. The two sandy loesses tested were nonplastic.

Calcium Carbonate

During field sampling, various forms of calcium carbonate were encountered. In most cases calcite was present as either root fillings or nodules. To a lesser extent calcite was found to exist as indurated sheets lying 6 in. to 1 ft behind the surface of a cut face. This appears to be an evaporation phenomenon similar to that noted in Mississippi *(12)*. Because of the discrete nature of most calcite deposits, the absence of calcium carbonate in an area where it might be expected does not necessarily imply that it is absent from the area as a whole.

It would appear that the presence or absence of calcium carbonate is related to mean annual precipitation. In areas averaging more than 20 in. 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 15 in. contained significant quantities of calcite.

Relationship Between Southeastern Washington Loess and Other Deposits

On the basis of these laboratory results, southeastern Washington loess appears similar to loessial deposits within the central United States. The range of grain size distribution is very similar to that found by Holtz and Gibbs *(2)* for Missouri River Valley loess and to the other deposits reported previously. Plasticity tends to be slightly lower in Washington loess than in other deposits, possibly because of greater illite and lower montmorillinite content *(23)*. Other properties such as calcium carbonate occurrence, variation of textural components with depth and distance from the source, as well as specific gravity appear consistent with results obtained for other deposits.

Therefore, it should be expected that the engineering behavior of southeastern Washington loess will be similar to that in the deposits in the central United States, and thus design experience from other loess areas should be helpful in the Washington deposit. Any differences in failure modes probably would be the result of the variation in climatic conditions between the Northwest and the Midwest.

CUT SLOPE DESIGN EXPERIENCE

Some of the most recent and comprehensive published data on cut slope design and performance in loess was provided by the Missouri State Highway Department (MSHD) *(1)* and the Tennessee Department of Transportation (TDOT) *(9, 10)*. The MSHD conducted an extensive study of cut slope design in loess, which resulted in correlation of the type and degree of failure, exposure, slope, moisture content, and loess type for 106 cut slopes. As a result, design specifications were developed that are based on two main criteria: *(a)* gradation boundaries similar to those established by Holtz and Gibbs *(2)* and *(b)* Kane's critical water content concept *(15)*.

The Missouri study concluded that vertical cuts perform well in silty loess if water content remains less than 17 percent (slightly higher water content is acceptable if slope exposure falls between southeastern and southwest).The cut is typically benched when the total height exceeds 25 to 35 ft, and benches 15 to 20 ft wide are placed approximately every 20 ft vertically. The benches help limit erosion of the cut face and provide increased stability of the overall slope.

Flattened slopes are recommended for silty loess with high water content and for all cuts in clayey loess. The Missouri study found that 2:1 slopes are generally flat enough from the standpoint of stability; however, slopes flattened to 2.5:1 show much less degradation by erosion. Whether vertical or flattened slopes are employed, a drainage diversion around the crest of the slope is an important design consideration.

The TDOT *(9, 10)* reported that vertical cuts in silty loess have performed better than flattened slopes. The flattened slopes experience significantly more damage from erosion of the face of the cut. Contrary to these findings, TDOT designs cut slopes 2:1 or flatter with 15- to 25-ft benches at 20- to 25-ft vertical intervals (Royster, unpublished data).

Regardless of the slope cut, Royster *(9)* and Royster and Rowan *(10)* stress the importance of surface drainage around the slope face and at the toe of the slope as well as erosion protection of the drainage channel by paving, sodding, or seeding.

WSDOT cut slope design criteria have varied somewhat over past years. Near-vertical cuts as well as many flattened slopes have been constructed; however, surface drainage structures frequently have been left out of the slope construction, or if built they often have been inadequate. WSDOT has constructed a number of near-vertical cuts (0.5:1 to 0.25:1) in silty loess in recent years, whereas the most common practice in clayey loess has been 2:1 cuts. An examination of selected cuts in eastern Washington during the spring of 1985 indicated a number of failure problems similar to those reported in Missouri. These are analyzed in detail by Higgins et al. *(13)*.

In general, vertical cuts appeared to be performing well in silty loess where the natural drainage diverted flow away from the cut face. Where surface water was allowed to accumulate near or flow over the slope face, severe damage was experienced because of erosion and piping (Figure 14). The area defined in Figure 11 as silty loess is relatively dry (generally less than 15 in. of annual rainfall). Therefore, the soils maintain a low water content, which would appear to be an ideal situation for the use of vertical cuts. The key design factor is adequate drainage.

Many slopes flattened to approximately 2:1 have been constructed in both silty and clayey loess in the eastern part of the deposit. Annual moisture in this area ranges from 15 to 20 in., much of it in the form of snowfall. In the spring, the upper few feet of soil often become saturated from snowmelt or rainfall or both, and shallow slides (or flows) of vegetation and a thin layer of soil result. These slides were very common during the spring of 1985 and ranged from small scale (1 to 10 ft wide with a depth of failure ranging between inches and 4 ft) to much

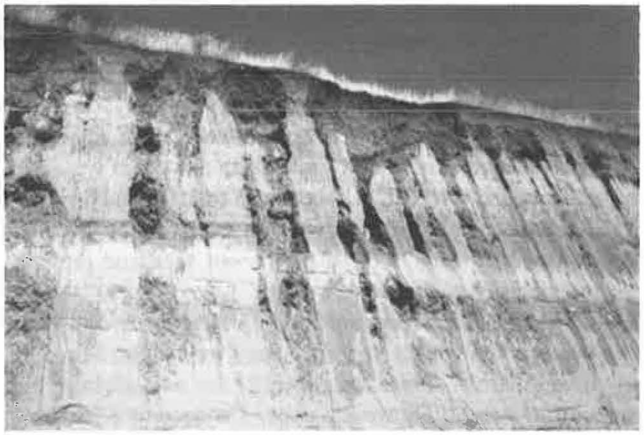

FIGURE 14 Erosion and piping damage in near-vertical cut in loess.

larger scale, involving the entire cut (Figure 15). In most cases the initial failure was followed by increased erosion due to the loss of vegetative cover with severe gully erosion a common result. A number of the cut slopes examined in the eastern part of the deposit have experienced this type of failure in the past, and as a result erosion gullies ranging up to 2 ft deep have formed on the cuts. Clearly, cuts of 2:1 in clayey loess are too steep to maintain a vegetative cover.

FIGURE 15 Shallow failure of road cut in loessial soils under melting snowdrift.

PRELIMINARY DESIGN AND MAINTENANCE GUIDELINES

Recommendations

On the basis of the similarities between the physical properties of southeastern Washington loess and loess in the central United States and the similarities in failure modes of cut slopes established in this paper, preliminary design and maintenance guidelines for routine cuts in loess slopes have been recommended. WSDOT will implement these guidelines in test sections over the next 2 years. These test sections will include some experimentation in use of slope angles, drainage ditch liners, and so on, to find the optimum design. Design of very deep cuts (much more than 50 to 60 ft) probably would require a more detailed investigation and analysis than that recommended here; that is, shear strength parameters and a slope stability analysis may be needed. The following recommendations rely heavily on the experience of MSHD *(1)*, TDOT *(9, 10)*, and observations of cut slope failures in southeastern Washington *(13)*.

Vertical Versus Flattened Slopes

If the soil at the site of the proposed cut is a silty loess with water content below critical, near-vertical cuts (0.25:1) may be considered. If vertical cuts are used they should be benched on approximately 20-ft vertical intervals when the total height of the cut exceeds 25 to 30 ft. Benches should be 15 to 20 ft wide and gently sloped toward the back of the cut. If either water content exceeds critical (17 percent can be used as an approximation based on experience in the Midwest) or the soil is a clayey loess, flattened slopes should be used. Generally 2.5:1 slopes should perform adequately, but if a water table is intercepted, flatter slopes may be required because of seepage forces. Although design criteria have not been developed for sandy loess, it is believed that content of clay-size material would be so low that vertical cuts would perform poorly.

Erosion Control

Erosion control practices similar to those reported by Royster *(9)* are suggested for Washington loess. With the possible exception of short excavations through small lobate ridges of loess, a drainage ditch approximately 10 to 15 ft behind the top of the cut should be constructed before the slope cut is made. The ditch should be seeded or lined, depending on the gradient. The drainage ditch should be constructed before the opening of the cut with as little disturbance to the surrounding vegetation as possible. Once the cut has been made, construction equipment should be kept away from the crest. If natural drainage channels are truncated by a cut, the drainage system should be adequate to transmit the flow around or over the cut face in protected channels or pipes.

Standard farming techniques in southeastern Washington entail cultivating to the edge of road cuts. This practice is not acceptable if the ditches above the slope crest are to remain operable. Continued cultivation over a drainage ditch will ultimately destroy its effectiveness. Therefore, the most desirable location for thedrainage ditch would be within a protected right-of-way.

It is suggested that for new construction, drainage ditches should be constructed approximately 10 ft away from the toe of the slope, and the ground surface should be gently sloped toward the ditch. Any material that spalls downslope between the toe and the ditch should be left in place. This practice will serve two purposes: *(a)* the spalled material will help protect and stabilize the toe of the slope, and *(b)* the location of the ditch will prevent maintenance equipment from accidentally undercutting the toe of the slope while the ditch is being cleaned.

In cases where benched cuts are required, the benches should be seeded or sodded. If the upper drainage system is properly constructed, it should not be necessary to employ ditches on the benches or use erosion control methods in excess of vegetative cover unless extremely long cuts are made.

Side ditches offer some of the most severe erosion problems. Gradients are generally steeper than along the cut and flows tend to be higher because of the concentration from various sources. In many cases it has been necessary to pave ditches or use halved culverts to prevent erosion.

If a flattened slope is constructed, the cut should be seeded immediately following construction. In addition, a protective cover should be placed over the slope, either a straw mulch or a synthetic material. These covers serve the dual purpose of preventing raindrop erosion, a major cause of erosion on newly opened cuts, and helping to retain moisture required to initiate a vegetative cover.

Periodic Maintenance

Because of its highly erosive nature, loess slopes will deteriorate rapidly once erosion has been initiated. Thus it is important to repair any erosion damage as soon as it is discovered. Maintenance may require repairs to, enlargement of, and removal of siltation from existing ditches. Increased erosion protection, such as installation of liners or filters 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 Midwest). In addition, some areas will not seed well the first time and may require a second and possibly a third seeding.

Removal of sediment from toe ditches on existing slopes should be done carefully to avoid undercutting of 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.

CONCLUSIONS

Previous investigations have demonstrated that loessial deposits from the central United States exhibit similar physical properties. Gradation generally falls within the range reported by Holtz and Gibbs *(2)* for Missouri River Valley loess. Plasticity characteristics are similar, provided the samples fall within the same gradational subdivision (sandy, silty, or clayey).

Analysis of samples from southeastern Washington loess reveals that the deposit is similar to deposits from the central United States. Gradation curves fall within the range reported by Holtz and Gibbs *(2)* and indicate a westerly source. Grain size distribution ranges from sandy loess at the western extremity of the deposit to clayey loess near the eastern boundary. No major north-south trend was observed.

Plasticity characteristics are similar to those for midwestern deposits. However, plasticity did appear to be slightly lower for southeastern Washington loess. Lower plasticity may be due to a higher illite and lower montmorillonite content than that found in midwestern deposits. The only substantial difference between Washington loess and deposits from the central United States that may affect engineering behavior is climatic and not due to physical properties.

Design criteria for routine cuts in loess in southeastern Washington have been recommended on the basis of studies in midwestern loess and observations of cut slope failures in the Washington deposit. Near-vertical cuts are appropriate in silty loess with low moisture content. Flatter cuts (2.5:1 or less) should be most suitable in all clayey loess and silty loess with a high moisture content. No matter what slope angle is excavated, a major part of the design is diversion of surface water around the slope cut. Extremely large cuts should be designed on the basis of a detailed analysis that includes an evaluation of shear strength parameters and a slope stability analysis.

ACKNOWLEDGMENTS

This paper is the direct result of work supported by the Washington State Department of Transportation and FHWA, U.S. Department of Transportation. The authors gratefully acknowledge G. Scott Rutherford and Keith Anderson of WSDOT for their strong support and review of this work.

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The contents of this paper reflect the views of the authors and do not necessarily reflect the official views or policies of WSDOT or FHWA.

Publication of this paper sponsored by Committee on Soil and Rock Properties.