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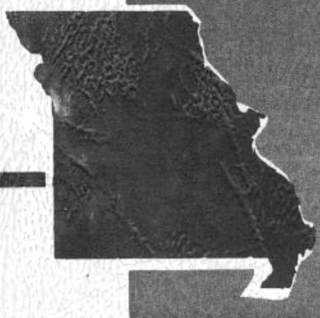
MISSOURI COOPERATIVE HIGHWAY RESEARCH PROGRAM
FINAL REPORT

74-1

DEVELOPMENT OF DESIGN CRITERIA FOR CUT SLOPES IN LOESS

MISSOURI STATE HIGHWAY DEPARTMENT



DEVELOPMENT OF DESIGN CRITERIA FOR CUT SLOPES IN LOESS

STUDY NO. 74-1

Prepared by

MISSOURI STATE HIGHWAY DEPARTMENT

DIVISION OF MATERIALS AND RESEARCH

FINAL REPORT

APRIL, 1978

In Cooperation With

U.S. Department of Transportation

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ABSTRACT

Highway cut slopes in loess were studied throughout Missouri to evaluate the relationship of performance to slope angle, orientation, stratigraphy and various physical properties. Deep cuts for which preconstruction data was available were studied in detail. Samples were obtained by various techniques to determine effects on density and moisture content. It was concluded that stratigraphic identification, while useful, was less valuable than determination of physical properties for prediction of slope behavior. Moisture content and grain size distribution were found to correlate well to observed performance and types of failure. Freeze damage, of a form analogous to subgrade frost heave, was found to be a significant source of degradation of vertical slopes. It was concluded that severe limitations should be placed on use of vertical slopes in loess. Procedures and criteria are proposed for slope selection, methods of stability analysis and types of sampling and testing to be performed during the soil survey. Particular emphasis is given to moisture and clay content, slope orientation, accurate logging of water tables and zones of saturation and to sampling from dry (augered) holes.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Loess, a wind deposited soil composed predominantly of silt sized particles, is found most prominently in Missouri in deep deposits along the bluffs flanking the flood plains of the Missouri and Mississippi Rivers. Where unaltered by geologic and hydrologic processes, the silt particles are coated with thin clay films, a "glue" that binds together the normally porous structure and from which springs the remarkable ability to stand on vertical slopes.

The practice of using vertical slopes for roads cut through loess was established by early roads and trails. Hooves, wagon wheels, wind and water eroded the friable soil and entrenched the trails while the sides remained nearly vertical, even establishing "overhangs" of sod and roots. Historic examples of such roads occurred most notably in the St. Joseph area but were also common in what is now the metropolitan areas of Kansas City and, to a lesser extent, St. Louis.

Roadway designers in the Kansas City and St. Joseph areas have continued to make extensive use of essentially vertical slopes (normally 1/4:1) for cuts through loess. However, modern design standards have resulted in cuts of unprecedented depths. Older loess strata with altered physical properties have been intercepted and these have not always performed well when cut on the vertical. Many of the recent vertical slopes have been subject to slides, sloughs, erosional problems and continuing, unsightly degradation. This has made apparent that more discrimination was necessary in the use of slopes approaching the vertical and that existing criteria for slope design in loess was inadequate. Figures 1, 2 and 3 illustrate some of the extremes in performance experienced with both near vertical and flattened slopes.

Until recently loess stratigraphy has received little attention within the Missouri Highway Department. Past soil surveys have generally classified loess only under such pedologic names as "Knox" or "Memphis". As recent exposures have revealed, the stratigraphy may be complex. Guidebooks prepared by regional geological societies are now available which provide identification of stratigraphy at several of the better exposures provided by new construction.

Recent researchers have advanced theories explaining the performance of loess in terms of soil mechanics principles. The critical moisture concept advanced by Kane(1) has related strength to moisture content, and the work of Holtz and Gibbs(3) has related performance to grain size distribution.

An evaluation of the application of these theories to predicting slope behavior is one of the objectives of this study. Other goals include determining means of improving the soil survey, including techniques for loess classification and sampling, the correlation of engineering data and stratigraphy to past performance and an evaluation of techniques of stability analysis.

Figure 1. Example of successful use of near vertical rises with benches (stepped slope) (Buchanan County, I-229)

Figure 2. Example of a stepped slope which has failed (Howard County, Route D(87)

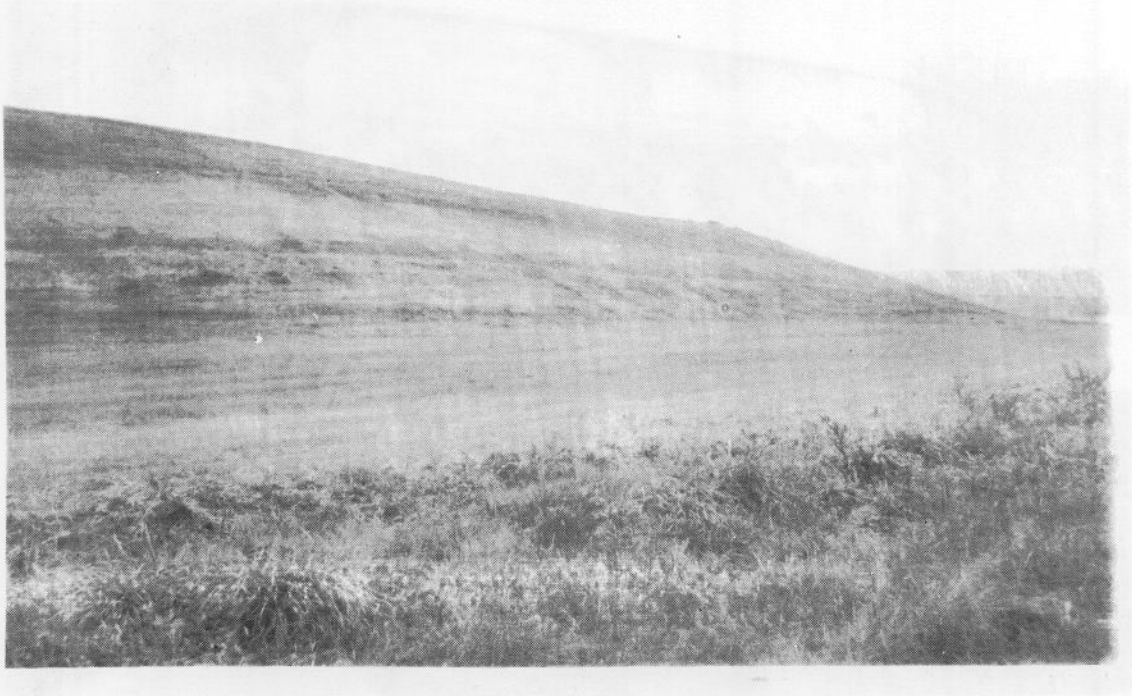

Figure 3. Example of a flattened slope (2½ on 1) performing adequately in highly erosive loess. (Howard County, Route D(87)

CONCLUSIONS

Soil surveys through areas of loess deposits must include some form of "undisturbed" sampling sufficient to establish the trend of horizontal and vertical variations in Atterberg limits, grain size distribution and natural moisture. Of utmost importance is accurate logging of water tables. Non-saturated loess should be sampled in dry holes (augered or drilled with air) to prevent moisture contamination of the samples.

While natural density would be a most useful index property of loess slope performance, none of the down-hole sampling techniques evaluated were so consistently free of sample compression that density could be determined reliably. This is an area deserving of further research.

Pedologic classifications generally furnish inadequate indications of performance of loessial soils except in shallow profiles located at some distance from the primary deposition. Stratigraphic classifications are more useful for thick deposits close to the river bottoms.

Stratigraphic units such as the Bignell and the upper portion of the Peoria can generally be associated with the physical characteristics found necessary for good performance of vertical slopes: low density, low moisture, low clay content and low plasticity. Contrary associations can generally be made for the lower portion of the Peoria, the Roxana and the Loveland.

Primary reliance in predicting slope behavior in loess should be placed on physical properties. Stratigraphic indentification, while useful and certainly of more value than pedologic classification, is relatively difficult from bore hole logging and sampling and probably does not warrant great expense and effort. In any case, the physical properties are diagnostic while stratigraphy is only indicative of those physical properties.

The study has furnished confirmation of the usefulness of the critical moisture concept advanced by Kane as well as classifying loess as "clayey" or "silty" (modified somewhat from Holtz and Gibb's definitions) as indicators of slope performance. These approaches are mutually supportive in that "silty" loesses are usually lower in moisture content than are "clayey" loesses. Survey data complemented by construction case histories suggest that an average moisture content of about 17 percent or less is indicative of probable success of stepped vertical cut slopes if the loess also meets the definition for "silty" loess. With favorable exposure of the cut face to sunlight and with drainage conditions favorable to drying, slightly higher moistures, but not more than 20 percent, may be tolerable for stepped vertical slopes.

Development of ice lenses behind the face (analogous to subgrade frost heave) was found to be a significant source of degradation of vertical slopes. This was particularly true of north facing slopes and where zones of saturation had been truncated by cut. Zones of saturation invariably were found to exhibit adverse behavior of various kinds where vertical slopes were used.

Flattened cut slopes in loess were found by the survey to evidence few serious problems. Erosion was found serious only during construction and until adequate vegetative cover developed. While slopes of 2 to 1 or even steeper are usually stable, suceptibility to erosion during construction is a major consideration reflected in Missouri's current use of 2.5:1 for flattened slopes in loess. Anticipation of seepage stresses would require flatter slopes or special treatments based on an analysis of the individual problem.

No substantiation was found for the concept of stabilizing vertical loess slopes by drainage from pilot trenches. While catastrophic slide failures can perhaps be avoided in this manner, it is certain that slopes in saturated loess will be free of long term degradation only if flattened substantially.

This study has indicated a need for severe limitations on the use of slopes approaching the vertical. However, such slopes should not be eliminated from consideration since those loesses most suitable for essentially vertical slopes are also most prone to erosion when flattened. Emphasis should be reversed; rather than assume that vertical cut slopes can always be used, it should be assumed that flattened slopes will be required unless vertical slopes are proven practical by an adequate soils investigation.

IMPLEMENTATION

During this investigation, many of the recommendations contained in this report have been implemented as they were developed. Soil surveys are now being conducted and reviewed in a manner generally consistent with the concepts discussed and proposed herein. This has been accomplished both by informal communications and by formal changes in policy.

Soil survey procedures have been modified to require more detailed sampling to better determine the physical index properties of all soils. "Undisturbed" samples at intervals of 5 feet or closer are now required, in addition to any composite augered samples, from every soil cut of 10 feet or more in depth to determine AASHTO and ASTM classifications, plasticity, grain size and natural moisture content. Use of a 5 foot long, slotted tube sampler is now routine for continuous sampling of loess soils. Administrative changes in the handling and distribution of soil survey reports now provide for more effective reviews at the Divisional level. This promotes consultation with the district office performing the soil survey and contributes to a more uniform approach to problems with loess soils.

Recently, use of these procedures on a job having cuts of 50 foot depth resulted in flattened slopes being proposed where essentially vertical slopes would once have been used routinely. Continued use of these concepts and practices should result in a more consistent and rational approach to loess slope design statewide.

Distribution of this report throughout the Department should contribute to a better understanding of the problems unique to loess soils. Final implementation will consist of formal requirements in policy manuals.

SCOPE

Highway cut slopes in loess were studied throughout Missouri to evaluate the relationship of performance to both stratigraphy and physical properties. A total of 106 slopes were surveyed. Soil samples were obtained and observations made about type and degree of failure, exposure, type and degree of slope and stratigraphy. Stratification was defined by color and physical properties and related to known stratigraphic profiles. Physical properties determined by testing included moisture content, plasticity and grain size distribution.

Samples obtained by various drilling techniques were compared against samples cut by hand from an excavation to determine the effects of sampling on density and moisture content. Borings were advanced by flight auger and by rotary drilling with water, bentonite slurry and air. Samples were obtained with split spoons, various thin wall tubes, core barrels, and piston samplers.

Three deep cuts for which preconstruction data was available were sampled and studied in detail to determine changes in moisture content and water tables occurring after construction and to establish the degree of success of the performance of the slopes.

Mechanistic theories of loess behavior were evaluated to relate moisture content and grain size distribution to both overall slope performance and to the types of failures encountered. Methods of stability analysis were considered in relation to the types of failures observed in the field.

Recommendations have been developed for procedures for slope selection, methods of stability analysis and types of sampling and testing to be performed during the soil survey.

STRATIGRAPHY

The general distribution of the major loess deposits across Missouri is shown in Figure 4. The stratigraphy of the major loess members and associated Pleistocene strata in this state has been defined and discussed most notably by the work of Bayne, Davis, Howe and O'Connor(4). The generalized stratigraphic succession is summarized in Figure 5, reproduced by courtesy of the Missouri Department of Natural Resources, Division of Geology and Land Survey(5).

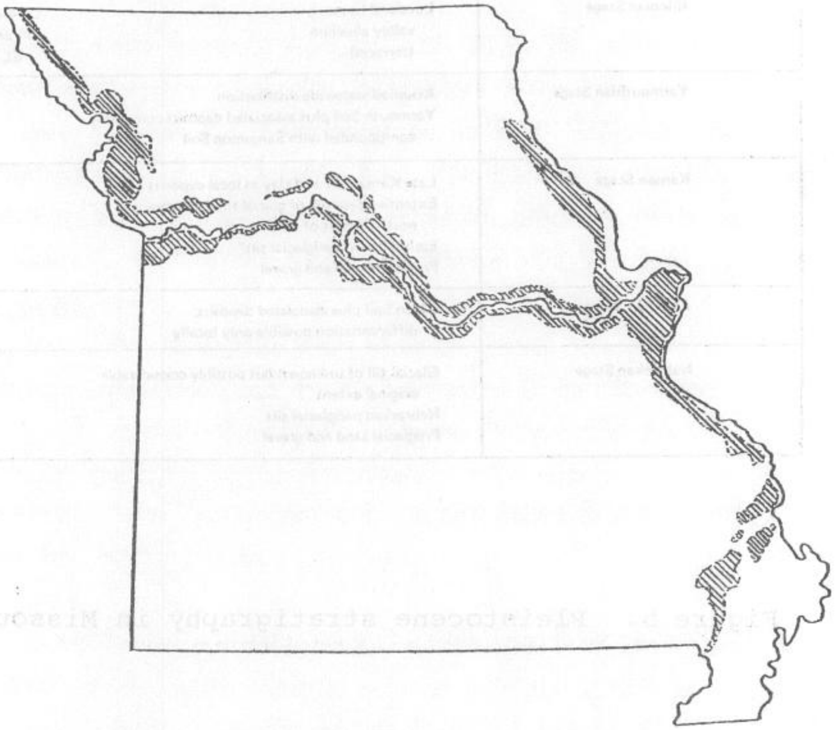

Figure 4 . Areal distribution of major loess depositions in Missouri

	Time-Stratigraphy	West	N Central	East
Wisconsinan Stage	Valderan Substage	Bignell Loess	Not differentiated	
	Twocreekan Substage	Brady Soil	Not differentiated	
	Woodfordian Substage	Peoria Loess	Peoria Loess	Peoria Loess
	Farmdalian Substage	Farmdale silt (?)	Farmdale (?)	?
	Altonian Substage	Absent (?)	Absent (?)	Represented by Roxanna silt at St. Louis
	Sangamonian Stage	Statewide distribution Sangamon Soil plus associated deposits		
	Illinoian Stage	Loveland Loess valley alluvium (terraces)		Loveland Loess Till deposits in St. Louis County
	Yarmouthian Stage	Assumed statewide distribution Yarmouth Soil plus associated deposits commonly compounded with Sangamon Soil		
	Kansan Stage	Late Kansan silt and clay as local deposits Extensive deposits of glacial till throughout northern part of state Early Kansan periglacial silt? Proglacial sand and gravel		
	Aftonian Stage	Afton Soil plus associated deposits; differentiation possible only locally		
	Nebraskan Stage	Glacial till of unknown but possibly considerable original extent Nebraskan periglacial silt Proglacial sand and gravel		

Figure 5. Pleistocene stratigraphy in Missouri.

In addition to the major stratigraphic units listed, numerous paleosols have been identified which are not discussed here. An exception is made for the Sangamon soil which is a prominent marker bed due to its thickness and color. Those members formed during Wisconsinan stage, Roxana and above, represent the vast bulk of loess encountered in construction.

Loveland

This Illinoian stage silt generally is found with low cementation and low strength, modified from the original deposition by overburden pressure to a relatively high density. Moisture contents are normally at or near saturation. The color typically is yellowish brown with a grayish tint (10 YR 7/3 on the Munsell soil color charts). It is infrequently exposed in cuts due to its depth in the profile.

Sangamon

This is a soil profile developed on a erosional surface, often on the Loveland. Due to intense soil development over a long period, it is normally of significant thickness. Compared to overlying loesses, it is dense and relatively impermeable due to its higher clay content. This profile is usually very evident when exposed due to the reddish brown color.

Roxana Loess

Although there is some disagreement as to the name, this or similar material is of widespread occurrence along the Mississippi River and especially in the St. Louis region. The lower portion has been reported to be of colluvial origin, at least in part, with a gradational transition to windblown. The Roxana is typically a dense silt to silty clay with relatively high plasticity and clay content, generally better graded than younger loess strata. Color is typically a yellowish brown (10 YR 6/4).

Lower Peoria Loess

The Peoria is the major loess member along the Missouri River. The lower part of the Peoria frequently can be differentiated from the upper part by the greater degree of modification from deposition of minerals and colloids leached from overlying units and from the pressure of the overburden. This results in a combination of higher density, lower permeability, higher clay content and higher moisture content than is usually associated with the upper Peoria.

Upper Peoria Loess

The upper Peoria normally retains a high degree of structuring, low density and high permeability. It normally exhibits no acid reaction. Color is light, typically yellow tan (2.5 Y 7/4). Density typically ranges from 74 pcf to 90 pcf. It generally has a clay content ($<$.002 mm) of 10 to 16 percent and moisture contents may be as low as 10 to 14 percent. It may be found standing essentially vertical to heights exceeding fifty feet.

Bignell Loess

Significant deposits of Bignell, the youngest of the major loess units, have been found in Missouri only along the hills immediately adjacent to the Missouri River.

It is generally darker than the underlying Peoria and often exhibits an acid reaction when tested. Normally, it is found as an open, porous structured loess of low density with its characteristics essentially unmodified. Color is typically a grayish brown (10 YR 6/3). As with the Upper Peoria, it may be found standing nearly vertical to great heights.

General

All of the loess strata are found in non-conformal relationships and absence of some is considered normal.

Sometimes found in association with the Lower Peoria and the Roxana are layers or lenses of silt with virtually no cohesion. These will not stand on vertical slopes.

Grain size and plasticity characteristics are shown in Table 18 for the Peoria, Roxana and Sangamon, the three major Pleistocene strata sampled during the performance survey. Correlations of performance and physical properties to stratigraphy are discussed under the section dealing with data correlation.

MECHANISMS OF LOESS BEHAVIOR

The unique ability of loess to stand on vertical slopes was once attributed by geology textbooks to cementation by calcium carbonate. Calcium carbonate is not readily soluble in water, a fact inconsistent with the rapid disintegration of dry loess when immersed. Later, it was recognized that the primary cementing agent in loess is a clay coating or film on the predominantly silt sized particles. Such a "glue" obviously would be weakest when totally saturated and capable of high cohesive strengths only at low moisture contents. Unmodified loess of low density and porous, open structure has a high permeability which tends to maintain the low moisture levels required for high strengths.

The minimal strengths available near or at saturation; however, permit settlements of large magnitude, sometimes occurring so rapidly as to appear as virtual "collapses". These characteristics have been definitively described by Holtz and Gibbs(3) and by Gibbs and Holland(2) and have been summarized by Sheeler(6). Loess which has undergone densification by this phenomenon has markedly altered properties. Consequently, density has been recognized as a key index property for predicting the behavior of in-situ loess.

Graphs relating moisture content of loess to strength typically include two curve segments of markedly different slope. One defines a zone where very large changes in strength occur with small changes in moisture and the other a zone where very little change in strength occurs with large changes in moisture. Kane(1) has advanced the concept of a "critical water content" which explains this phenomenon. Small increases in total moisture first result in much larger increases within the clay fraction only as negative water tensions are satisfied. Once the clay fraction is saturated, the critical water content, strength remains relatively constant with increasing moisture until the total soil is saturated.

Kane reported that an Iowa loess, with 19 percent clay and a critical moisture range of 15 to 20 percent, had a corresponding moisture content within its clay fraction of 78 to 104 percent. Saturation of the clay portion was found to occur at approximately 60 percent saturation for the total sample.

Available data for Missouri loess is included in Figure 6 where hand held, calibrated penetrometer test data is compared to moisture content. A best fit curve tends to confirm the critical moisture relationship. If this relationship is examined further in terms of varying liquid limit the points of change on the curves are found to occur over a moisture range of about 16 percent for a liquid limit of 28 to 22 percent for a liquid limit of 38. This is shown on Figure 7 where best fit curves are based on data from 250 hand held, calibrated penetrometer tests and 60 unconfined compression tests.

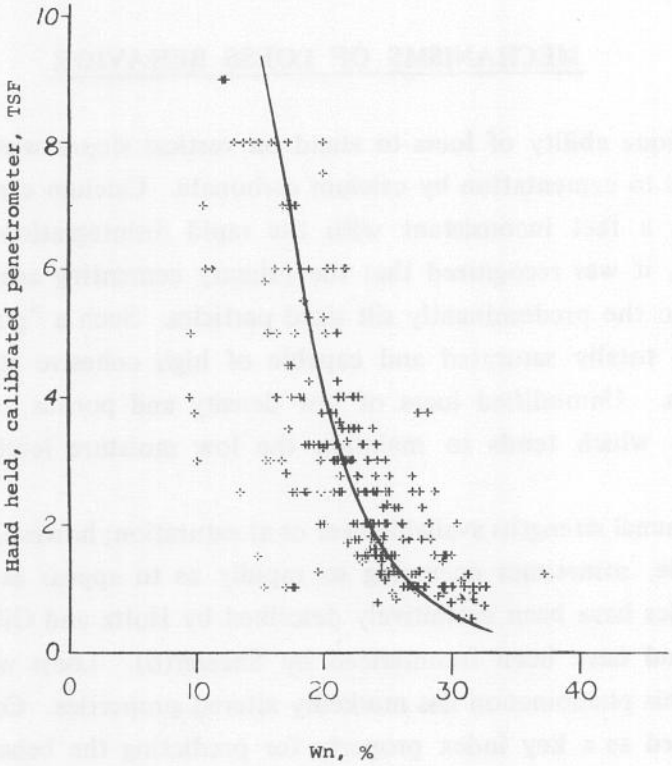

Figure 6. Correlation of moisture content to hand held, calibrated penetrometer test data

Textural variations in loess from throughout the central United States have been subdivided by Holtz and Gibbs(3) into three subgroups, "sandy", "silty" and "clayey", having characteristic properties. These groupings were evaluated in this study and found to provide a basis for correlation to performance of cut slopes. For purposes of this correlation, "silty" and "clayey" loess were redefined in terms of specific particle sizes. This is discussed elsewhere in this report.

Frost damage was found by this study to be a serious problem with vertical slopes in loess. References to this phenomenon have not been found in the literature with respect to slope problems. The mechanism appears analogous to subgrade frost heave in that three conditions are required:

1. The soil must be permeable enough to transmit sufficient water during the freezing period to enable ice lenses to form (silts are notoriously susceptible).

2. Sufficient water must be available. This seems true whenever a water table has been truncated by cut but this is not a requirement.

3. Freezing must occur over relatively long periods in which thawing does not occur. Vertical cuts with northern exposure appear especially susceptible as they have no exposure to the sun during prolonged periods of freezing temperatures.

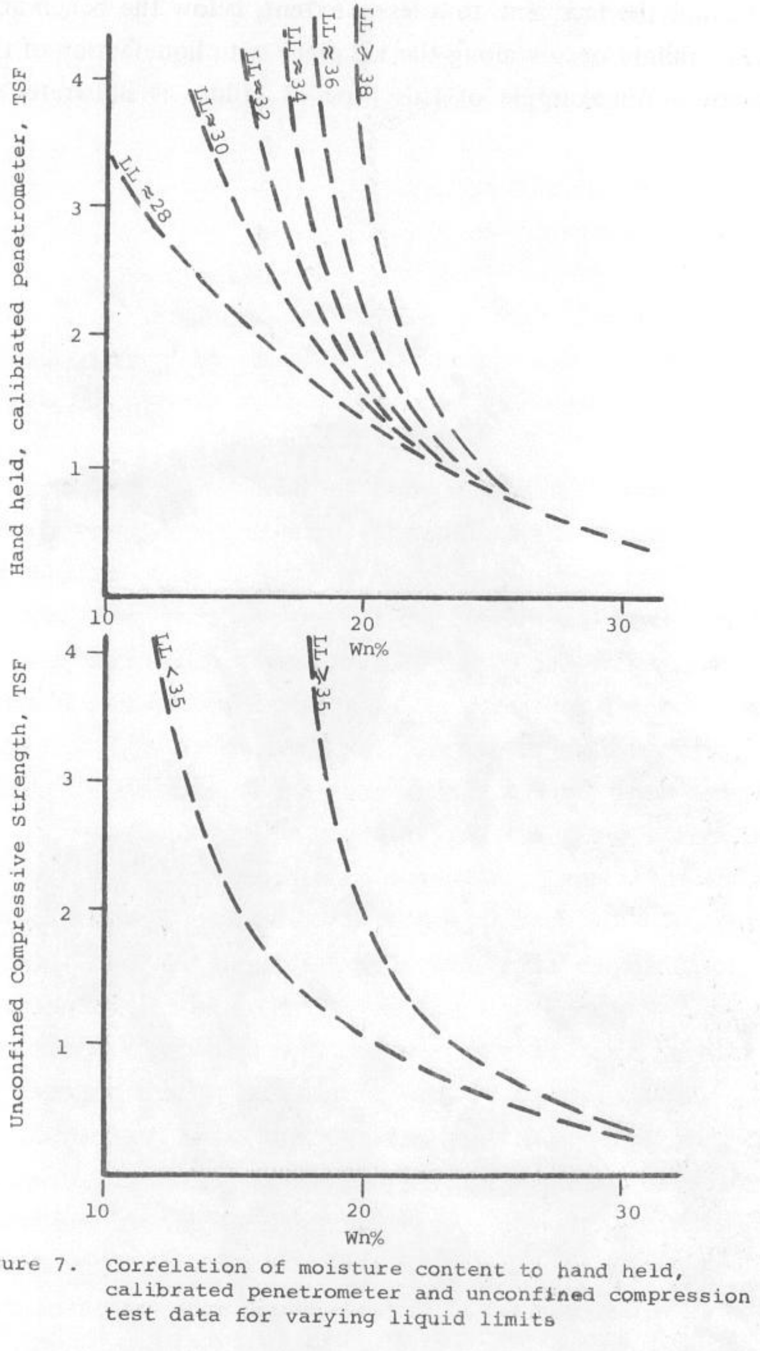

Figure 7. Correlation of moisture content to hand held, calibrated penetrometer and unconfined compression test data for varying liquid limits

A fourth requirement, unique to loess slopes, is that the slope be steep enough to fail after the ice lense melts. Ice lense development was found to occur approximately 18 to 24 inches behind the face and, to a lesser extent, below the bench above a vertical slope. With thawing, failure occurs along the ice plane with liquefaction of the soil usually apparent after failure. An example of this type of failure is illustrated in Figure 8.

Figure 8. Freeze damage to a north facing stepped slope (Holt County, Route I-29)

SOIL SURVEY TECHNIQUES

Until fairly recently, soil surveys for highway construction in Missouri have generally logged, sampled and tested a loess succession as a single unit. Probably because most such work was based on augered cuttings and composite samples, little consideration was given to variations in individual strata if indeed such could even be detected by the methods used. Tests performed on such composite samples usually included AASHTO group and index determination, moisture-density relations, grain size analysis and liquid and plastic limits. Beginning in 1974, it was required that detailed sampling, defined as within intervals of 5 feet or less, also be performed in all cut sections of any substantial depth, and tests be performed to establish both ASTM and AASHTO classifications, natural moisture, liquid limit and plasticity index. Samples were obtained by any convenient means, usually split spoon, thin wall "Shelby" tube, or slotted tube (Giddings) samplers.

An attempt was made to evaluate the effectiveness of these methods at three locations by comparative sampling to determine the consistency of the moisture and density data obtained using various types of samplers and employing various drilling methods to advance the bore hole.

One series of sampling efforts, designated as location 1, was conducted behind the face of a cut slope on Route 210, Clay County to evaluate various down-hole sampling procedures in loess. The dry densities, the methods of drilling, the equipment and the drilling media used are summarized in Table 1 along with average moisture contents and densities determined to a depth of 15 feet. Hand cut block samples were taken from an open excavation made with a backhoe for comparison with samples recovered by down-hole methods (see Table 2).

TABLE 1. Comparison of average density and moisture values obtained by various methods at location 1*

Sampling Equipment	Hole Dia.	Drilling Technique	Ave. Wn %	Ave. Density (pcf)
		Flight Auger		
2" Dia. Split Spoon Sampler	3"		18.1	93.2
Double Tube Auger Sampler (2" Dia.)	4"		18.7	101.2
3" Dia. Shelby Tube Sampler	4"		17.4	101.1
		Rotary Boring		
3" Dia. Shelby Tube Sampler	4 3/4"	Water	19.5	102.7
5" Dia. Shelby Tube Sampler	6 3/4"	Water	18.4	98.7
5" Dia. Shelby Tube Sampler	6 3/4"	Bentonite - Water Mixture	19.2	103.3
5" Dia. Osterberg Sampler	6 3/4"	Bentonite - Water Mixture	19.8	100.3
4" Double Tube Barrel (Denison)	6 3/4"	Compressed Air	19.6	98.9
4" Double Tube Core Barrel	6 3/4"	Compressed Air	18.5	99.8
		Backhoe Excavation		
Hand Cut			18.5	89.9

*Clay County, Route 210, Station 140

TABLE 2. Densities and moistures of hand cut block samples from a trenched excavation at location 1*

Depth	% Wn	Density (pcf)
4'	23.4	--
5'	19.3	83.7 87.3
6'	20.7	--
7'	19.3	--
8'	19.6	91.8 92.3
9'	19.0	--
10'	19.8	--
11'	17.0 18.5	94.3 89.9

*Clay County, Route 210, Station 140

The moisture contents determined at comparable depths from auger borings averaged 17.8 percent. Moistures determined from samples obtained from rotary wash borings using water averaged 18.5 percent and, where a bentonite and water mixture was used, 19.7 percent. Where compressed air was used with rotary coring, moistures averaged 18.3 percent. Considering that some distance was required between each bore hole to prevent water contamination and that there is no way of proving that natural moistures were consistent at a given depth, average moistures show relatively good agreement although individual results may be suspect.

Although it is felt that drilling with a bentonite mud mixture can be used to obtain accurate moisture samples in dry loess, good technique is essential including a thick mixture, rapid penetration and securing of the moisture sample from the middle of the recovery. Wet drilling of any type can not be generally recommended for sampling dry loess for moisture determination. A laboratory demonstration illustrates the potential for error. Four inch diameter loess samples with a natural moisture content of 16.5 percent, when immersed in a thick bentonite-water mixture, were tested and found to gain moisture quickly without visible evidence of either water or bentonite infiltration. In 30 minutes, the moisture was 27.4 percent at the center of the sample.

Average densities obtained by various bore hole sampling techniques ranged from 93.2 pcf to 103.3 pcf all significantly higher than the 89.9 pcf obtained by hand sampling. The minimum density obtained by hand sampling was 83.7 pcf while 88.2 pcf, obtained by rotary coring with compressed air, was the lowest density obtained by down hole sampling. Logs of individual borings are included in Tables 3 through 11.

TABLE 3. Densities and moistures of samples obtained using flight augers and a split spoon at location 1*

Depth	% Recovery	P.P. (tsf)#	% Wn	Density (pcf)
4.8-6.3	93	--	18.5	86.3 101.1 92.2
10-11.5	100	--	18.8	
15-16.5	100	--	17.1	

TABLE 4. Densities and moistures of samples obtained using flight augers and a double tube auger sampler** at location 1*

Depth	% Recovery	P.P. (tsf)#	% Wn	Density (pcf)
4.9-6.2	100	2.1	19.7	--
9.7-10.9	58	--	19.2	100.4 99.0
14.8-16	50	2.75	17.1	104.1

TABLE 5. Densities and moistures of samples obtained using flight augers and a 3 inch "Shelby" tube at location 1*

Depth	% Recovery	P.P. (tsf)**	% Wn	Density (pcf)	LL	PL	PI	ASTM Classification
5-7.3	48	2.0 4.5	17.9	98.5 105.3				
9.7-11.9	68	3.5	18.0	96.8 104.2 99.4	29	24	5	ML
14.8-17.3	68	3.0 3.75	16.2	97.2 106.4				

*Clay County, Route 210, Station 140±
#Hand held, calibrated penetrometer test
**2" inner diameter, rotary outer barrel, stationary inner barrel

TABLE 6. Densities and moistures of samples obtained using rotary Circulation drilling with water and a 3 inch "Shelby" tube at location 1*

Depth	% Recovery	P.P. (tsf)#	% Wn	Density (pcf)
5-7.5	100	2.25 3.5	20	100.9
10-12.5	72	3.0	20.6 20.6	104 101.4
15-17.5	60	--	17.9 17.5	104.3

TABLE 7. Densities and moistures of samples obtained using rotary circulation drilling with water and a 5 inch "Shelby" tube at location 1*

Depth	% Recovery	P.P. (tsf)#	% Wn	Density (pcf)
5-7.5	84	3.5 2.75	19.8 19.8	93.2 100.5
10-12.5	76	4.25	19.3 17.8	98.3 103.3
15-17.5	80	--	17.0 16.9	96.5 99.8

TABLE 8. Densities and moistures of samples obtained using rotary circulation drilling with "mud" and a 5 inch "Shelby" tube at location 1*

Depth	% Recovery	P.P. (tsf)#	% Wn	Density (pcf)
5-7**	45	3.25	21.4	101.3
10-12.5	60	3.75	20.5	103.1 101.5
15-17.5	72	3.5	17.4	104.7 106.0

*Clay County, Route 210, Station 140±
#Hand held, calibrated penetrometer test

TABLE 9. Densities and moistures of samples obtained using rotary circulation drilling with "mud" and a 5 inch piston (Osterberg) sampler at location 1*

Depth	% Recovery	P.P. (tsf)#	% Wn	Density (pcf)
5-7.5	92	1.5 2.75	21.9 20.5	90.1 99.4
10-12**	100	2.0 3.25	20.6 21.9	101.9 101.4
15-16.6**	100	3.0	17.0 17.1 19.8	103.5 105.5 100.3

TABLE 10. Densities and moistures of samples obtained using rotary circulation drilling with air and a 4 inch double tube (Denison) sampler at location 1*

Density	% Recovery	P.P. (tsf)#	% Wn	Density (pcf)	LL	PL	PI	ASTM Classification
3.3-8.3	40	3.0(Top) 1.25(Middle) 2.25(Bottom)	18.8	98.7	30	24	6	CL-ML
8.3-10.3	83	2.75	19.6	101.3 102.3				
10.3-13.3	30	3.9	20.5	97.8 101.5	29	24	5	ML
13.3-16.0	37	2.75	19.1	103.2				
16.0-18.0	43	--	15.8	105.1	28	23	5	CL-ML
18.0-23.0	38	--	17.0	---	29	23	6	CL-ML

*Clay County, Route 210, Station 140
**Maximum penetration with weight of Failing 1500 drill
#Hand held, calibrated penetrometer test

A second location on Route 210, having much lower natural moistures averaging 12 percent, was also sampled with both a rotary core barrel and a 5 inch diameter thin wall "Shelby" tube using air as the drilling medium. All samples obtained by both methods appeared relatively undisturbed, being dry, hard, and free of fractures with full recovery achieved. These results are tabulated in Table 12. No hand cut samples were available for comparison however.

TABLE 11. Densities and moistures of samples obtained using rotary circulation drilling with air and a 4 inch double tube core barrel at location 1*

Depth	% Recovery	P.P. (tsf)#	% Wn	Density (tsf)	LL	PL	PI	ASTM Classification
5-7.0	100	2.7	26.7	96.1	30	23	7	CL-ML
7-9.0	100	2.5 3.5	18.1	106.4				
9.0-11.0	100	--	18.7	98.8 99.9				
11.0-13.0	100	4.25	18.9	100.3 100.8				
13.0-15.0	30	2.0	18.4	90.1	30	24	6	CL-ML
15.0-17.0	25	3.25	16.9	--				

*Clay County, Route 210, Station 140
#Hand held, calibrated penetrometer test

TABLE 12. Densities and moisture of samples obtained by rotary circulation drilling with air at location 2*

Depth	Type# Sampler	% Recovery	P.P.** (tsf)	% Wn	LL	PI	ASTM Class.	Density (pcf)
17-18	5" ST	45	5.0	11.1	35	12	CL	91.7
18-23	4" DTCB	100	5.0	11.1				91.7
27.5-29	5" ST	97	4.0	12.9	31	7	ML	87.4
29-31	4" DTCB	100	9.0+	12.9				95.9

*Clay County, Route 210, Station 60±
**Hand held, calibrated penetrometer test
#ST denotes "Shelby" thin wall tube sampler, DTCB denotes double tube core barrel

A third location at the top of a deep, benched cut on Route I-229 in Buchanan County was sampled by rotary coring using air. Moisture content averaged 16.5 percent, density 82.2 pcf and recovery was 87 percent using a "Denison" double tube sampler. One sample recovered had a density of 74.5 pcf and appeared totally undisturbed. These results are shown on Table 13. Again, no comparison samples were available.

Coring with air appeared generally successful in securing undisturbed samples where moisture contents were below about 18 percent. At higher moisture contents, blocking of the core barrel and sample disturbance occurred with loss of portions of the sample. It can only be concluded that, while natural density can sometimes be accurately determined by down hole sampling, no method is so reliable that any great confidence can be placed in the results. This suggests strongly that more reliable data than can be obtained for natural density would be preferable as an index of loess slope performance.

Atterberg limits and grain size analyses are not affected by any of the so called undisturbed sampling techniques. However, it should be recognized that strength data may be affected by either compression disturbance or by moisture contamination.

The best and most effective sampling technique, to establish the data most reliable for predicting slope behavior, moisture and grain size distribution, appears to be the slotted tube (Giddings) sampler used in dry (augered) holes.

TABLE 13. Densities and moistures of samples obtained by rotary coring with air at location 3*

Depth	% Recovery	P.P.** (tsf)	% Wn	LL	PI	ASTM Classification	Density (pcf)
2.5-5	100						
5.0-7.5	92	2.5	11.7	30	1	ML	83.3
10-12.5	92		14.7	33	8	ML	
12.5-15	88	2.25	17.7				89.6
15-17.5	80			30	5	ML	
17.5-20	100		18.3	32	8	CL-ML	
20-23.5	67		19.7				
23.5-26	100			29	3	ML	74.5
26-28	100		16.2				78.4
28-30.5	67	1.0		32	6	ML	
30.5-33	100						
33-35.5	100		14.7				79.9
35.5-38	100	1.0	18.3	32	6	ML	
38-40.5	100						83.6
45-47.5	100	3.0	16.8	31	7	CL-ML	88.2

*Buchanan County, Route I-229, Station 131, sampled with 4" diameter tube "Denison" core barrel

**Hand held, calibrated penetrometer test

PERFORMANCE SURVEY

The performance of highway cut slopes in loess was surveyed and monitored throughout Missouri over a 2 year period. A total of 106 slopes having an average vertical relief of 45 feet were photographed, inspected, sampled and indexed with respect to dimensions, physical properties and other factors possibly related to performance. Included in the information recorded for correlation were the length and maximum height of slope, the type of slope (vertical or flattened), the height of individual vertical faces, the number and the gradient of benches, the direction of slope exposure, soil colors, plasticity, moisture and grain size data, evidence of seepage, type of vegetative cover, types of distress and an overall performance rating.

Each individual slope was rated on a basis of 1 through 4 as a general judgement of its performance and the estimated degree of maintenance required. A rating of excellent(1) indicated the slope to be performing as designed without need of maintenance. Good(2) indicated generally satisfactory performance but evidence of some deterioration with minor maintenance required. Fair(3) indicated moderate to serious deterioration but with the original slope still salvageable by maintenance. Poor(4) indicated failure of the original slope to the extent that reconstruction and possibly redesign would be required.

Although loess slope failures are usually due to a combination of causes (see Figure 9), five distinct types of distress were defined and logged in the performance survey:

A. Erosion

ML soils by ASTM classification are particularly erosive and most Missouri loesses are either in or borderline to this category. Where runoff becomes concentrated, enormous ditches can develop from one major rainfall. Such rapid erosion is particularly apparent where flattened slopes are exposed by new construction, and often occurs near stream channels, behind terraces or anywhere runoff is concentrated. Although not the main problem, erosion is also a source of continual slope degradation on vertical slopes. Figures 9 through 22 show some of the various types of erosion and some of the associated maintenance problems.

Piping is a unique type of erosion to which loesses of low plasticity and low density are especially susceptible. The open, porous structure of such soil is prone to collapse with saturation and channels established by roots or rodents are readily developed as piping fissures where sufficient water is available. This can cause erosion of a vertical rise and a bench which in turn can lead to failure of the entire slope.

Figure 9. Slides and heavy frost damage due to truncation of a water table at the level of the second bench in northeast facing cut (Howard County, Route D(87)

Figure 10. Collapse and erosion due to excessive water concentration at the end of a sodded V-shaped bench (Holt County, Route I-29)

Figure 11. Slope damage due to persistent seepage from a truncated water table. Piping outlets in the face above are also evident (Holt County, Route I-29)

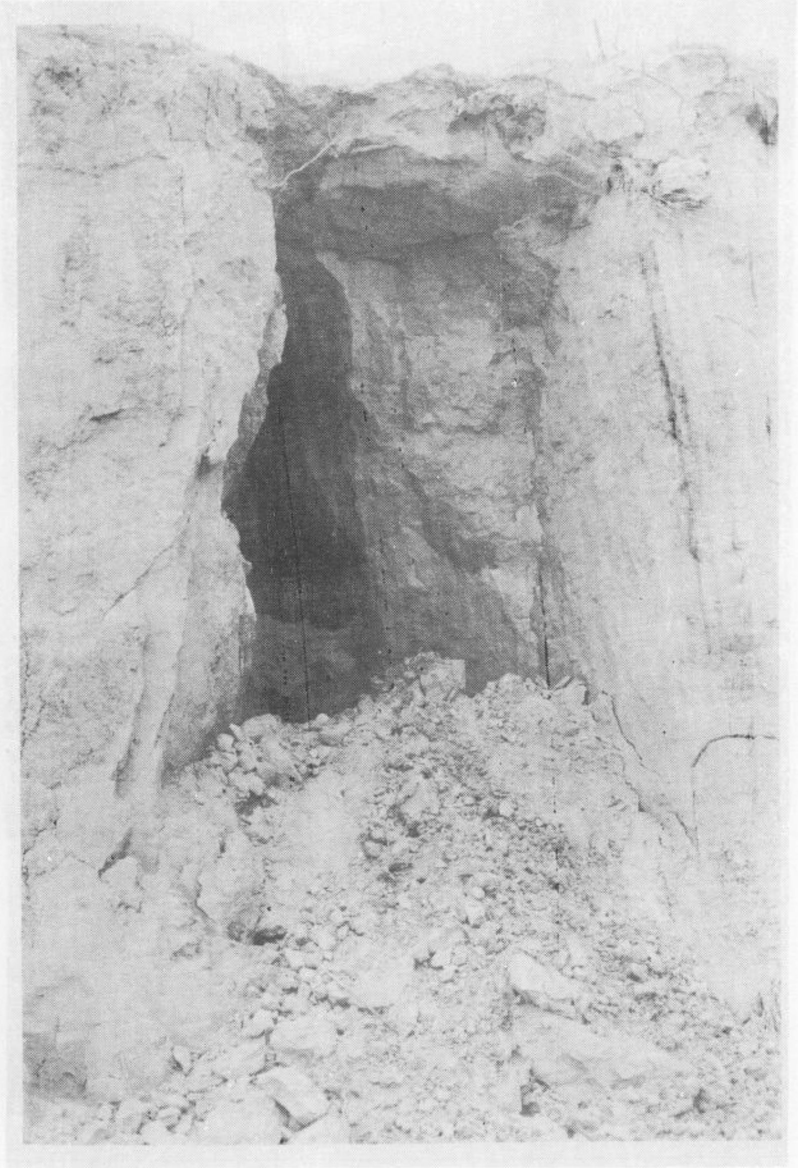

Figure 12. Piping damage to a vertical face (Holt County, Route I-29)

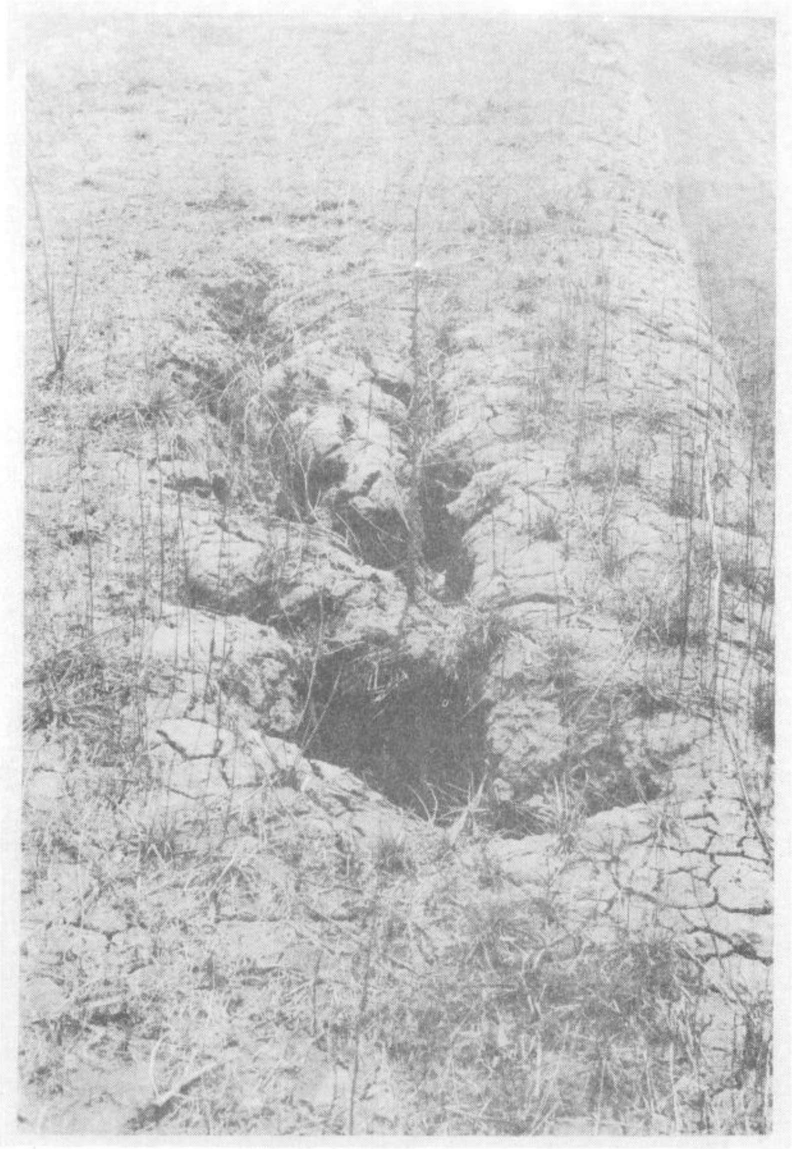

Figure 13. Piping inlets on a bench orginating from frost damage (Holt County, Route I-29)

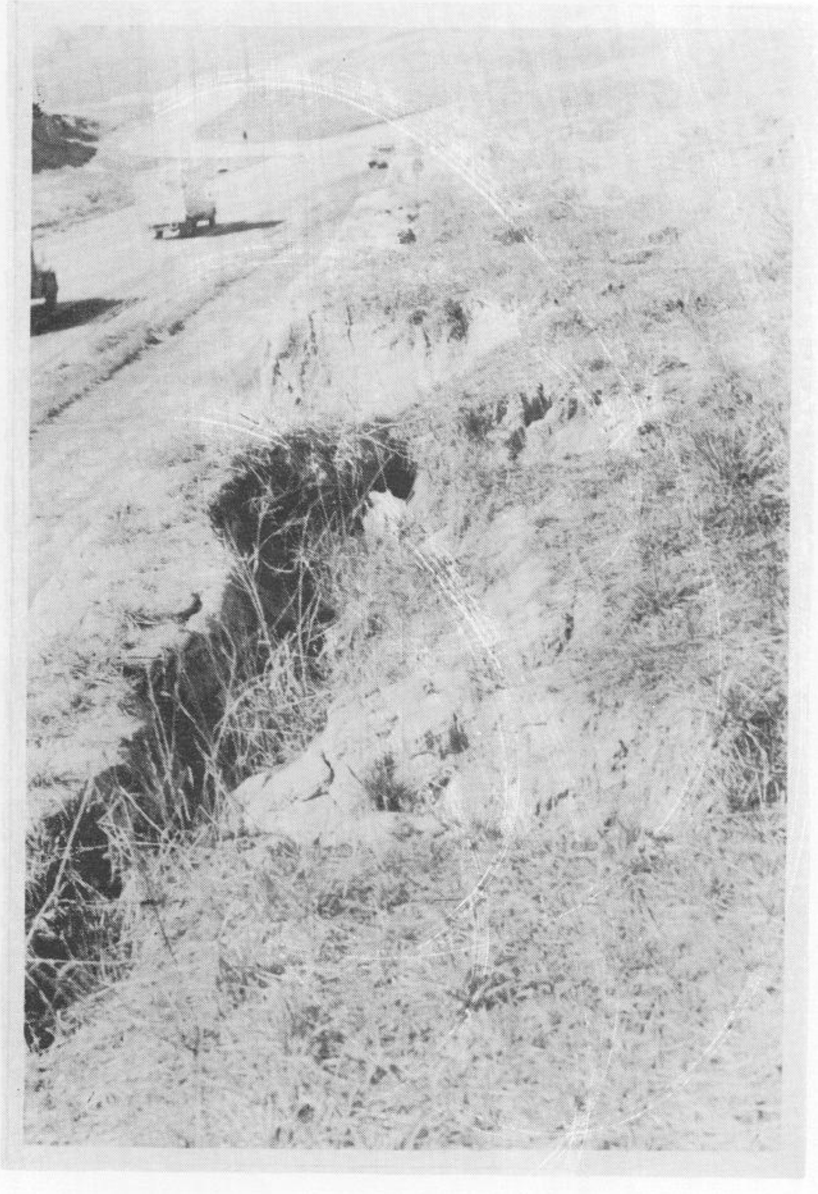

Figure 14. Bench erosion following frost damage (Atchison County, Route 136)

Figure 15. Piping damage and progressive erosion due to insufficient bench gradient (Holt County, Route I-29)

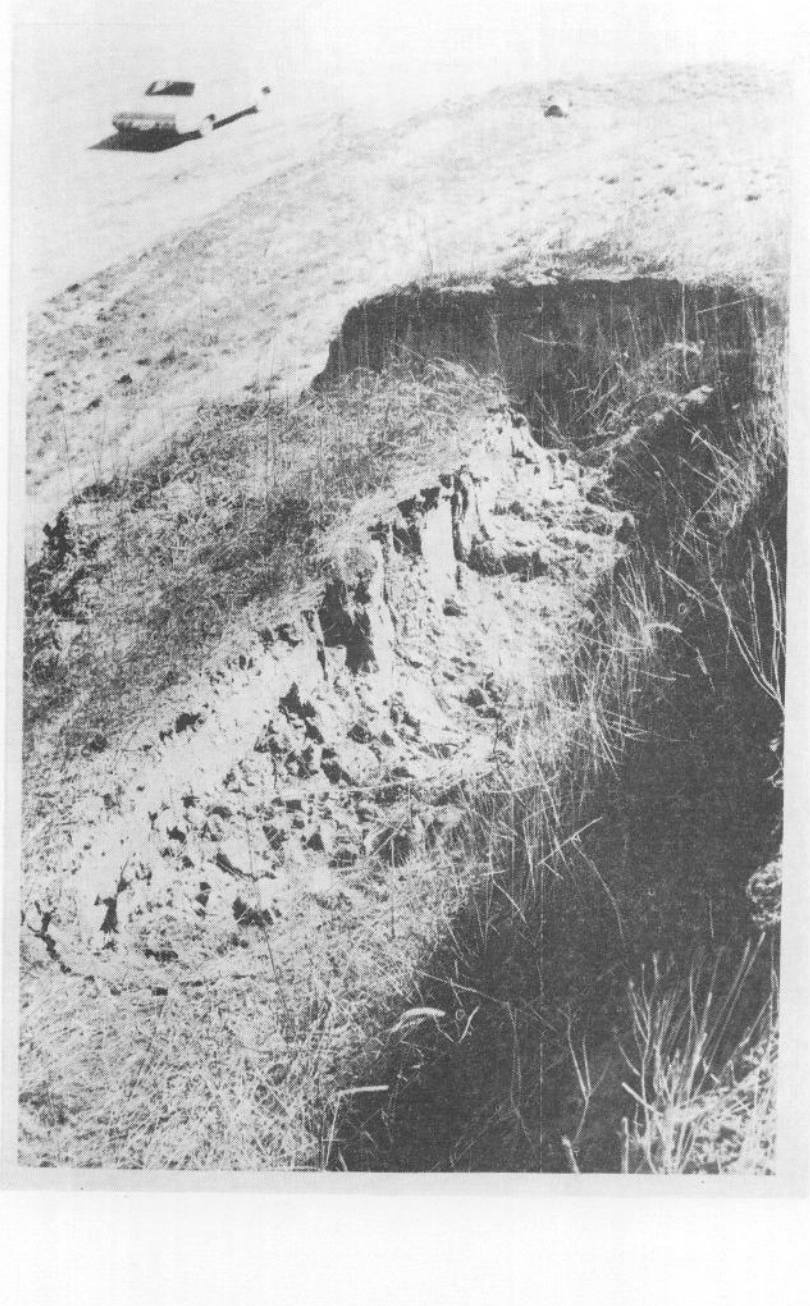

Figure 16. Collapse failure progressing in a sodded bench (Atchison County, Route 136)

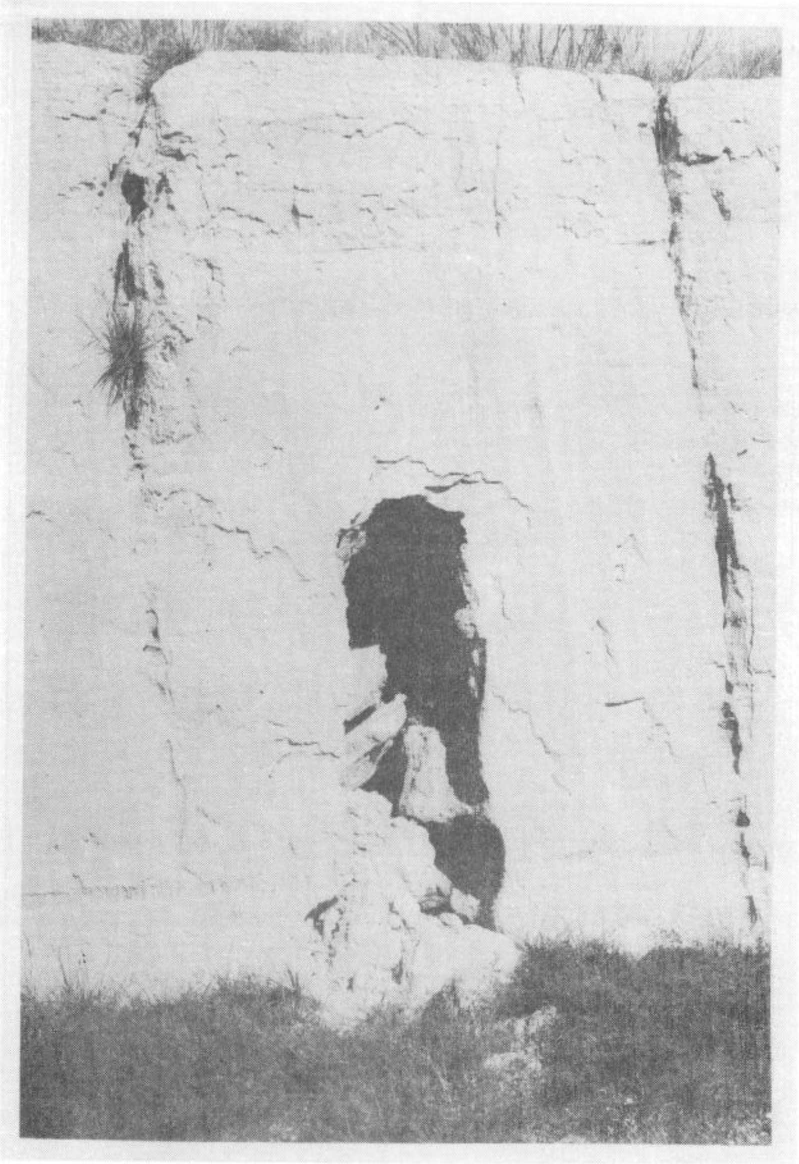

Figure 17. Piping outlet in a near vertical face (Holt County, Route I-29)

Figure 18. Piping inlets above the face shown in Figure 17 (Holt County, Route I-29)

Figure 19. Rodent damage on a bench which can cause piping (Atchison County, Route 136)

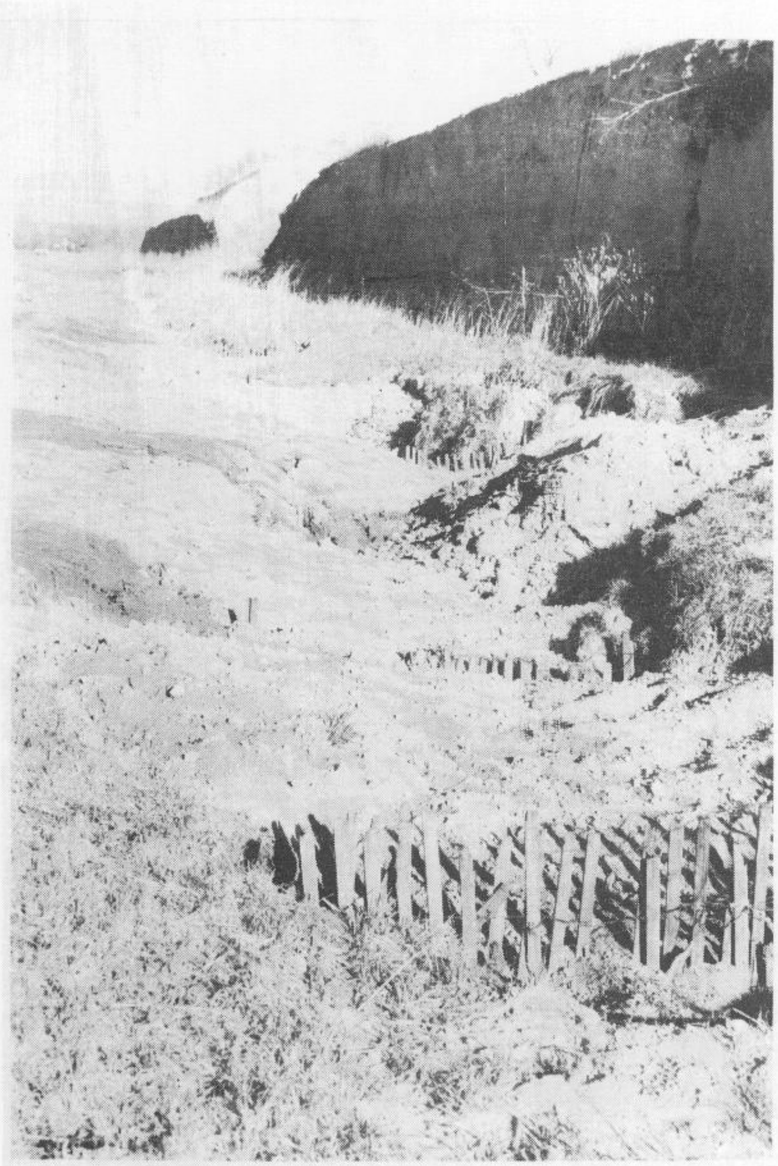

Figure 20. An attempt to control ditch erosion by catching siltation from erosion of the cut slopes (Holt County, Route F(159)

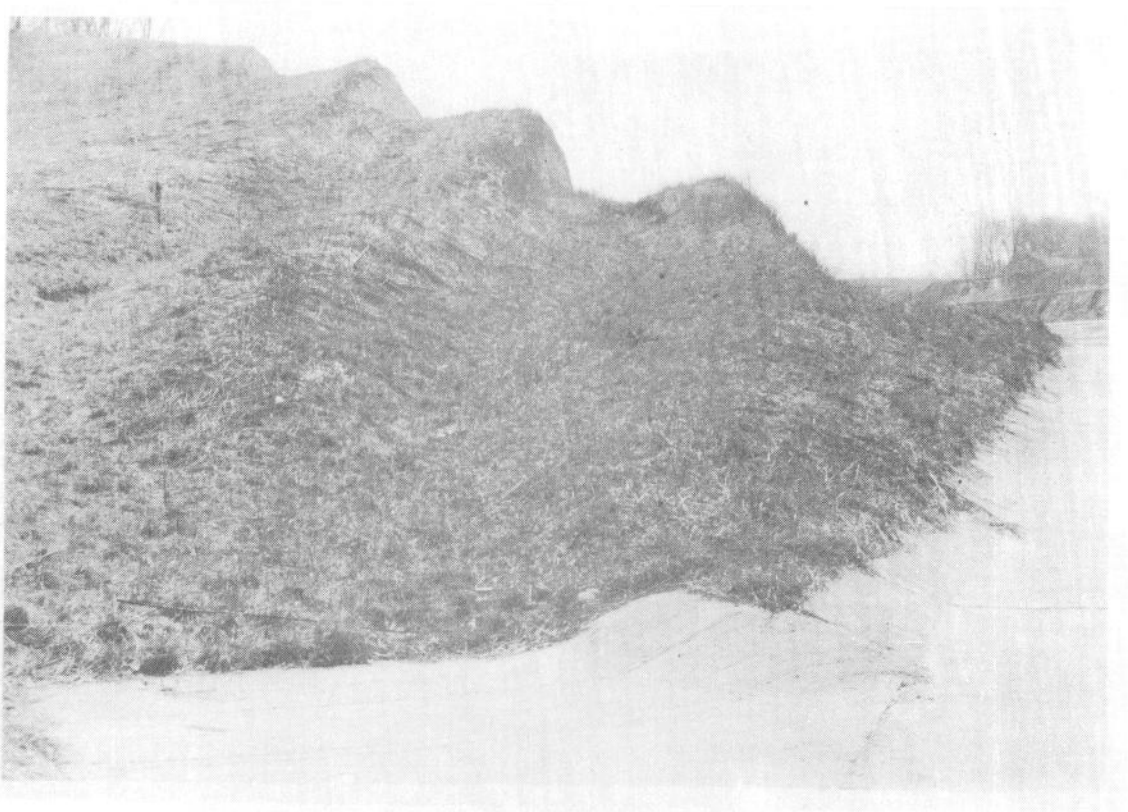

Figure 21. Erosion on a sodded V-shaped bench (Holt County, Route I-29)

Figure 22. Extensions on paved ditches to control bench erosion (Holt County, Route I-29)

B. Volume Change

Blocks and slabs of hard soil often fall from vertical faces of loess due to shrinkage cracks developing from volume change. With shrinkage potential a function of clay content, density, and moisture, most failures occur shortly after faces of wet, "clayey" loess are first exposed to drying. Typical pictures of volume change effects are shown as Figures 23 and 24.

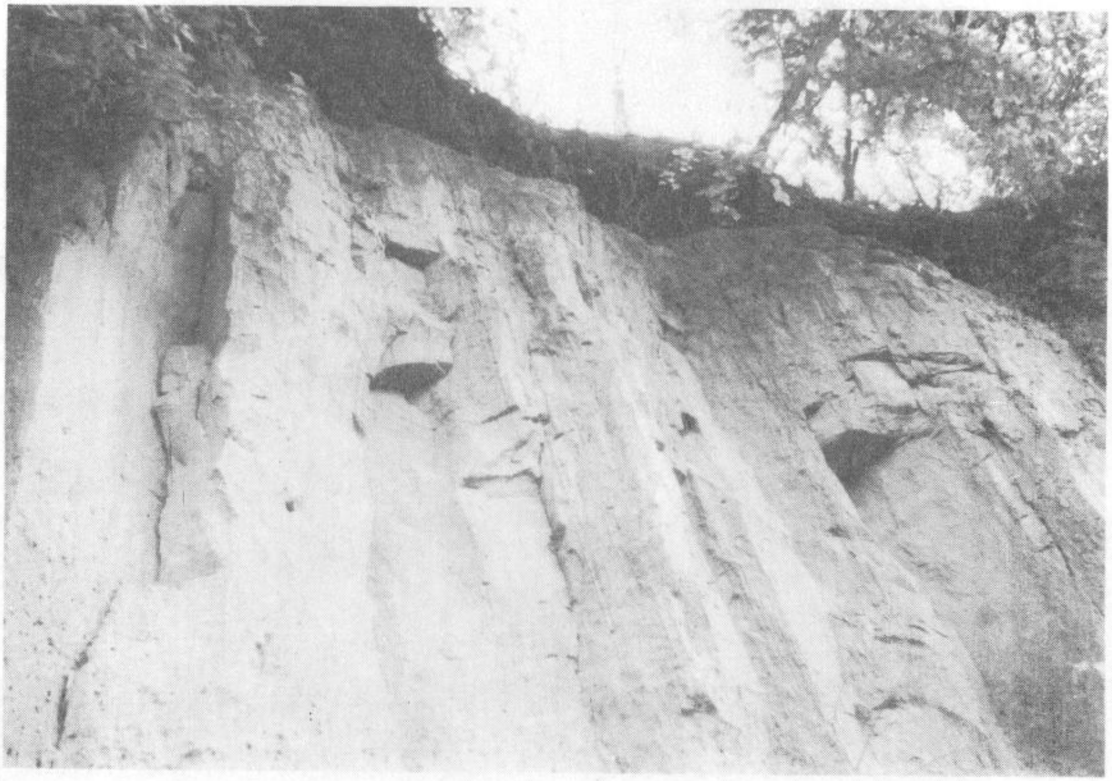

Figure 23. Slabbing occurring along natural joints in loess (Boone County, Route 40)

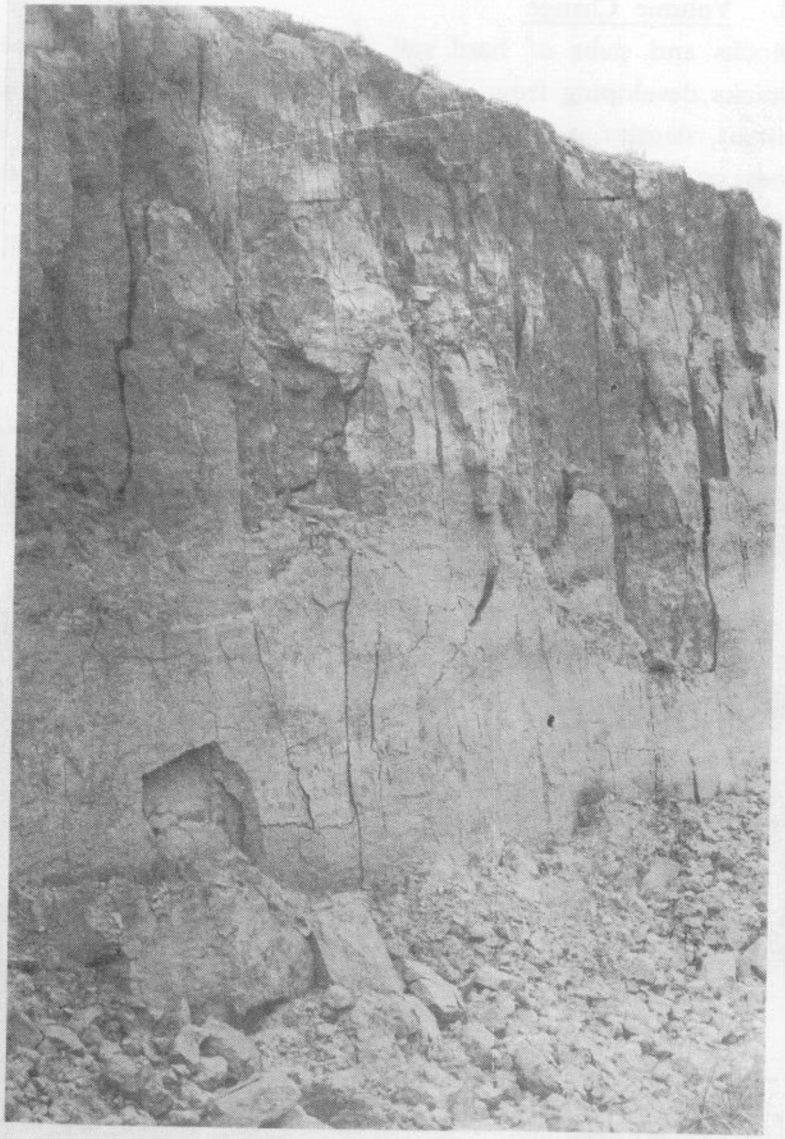

Figure 24. Shrinkage cracks in "clayey" loess (Clay County, Route 210)

C. Slides

Slides usually follow a parabolic or semi-circular failure arc in loess. A slide failure of a 50 foot near vertical (1/4:1) slope is shown in Figure 25. A schematic of typical slide failure, with the characteristic steep scarp and large slump berm is shown as Figure 26

Figure 25. A slide in a 50 foot near vertical face (Atchison County, Route 136)

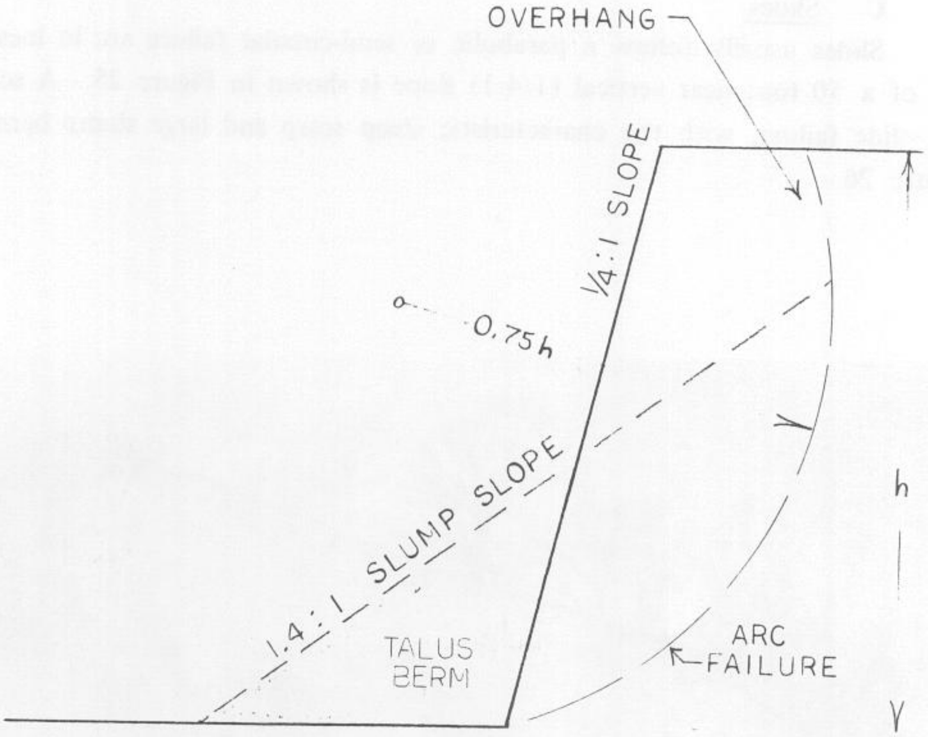

Figure 26. Schematic of a slide failure surface in a near vertical slope

D. Undercutting

This is a progressive type of distress originating as a local slough near the base of a vertical slope. It effectively steepens the slope, sometimes establishing an overhang, and eventually contributes to a stability failure. It is most frequently found where a vertical rise truncates a water table or a stratum having very low cohesive strength (as a sand lense) or excessive moisture content. A typical example which will probably progress to slope failure is shown in Figure 27.

Figure 27. Slope damage due to a truncated water table (Holt County, Route I-29)

E. Freeze Damage

Freeze damage is a form of slope distress unique to the steep slopes used with loess soils. The mechanism, which is analogous to subgrade frost heave, involves ice lense formation at a shallow depth within the slope. With thawing and the accompanying hydrostatic stresses, failure occurs along the resulting plane of weakness. Figures 28 through 31 indicate the severity of this problem. The erosion which may follow the slumping of ice damaged faces may totally destroy a benched vertical slope.

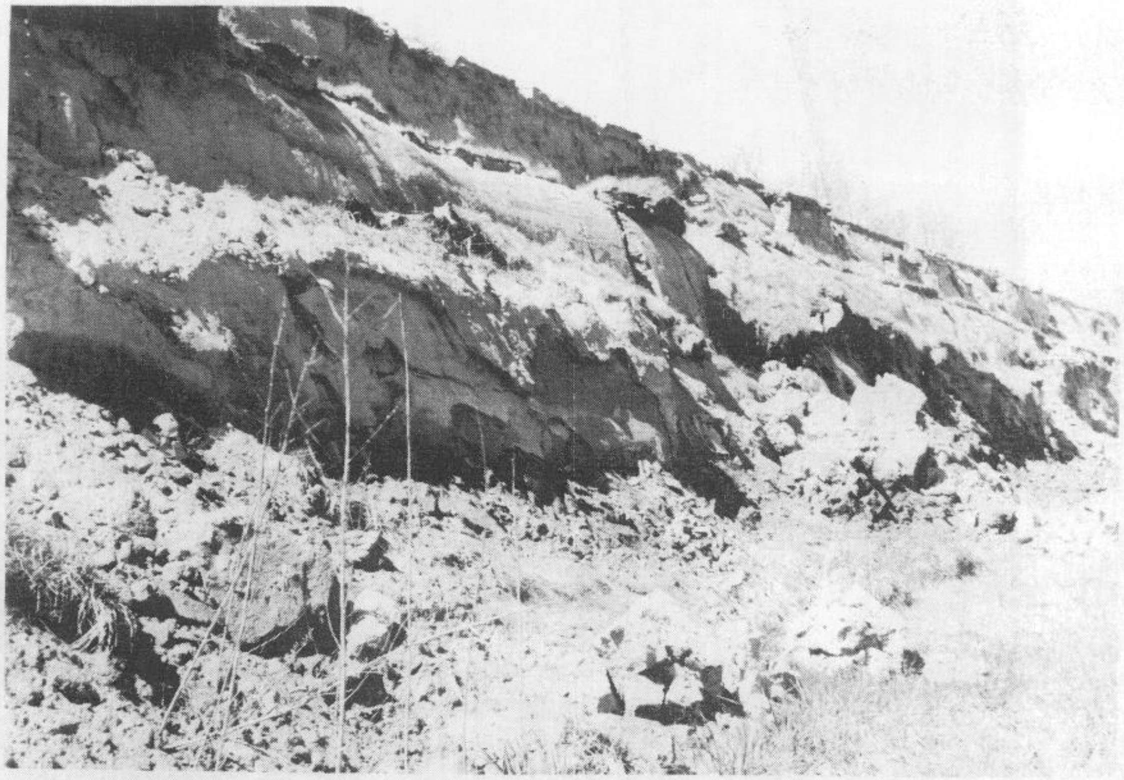

Figure 28. Stepped slope approaching an effective 1.5 to 1 with degradation by erosion and slides (Holt County, Route I-29)

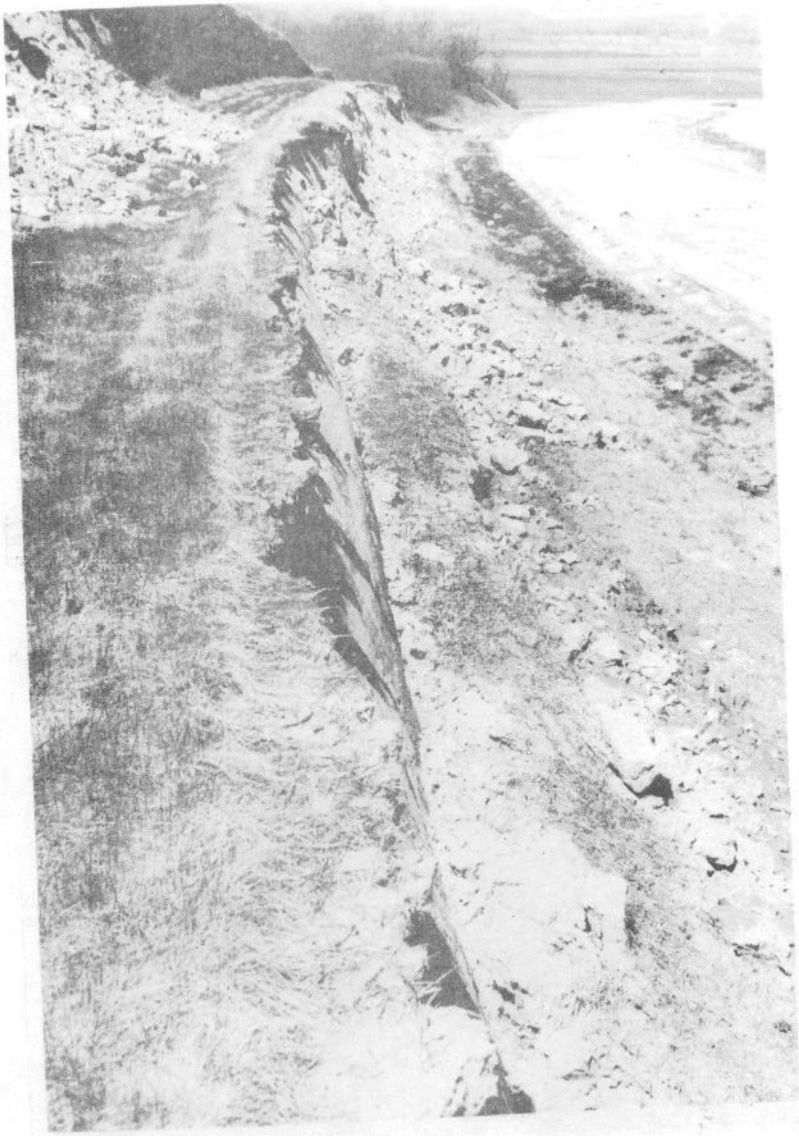

Figure 29. Slump blocks resulting from frost damage are evident on this north facing slope (Holt County, Route I-29)

Figure 30. Failure plane from ice lense development is evident on this north facing slope (Holt County, Route I-29)

Figure 31. Frost damage to a vertical slope (Clay County, Route 210)

CONSTRUCTION CASE HISTORIES

During recent years, deep cuts through loess were constructed in three areas which had been sampled in some detail during preliminary design. This provided opportunities to study and resample during the course of this investigation to detect changes in moisture content and water tables and to relate observed performance to the measured changes.

1. Holt County, Route I-29, Vicinity Station 1000±.

At this location, 86 feet of loess was found overlying glacial till with an original water table 20 feet above the till contact (see Figure 32). The loess strata intercepted are tentatively identified as Bignell, Peoria and Roxana with pockets of fine sand and silt with low cementation near the base of the cut (Loveland).

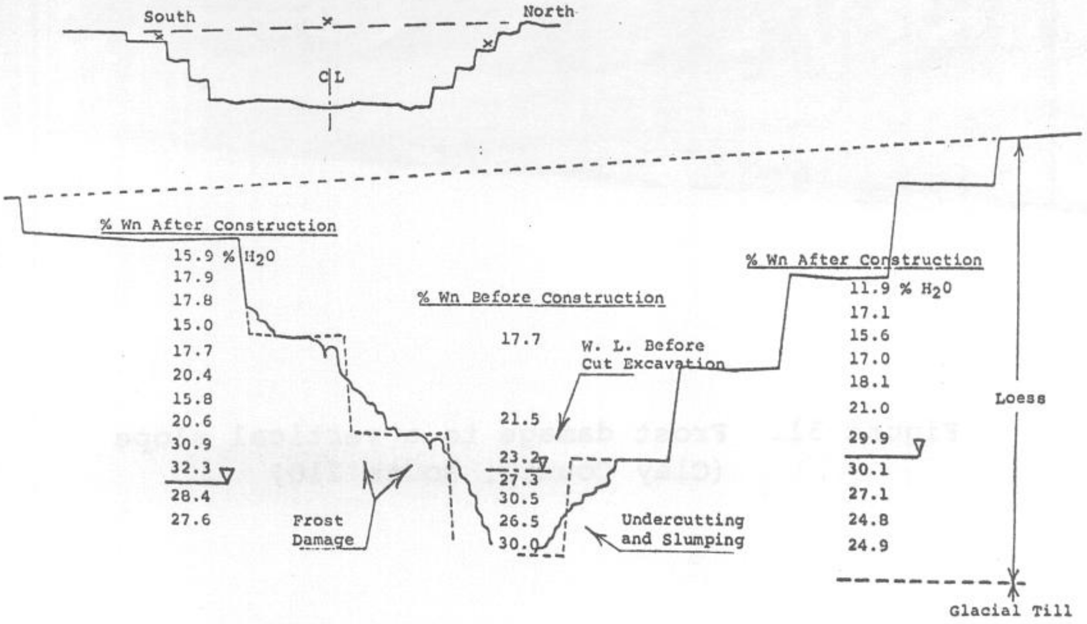

Figure 32. Comparison of moistures before and after construction at Station 1000, Holt County, Route I-29.

The roadway is oriented northwest to southeast with grade just above the till contact and about 18 feet below the original water table. Preconstruction moisture contents in the loess averaged about 17 percent above the water table and 28 percent below. The planned design for this area called for 20 foot wide, sodded V-shaped benches and nearly vertical rises (1/4:1) to a maximum of 20 foot height. Five rises were used on the southwest facing slope and four on the northeast facing slope. A basic design assumption was that pilot trenching of the cut would lower permanent water levels and reduce the high moisture content of the loess below the original water table.

Many problems were evident through this area during construction. The predominantly "silty" (ML) loess was subject to numerous instances of piping. Paved ditches had to be extended to carry drainage from the benches due to the erosion which occurred wherever runoff was concentrated. The southwest facing slope experienced undercutting due to local failures along the toe of the bottom face as a consequence of the low strengths and seepage stresses from the truncated water table. Pictures of these multiple problems are included as Figures 10, 11, 12, 13, 15, 17, 18, 21, 22 and 27.

During the following winter, severe freeze damage occurred to the lower two faces of the northeast facing slope. Slumps occurred continuously along the total length of the cut, approximately 1/2 mile, and the sodded benches were in some areas completely covered with talus. This damage is shown in Figures 8, 28, 29 and 30. Subsequently the loss of runoff control effectively modified this slope to an approximate 1.5:1. Over a period of two years the lower face of the southwest facing slope collapsed from the effects of the truncated water table.

This area was resampled, behind both backslopes, two years after the cuts were excavated. The water tables behind both slopes were found to be at approximately the same elevation above the till contact as when originally sampled. The moisture contents still averaged approximately 17 percent above the water table and 28 percent below (see Table 14). The slopes had experienced severe damage wherever the water table had been truncated. Severe freeze damage had even occurred in the second northeast facing near vertical rise which was found to be above the water table at the time sampled and with moisture contents locally averaging only 18 percent. The two overlying northeast facing rises, and the four southwest facing rises above the water table, where moisture contents averaged 17 percent, had performed quite well.

TABLE 14. Comparison of physical properties before and after construction, Case History No. 1*

	Before Construction	After Construction				
	11/27/64	7/16/75				
	℄	150'LT.	150'RT.			
Elevation**	Wn, %	Wn, %	Wn,%	LL	PI	ASTM
90		11.9	15.9	NP	NP	ML
85		17.1	17.9			
80		15.6	17.8	30	3	ML
75			15			
70	17.7	17	17.7	32	4	ML
65		18.1	18.7			
60	21.5	21	20.4	36	11	CL-ML
55	23.2	29.9	15.8			
50	27.3	30.1	20.6	32	6	ML
45	30.5	27.1	30.9			
40	26.4	24.8	32.3	NP	NP	ML
35	30.0	24.9	28.4			
30			27.6			

*Holt County, Route I-29, Station 1000±

**Referenced to assumed elevation 100 for natural ground at ℄

2 Howard County, Route D(87), Vicinity Station 23±.

This north-south oriented, 90 foot deep cut is on the south bank of Greggs Creek immediately east of the Missouri River. Original sampling at this location revealed a high water table with moisture contents averaging slightly less than 17 percent above the water table and 26.2 below. The cut was designed with 5 near vertical rises of 1 on 10 to 20 foot height with 15 foot wide sodded benches. The original water table was found at an elevation corresponding to the first bench at the toe of the second 20 foot rise (see Figure 33).

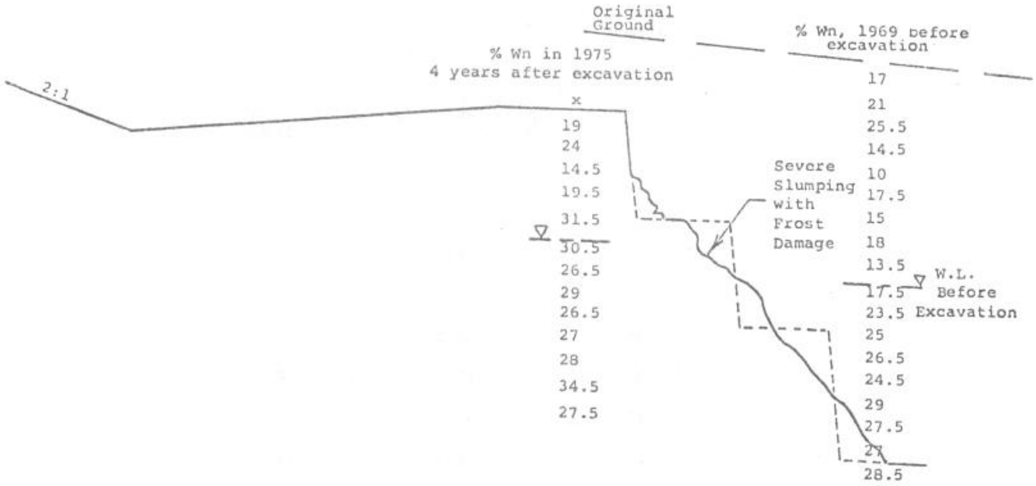

Figure 33. Comparison of moistures before and after construction at Station 23, Howard County, Route D(87).

Erosional losses on the project led to extensive borrowing of soil from the top of the slope so that the original design was extensively modified, resulting in only three rises of 20 foot height with a 2 1/2 to 1 slope of 27 feet height at the top of the slope behind a flat bench approximately 100 feet wide.

Slides began occurring in the wet loess immediately after excavation. Massive freeze damage occurred during the first winter after exposure and seepage has persisted in the lower faces (see Figures 2 and 9).

Resampling of this area, at the top of the benched vertical rises, indicated no significant change in the water table behind this slope. Average moisture contents actually increased to slightly above 19 percent above the water table, possibly a seasonal fluctuation (see Table 15).

TABLE 15. Comparison of physical properties before and after construction, Case History No. 2*

	Before Construction 8/12/69	After Construction 7/17/75			
Elevation**	Wn %	Wn %	LL	PI	ASTM Class.
95	19				
90	20	19	33	4	ML
85	10	24.1			
80	17.5	14.5	31	2	ML
75	15	19.5			
70	18	15.6	32	4	ML
65	15.5	31			
60	23.5	26.5	40	19	CL
55	25	27			
50	26.5	28	29	1	ML
45	24.5	34.5			
40	29	27.5			
35	27.5				
30	27.8				

*Howard County, Route D(87), Station 22+60, before construction sampling at 40'RT., after construction sampling at 105'RT.
**Referenced to assumed elevation 100 for natural ground at 40'RT.

Over a six year period, the 2 1/2 to 1 slope section has performed well (see Figure 3). The vegetative cover has prevented serious erosion and seems to have "healed" the initial erosion that occurred with exposure. The highest vertical rise, which was above the water table and where moisture contents now average 19 percent, is performing fairly well with only minor sloughing near the base of the rise. The lower two rises have deteriorated to the point of starting to undercut the upper rise. The benches are gone and the slope is approaching an effective 1 to 1. Erosion has been out of control for several years and continual ditch siltation is occurring.

3. Buchanan County, Route I-229, Vicinity Station 131±.

Three cuts with north-south orientation and up to 105 feet in depth were constructed through loess in a hill immediately east of the Missouri River and within the northwest urban limits of St. Joseph (see Figure 1).

All of these cuts were sampled prior to excavation and no permanent water table was found. The results of all of the soundings were similar. Data from one of the cuts in the vicinity of station 131 is included as Table 16. Moisture contents averaged about 17 percent and the loess was found to overlie sand and gravel of glacial outwash origin (see Figure 34).

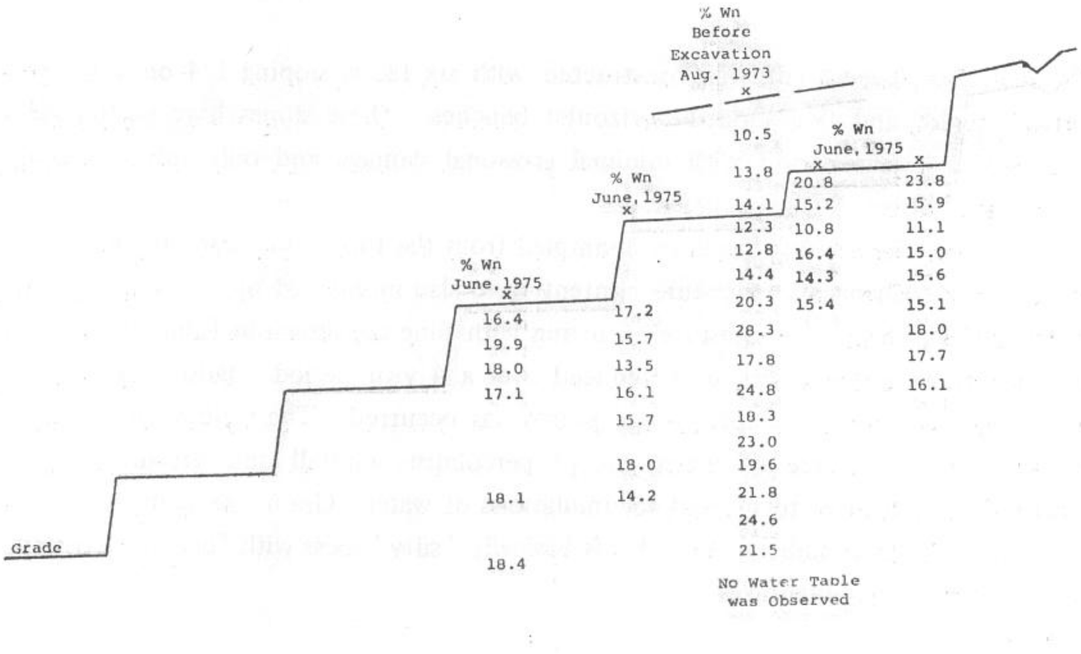

Figure 34. Comparison of moistures before and after construction at Station 131, Buchanan County, Route I-229.

TABLE 16. Physical properties prior to excavation, Case History 3*

Depth	% Recovery	PP** (tsf)	TV# (tsf)	Density (pcf)	% Wn	LL	PI	ASTM Classification
5 to 10'	44	1.0	0.1	89.3	10.6	30	1	ML
10 to 15'	36	2.0	.25	87.4	13.8	33	8	ML
15 to 20'	38	4.0	.37	--	19.1	30	5	ML
20 to 25'	56	1.8	.50	86.0	12.3	32	8	CL-ML
25 to 30'	20	2.0	.50	--	12.8	29	3	ML
30 to 35'	98	3.0	.50	88.2	14.4	32	6	ML
35 to 38'	77	4.0	.30	81.8	20.3	32	6	ML
38 to 43'	88	2.4	.37	93.2	28.4	34	6	ML
43 to 45'	50	5.0	.25	98.9	17.8	31	7	CL-ML
45 to 50'	90	3.0	.32	--	24.8	31	7	CL-ML
50 to 55'	86	4.2	.37	91.7	18.3	32	7	ML
55 to 60'	92	1.5	.17	97.7	23.8	32	9	CL
60 to 65'	64	2.0	.30	100.5	19.6	31	9	CL-ML
65 to 70'	98	7.0	.32	96.0	21.8	33	10	CL-ML
70 to 75'	96	2.0	.32	94.9	24.6	32	9	CL-ML
75 to 80'	98	2.7	.50	98.7	21.5	32	11	CL

*Buchanan County, Route I-229, Station 131±. Sampled with 4 inch double tube core barrel using circulation drilling with bentonite added.
**Hand held, calibrated penetrometer test
#Hand held, calibrated torsional shear test

The deepest cut was constructed with six faces, sloping 1/4 on 1 to 20 foot vertical height, and five sodded horizontal benches. These slopes have performed very well over a 4 year period with minimal erosional damage and only minor spalling on the vertical faces.

The deepest cut has been resampled from the top of the slope three times since construction. Changes in moisture content were also monitored by moisture cells buried in drill holes. Changes in moisture occurring with time are shown in Table 17 and indicate that moisture contents have been reduced over a 4 year period. Below 15 foot depth, an average decrease of 2.5 percentage points has occurred. The topography is such that the area has no source of water except percolating rainfall and subsurface drainage apparently is adequate to prevent accumulations of water. Grain size analyses of samples taken from the faces indicate that this is basically "silty" loess with "clayey" loess present in only very small quantities.

General

In summary it may be said that moisture contents did not change substantially behind cut slopes in loess wherever a water table was truncated. The high water tables at the first two locations did not change substantially even though a steep drainage gradient was established to the roadway ditch. The long term effects of the water tables resulted in severe damage to the vertical slopes due to slides and freeze damage. At the third location, where no water table was initially logged, there were indications of drying over the four year period of observation.

TABLE 17. Comparison of moistures before and at varing intervals after construction, Case History No. 3*

	Pre-Construction Wn, %	Post Construction Wn, %		
	8/23/73	4/2/74	10/26/74	6/28/75
Top of slope				
@7.7'	13.8	18.1	14.7	16.4
@13.7'	14.1	17.2	18.3	16.9
@28.0'	14.4	12.4	14.7	12.2
1st bench (25' from face)				
@11.0'		11.1		15.9
@30.0'		15.0	17.2	15.1
@45.0'		17.9	17.8	17.7
@60.0'		19.4		17.6
1st bench (6' from face)				
@7.5'		14.5	16.1	16.4
@13.5'		12.3	17.6	17.0
@26.0'		15.9	17.2	12.2
2nd bench (5' from face)				
@15.0'	20.3	17.5	16.3	15.9
@34.0'	18.3	18.2	17.4	15.7
@60.0	21.5	19.1		14.2
3rd bench (6' from face)				
@3.0'		16.4	16.9	
@7.0'		19.9	18.2	22.2
@13.0'		18.0	17.0	19.6
@17.0'		17.1	18.9	17.6
@38.0'		18.1		18.1
@57.0'		18.4		18.6
4th bench (6' from face)				
@4.0'			19.8	
@16.0'			18.9	18.5
@27.0'			20.8	16.1
@51.0'				16.5
5th bench (6' from face)				
@5.0'		15.0	20.6	21.8
@10.0'		14.9	17.2	15.1
@15.0'		14.4	16.9	12.4
@25.0'		11.8	17.2	12.9
@40.0'		17.4		17.5
Average	17.1	16.2	16.9	16.6
Average (below 15' depth)	18.6	16.6	17.6	15.9

*Buchanan County, Route I-229, Station 131±

"Clayey" loess was prevalent in the lower two vertical rises of the cut in Howard County which are performing poorly. In the other two areas, "clayey" loess is not prevalent. Volume change problems were not apparent at any of the three locations. However, it is likely that this would have been a problem at the Howard County site if the slope had not first disintegrated from other problems associated with the continuous seepage.

There has been an assumption that loess cuts could be pilot trenched for rapid relief of seepage pressures and that high moisture contents could be reduced over the long term by the construction of a roadway cut. At the locations studied, where water tables were truncated by a cut and in spite of the steep drainage gradients provided, water tables behind the slope were not affected significantly. Serious damage occurred to all vertical slopes at or below the elevation of the original water table logged, both due to freeze damage and due to slumping from inadequate strength.

DATA CORRELATION

Samples of two major loess units, the Peoria and Roxana, and of the underlying Sangamon soil were tested and the averaged results tabulated in Table 18. An average plasticity index of 6.9 was found for 102 samples taken from all loesses with a standard deviation of 4.4.

TABLE 18. Average plasticity and grain size characteristics for major Pleistocene strata***

	No. of Obs.	PI	D_{10}** (mm)	D_{30}** (mm)	D_{60}** (mm)	Uniformity Coefficient C_u	Coefficient of Curvature C_c
Peoria loess	30	4.3 (2.6)*	.0024 (.0015)*	.016 (.004)*	.033 (.004)*	17.7 (7.5)*	4.3 (2.6)*
Roxanna loess	5	9.2	.0004	.012	.034	96.6	11.5
Sangamon soil	3	7.0	.00012	.0094	.030	26.6	29.1

*Standard deviation of data
**That size which the noted percent is smaller than
***Based on tentative identifications of exposures in roadway cuts

The Peoria is shown to have a plasticity index of only 4.3 and to be poorly graded with a uniformity coefficient (C_u) of 17.7 and a coefficient of curvature (C_c) of 4.3, values consistent with its relatively high permeability and low density. The underlying Roxana is indicated to have a higher plasticity index of 9.2 and, with a C_u of 96.6 and a C_c of 11.5, to be more uniformly graded, indicative of a denser and more impermeable soil. (The Sangamon soil is shown to have a poorly graded, clayey texture, confirming field experience as a wet, dense soil of low permeability.)

The foregoing data indicate a relatively narrow range of plasticity and textural variation and it is evident why visual logging from bore holes, and especially augered cuttings, is a difficult means of determining stratigraphy.

Table 19 relates slope type, direction of exposure, degree and type of distress, performance rating, and physical properties including moisture content. The physical properties and moistures were determined from samples taken near the base of slopes, approximately 3 feet up and 8 inches deep. The direction of slope exposure was tabulated into 3 groups, (1) north facing, encompassing north 75° west through north 75° east; (2) south facing, encompassing south 75° east through south 75° west; and (3) east or west facing, encompassing north 75° east through south 75° east and from south 75° west through north 75° west.

TABLE 19. Relationships of performance and physical properties to type and orientation of slope

Slope	Exposure* Group	% of a Face Failing	Number of Slopes	Ave. Max. Ht. Ft.	Ave. Wn	Ave. LL	Average % Smaller Than		Average Performance Rating**	Average % Distressed by Type***				
							.007 mm	.002 mm		A	B	C	D	E
Vertical	N	0-100	22	24.9	20.0	32.8	23.2	14.5	3.3	45	59	23	9	68
		>60	15	23.4	21.6	33.3	22.3	14.3	3.5	47	68	27	13	87
		<60	7	28	22.8	31.7	25.2	14.8	2.7	43	57	14	0	29
"	S	0-100	30	28.5	18.6	33.6	25.0	16.1	2.6	70	53	27	17	0
		>60	13	28.5	19	35.7	25.5	16.3	2.9	69	6	38	23	0
		<60	17	28.5	18.3	31.9	24.6	15.9	2.4	71	47	35	12	0
"	E & W	0-100	21	23.6	18.0	30.8	21.7	14.6	2.3	76	43	10	19	5
		>60	8	28.1	16.6	33.5	25.5	18	3.6	75	88	25	13	13
		<60	13	20.9	20.3	31.5	21.0	13.7	1.5	77	15	0	23	0
"	All	0-100	73	26.0	18.9	32.6	23.5	15.2	2.7	64	57	25	15	22
Flattened	N	0-100	8	34.5	27.5	32	23.2	15	1.3	100	0	0	0	0
"	S	0-100	6	34.2	19	35	24.5	16.8	1.3	67	33	17	0	0
"	E & W	0-100	3	30	30	32	29.3	22.7	1.0	100	0	0	0	0
"	All	0-100	17	32.9	23.2	33.1	23.5	14.8	1.3	88	17	6	0	0

*Exposure Groups N = N75°W - N75°E
S = S75°E - S75°W
E or W = N75°E - S75°E and S75°W - N75°W

**Performance Rating 1 = Excellent
2 = Good
3 = Fair
4 = Poor

***Distress Type A = Erosion
B = Sloughs & Slabbing
C = Slides
D = Undercutting
E = Freeze Damage

Significantly, 68 percent of north facing vertical slopes are shown to have experienced freeze damage. Moisture contents were higher, averaging 20.0 percent versus 18.4 for all other vertical slopes. The average performance rating of this group was 3.3, on a scale of 1.0 (excellent) to 4.0 (poor). This was the worst score of any exposure group.

Regardless of direction of exposure, Table 19 shows that flattened slopes consistently rank higher in performance ratings (1.0 to 1.3) than do vertical slopes (1.3 to 3.3). Flattened slopes show none of the types of distress associated with vertical slopes except for erosion, a problem normally of minor significance on flat slopes.

About half (49%) of the vertical slopes have faces which show serious distress arbitrarily defined as 60 percent or more of a face failing. None of the flattened slopes meet this definition of serious distress. As compared to better performing vertical slopes, soils from these failing vertical slopes, excepting those with north exposure, had average liquid limits higher by 3.2 percentage points, 2.5 percentage points more finer than 7 microns and 2.0 percentage points more finer than 2 microns. This confirms the association of the clayier loesses with serious slope problems.

As discussed in the section titled "Mechanisms of Loess Behavior", Holtz and Gibbs have classified loess into three subgroups, "clayey", "silty" and "sandy". "Clayey" loess was redefined, for purposes of this correlation, as having either 22 percent or more finer than 7 micron size or 16 percent or more finer than 2 micron size, the latter percentage being based on a projected extension of the boundary values established by Holtz and Gibbs. In these discussions, use of the terms "clayey" and "silty" is based upon these modified definitions.

Loess soils falling in the "sandy" category as defined by Holtz and Gibbs were only found in very localized deposits in the survey and were not included or evaluated.

The "silty" loesses, reference Table 20, surveyed are shown to have an average liquid limit of 30.1 and a plastic index of 4.9 while "clayey" loesses have an average liquid limit of 34.8 and a plastic index of 12.4. The average Peoria loess then falls in the "silty" range and the average Roxana loess in the "clayey" range. Correlation of plastic index values to grain size distribution suggests that a plastic index of 7 or greater, in the absence of grain size analyses, could be used as an indicator of "clayey" loess.

TABLE 20. Average physical properties of silty and clayey loesses

	Wn,%**	LL	PI	% Clay <2u	No. of Tests
Silty Loess	14.7 (4.5)*	30.1 (3.2)*	4.9 (2.2)*	13.8 (5.6)*	85
Clayey Loess	21.7 (5.5)	34.8 (4.5)	12.4 (5.6)	19.1 (6.6)	32

*Standard deviation of test data shown in parenthesis

**Taken at approximately 8 inches depth in vertical face, 3 feet above toe of slope

The five types of slope distress, as defined in the section entitled "Performance Survey", are related to the "silty" and "clayey" gradation bands in Figures 35 through 39. Figure 35 indicates the range of grain sizes found for samples obtained from slopes with erosion as a primary problem. The cross hatched area marked A indicates that, as would be expected, these curves fall in the "silty" loess range. These are mostly ML soils with an average liquid limit of 31.

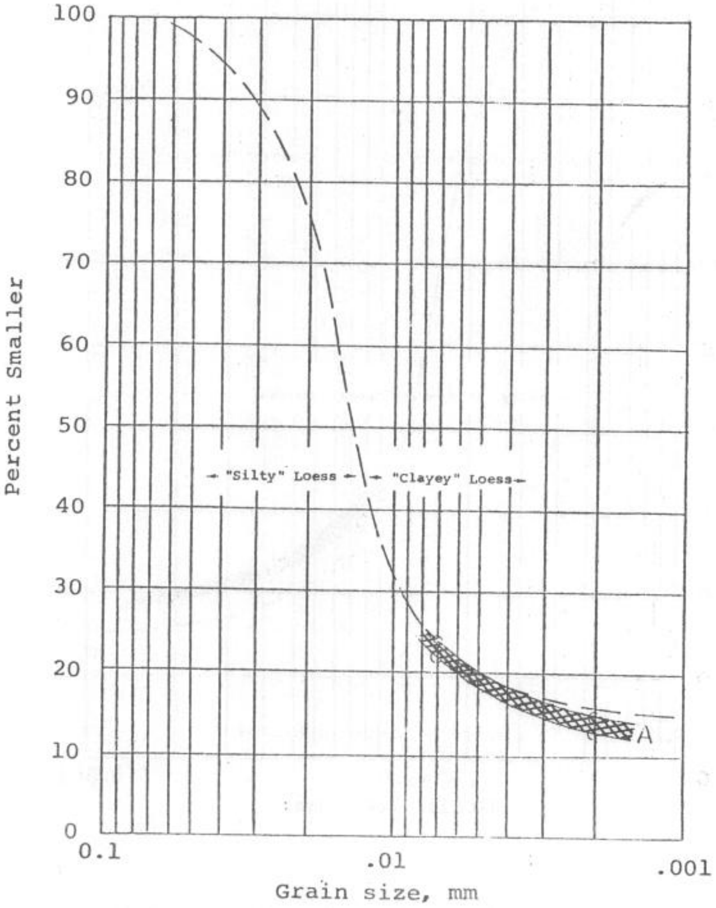

Figure 35. Samples obtained from loesses having erosion problems have gradation curves which fall within the hatched area.

Figure 36 indicates the range of grain size distributions found for samples taken where volume change failures are occurring as sloughing and slabbing. The cross hatched area marked B indicates that these samples fall well in the "clayey" loess range with an average liquid limit of 35.

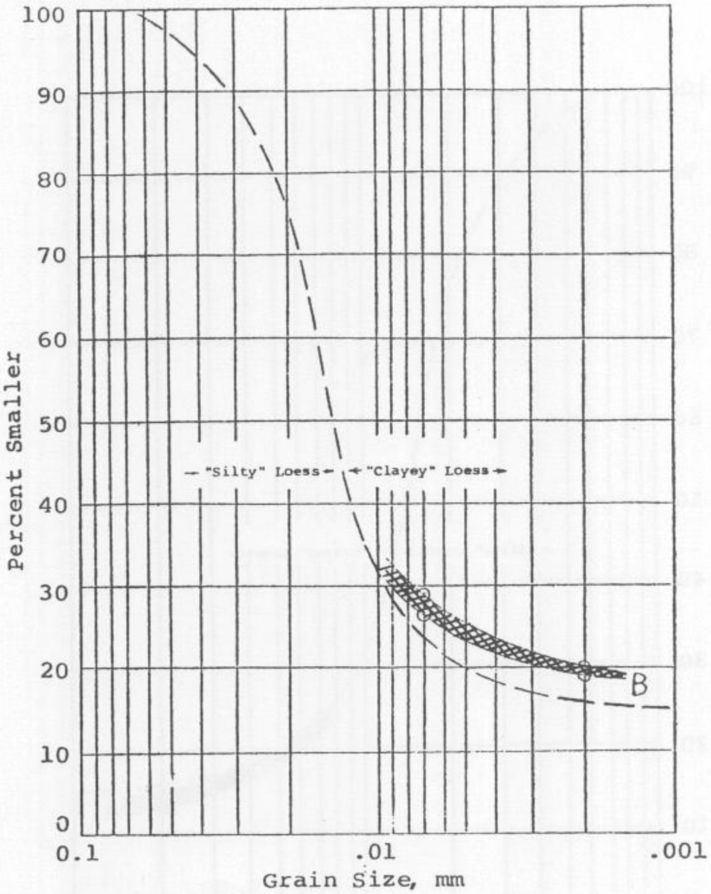

Figure 36. Samples obtained from loesses having volume change problems have gradation curves which fall within the hatched area.

Figure 37 indicates the range of grain size curves for samples taken where slides were found. The cross hatched area marked C falls in the "clayey" range with an average liquid limit of 35.

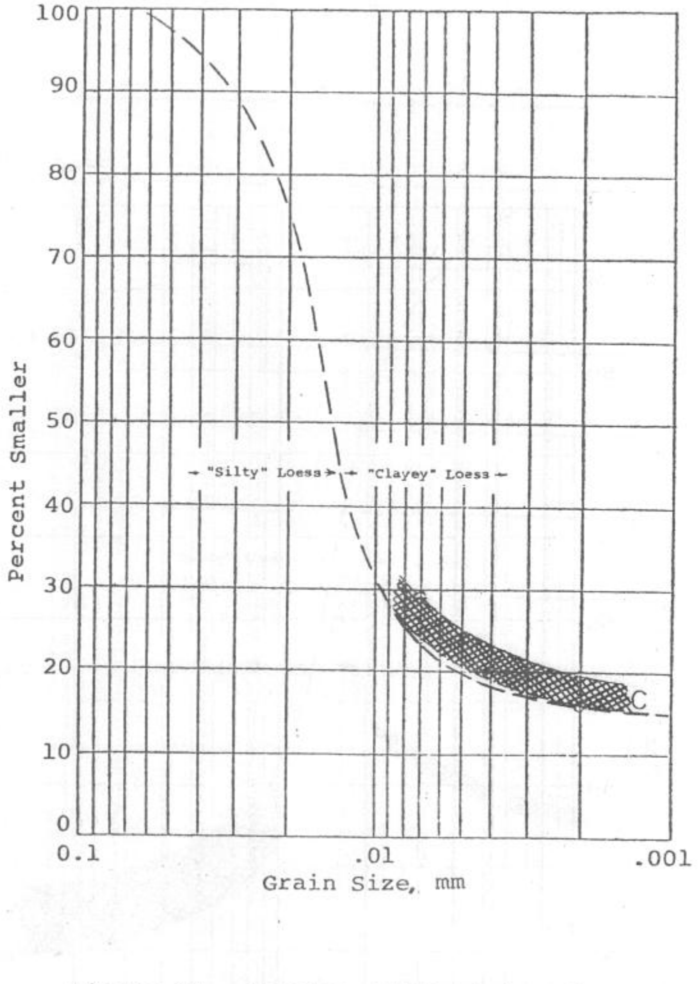

Figure 37. Samples obtained from loesses in areas of slides have gradation curves which fall within the hatched area.

Figure 38 indicates the grain size range for samples taken where undercutting was occurring. The cross hatched area marked D indicates grain size curves to vary from "silty" to "clayey" in range. The corresponding liquid limit range is 31 to 34. This seems reasonable as the local failures which comprise this category are most often a consequence of high moisture contents, included truncated water tables, which cause problems in either category of loess when vertical slopes are used.

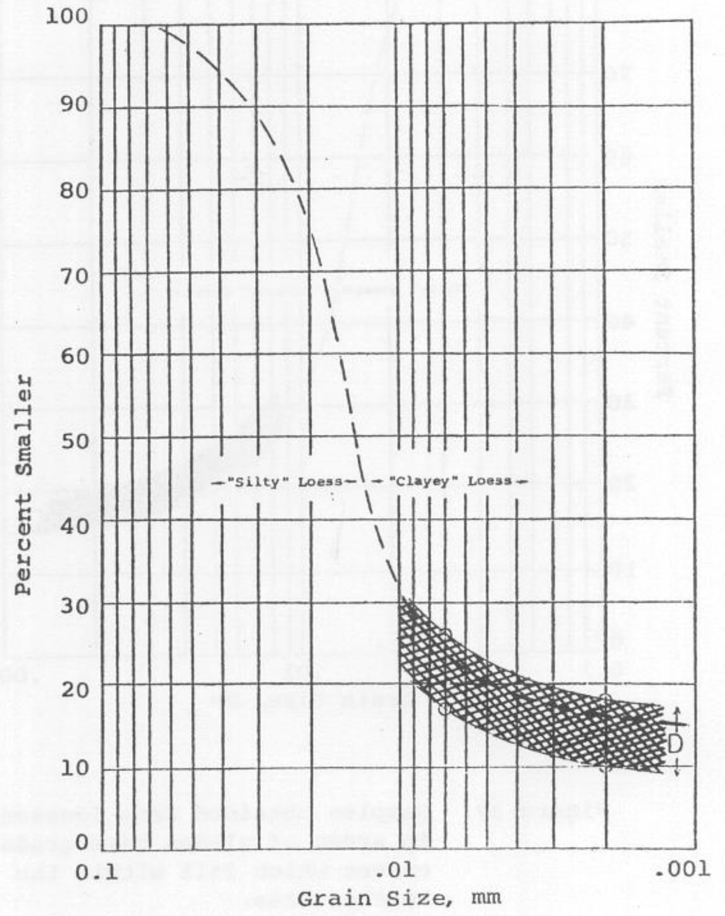

Figure 38. Samples obtained from loesses where undercutting is occurring have gradation curves which fall within the hatched area.

Figure 39 indicates the grain size range of samples secured in areas where frost damage was evident. The cross hatched area marked E indicates the "silty" loess soil normally identified with this type of failure.

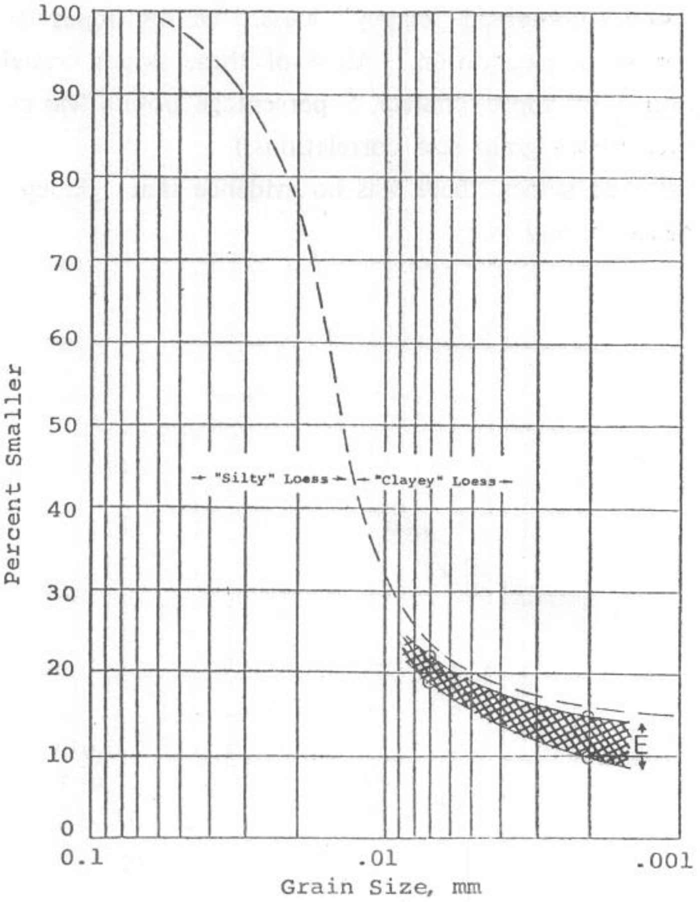

Figure 39. Samples obtained from loesses where frost damage has occurred have gradation curves which fall within the hatched area.

Other summaries of performance survey data indicate significant correlations of the occurrence of "clayey" loess to distress in vertical slopes. Soil from 48 slopes having a performance rating of 4 (poor) contain an average of 25 percent material finer than 7 microns and 17 percent finer than 2 microns, well in the "clayey" range. Soils from 26 slopes having a performance rating of 1 (excellent) contain an average of 18 percent material finer than 7 microns and 13 percent finer than 2 microns, well in the "silty" range. Slopes having a performance rating of 2 (good) and 3 (fair) had soil with an average grain size distributions falling in, but borderline to, the "clayey" loess classification. Of 47 slopes having slides, 6 are in serious condition (slope performance rating 3 or 4). Five of these 6 slopes contained "clayey" loess. Of 48 slopes having volume change problems, 4 are in serious condition. All 4 of these slopes contained "clayey" loess. (A standard deviation of approximately 5 percentage points was consistent through all of the performance versus grain size correlations.)

With flattened slopes, there was no evidence that "clayey" loess detrimentally affected performance in any way.

STABILITY ANALYSIS TECHNIQUES

Loess slope stability may be analyzed using total or effective stress parameters. The selection should be based upon the type of slope determined to be necessary. This in turn is dependent upon the type of loess, "silty" or "clayey", and the moisture content with particular attention to zones of saturation. Total stress parameters must be used to design slopes approaching the vertical as loesses suitable for such slopes have low moisture contents and strengths which are a function of negative intergranular stresses, not amenable to effective stress analysis. Effective stress methods are particularly applicable in dealing with saturated loess and with seepage stresses where flattened slopes are required.

Charts and tables such as those of Taylor(7) or Bishop and Morgenstern(8) often may be used for preliminary stability calculations using either total or effective stresses.

Strength parameters must be determined by testing methods appropriate to the type of analysis anticipated. While undrained triaxial tests are undoubtedly best for total stress analysis, the quicker and cheaper unconfined compression test may be preferable where a greater number of tests can offset any deficiencies in quality. The reliability of either test can be increased by correlation to supplemental data obtained using hand held, calibrated penetration and torsional shear devices.

Strengths obtained by any means require interpretation as to the probability of strength increase or decrease with long term moisture changes to relate the "quick" laboratory tests to long term stability. It appears appropriate to use a reduction factor with total strength values, at least where topography, drainage and direction of exposure of the cut face are not conducive to long term drying and strength increase. To relate the strengths measured by undrained laboratory or field vane shear tests to long term strain conditions for clays of high plasticity, Peck, Hansen and Thornburn(9) state that a reduction factor (Cr) may be approximated by the equation $Cr = 1.0 - 0.5 \log (PI/20)$. If it is assumed that the undrained strength of loess is solely a function of the clay binder and further assuming a PI of 100 as found by Kane for the colloidal portion of an Iowa loess, a typical Cr value for loess would be about 0.65. Such a reduction, along with a design factor of safety of at least 1.5, should offer reasonable protection against changes in long term stress conditions as well as temporary strength reductions due to seasonal moisture changes.

Effective stress parameters can be determined by the consolidated, undrained triaxial tests with pore pressures measured and corrected ($\overline{R}$), or by consolidated, drained triaxial or direct shear tests(S). The direct shear(S) test is relatively inexpensive and can be performed quickly on loess due to the rapid dissipation of pore pressures in such highly permeable soils. Consequently, this test has been used most extensively by Missouri.

Effective angles of internal friction obtained generally do not vary greatly, ranging from a low of about 30 degrees for some "clayey" loesses to a high of about 36 degrees for some "silty" loesses. The cohesion intercept for saturated loess typically may vary from 100 psf or less to 500 psf depending upon clay content and density. For preliminary estimates of stability, effective stress parameters may be estimated from correlations to plasticity index and to moisture. Such estimates, and particularly the value of cohesion, should be interpreted conservatively.

A. "Silty" Loess

Slope design in "silty" loess may require either vertical or flattened slopes depending upon the moisture content existing and anticipated:

1. Vertical slopes are often feasible at moisture contents below the critical moisture range and should be analyzed using total stress parameters.

2. With existing or anticipated moisture contents above the critical moisture range but less than saturation, 2:1 slopes will normally be indicated to be adequately safe using either total or effective stress analysis. Slope selection under these conditions is not critical and, for low to moderate heights, will rarely require analysis. The selection is usually empirical and influenced by considerations of erosion. (Missouri's current criteria for ML and CL soils calls for 2 1/2:1 except that 2:1 may be used where spill slopes of less than 20 feet in height are afforded some form of slope protection.)

3. With saturated soils, effective stress analyses are required for flattened slope designs with realistic assumptions as to seepage forces existing during excavation and likely to persist after the cut is opened. Depending upon the degree of seepage forces considered and the strength parameters used, slopes will be no steeper than 2 1/2 to 1 and probably much flatter. The possibility of artesian pressures transmitted through saturated silty or sandy loesses or underlying glacial outwash sands should be given consideration.

B. "Clayey" Loess

Previous discussion of "clayey" loess has indicated that, regardless of moisture content, vertical slopes are not practical and that flattened slopes must be used. Techniques discussed under 2 or 3 above are applicable depending upon the need to consider seepage forces.

RECOMMENDATIONS FOR DESIGN PROCEDURE

The following procedure is proposed for design of loess cut slopes and is summarized by a flow chart included as Figure 40.

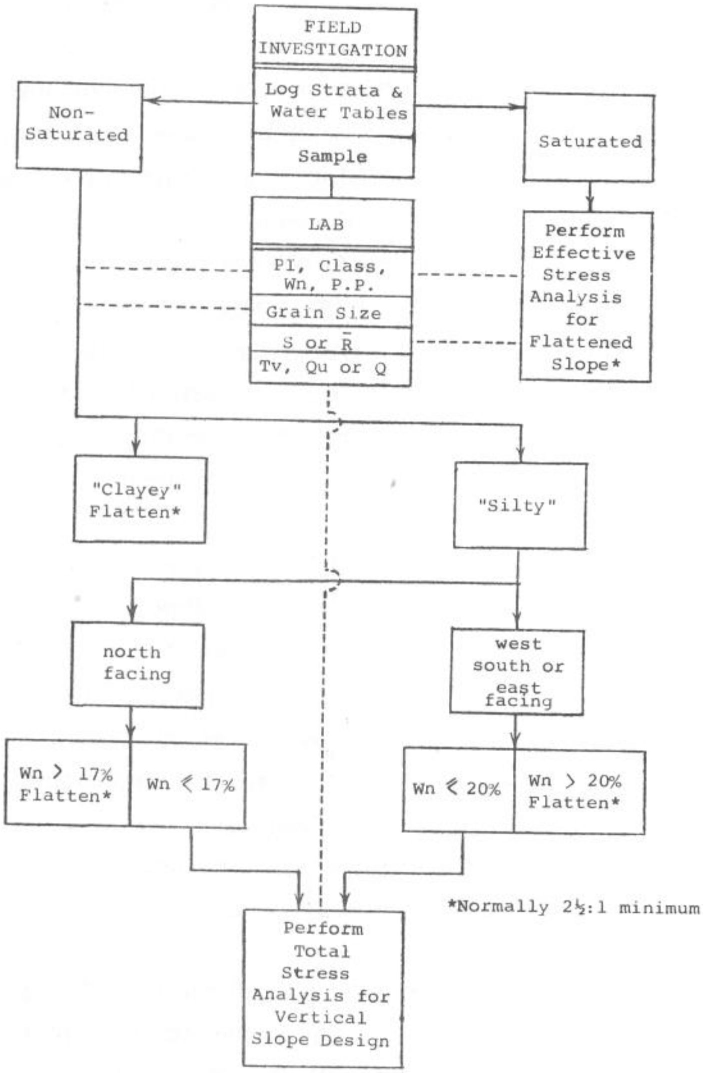

Figure 40. Flow chart of decision making process for loess cut slope design.

The field investigation should consist of logging and "undisturbed" sampling from bore holes free of drilling fluid above any water table. For optimum results in non-saturated loess, a 3 inch slotted-tube (Giddings) sampler in an auger hole is recommended to obtain continuous samples. Sufficient holes should be drilled to establish stratigraphy and water tables throughout the area of the cut.

Field logging should include careful notations of colors (always with the soil in a wetted condition) and any apparent structure and stratigraphy including old soil profiles and obviously wet or clay enriched zones. Field logs should be supplemented with field test data from hand held, calibrated penetrometers and torsional shear devices.

Representative samples should be taken from each obvious change in stratification, or at no more than 5 foot intervals in the absence of such evidence, for moisture, ASTM and AASHTO classification (which would include the plasticity index) and for grain size analysis. Reserve samples should be retained for shear testing. Alternately, shear tests could be obtained at a later date, after it is determined that the tests are needed, if the site is readily accessible.

If water tables exist, flattened slopes are required and, if of substantial height, should be based on effective stress stability analyses using $\bar{R}$ or S shear strengths.

If the loess is not saturated, it is necessary to determine, from grain-size analyses, if the loess is "silty" or "clayey". "Clayey" is defined as either 22 percent or more finer than 7 micron size or 16 percent or more finer than 2 micron size. For unambiguous situations or where the cut is small, this judgement can be based on a plasticity index of 7 or more for "clayey" loess.

If the loess is "clayey", flattening to 2 1/2:1 will normally suffice. A stability analysis will not normally be required unless the slope is of considerable height.

If the loess is "silty", consider orientation and moisture content to determine if vertical faces can be used. For north exposures subject to little or no sunlight, consider vertical slopes only if natural moistures are 17 percent or less. For more favorable exposures, and where surface and subsurface drainage conditions are favorable, this can be increased to a maximum of about 20 percent.

If these criteria for vertical slopes are not met, 2 1/2:1 slopes should normally be used with a stability analysis required only in unusual circumstances, as when the slope is of considerable height.

If criteria for vertical slopes are met, perform total stress analyses using Q triaxial or unconfined compression tests, supplemented by test data from hand held, calibrated penetrometer (P.P.) and torsional shear (Tv) devices, to determine safe allowable heights. If conditions are favorable for long term drying (orientation, topography, subsurface drainage gradients, etc.), use measured strengths; otherwise, reduce by up to 35 percent. Provide horizontal benches so that the average effective slope is 1:1 or flatter. Analyze overall stability of the total slope as well as the individual rises.

In deep cuts, it will not be unusual to find that the lower part of the cut requires a flattened slope while the upper part meets the requirements to permit use of vertical slopes. Such a combination is perfectly feasible. All that is required is a bench at the top of the flattened portion and that stability of the total slope be analyzed as well as the individual components.

REFERENCES

1. Kane, H. A., "Mechanistic Explanation of the Physical Properties of Undisturbed Loess", Research Project HR-126 for Iowa State Highway Commission by Department of Civil Engineering, University of Iowa, February 1968.
2. Gibbs, H. J. and Holland, W. Y., "Petrographic and Engineering Properties of Loess", Bureau of Reclamation Engineering Nomograph No. 28, 1960.
3. Holtz, W. G. and Gibbs, H. J., "Consolidation and Related Properties of Loessial Soils", Special Technical Publication No. 126, pp. 9-26, American Society for Testing Materials, 1951.
4. Bayne, C. K., Davis, S. N., Howe, W. B., and O'Connor, H. G., "Pleistocene Stratigraphy of Missouri River Valley Along the Kansas-Missouri Border", Guidebook 20th Annual Meetingof the Friends of the Pleistocene, pp. 5-19, 1971, State Geological Survey and University of Kansas Special Publication No. 53.
5. Howe, W. B., "Guidebook to Pleistocene Deposits and Pennsylvanian Bedrock Formations in the St. Joseph Area", Missouri, Association of Missouri Geologists, 15th Annual Field Trip and Meeting, pp. 9, Oct. 4-5, 1968.
6. Sheeler, J. B., "Summarization and Comparison of Engineering Properties of Loess in the United States", Highway Research Board Record No. 212, pp. 1-9, 1968.
7. Taylor, D. W., Fundamentals of Soil Mechanics, John Wiley and Sons, pp. 455- 479, 1948.
8. Bishop, A. W., and Morgenstern, "Stability Coefficients for Earth Slopes", Geotechnique, Vol. 10, No. 4; pp. 129-150, 1960.
9. Peck, R. B., Hansen, W. E. and Thornburn, T. H., Foundation Engineering, John Wiley and Sons, pp. 96, 1974.