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Geotechnical Evaluation of Loessial Soils in Kansas

S.S. BANDYOPADHYAY

Much of western, central, and northeastern Kansas is covered with loess deposits from Bignell, Peoria, and Loveland formations along with Sangamon soils above Loveland unit. In this paper their significant geological and engineering properties are defined, and design guidelines are presented. Montmorillonite is the chief cementing agent in Kansas loess. The Sangamon soil and the Loveland loess contain more clay than the Bignell loess and the Peoria loess and have higher in situ density and less permeability. The in situ density of Bignell loess and Peoria loess is less than 85 pcf, and consolidation tests and field experience indicate that they are highly susceptible to hydroconsolidation. A key factor in the collapse potential of Kansas loessial soils appears to be the mineralogy of the soils, specifically the presence of montmorillonite as the chief cementing agent; montmorillonite has the ability to adsorb more hydrogen cations than kaolinite and thus is able to adsorb more water. Total stress parameters must be used to design loess slopes approaching the vertical, and effective stress methods are particularly applicable in dealing with saturated loess and with seepage stresses where flattened slopes are required. Saturated loess may liquefy due to the cyclic nature of earthquake loading. Stabilization and compaction of loess represent not only an antisubsidence but also an antiliquefaction measure. Proper consideration should be given to zoning of areas of collapsible loessial soils.

Loess, a wind-deposited soil composed predominantly of silt-sized particles, is found in western, central, and northeastern Kansas. Loess is also found in approximately 17 percent of the United States, 17 percent of Europe, 15 percent of Russia and Siberia, and large areas of China as well as in New Zealand and the plains region of Argentina and Uruguay. Loess appears to be formed by wind-borne deposits traveling over glacial outwash with the higher humidity of the outwash causing precipitation of the soil particles. The geotechnical properties of loess deposits and their unique characteristics are of special practical importance to the geotechnical engineer, as well as to the agriculturist. Even though Terzaghi (1) described the properties of loess as "international" when comparing the data presented by Scheidig (2) and Holtz and Gibbs (3), Peck and Ireland (4) regarded loess "not as a soil of remarkably constant and uniform properties, but as one possessing local and regional variations almost as striking as those of some glacial materials."

Present foundation and earthwork design procedures, used in connection with this incompletely understood deposit, are still nearly all empirically based. The purpose of this paper is to define the significant geologic and engineering properties of Kansas loessial soils, to identify the potential geotechnical problems associated with them, and to present design guidelines related to these soils. Data from numerous open project files of the Kansas Department of Transportation have been used in developing this paper as well as material from a variety of published reports.

GEOLOGY

The major sources of loessial soils in Kansas are the Platte River valley of western Nebraska, the Missouri River valley, and the Republican River valley. The deposition of silts from these sources is generally attributed to eolian action. The stratigraphy of the major loess members and associated Pleistocene strata in Kansas is shown in Figure 1.

Bignell Member

Significant deposits of Bignell, the youngest of the major loess units, have been found in northwestern (thin and discontinuous) and northeastern (Missouri River valley bluffs in Doniphan County) Kansas. Bignell loess is so similar to Peoria loess that they can hardly be distinguished unless the Brady soil occurs stratigraphically below it (5). The Brady soil was formed during a short interglacial interval known as the Bradyan substage. The Brady profile is moderately to poorly drained and the depth of leaching ranges from 1 to 3 feet. Molluscan fauna fossils are sometimes contained within the Bignell loess.

Peoria Member

Typically yellow-tan in color, the Peoria loess occurs predominantly in Kansas and was deposited during the interval between the Iowan and Mankato glacial substages in Iowa. The deposition of the Peoria loess may have occurred during the relatively dry cycle following the melting of the ice sheet. The Peoria member ranges in texture from a very fine

Figure 1. Pleistocene stratigraphy in Kansas.

Time - Stratigraphy	Rock - Stratigraphy
RECENT STAGE	Low Terraces and Alluvium
WISCONSINAN STAGE	Bignell Loess
	Fluvial Deposits
	Brady Soils
	Peoria Loess
	Fluvial Deposits
SANGAMONIAN STAGE	Sangamon Soils
ILLINOISAN STAGE	Loveland Loess
	Fluvial Deposits
YARMOUTHIAN STAGE	Yarmouth Soils
KANSAN STAGE	Pearlette Ash Bed Fluvial and Eolian Deposits Till
AFTONIAN STAGE	Afton Soils
NEBRASKAN STAGE	Fluvial and Eolian Deposits Till

sand along the Republican River in northwestern and north central areas of Kansas to medium silt and silty clay in northeastern Kansas. It is at or near the surface in approximately one-third of the area of Kansas and can be as much as 90 ft thick in some areas (Cheyenne and Doniphan Counties). The Peoria member is usually fossiliferous and calcareous (5). The base of the Peoria loess frequently displays a leached zone above the Sangamon soil.

Loveland Member

Loveland loess is well exposed in northeastern Kansas (Doniphan and Brown Counties) and has been studied in auger borings and cuts in Atchison, Leavenworth, and Wyandotte Counties. The Loveland loess is also encountered in some localities in central Kansas, particularly in Rice and McPherson Counties. The Loveland loess is yellowish brown with a grayish tint. The soil developed on the Loveland loess has been termed the Sangamon soil (5), occurs from the Missouri River valley to the Colorado state line, and has been used successfully as a stratigraphic datum. When exposed, the Sangamon soil profile is usually quite evident because of its reddish brown color.

ENGINEERING PROPERTIES

Texture, Fabric, and Clay Mineralogy

Most of the Kansas loess can be classified as silty clay loam or silt loam according to the textural classification system followed by the Kansas Department of Transportation. Results of numerous grain-size analyses on loess samples from different counties clearly show that, in general, there is a decrease in the average clay content of the samples from east to west across the state. The Sangamon soil and Loveland loess each contains more clay than the Bignell loess and Peoria loess. A general decrease in clay content with depth in Peoria loess is also noticed throughout the state. There is, however, an increase with increasing depth within the Sangamon soil. Typical grain-size distributions of four loess samples obtained from four Kansas counties and their gradation range are shown in Figure 2; the samples are identified in Table 1. About 75 percent of Kansas loess can be classified as silty loess, 20 percent as clayey loess, and the rest as sandy loess. Almost all of the loess has some plas-

Figure 2. Typical grain-size distribution of Kansas loess.

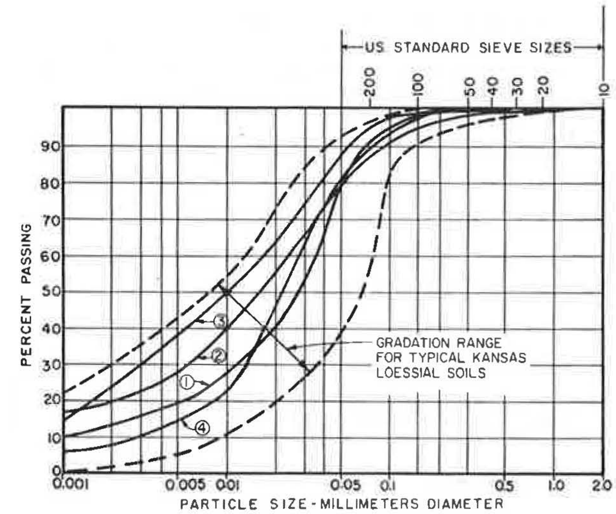


Table 1. Identification of four samples shown in Figure 2.

Sample No.	County	Member	Depth (ft)	Liquid Limit	Plasticity Index	Specific Gravity
1	Finney	Peoria	1.2	32	12	2.59
2	Wyandotte	Loveland	3.5	40	19	2.67
3	Phillips	Sangamon	4.6	47	17	2.65
4	Rawlins	Bignell	0.4	28	6	2.62

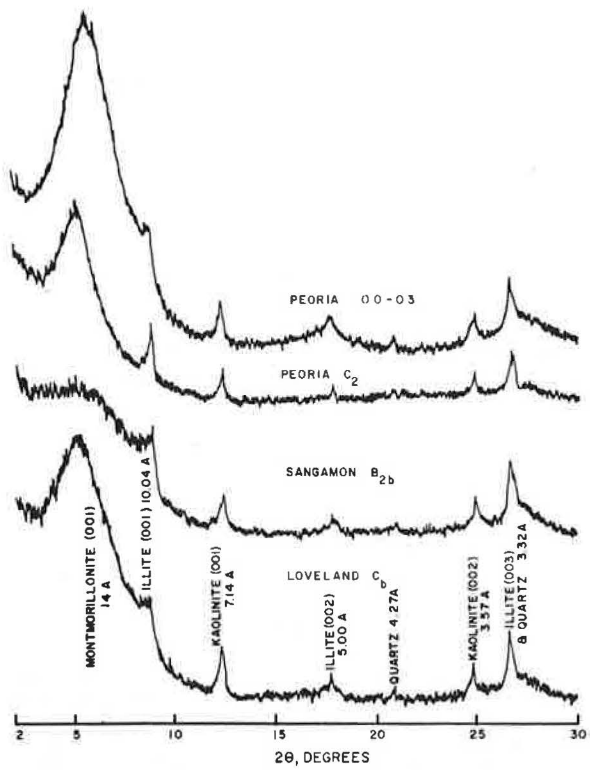
ticity when remolded. The amount of clay present has a significant influence on the engineering properties of the loess.

A study (6) of the elementary fabric of 224 loess samples obtained from nine counties of northeastern, north central, and northwestern Kansas revealed that the nonclay mineralogy of the sand and silt grains of all three loess units was similar. The units contained from 40 to 50 percent quartz grains, and feldspars made up about 40 percent of the nonclay mineralogy. Peoria loess had about 7 percent volcanic-ash shards. The mineral grains were partly coated with clay and sometimes carbonate and were held together by intergranular braces of clay. The Sangamon soil and Loveland loess contained more intergranular braces of clay than did the Peoria loess. The Sangamon soil also contained waxy coatings of dark-colored humic substances that must have been in the peptized state during Sangamon formation. Binocular microscope studies of 3-in. blocks of loess revealed an open, loose-textured fabric with many root holes, worm holes, and irregular openings in all three loess units.

The silt-size fraction of the loessial deposits in Kansas contains quartz, feldspars, volcanic-ash shards, carbonates, and micas, with quartz making up more than half the volume (7). The clay fraction consists of montmorillonite, illite, calcite, quartz, and feldspar, with a trace of kaolinite mineral. Montmorillonite or montmorillonite-illite interlayers are the most predominant clay constituents in Kansas loess. The presence of montmorillonite is attributed to the weathering of volcanic glass.

Figure 3 shows the X-ray diffraction patterns of the clay fraction of part of a series of samples from a failed section of road in Jewell County, Kansas (6). The major difference in the X-ray pat-

Figure 3. Typical X-ray diffractograms representative of clay fraction in Kansas loess (6).



terns of the various zones is shown by the intensity of the montmorillonite 001 reflection. The Sanagamon soil A_{1b} and B_{2b} horizons usually show a broad diffuse peak of low intensity attributed to interstratification of montmorillonite and illite. The intensity of the illite 001 and kaolinite 001 peaks does not vary significantly from one horizon to the next.

Physicochemical Characteristics

The results of chemical analyses are routinely reported by the Kansas Department of Transportation in connection with earthwork projects. A study of the test results involving loessial soils is summarized in Table 2.

Table 3 presents selected chemical characteristics of three horizons in three western Kansas loessial soils (8). The Colby soil is a light-colored well to excessively drained Regosol developed in Peorian loess. The Keith soils have a darker surface layer and a more clayey subsoil than

Table 2. Physicochemical characteristics of Kansas loessial soils.

Chemical Characteristics	Range
pH	7.1 to 8.7
Soluble salts	0.06 to 0.90 millimhos/cm
Available phosphorus	0.01 to 0.5 meq/100 gm
Exchangeable potassium	0.4 to 2.6 meq/100 gm
Exchangeable magnesium	1.1 to 10.5 meq/100 gm
Exchangeable calcium	11.6 to 22 meq/100 gm

the Colby soils. The Richfield soils are dark-colored, moderately fine-textured, chestnut soils. The moderate amounts of organic matter and its decrease with depth are characteristic of soils formed under grass in this climatic area. The high organic matter content of Colby A horizon, compared with that of the other soils, occurred because the Colby soil was in native grassland whereas the other soils were cultivated. All profiles were on the alkaline side of neutrality. The lower pH of the surface layers compared with the underlying horizons of the loessial soils is a normal relationship. Calcium and magnesium cations constitute from 75.9 to 91.7 percent of the exchangeable cations, a normal percentage for western Kansas soils.

Loess soils with high silt content and medium salinity are dispersible and therefore may cause piping in dams built of such soils. The main physicochemical factor governing the sensitivity of a dam to piping or tunneling is the dispersion-deflocculation characteristic associated with the hydraulic conductivity of the material. For piping to set in, the soil particles must disperse and go into suspension in the seepage water passing through the dam. Increased dispersion of a soil is associated with (a) increase in cation exchange capacity, (b) decrease in cation valency, (c) decrease in ionic concentration of the pore fluid, and (d) increase in water content. The effect of dispersion can be reduced by proper compaction, but loess soils with total cation exchange capacity greater than 15 meq/100 gm (9) should be avoided in small dam construction.

Plasticity, Density, Permeability, and Shear Strength

The plasticity index of unweathered Kansas loess units tends to be highest in the eastern counties (except for Doniphan County, where the texture of the loess was undoubtedly modified by wind-deposited sediments from the Missouri River basin) and lowest in the western counties. Plasticity data of loess samples obtained from various counties are plotted as a function of 5-micron clay content (c) in Figure 4. The nature of the curve is similar to that Sheeler (10) obtained for loess in the United States, except that the plasticity index values of Kansas loessial soils are relatively higher. The high values of the plasticity index can generally be

Figure 4. Plasticity index as a function of 5-micron clay content.

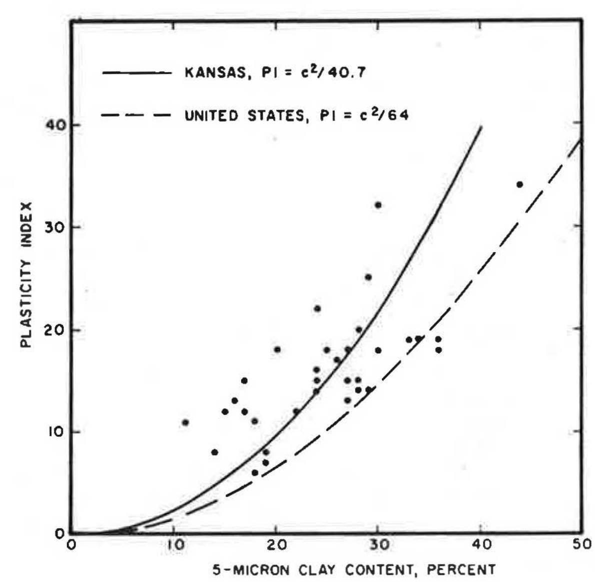


Table 3. Selected chemical characteristics of three horizons in three western Kansas loessial soils (8).

Depth (in.)	Horizon	Organic Matter (%)	pH	Exchangeable Cations (meq/100 gm soil) Na^+	K^+	Ca^{++}	Mg^{++}	Total	Cation Exchange Capacity (meq/100gm)	Base Saturation (%)	Exchangeable Sodium (%)	Ca/Mg
Colby Silt Loam												
0 to 5	A_1	2.3	7.5	.63	1.81	5.88	1.80	10.12	11.48	88.2	6.2	3.3
5 to 24	AC	0.9	7.7	.67	1.07	5.31	2.20	9.25	10.82	85.5	7.2	2.4
24 +	C	0.5	7.9	.67	1.02	5.91	2.10	9.70	10.53	92.1	6.9	2.8
Keith Silt Loam												
0 to 11	$A_p + A_1$	2.2	7.2	.39	2.56	9.11	2.31	14.37	17.10	84.0	2.7	3.9
18 to 24	B_{21}	1.4	7.3	.37	1.66	10.52	3.42	15.97	18.54	86.1	2.3	3.1
28 to 40	B_{ca}	0.7	7.7	.41	1.17	10.61	3.06	15.25	16.86	90.4	2.7	3.5
Richfield Silt Loam												
0 to 5	A_p	1.4	7.1	.37	1.43	9.12	2.61	13.53	15.64	86.5	2.7	3.5
5 to 18	$B_{21} + B_{22}$	1.2	7.3	.32	1.66	9.71	2.84	14.53	16.96	85.7	2.2	3.4
27 to 38	C_{ca}	0.8	7.8	.47	0.82	10.45	2.30	14.04	15.70	89.4	3.3	4.5

associated with the relatively high percentage of montmorillonite present in the Kansas loess.

The specific gravity of loess in Kansas ranges from 2.55 to 2.67. Typical in-place density in the top 10 ft ranges from 75 to 90 pcf for Bignell loess and is always less than 85 pcf for Peoria loess. Sangamon soil and Loveland loess, because of their dense fabric, generally have higher densities than do Bignell and Peoria loess. The density of loess is a significant parameter with respect to the usefulness of loess as a foundation material. The moisture content of undisturbed loess is usually about 10 percent.

The Peoria loess shows good internal drainage and its vertical permeability is greater than its horizontal permeability (11, p. 1909). The high vertical permeability of Peoria loess, typically on the order of 9×10^2 ft/yr (9×10^{-4} cm/sec), is partly due to the existence of vertical tubules and shrinkage joints within the soil mass. Some of the root and worm holes within the loess are lined with a few thin layers of barrel-shaped calcite crystals found in a parallel arrangement forming crystal tubes in dendritic patterns. Sangamon soil and Loveland loess, because of their higher field densities and smaller pore space, have lower permeability than does Peoria loess. Remolded loess shows considerably lower permeability than in situ loess, and the vertical coefficient of permeability of remolded Peoria loess generally ranges from 1.3 ft/yr (1.3×10^{-6} cm/sec) to 8.6×10^{-2} ft/yr (8.6×10^{-8} cm/sec). The low permeability values are believed to occur because of densification and destruction of the tubules and joints. The permeability of in situ and remolded soil is of importance in the design of landfills, waste ponds, and hazardous waste impoundments. To avoid piping in loess dams, the upper limiting value of permeability for collapsible soils should be set at 10 ft/yr (10^{-5} cm/sec) (12).

Clay content as well as moisture and density at the time of testing control the shearing strength of loess. A study of numerous Kansas Department of Transportation open file reports revealed that in undrained triaxial tests, the angle of internal friction for Kansas loess fell between 11 and 29 degrees for samples tested with moisture contents below saturation, while the cohesion value ranged from 600 to 2,000 psf. Samples that were tested at low density and near saturated moisture conditions gave internal friction angles of zero or near zero at low normal stress. High values of cohesion resulted from high density, low moisture content, and high clay content. Plate-bearing tests reported by Holtz and Gibbs (3) and Clevenger (13) indicate that the bearing capacity of dry loess may exceed 5 tsf and may drop to 0.25 tsf when loess is wetted. The variance of density and moisture content, even within limited areas, necessitates investigations at each important site.

DESIGN CONSIDERATIONS

Foundation Design

Loessial soil found in many parts of the United States is typically considered unstable as a foundation material because of its potential for large settlements due to inundation or rise in groundwater levels (3,13-17). Terms like "collapse," "hydroconsolidation," or "hydrocompaction" have been used to describe this phenomenon that differs from classical consolidation because no water is being forced out, and, in fact, soil may be adsorbing additional water and progressively losing strength. Because not all loessial soils are susceptible to hydroconsolidation (18-20), identification of collapsible loess is of utmost importance to geotechnical engineers when structural safety and foundation economy are concerns.

The literature (3,13,17,21,22) suggests that soils susceptible to hydroconsolidation can be identified by a density criteria--that is, if density is sufficiently low to give a space larger than needed to hold the liquid-limit water content, collapse problems on saturation are likely. In general, if the density is greater than 90 pcf, the settlement will be rather small. As noted earlier, the in situ density of Kansas loess, especially Bignell and Peoria loess, in the top 10 ft is generally less than 85 pcf, which indicates potential hydroconsolidation problems. The Bureau of Reclamation (22) proposed the use of the natural dry density and liquid limit as criteria for predicting collapse as shown in Figure 5. Soil densities that plot above the line shown in Figure 5 are in a loose condition and, when fully saturated, will have a moisture content greater than the liquid limit. Another criterion proposed by the Bureau of Reclamation is based on an empirical relationship between D, dry density in place, divided by Proctor maximum dry density, and w_o-w, optimum moisture content minus in-place water content (see Figure 6). Use of clay activity to identify potentially collapsible soils has also been suggested (18,23).

Some investigators have questioned the use of density for identification. Use of a consolidation

Figure 5. Criteria for evaluating looseness and probability of collapse (22).

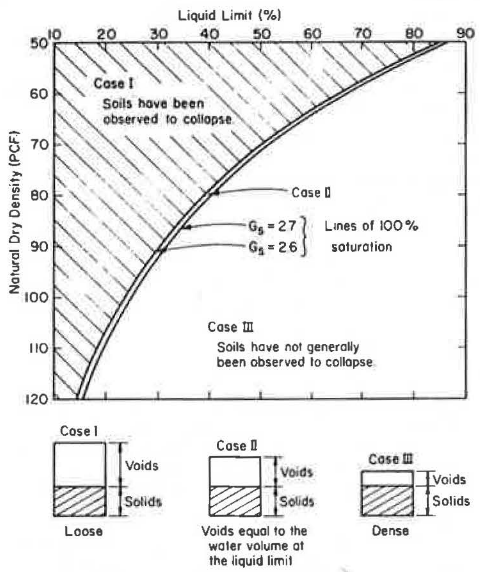
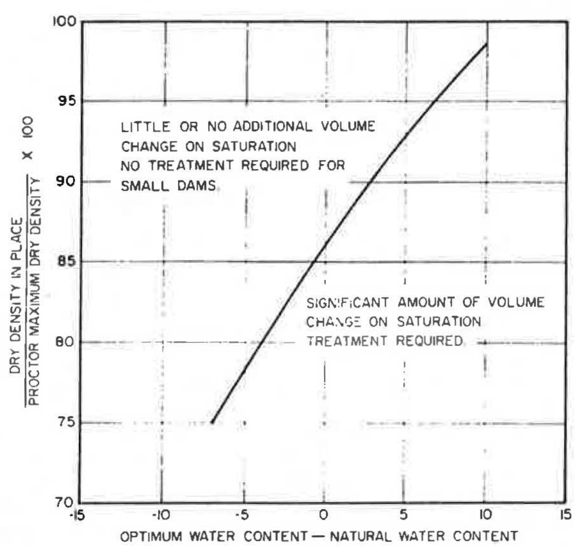
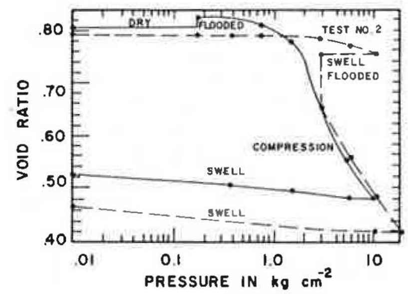


Figure 6. Criteria for treatment of relatively dry loessial soils (22).



test to predict the collapse potential is generally favored (13,15,18,19,24,25). The consolidation test will give not only a qualitative determination of the possibilities of collapse but also quantitative information to permit estimates to be made of the magnitude of the collapse. Results of such a test on a loess sample obtained from Grant County, Kansas (26, pp. 233-235), are shown in Figure 7. The loess was obtained in relatively dry condition from a test pit. Consolidation tests were performed on two, as nearly identical as possible, specimens of the sample. The first test was loaded to about overburden pressure and flooded; increments of loads were then added at 48-hr intervals. In the second test, the dry specimen was loaded, unloaded, then flooded, reloaded, and unloaded again. From the results, it can be concluded that dry loess will support fairly heavy loads with only small settlements and that saturation may produce sudden large settlements. Results of similar tests and field experience indicate that Kansas loessial soils, especially the Bignell and Peoria members, are susceptible to hydroconsolidation.

Figure 7. Void ratio-pressure curve for Grant County loess (22).



Many failures in flexible surfacing in Kansas have been attributed to moisture buildup in the loessial subgrade (27-30), especially if the surfaced grade fell within 3.5 ft of the top of the Sangamon soil. It has been found repeatedly that there is an increase in moisture content of the Peoria loess just above the Sangamon soil; this results in weakening of the subgrade. The moisture buildup just above the Sangamon soil is due to the good internal drainage and vertical permeability of Peoria loess and the high field density, smaller pore space, and more clay braces in Sangamon soil. As a result, in Kansas, Sangamon soils are generally subgraded if they are located within a few feet of the finished grade on new construction projects.

The high susceptibility of Kansas loess, especially Bignell and Peoria loess, to hydroconsolidation [in contrast with that of Palouse loess in southeastern Washington, for example, (19,20)] may be partly due to the mineralogy of the clay. The chief cementing agent in most Kansas loess deposits is montmorillonite, whereas the chief cementing agent of Palouse loess is illite, with only a trace of montmorillonite (19). Different clay minerals vary in their ability to adsorb hydrogen cations and thus in their ability to adsorb water. The number of hydrogen cations per 100 mg adsorbed by montmorillonite ranges from 360 x 10^{20} to 50 x 10^{20}, whereas the number for illite ranges from 120 x 10^{20} to 240 x 10^{20}. Therefore, montmorillonite adsorbs 1.5 to 4 times more hydrogen cations (water) than does illite. Because Kansas loess units are cemented by montmorillonite not illite, softening can be expected when the moisture content is increased. If the effective stress is sufficient, the weakened clay will fail in shear at points of contact between grains. Destruction of the intergranular supports allows the grains to move into void spaces yielding a net decrease in volume and permanent settlement.

Foundation design in loessial soils depends to a large extent on the proper identification of collapse potential and on the amount of collapse that may occur. In many cases, deep foundations (e.g., piles or caissons) may be required to transmit foundation loads to suitable bearing strata below the collapsible soil deposit. However, if the loess deposit is not susceptible to hydroconsolidation, spread footings can be successfully used (19) and are economically preferable to deep foundations. In cases where it is feasible to support the structure on shallow foundations on or above loessial soils, continuous strip footings may provide a more economical and safer foundation than isolated footings (15). Differential settlement between columns can be minimized, and a more equal distribution of stresses may be achieved with the use of strip footings. Foundation systems comprised of reaction beams formed by footing beams and load-balancing beams in the longitudinal direction have also been suggested (31) for collapsible soil. The load-balancing beams are reinforced to make the system sufficiently stiff. The performance of continuous footings, as well as other shallow foundation schemes, may be improved [i.e., the vertical displacements may be reduced, and more load-carrying capacity may be gained by the use of compensated footings (31)]. If the footing area becomes greater than 50 percent of the entire area of the building, a mat foundation should be considered for the entire foundation.

The results from laboratory or field tests can be used to predict the amount of settlement to be expected. Sometimes the cost associated with obtaining relatively undisturbed specimens, transporting the specimens in a manner that will not result in additional disturbance, preparing the specimens when they reach the laboratory, and performing elaborate time-consuming tests may prove too high; in these cases in situ testing may be used. Density-in-place measurements for loessial soils by means of standard penetration tests are not sufficiently reliable (13,32). In situ testing with plate-bearing equipment is more reliable. The test can be conducted by placing the plate apparatus at the footing bearing level and jacking against a heavy construction vehicle such as a dozer or backhoe (19). The test area is then inundated and the water level maintained for a time commensurate with the adverse hydraulic conditions being designed for. Field testing is, of course, not without its limitations and is not practical where field saturation occurs from rises in the groundwater table.

In the natural state, loess is protected against excessive wetting by a blanket of topsoil and vegetation. Stripping these materials leaves the porous loess vulnerable to rapid wetting by rainfall. Water from construction operations and from leaking pipes and improper site drainage is another cause of excessive wetting and loss of structure in loess (33). Attention to grading and drainage can do much to prevent settlement or failure of loess soils. Clevenger (13) reported the case of a grain elevator in Kansas that tilted very badly on the north side because of ponding of water on that side after heavy rains. The tilting was partly corrected by wetting beneath the southern part of the foundation. Peck and Ireland (4), however, have disputed this claim. Preconsolidation of loess foundations by ponding has been successfully applied for hydraulic structures such as dams (13) and canals (13,17,34) where the material will eventually become wetted.

Stability Analysis

The loess of Kansas occurs in flat to undulating areas in the south central portion of the state, whereas in the northeastern part the area is dissected and rough. The vegetation-covered, windblown, silt hills give the landscape a characteristic hummocky but soft appearance. Where there is severe erosion nearly vertical slopes prevail. Highway engineers have long been familiar with this peculiarity and have constructed cuts through these silt hills with vertical slopes.

> Loess slope stability may be analyzed using total or effective stress parameters. The selection is dependent 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 [are used in Kansas] 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 (35, p. 65).
>
> Slope design in "silty loess" may require either vertical or flattened slopes depending upon the moisture content existing and anticipated (35). [In Kansas,] vertical slopes are often feasible at moisture contents below the critical moisture range and are analyzed using total stress parameters. 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 total or effective stress analysis. Slope selection under these conditions is not critical and, for low moderate heights, will rarely require analysis. 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 (35, p. 66).
>
> Regardless of moisture content, vertical slopes are not practical in clayey loess and flattened slopes are used. Procedures discussed above (except vertical slopes) are also applicable depending upon the need to consider seepage forces (35, p. 66).

Seismic Response and Current Treatment Methods

A saturated loess may collapse under its own weight or when additionally loaded, and subsidence caused by earthquakes may be expected. Soil liquefaction is also probable due to the cyclic nature of earthquake loading. Although no report is available on the seismic response of Kansas loess, subsidence and liquefaction of loess due to earthquake loading have been reported elsewhere (36). From a detailed study of buildings and other structures after the March 4, 1977, earthquake (magnitude 7.4) in Romania, Minkov and Evstatiev (36) concluded that other conditions being equal (equal depth of the rock bed, equal thickness of the loess cover), buildings and installations built on stabilized or compacted loess bases suffered practically no damage during the earthquake. Their seismic performance is evaluated at degree VI according to the modified Mercalli intensity scale. Buildings and installations built on natural loess were affected at degrees VII and VIII. It is important to emphasize that in all buildings examined, no antiliquefaction measures had been taken. It has been reported (37) that the seismic intensity decreases by 1 to 2 degrees and the elastic modulus increases 5 to 7 times when the base density is increased by 20 to 30 percent. Stabilization and compaction of loess, therefore, represent not only an antisubsidence but also an antiliquefaction measure.

The type and amount of treatment depends on the depth of collapsible soil and the support requirements for the proposed facility. A great variety of treatment methods have been used in the past. Table 4 presents a summary by Bara (38) of various treatment methods. Further technological advances are necessary before heat treatment, ultrasonics, or chemical additives (other than lime or cement) are feasible.

The Soviets have conducted extensive studies of

Table 4. Methods of treating collapsible foundation soils (38).

Depth of Subsoil Treatment Desired (ft)	Treatment Method	
	Past and Current	Possible Future
0 to 5	Moistening and compacting (conventional extra-heavy, impact, or vibratory rollers)	Heat treatment to solidify soils in place Ultrasonics to produce vibrations to destroy bonding mechanism of metastable soil Chemical additives to strengthen bonding mechanism of metastable soil structure (possible electrochemical methods of application) Use of groutlike additives to fill pore spaces before solidification
5 to 30	Overexcavation and recompaction (earth pads with or without stabilization by additives such as lime or cement) Vibrofloation (free-draining soils) Rock columns (vibroreplacement) Displacement piles Injection of silt or lime Ponding or flooding (if no impervious layers exist)	
30+	Any of the above or combinations thereof Ponding and infiltration wells Ponding and infiltration wells with use of explosives	

chemical stabilization techniques (39,40). The methods currently employed are (a) gaseous silicatization of sandy and loessial soils, (b) strengthening of carbonate cements by polymers, and (c) chemical strengthening of alluvial soils by clay-silicate solutions. The gaseous silicatization treatment involves a mixture of soil, carbon dioxide, and a sodium silicate solution. Recent investigations by Sokolovich (40) have shown that stabilization of loessial soils by treatment with ammonia is possible. In this method, gaseous ammonia is injected via boreholes into loessial soil prone to slump-type settlements (15). The ammonia is absorbed by water films of the loessial soil and reacts with its absorbing complex. As the result of an exchange reaction with the absorbed calcium, highly dispersed calcium hydroxide is formed. Reaction of the precipitated calcium hydroxide with the silica and colloidal silicic acid of the soil leads to formation of a calcareous-siliceous binder that stabilizes the soil (15).

Zoning Considerations

Because significant differences occur in the loessial soils of different regions, a preliminary zoning of the areas of collapsible loessial soils will be beneficial to highway agencies, geotechnical engineers, geologists, and technical agencies. Factors that should be considered for zoning of loessial soils include thickness of collapsible soils; sensitivity to wetting of soils, particularly their susceptibility to self-subsidence on wetting; degree or category of collapsibility; and local experience in highway and building construction. Such zoning, if developed, will help in regional planning, site selection, and development of construction measures compatible with local soil conditions. China, where loess and loesslike soils are widely distributed in the north and the northwest and cover 6.6 percent of the country's land surface, has developed a zoning map (41-43).

SUMMARY

The widely distributed loessial soils of Kansas inevitably bear the imprints of local geographical and geological conditions. The major loess members associated with the Pleistocene age are Bignell, Peoria, and Loveland along with Sangamon soil above the Loveland unit. A trend of gradual, steady reduction in the average clay content is found from east to west across the state. The Sangamon soil and Loveland loess each contain more clay than do Bignell loess and Peoria loess. Montmorillonite is the most predominant clay constituent in Kansas loess. Calcium and magnesium cations constitute 75 to 92 percent of the exchangeable cations. Plasticity index values of Kansas loess are relatively high compared with those for the rest of the United States, and vertical permeability is greater than horizontal permeability. Kansas loess, especially the Bignell and Peoria formations, is highly susceptible to hydroconsolidation. Low in situ density and presence of montmorillonite as the chief cementing agent are two key factors responsible for the collapse potential of Kansas loess. The results from appropriate laboratory or field tests can be used to predict the amount of settlement that can be expected. Where severe erosion is present, nearly vertical slopes prevail in Kansas silty loess. Total stress parameters are used to design loess slopes approaching the vertical, and effective stress methods are particularly applicable in dealing with saturated loess and with seepage stresses where flattened slopes are required. Stabilization and compaction of loess represent not only an antisubsidence but also an antiliquefaction measure. Consideration should be given to proper zoning of areas of collapsible loessial soils.

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