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PETROGRAPHIC AND ENGINEERING PROPERTIES OF LOESS

by H. J. Gibbs and W. Y. Holland

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Engineering Monograph

No. 28

PETROGRAPHIC AND ENGINEERING PROPERTIES OF LOESS

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INTRODUCTION

This monograph summarizes knowledge of the physical and physical-chemical properties of loess gained from Bureau of Reclamation experiments, investigations, and observations. Because of the unstable properties of loess which may cause settlement of foundations of structures, such knowledge of the limitations of loess for engineering purposes is important not only to the geologist and soil mechanics engineer but also to design and construction engineers who are required to build structures on loessial soils.

The Bureau of Reclamation has particular interest in the engineering properties of loess because of its requirements for large hydraulic structures in loessial regions of the western United States. To design and construct such structures as dams and canals in these areas, the Bureau required information on the characteristic properties of loess, particularly those properties which would be affected by moisture changes resulting from the operation of hydraulic structures. This monograph discusses the origin of loess and presents detailed descriptions of the pertinent characteristics of loessial soils including matrix, cementation properties, and particle shape. It discusses physical properties including permeability, compaction, consolidation and shear resistance characteristics, and summarizes the results of loading tests of footings and piles. A criterion for determining the critical nature of loess in respect to the probability of settlement is given on the basis of observations and tests in the Nebraska-Kansas area.

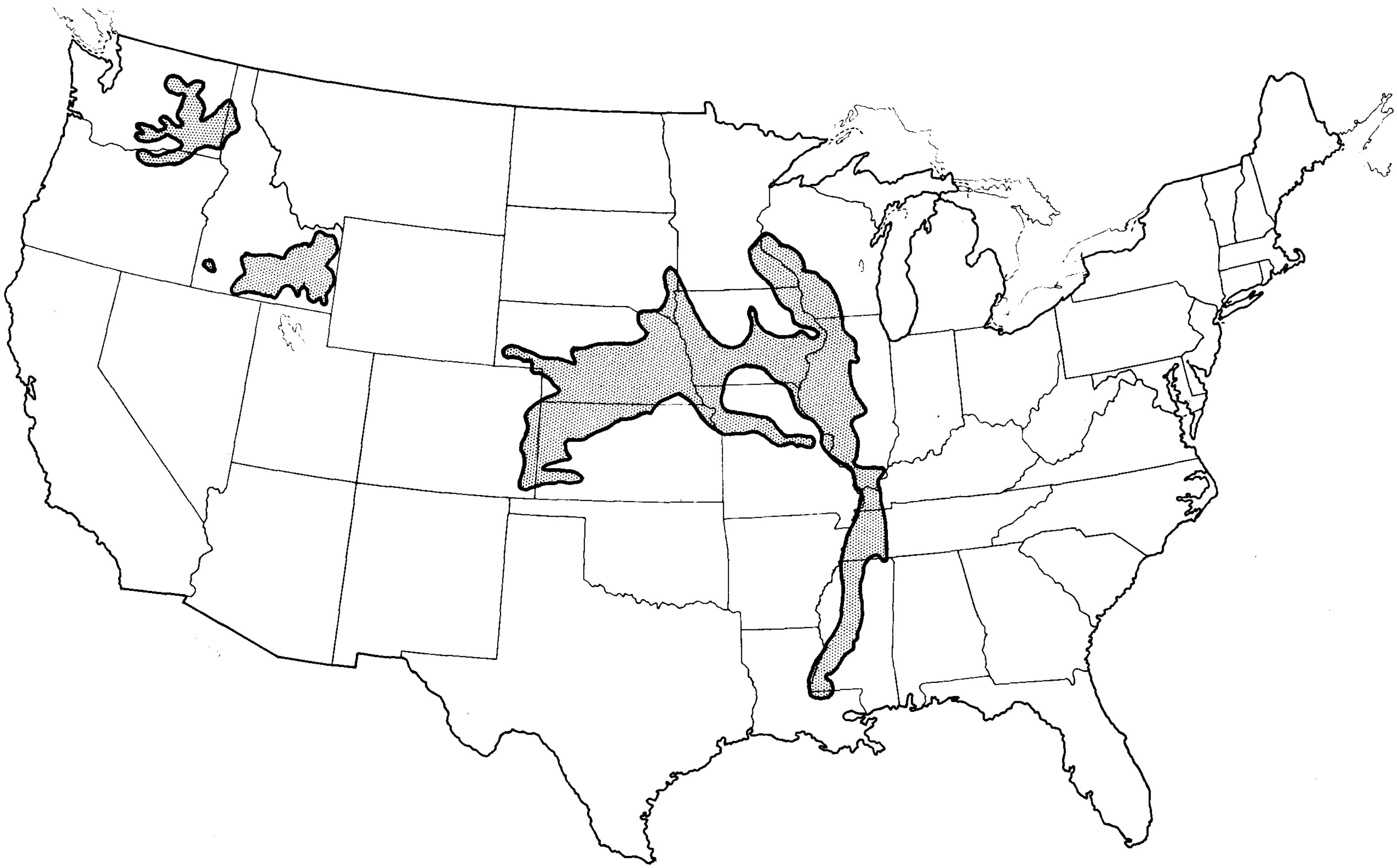
GENERAL DESCRIPTION OF LOESS

Loess is an earth material which covers vast areas of the central part of several continents of the world. The major loessial deposits in the United States are shown on the map in Figure 1. The most extensive loessial area is in Nebraska, Kansas, Iowa, Wisconsin, Illinois, Tennessee, and Mississippi. Other loessial deposits occur in southern Idaho and Washington. The deposits of major concern to the Bureau of Reclamation are in Nebraska, Kansas, Idaho, and Washington.

Because the particle structure of natural loess is often very loose and contains appreciable voids, problems related to large consolidation under certain moisture and load combinations, poor stability, seepage, and erosion frequently arise. On the other hand, loessial soils which have been reworked by water action are usually in a more dense state and exhibit better engineering properties. Likewise, loessial soils, which are remolded and compacted as construction materials, also exhibit better engineering properties. Naturally dry loess exhibits considerable stability permitting it to stand on steep cut slopes, as shown in Figure 2a, provided the natural moisture contents are not increased. Natural drainage troughs where higher moisture contents accumulate display slumping and subsidence, as shown in Figure 2b, which illustrates a critical condition that can occur in hydraulic structures that eventually saturate portions of their foundations. Wetted loessial soils are also weakly resistant to moisture movements as displayed by the erosion patterns of natural drainage streams, as shown in Figure 2c.

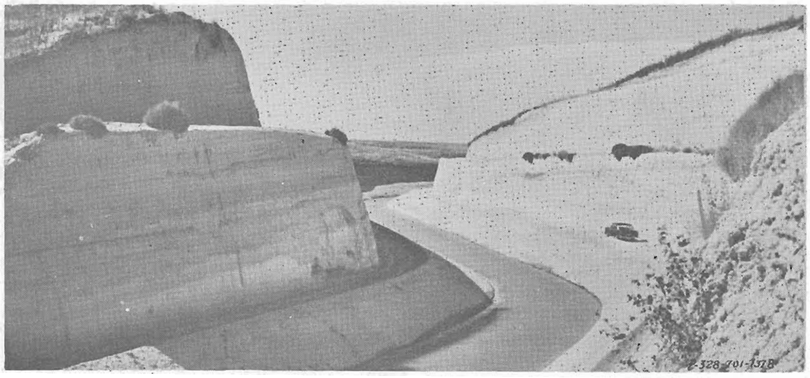
Our studies lead us to support the theory that the finely divided rock-powder silt of which loess is primarily composed was produced by interaction of several geological processes, but mainly by abrasion resulting from movements of continental glaciers. With retreat of the continental glaciers, the silt was deposited along flood plains of rivers. This silt was then transported, sorted, and redeposited by wind action. Loess is composed primarily of fine, angular grains of silt, fine sand, and calcite admixed with relatively small amounts of clay and clay coatings on the larger grains. Some organic matter occurs in the form of roots and root hairs. The particle arrangement in the soil mass resulting from the wind-blown method of deposition is frequently very loose. Therefore, loess is susceptible to high degrees of consolidation. However, the dry loess which exists in the arid regions of the midwestern states has high strength owing to the binding characteristics of the clay and is often capable of supporting relatively large loads without excessive settlement. It is easily collapsed by heavy loading and wetting, and the bond between particles can be reduced to practically no strength by wetting.

Loessial soils have been analyzed in



OUTLINE OF MAJOR LOESS DEPOSITS IN THE UNITED STATES

FIGURE I

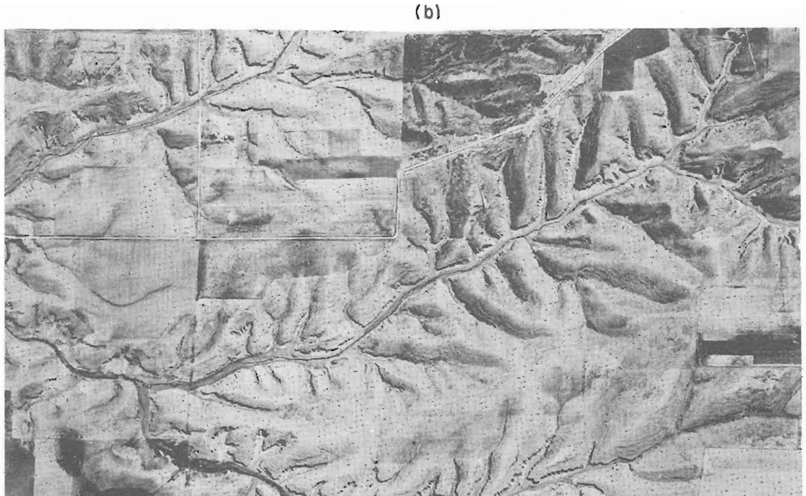


STEEP SLOPES CONSTRUCTED IN NATURALLY DRY LOESS SHOWING CONSIDERABLE STABILITY

(a)

A NATURAL DRAINAGE CHANNEL WHERE HIGH MOISTURE CONTENTS ACCUMULATE, CAUSING SLUMPING AND SUBSIDENCE

(b)



TYPICAL EROSION PATTERN OF NATURAL DRAINAGE STREAMS IN LOESS

(c)

PHOTOGRAPHS OF TYPICAL CHARACTERISTICS OF LOESS DEPOSITS

FIGURE 2

considerable detail by the Earth and Petrographic Laboratories of the Bureau of Reclamation. The initial summary of consolidation and related properties of loess observed by the Bureau of Reclamation* was reported by Holtz and Gibbs in a 1951 paper 1/.

The undisturbed structure and the mineralogical characteristics of loessial soils have been observed. The internal structure of loess is shown in Figure 3. Figure 3a is a photomicrograph of undisturbed loess soil taken with a magnification of 12X. This photograph shows the loose arrangement of silt particles with typical numerous voids and rootlike channels. The structure is typical of natural wind-blown deposits of loess which have not been reworked. Figure 3b is a photomicrograph of a thin section which was cut from a similar undisturbed sample of loess. This photomicrograph has a magnification of 30X, and shows the relative size of the void spaces. The preparation of this thin section and other sections was accomplished by impregnating a carefully cut specimen with a thermoplastic resin which acted as a binder during the grinding process.

*Numbers in superscript refer to publications in the List of References.

The majority of the silt grains in loess are coated with very thin films of clay. This clay is generally montmorillonite and forms intergranular supports or braces within the structure. Calcite usually occurs in distinct silt-sized grains throughout the loess in a finely dispersed state rather than as a cementing material. The thin clay coatings and, to a lesser extent, the calcite, apparently bond the particles together. Upon wetting, this bond is easily loosened causing great loss in strength.

ORIGIN OF LOESS

Certain conditions must be present for the development of loessial deposits. These conditions are:

(1) A source of intermixed silt and clay adequate enough to account for the known deposits

(2) A period of strong winds prevailing from one direction

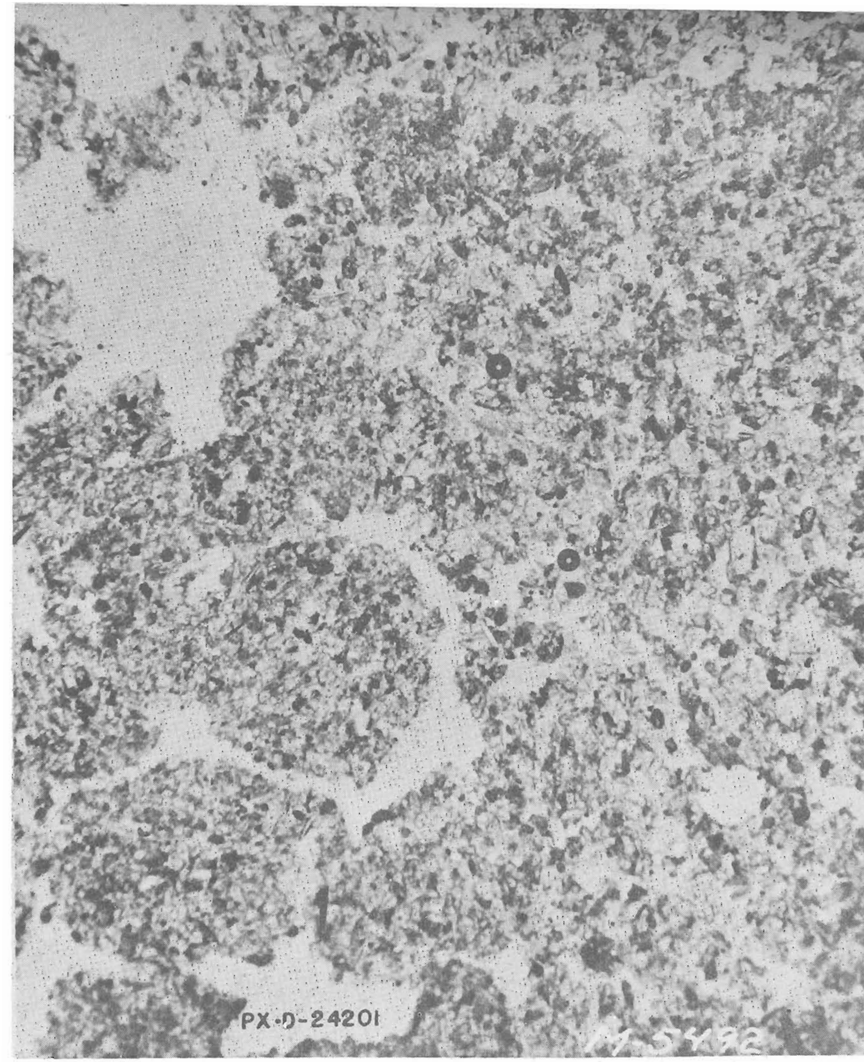
(3) A place of deposition

(4) Arid to semi-arid conditions at least following the issuance of silt from the glaciers and at all times following deposition

The origin of loess has been a subject of much debate for many years. It is now generally agreed that loess was wind transported and deposited, and that the sediments were of glacio-fluvial origin. The finely divided rock powder of which loess is composed was produced by the interaction of several geological processes, but mainly by abrasion resulting from movement of continental or large mountain glaciers. With the retreat of the glaciers, the suspended load of the glaciers was deposited in outwash plains and subjected to erosion both by wind and by water. The material carried off by the streams was later deposited as silt along the flood plains of rivers and then redeposited by wind action. As noted by Hobbs 2/, anticyclonic winds blowing from the retreating glaciers could have acted upon the melt-water silt issuing from glaciers after the silt had dried upon outwash plains, and redeposited this silt in regions bordering the glaciers. Other sources probably contributed to the formation of loess but their contribution was small.

In the Missouri River Basin and Upper Mississippi River Valley the source of the wind-blown silts is generally agreed upon to be of glacio-fluvial origin. At various interglacial periods and at the close of the Pleistocene ice epochs, large areas along the flood plains were left devoid of plant cover and exposed to strong winds. The flood plains of these rivers were composed mainly of sand, silt, and clay derived from the abrading action of the glaciers. The silt and clay particles with intermixed fine sand were sorted from the coarser sand, transported, resorted, and redeposited by wind, the coarser sized particles being deposited close to the source and the finer particles deposited at greater distances from the source. Smith 3/ in his investigation of the Illinois loess, and Swineford and Frye 4/ in their investigation of Kansas loess showed that the grain size of loess decreases logarithmically away from the source. Swineford and Frye traced the source of most of the Kansas loess by particle size distribution to the Republican and Platte Rivers. These rivers carried much silt which had been derived by the abrading action of glaciers in the Rocky Mountain region.

(A) PHOTOMICROGRAPH SHOWING THE TYPICAL LOOSE OPEN STRUCTURE OF SILTY LOESS SOILS. THE MICROBOTRYOIDAL TYPE OF STRUCTURE WHICH OCCURS FREQUENTLY THROUGHOUT THE LOESS IS ALSO SHOWN IN THE LOWER CENTRAL PORTION OF THE PICTURE. MAGNIFICATION 12X



(B) PHOTOMICROGRAPH OF A THIN SECTION OF LOESS TAKEN TO SHOW THE MICROSTRUCTURE OF AN AREA SIMILAR TO THAT SHOWN IN FIGURE 4. NOTE THE EXTREME POROSITY (LIGHT AREAS) OCCURRING IN SUCH AREAS. MAGNIFICATION 30X

PHOTOMICROGRAPHS OF LOESS STRUCTURE
FIGURE 3

Vegetation, as pointed out in some theories, may have contributed to holding the soil together after its deposition. Fine clayey silt materials, however, are not generally disturbed by wind and are picked up only if there is intermixed silt or sand. Loess then could have been deposited without the sustaining benefit cover of grasses, and the advent of grasses after the deposition of the wind-blown silt would provide an excellent growing material for larger plants. The development of approximately vertical root systems might give the loess its vertical cleavage and would contribute in forming in loess its vertical porosity and permeability.

Wind-blown, intermixed silt and clay that eventually became loess must have been deposited directly to the ground surface from aerial transportation. Silts transported by wind, but deposited under subaqueous conditions do not have the typical loessial fabric. Adequate sources for loess may exist, but if no suitable terrestrial areas for deposition exist, no deposits of loess will form. For example, the Sahara Desert probably was and continues to be a source of intermixed silt and some clay but the wind-blown material is deposited either in the Atlantic Ocean, or as in the Arabian Desert, the wind-blown material is deposited into the Red Sea or the Persian Gulf.

Intermixed silt and clay may be picked up by the wind from its source only when dry climatic conditions exist following their deposition from either a fluvial or glaciofluvial environment. Winds are unable to pick up intermixed wet silt and clay. Climatic conditions, favorable to deposition, therefore, do not necessarily have to be arid or semi-arid but may be Arctic. Deposits of loess have been noted in the Matanuska Valley, Alaska 5/, and Greenland 6/. Photographs of silt rising from the dry flood plains of the Tanana River, Alaska, illustrate that the material must be dry before it can be transported. After deposition and the development of a cohesive fabric, the climatic conditions must remain arid or semi-arid for loess to retain its open fabric.

DETAILED DESCRIPTION OF LOESS

Loess is a quartzose, somewhat feldspathic clastic sediment composed of a uniformly sorted mixture of silt, fine sand, and clay particles arranged in an open, cohesive fabric frequently resulting in a natural dry density of 70-90 pounds per cubic foot. Deposits may reach considerable thickness.

Materials which are not cohesive and which are composed predominately of either granular silt, and fine sand particles, or clayey silt and fine sand size aggregations, are not considered as loess. Dust deposits which may be composed of particles finer than or equal to predominant grain sizes found in loess are not considered as loess. The dust deposits may be potentially capable of forming loess, but until the coarse wind-blown material develops cohesion, the term loess cannot be applied. Similarly, clayey silt and fine sand size aggregations may acquire cohesive properties and an open fabric similar to loess, but these materials cannot be classified as loess if the wind-blown clay consolidates and the mineralogical composition is different from loess. Deposits which consist of cohesionless silts, fine sands, or clayey silt and fine sand size aggregations transported and deposited by wind should be referred to as aeolian or wind-deposited silts or fine sands or clays.

Many materials transported by either water or glaciers alone or a combination thereof yield silts which resemble loess in grain size, distribution, and mineralogical composition. In the majority of water-laid sediments, however, the constituent grains are fairly closely packed after the deposit has been subjected to several cycles of alternate wetting and drying and burial. It is possible that freshly deposited water-laid silts may develop an open fabric similar to loess and may be cohesive to some extent. However, with subsequent wetting and the deposition of another layer of silt the open fabric is lost and consequently the unit weight or density of the water-laid silt increases over the freshly deposited silt.

Since wind-blown silt, which is deposited under subaqueous conditions, is not considered as loess and will have a different fabric from the wind-deposited silt, it is not impossible to have wind-blown silts deposited under lacustrine or playa conditions to be mixed with or graded into loess. Small lakes most likely existed after Pleistocene glaciation and gradually became filled with wind-blown silt, fluvial silts, or sands and could have been covered over with loess.

Silts transported and deposited by wind vary considerably in their dynamic physical properties depending upon whether the silt was deposited under arid, semi-arid, or humid conditions. The wind-blown silts deposited directly to the ground surface under arid and semi-arid conditions develop an open cohesive fabric and retain this fabric as long as the climatic conditions do not change. Local variations in the density or closeness of packing in the massive loess probably occur, as local heavy rains would collapse some of the open fabric. Loess deposited under semi-arid conditions would probably develop a protective rather than impervious surface layer, as the effect of rainfall over a long period of time would tend to be distributed over a large area rather than being localized as in an arid region.

Wind-blown silt deposited under humid conditions or under arid conditions and later subjected to humid conditions develops a close packed fabric by a collapse of intergranular supports or a gradual bringing together of the granular components by wetting and drying. The densities of these wind-blown silts are frequently more than 100 pounds per cubic foot. Samples of material obtained from Natchez and Vicksburg, Mississippi, have densities ranging from 102 to 112 pounds per cubic foot.

The upper few feet of loess frequently show a collapsed or a denser fabric than the underlying loess. This collapse in fabric may be produced by a variety of factors such as the activities of man, a progressive change to a more humid climate with increased weathering, or by sheet erosion. The upper few feet of loess form top-soil. The primary or open fabric of the top-soil is destroyed by man during plowing and farming operations and possibly irrigation. These operations tend to disperse the clay fraction more evenly throughout the granular components and produce a soil in which the granular components tend to be in contact. If loess is subjected to humid climatic conditions, it gradually consolidates and the whole deposit attains a dense fabric. However, the upper few feet in this case are subjected to weathering and sheet erosion, and the components begin to alter. Also the clayey components are more evenly distributed throughout the granular components.

The upper few feet of loess or the whole massive loess deposit may be affected by slope wash. If loess is deposited on a slope, gravitational forces act upon the body and the mass slowly moves down the slope. In this process the open fabric is destroyed and a closely packed fabric results. Gravitational forces become more active when there is an increase in moisture content of the loess body and the moisture content may become so large that soil flow results.

From an engineering standpoint, loess is a potentially unstable clastic sediment. Loess is in equilibrium with its environment, but as the moisture conditions change or the overburden load becomes too great, loess tends to consolidate and assume a more stable arrangement of its grains. Consolidated loess assumes properties similar to those of any other water-laid silt having a similar granular and mineralogical composition.

The properties of loess, whether considered from a physical or physical-chemical viewpoint, are dependent upon two factors, namely, fabric and mineralogical composition. If two loessial materials with the same fabric and mineralogical composition are subjected to physical tests, they should and do act similarly. However, if any one of the factors constituting fabric changes or the composition of the clayey fraction changes, the properties are changed materially. A change in the granular components, such as substituting feldspar for quartz, does not affect the physical properties materially, but with the introduction of volcanic glass with its shard-like form as a granular component, the properties of the loess would certainly change.

Type of Matrix

The type of matrix in loessial materials is commonly clayey and less commonly calcareous. Calcite is present in many loessial materials as grains and crystals but may be secondary. In the open fabric types of loessial materials the larger silt grains are connected by what might be called intergranular supports which are composed mainly of a montmorillonite-type clay mineral and possibly intermixed with small amounts of illite.

In other types of loess, the clayey components are distributed interstitially but with the silt grains not in contact. Voids may be distributed throughout the matrix but are usually not distinct. This type of fabric seems to be the more common type. The density of loess with this type of fabric is generally less than or equal to the loess with intergranular supports. In a loess from Kennewick, Washington, the granular components are so fine grained that the arrangement of the grains in respect to the matrix is difficult to see. The silt grains are evidently dispersed throughout the clay, which is mainly illite, and a petrographic thin section reveals only a continuous fabric.

In wind-blown silts which have been deposited under subaqueous conditions or humid conditions the matrix remains clayey, but in these materials the clay evidently is slightly more compacted and the grains are in contact which gives stability to the mass.

Calcite may occur as a secondary matrix material in loess owing to leaching from above or by the evaporation of capillary water from ground water below. However, zones containing calcite are generally not of great thickness under semi-arid conditions.

Cementation

Many investigators have stated that the primary cementing material in loess is calcite and/or dolomite, mainly because the sample effervesces if hydrochloric acid is added. In samples of loess from Kansas, Nebraska, Iowa, Washington, and Israel which were analyzed by the Bureau of Reclamation laboratories, calcite and dolomite were found by microscopic investigation to occur as anhedral detrital silt-size grains and as euhedral crystals, whereas the clay minerals occurred as the main cementing materials. In samples of loess from Natchez and Vicksburg, Mississippi, calcite and dolomite also occur as crystals and grains. Calcite and dolomite may help slightly to bind the soil particles together, but the major cementing materials appear to be the clay minerals.

If the main cementing minerals were carbonates, the loessial materials should not slake or soften appreciably in water. All of the samples of loess examined slake readily in water, either immediately or within one or two minutes. Further evidence that the carbonates are not the cementing material in loess is shown in consolidation and triaxial shear tests. If the carbonates were the main cementing material, the test specimens should not show (as they do) immediate consolidation when water is added to the soil having low natural moisture content.

Zones of loess may contain carbonates as the principal cementing material where the carbonates have been leached from the upper loessial material and redeposited at lower depths. The introduction of carbonates may be accomplished also by capillary action. If the ground water table is sufficiently close to the loessial body, water carrying Ca++ in solution as the bicarbonate may be drawn up into the loess, and with a change in pressure or temperature, calcium carbonate would be precipitated in the pore spaces. In the large pore spaces the evaporation should be greater and calcium carbonate would tend to concentrate in these pores with formation of concretions. With repeated dissolution and precipitation the carbonates would tend to develop better crystalline forms as are observed in many loessial masses.

Particle Shape

The shape of the individual granular components of loess ranges from irregular to platy, fibrous, or prismatic. The degree of rounding ranges from subround to angular. Quartz and the feldspars are commonly irregular in shape, whereas the mica minerals are platy or shred-like. Hornblende, zircon, pyroxenes, and apatite are commonly in prismatic form and sillimanite in fibrous form.

Calcite is present as irregularly shaped grains, rhombohedral crystals, and as patches composed of very fine-grained particles. Dolomite is usually present as rhombohedral crystals.

Acidic volcanic glass in the shape of volcanic shards is often observed in loess from the western United States. These shards have a variety of shapes and are fresh or moderately altered to montmorillonite. Diatoms and globigerina tend to occur rarely in loess. In some loessial materials, very small tubes composed of opal are present. The tubes are thin walled and have a very irregular surface. These tubes are thought to have formed around the fine root hairs of plants.

The clay minerals, montmorillonite and illite, occur as very fine platy crystals which are commonly cemented into aggregates between the granular components. Montmorillonite commonly occurs as thin hulls around the grains. Illite, however, has a tendency to occur as individual shred-like crystals. Platy crystals of kaolinite and octohedral crystals of cristobalite in loess deposits in Kansas have been observed by Swineford and Frye 4/ with the electron microscope.

Organic matter, which is visible under the petrographic microscope, ranges from fine capillary root hairs to plant stems. These plant stems may be partially decomposed or totally carbonized.

The majority of the granular components are subangular in shape, the grains becoming more angular as the grain size decreases and more rounded as the grain size increases towards the fine sand size.

Granular Components

The granular components, as determined by X-ray diffraction and petrographic analysis of the loessial materials from Sherman Dam site and Trenton Dam site, Nebraska, range in value as follows:

Quartz	25 to 37 percent
Feldspar, including orthoclase (which is predominant), plagioclase, and microcline	10 to 22 percent
Acidic volcanic glass	5 to 10 percent
Biotite and muscovite	4 to 6 percent
Green and brown hornblende and chalcedony	0.5 to 1 percent

Minor accessories include clinozoisite, epidote, chlorite, zoisite, sillimanite, augite, sphene, garnet, rutile, zircon, apatite, magnetite, tourmaline, hematite, and a glauconite-like mineral. Small amounts of gypsum, 0.1 percent, are occasionally associated with loess. Similar mineralogical compositions of loess from various parts of Kansas have been reported by Swineford and Frye 4/ except that the samples examined from the various dam sites are lower in quartz and higher in clay content than other samples from Kansas examined.

Grain Coatings

Most of the granular components of loess from Kansas, Nebraska, and Iowa are coated with a very thin hull or shell of a montmorillonite type of clay mineral. These clay hulls are firmly attached to the grains and cannot be removed even after long dispersion in a dispersion machine and subsequent treatment with 1:1 hydrochloric acid. Swineford and Frye 4/ also have observed these clay coatings on the silt grains in loessial material from Kansas.

In some instances, the clay coatings completely envelop the grains, whereas in a few instances the grains are only partially enclosed. In petrographic thin sections tabular or prismatic grains which have a complete clay coating have been observed in which the coatings on opposite sides of the grain extinguish together as the microscope stage is rotated.

It has been observed that in the majority of instances water-laid silts that are derived from the decomposition of pre-existing rocks do not carry clay hulls, whereas the grains in wind-blown silts commonly do. Clay hulls may be formed on the grains of some present soils because of the downward concentration of colloidal clay. These clay hulls probably aid in bonding the granular components together and in bonding the grains to the clay in the matrix. The presence of these clay hulls would also aid in retaining a certain minimum moisture content, and the presence of moisture in these hulls would exert a surface tension effect thereby binding the grains more tightly together with evaporation or rise in temperature. Hence, moisture films or moisture associated with the clay rims and matrix are important in the binding action of loess.

OBSERVATIONS OF PHYSICAL PROPERTIES

Location of Engineering Studies

Numerous Bureau of Reclamation structures are proposed, are under construction, or have been constructed on the Missouri River Basin Project. Investigation for several structures, as well as special research studies, have permitted the gathering of test data from several locations throughout the major loessial regions of Nebraska and Kansas. These particular locations are shown on the map of the Missouri River Basin area in Figure 4. The portion of this map bounded by the heavy line shows the location of the large loessial area which is of major concern to the Bureau of Reclamation and from which most of the test data for this monograph were obtained.

The physical properties of loess, when summarized for loesses from locations spread over wide areas in Nebraska and Kansas, indicate basic characteristics which are useful for engineering purposes. Based on numerous tests of soil samples from these areas, it was found that the basic

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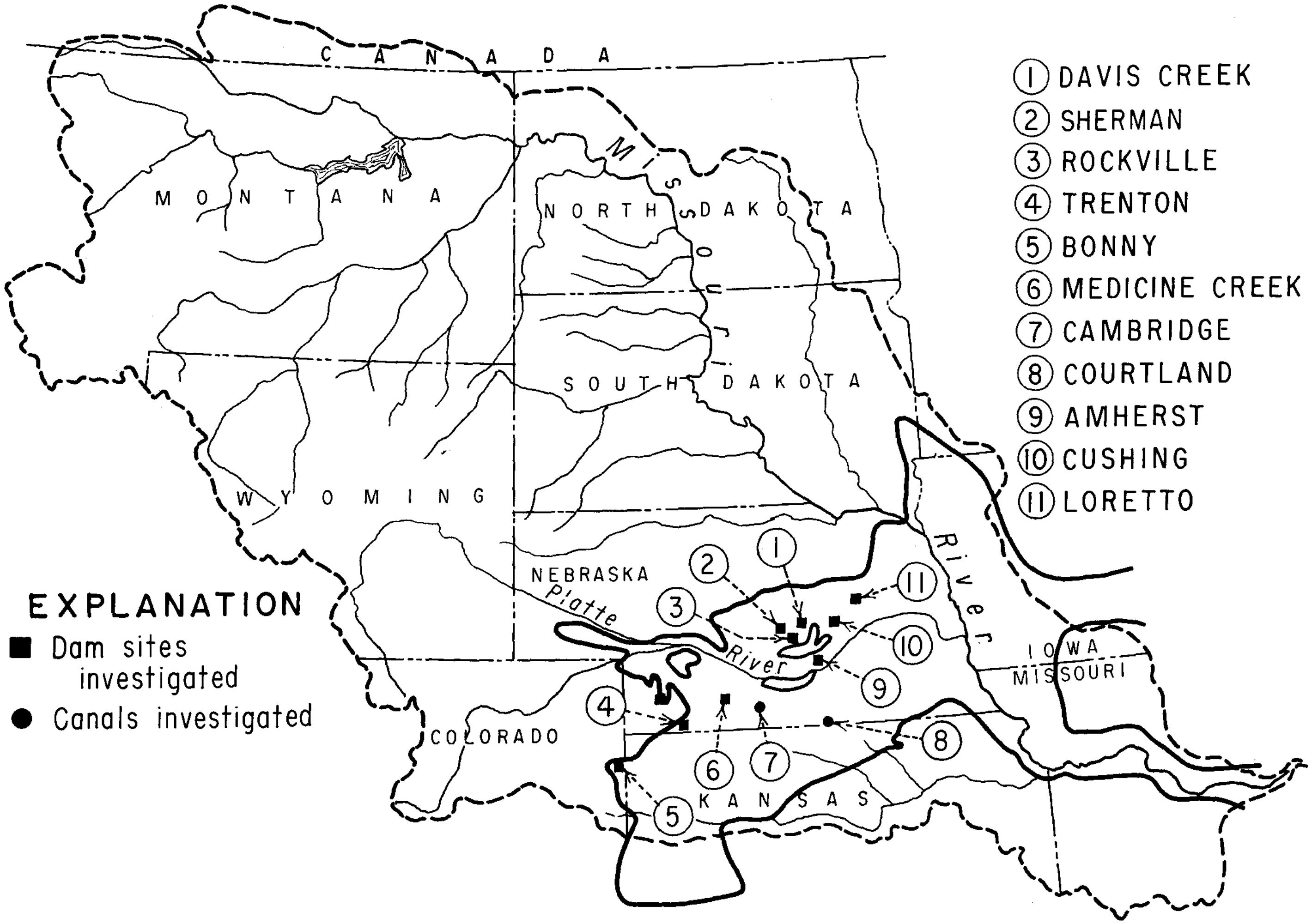

LOCATION OF MAJOR LOESS DEPOSITS IN THE MISSOURI RIVER BASIN

FIGURE 4

properties of the loess are quite similar and, predominantly, the loess has silty characteristics. However, some of the loesses are more clayey and others are somewhat sandy. Other investigators, Davidson and Sheeler 7/, have shown that the changes in properties of loess are related to the distance of the deposits from their probable source. The coarser or more sandy loess is deposited nearest to the source and the predominance of the clayey and finer loess increases farther from the source. Although this trend is apparent, it is believed that properties of the loess, especially those of the Nebraska and Kansas area, are sufficiently similar to establish certain important generalized findings for resolving soil mechanics and foundation problems.

Gradation

The graph in Figure 5 shows that gradations of loess are of uniform particle size and are consistently similar for different samples. From 148 samples which were geologically described as loess, 76 percent had gradation curves which were in the silty loess range shown in the figure, 18 percent were in the clayey loess range, and 6 percent were in the sandy loess range.

Specific Gravity

The specific gravities of these samples were found to range between narrow limits of 2.57 and 2.69; the average was 2.65.

Plasticity

The plasticity characteristics were determined by consistency (Atterberg limits) tests on many samples from 11 locations. The results are plotted in Figure 6 for the purpose of showing the areas on a graph in which values are concentrated; a standard classification chart was used. It is evident that the major concentration of points occurs for plasticity indices from 5 to 12 combined with liquid limits from 25 to 35 percent. When these data were studied in conjunction with the gradation curves, it was observed that this group is generally characteristic of the material which was previously identified as silty loess. Points of higher plasticity indices and liquid limits represented more clayey loess, and points of lower plasticity indices and liquid limits represented the sandy-loess soils.

Davidson and Sheeler 7/, in their studies of loess in western Iowa, showed that the loess becomes more clayey when the distance of the wind-blown deposits is farther from their probable sources. The loess in western Iowa was very similar to the predominating silty loess of the Nebraska-Kansas area; loess farther east had increased plasticity and cation exchange capacity, and was thus more clayey in characteristics. Some clayey loess was also found in the Bureau of Reclamation investigations. Although systematic traverses of locations were not studied, it is probable that distances of deposits from sources may also be an explanation for these differences in properties.

Compaction

This monograph primarily concerns undisturbed loess since it is this condition which involves the special properties of loess. Recompacted loess is not considered a special type of material but can be said to have typical properties of a fine-grained soil of silt and silty clay characteristics. Because of the relatively uniform properties of loess, the compaction characteristics do not vary appreciably.

Compaction characteristics of loess were not analyzed in detail. However, Figure 7b, which is discussed below in regard to permeability, contains data on soils recompacted at maximum Proctor density which range from 100 to 112 pounds per cubic foot.

Permeability

The permeability of natural loess is principally related to the density when it is considered that basic properties of gradation and plasticity, as previously shown, are relatively uniform. However, there are other features which influence this trend to some degree. Natural loess is known to have rootlike voids which would cause considerable variations in permeability; however, to some extent these rootlike voids are also reflected in the low density. In very dense and reworked or recompacted loess, these natural rootlike voids are not present, and permeability values are lower. Although loess is considered relatively uniform in basis properties, the loessial soils which fall in the more clayey or more sandy groups should be expected to have somewhat lower or higher permeability values, respectively.

In Figure 7a, all of the permeability test results are for undisturbed natural loess with tests made in the vertical direction using the one-dimensional consolidation apparatus. By enclosing the concentration of points with lines a trend is shown. In reviewing the gradation and plasticity of each sample it was found that the points

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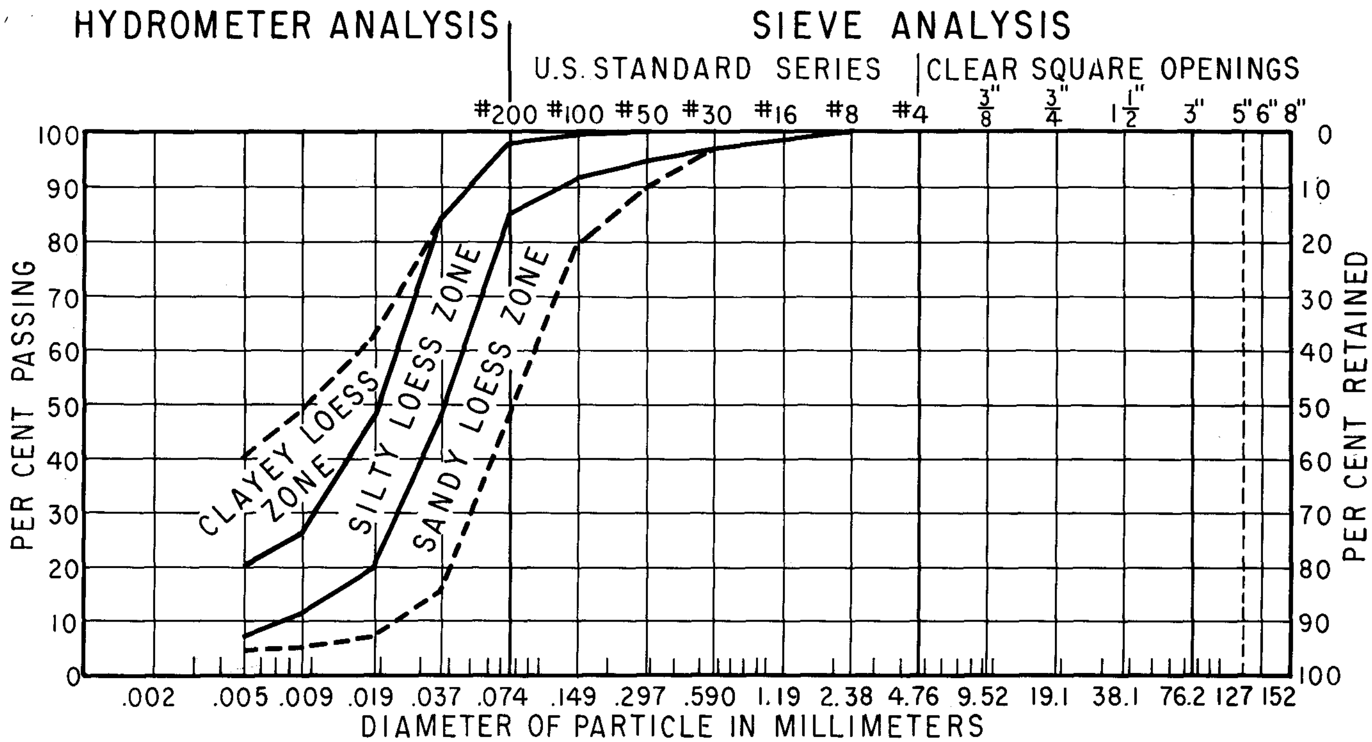


CLAY (PLASTIC) TO SILT (NON PLASTIC)	SAND			GRAVEL		COBBLES
	FINE	MEDIUM	COARSE	FINE	COARSE	

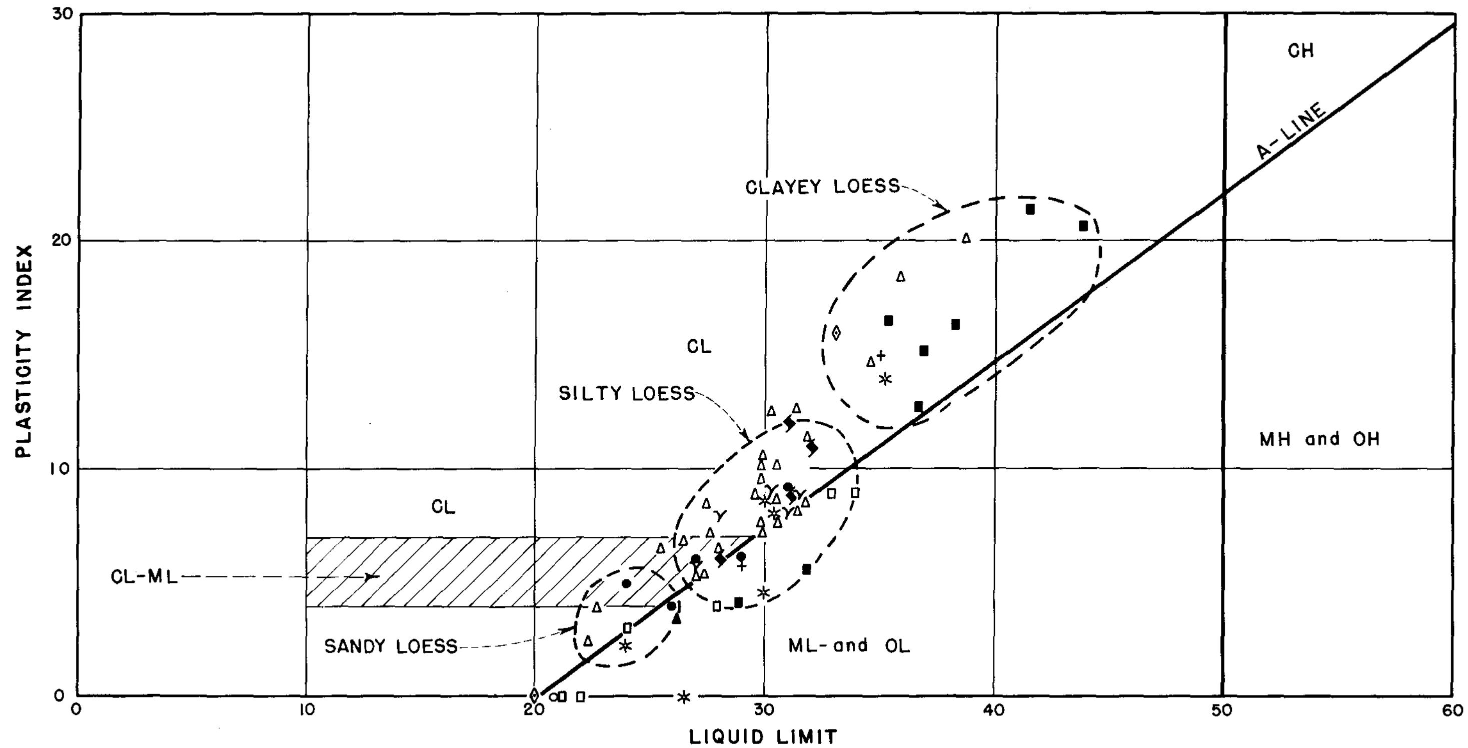
Gradation data was obtained on 148 samples from projects in the Missouri River Basin area

The curves generally take the direction shown by the boundary lines

For all samples tested,
76% were in the silty loess zone
18% were in the clayey loess zone
6% were in the sandy loess zone

TRENDS OF GRADATION CURVES FOR LOESS

FIGURE 5



Consistency limits data were obtained for samples from the following structures:

- ● Trenton Dam and Railroad Relocation
- ▲ Bonney Dam
- ✱ Davis Creek Dam
- △ Ashton pile test area
- □ Rockville Dam
- ⋎ Medicine Creek Dam
- + Cushing Dam
- ○ Milburn Dam
- ■ Amherst Dam
- ♦ Courtland Canal
- ◊ Cambridge Canal

TRENDS OF PLASTICITY CHARACTERISTICS OF LOESS

FIGURE 6

falling within these lines were generally for the silty loess. Points falling above these lines and toward values of higher permeability were for sandy loess, and points falling below these lines and toward values of lower permeability were for clayey loess and possibly reworked natural loess.

Using these trends in Figure 7a as a standard for comparison, the results of recompacted and reworked loess are shown in Figure 7b. Most of these tests were made on specimens which were recompacted for the purpose of embankment investigations. Therefore, it will be noted that most of the specimens have a density range from 102 to 112 pounds per cubic foot. For these tests, the permeability range is rather low, from 0.01 to 0.5 foot per year. Such values correspond to values observed for dense natural loess. Compacted samples having lower densities were not available.

Consolidation

Only general trends are evident in the settlement characteristics shown in Figure 8, because considerable variations occur in density and moisture. Slight variations in clay content and differences in moisture conditions influence the bonding characteristics from particle to particle.

The prominent effect on the amount of settlement is found to be initial density. Under a loading of 100 psi and at wetted conditions, natural loess, which varied in initial density from 73 to 92 pounds per cubic foot, consolidated to densities from 95 to 103 pounds per cubic foot, or as much as 30 percent or as little as 5 percent, as shown in Figure 8a. However, as shown in Figure 8b, under relatively dry natural conditions, loess consolidated little until loads are in excess of 100 psi. This indicates that loading alone does not break down the particle-to-particle bonding characteristics until relatively large loadings are reached, whereas increased moisture appreciably affects settlement.

Figure 8c is another generalized picture, published previously by Holtz and Gibbs 1/, of the consolidation characteristics plotted to linear scales. The trends for loess which is thoroughly wetted (shaded area) show that it consolidates quite easily under small loads. Three examples of consolidation tests show the contrast of low settlement under dry conditions and high settlement under wet conditions. When water is added during the test the curves drop to values near those obtained by companion prewetted tests. These curves demonstrate settlement characteristics which may develop in structures placed on wetted loess, on dry loess, or on dry loess which is wetted after construction.

Using the data of the actual tests in Figure 8 as guides for establishing consolidation trends, the curves of Figure 9 were drawn. These curves demonstrate distinct contrast in settlement between loess of wet and dry conditions for loads of 10 to 100 psi, which is the general range of loading for most foundations. It is evident that the most pronounced settlements occur for loess at densities less than 80 pounds per cubic foot, and relatively smaller settlements occur for loess at densities more than 90 pounds per cubic foot.

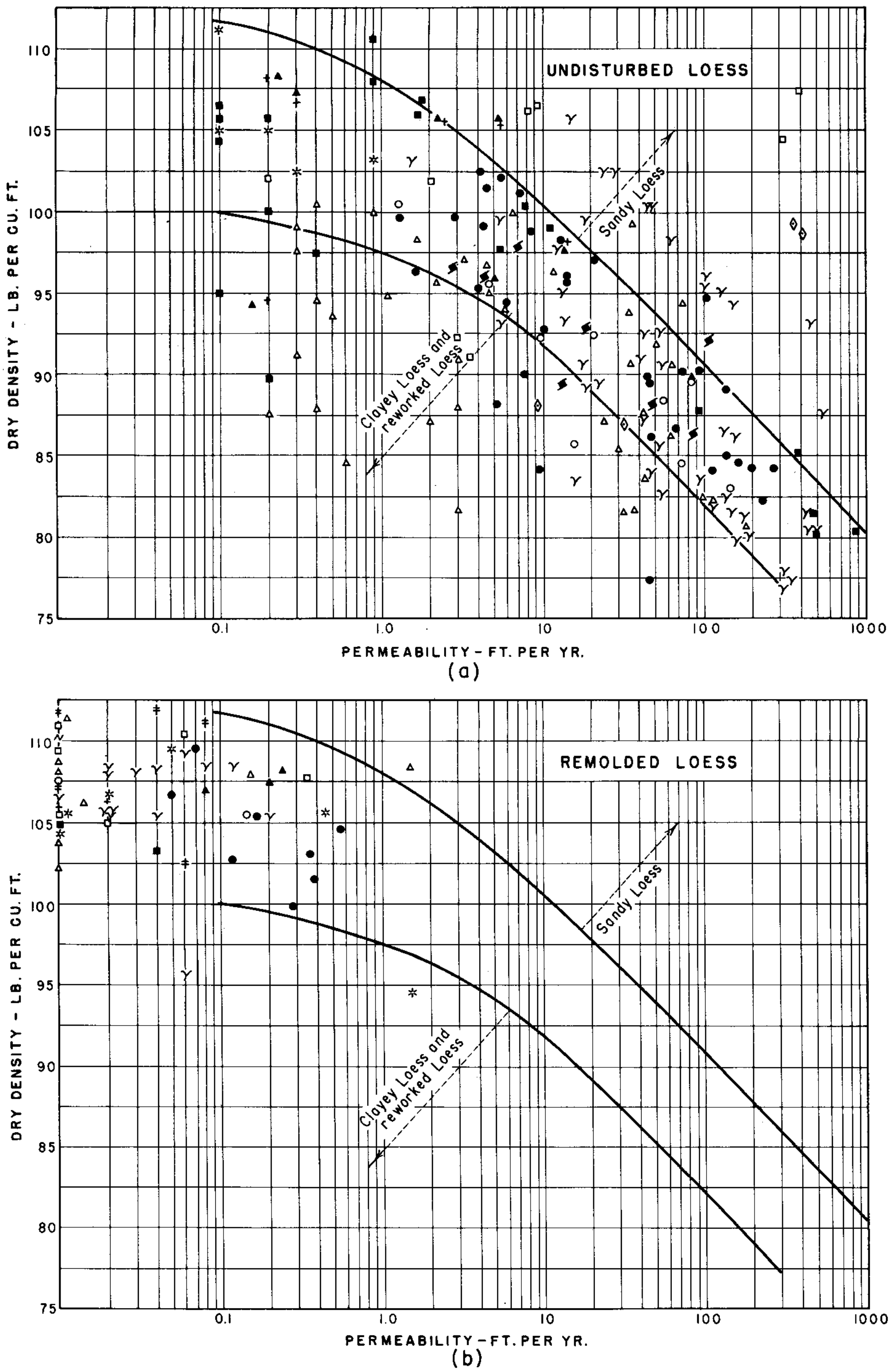
Shear Resistance

The variations in shear resistance may be attributed to the same general factors which cause variations in consolidation. There is evidence of definite influences of initial density, initial moisture content, and clayeyness of the loess.

In Figure 10, the solid lines represent the shearing resistance curves (Mohr envelopes of triaxial shear tests) of natural undisturbed loess and the dashed curves represent loesses which were prewetted. Although the tests include both sealed and drained specimens, the results have been adjusted for pore pressure, and the shear resistance curves represent strengths for effective (grain-to-grain) stresses.

The curves are generally of similar slope indicating similar frictional resistance. This would be expected because loess has such similar basic physical properties. However, there is considerable difference in the position of the resistance curves. This is caused by the variations in cohesion which are related to the clay content, moisture content, and density. The several curves which are bracketed and located high on the graph are those showing high cohesive characteristics. It may be noted in the table in the figure that these soils are either clayey, of very high density, or of very low moisture content, or are soils having combinations of these properties.

The curves bracketed at the lower levels on the graphs are those of typical silty loess generally of relatively low density. The majority of the curves are contained in this grouping. This lower group of curves contains test results for two test methods; the solid lines represent tests on loess at natural (dry) moisture content, and the dashed curves represent tests on natural loess which has

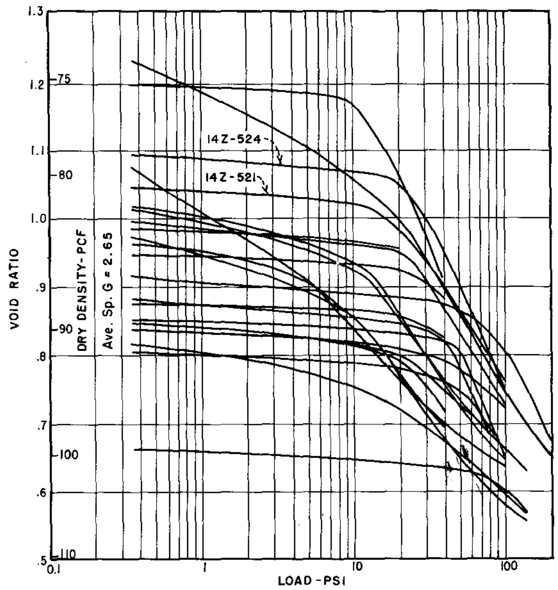


EXPLANATION

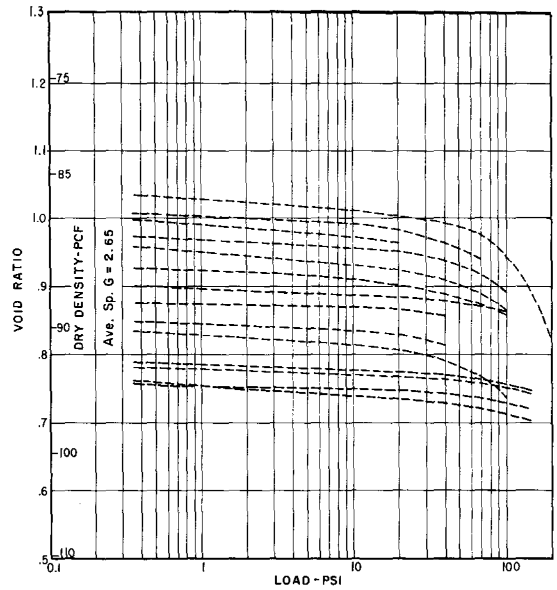
- ● Trenton Dam and Railroad Relocation
- ▲ Bonny Dam
- ✳ Davis Creek Dam
- △ Ashton pile test area
- ▫ Rockville Dam
- Y Medicine Creek Dam
- \+ Cushing Dam
- ○ Milburn Dam
- ■ Amherst Dam
- ⚡ Courtland Canal
- ◊ Cambridge Canal
- ‡ Enders Dam
- ~ Erickson Dam

TRENDS OF PERMEABILITY FOR LOESS

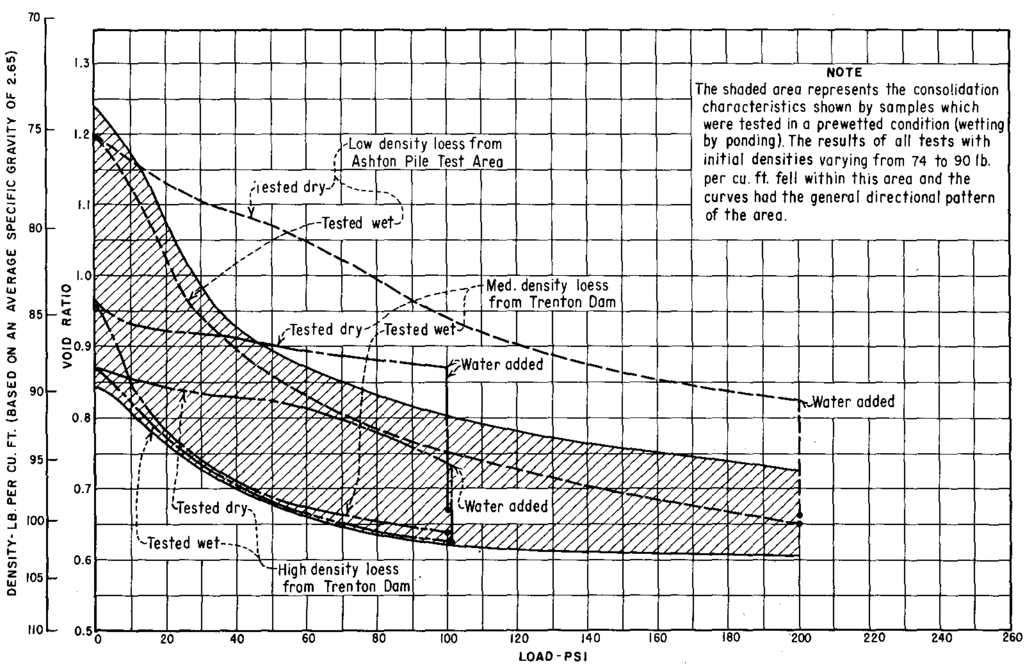
FIGURE 7



(a) SUMMARY OF CONSOLIDATION CHARACTERISTICS OF NATURAL UNDISTURBED LOESS WHICH HAS BEEN WETTED PRIOR TO TESTING TO MOISTURE CONTENT ABOVE 20 PERCENT



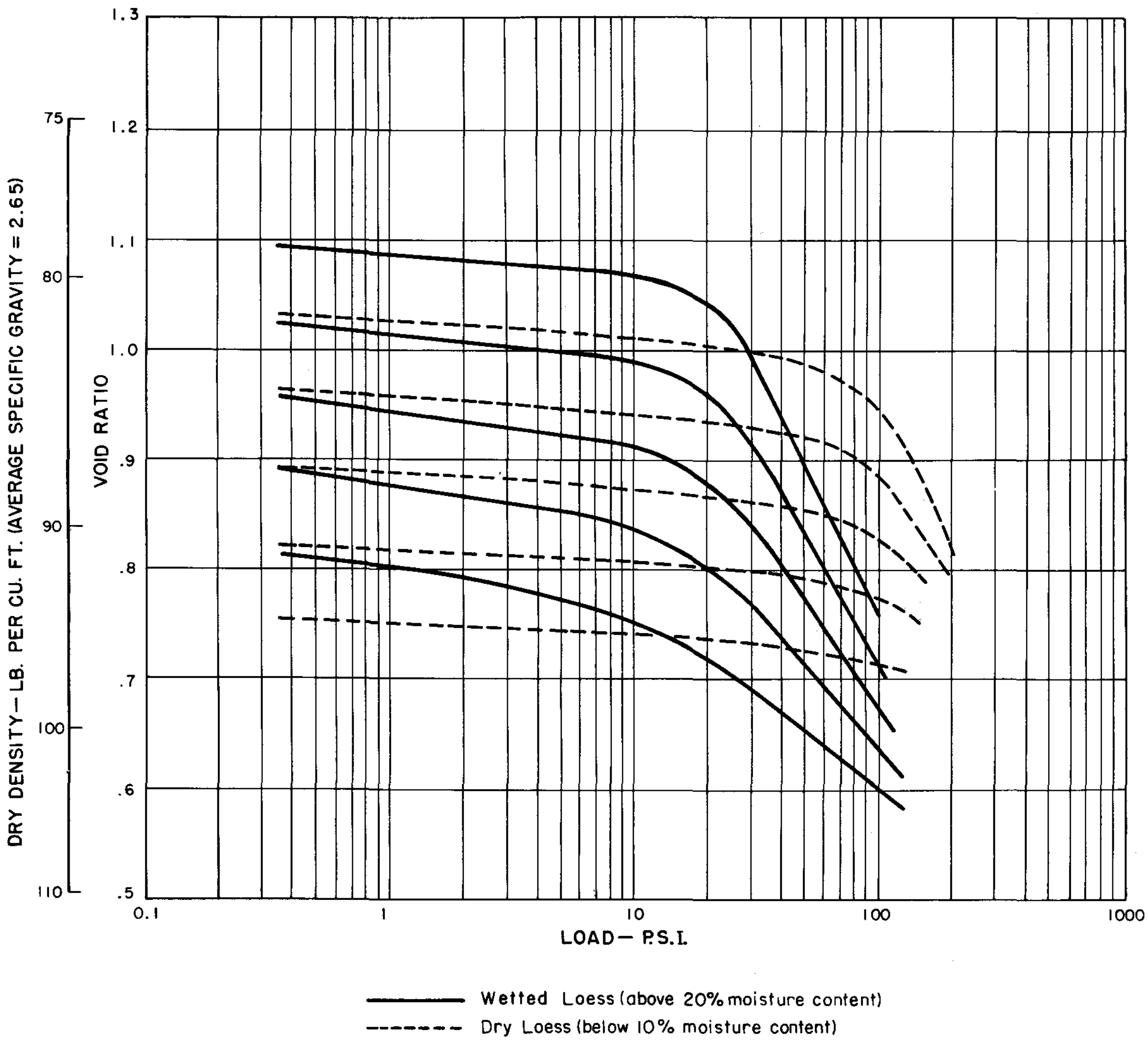
(b) SUMMARY OF CONSOLIDATION CHARACTERISTICS OF NATURAL UNDISTURBED LOESS TESTED AT NATURAL MOISTURE CONTENT OF LESS THAN 10 PERCENT



(c) SUMMARY OF CONSOLIDATION CHARACTERISTICS OF DRY AND WETTED LOESS OF VARYING INITIAL DENSITIES

CONSOLIDATION CHARACTERISTICS OF LOESS

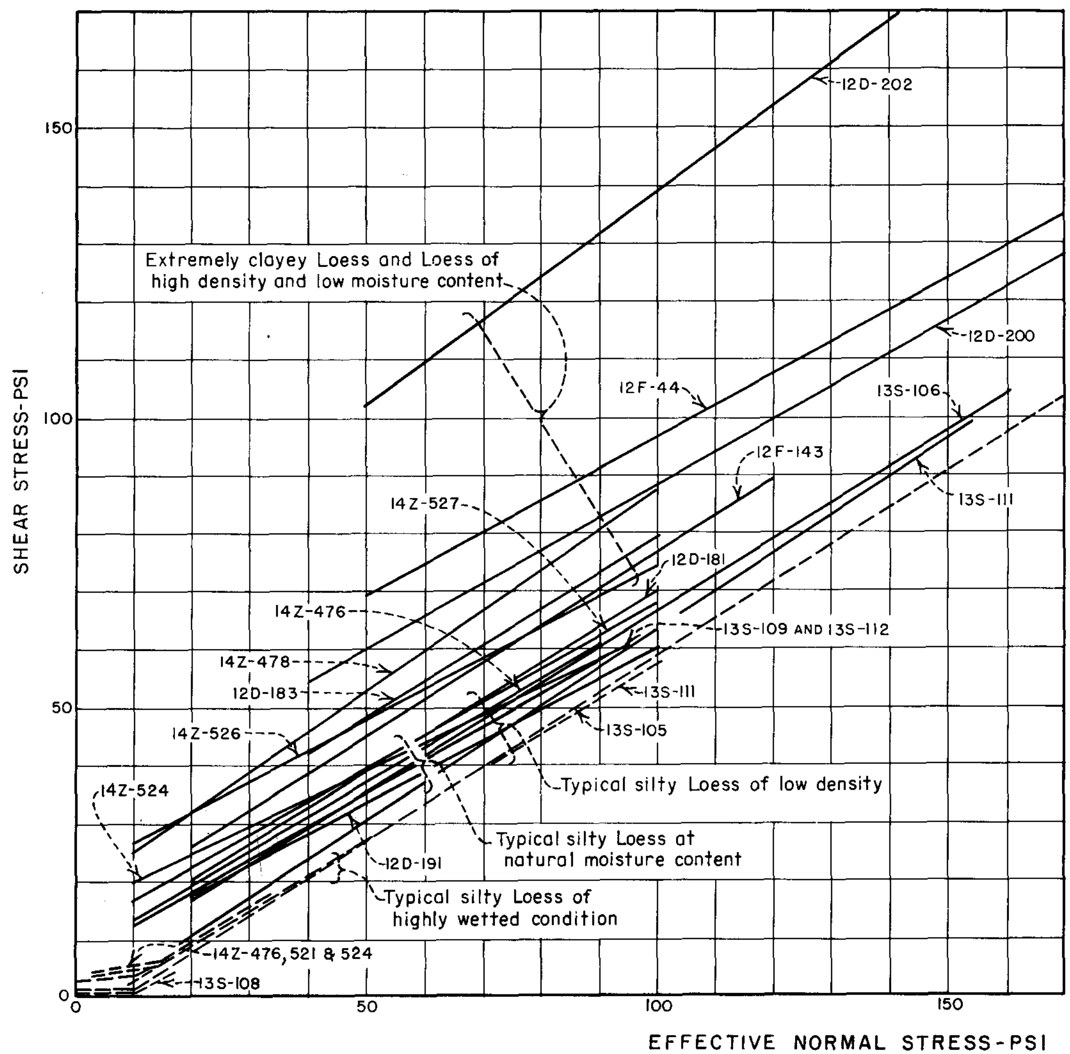
FIGURE-8



GENERALIZED CONSOLIDATION TRENDS
FIGURE 9

been wetted prior to testing. It can be seen that the low density loess which has been thoroughly wetted is of very low shear resistance. Under low normal stress, this loess shows a flat shear resistance curve, and on some occasions it has virtually no shear strength. Under higher normal stress, this strength increases because frictional resistance was developed after consolidation took place.

As a further explanation of the difference between wet and dry conditions, the curves in Figure 11 are shown. These curves are for a typical silty loess of relatively low density. The solid curves are for the undisturbed loess at natural moisture conditions, and the dashed curves are for the same material which has been wetted prior to testing. The shear curves in Figure 11a show distinct differences in shear resistance between wet and dry conditions. The larger circles for dry loess indicate greater shearing resistance under applied pressures. The higher level of the envelope line indicates pronounced cohesion. The smaller circles for prewetted loess indicate lower shear resistance for applied stresses similar to those used in the dry tests. In the wet tests, appreciable pore pressure developed causing lower effective normal stress values.



LAB. SAMPLE NO.	TEST CONDITIONS	TYPE OF LOESS	DENSITY AT TIME OF TEST	MOIST. AT TIME OF TEST	REMARKS
12D-202	NATURAL	CLAYEY	100.2	10.1	Extremely clayey Loess and Loess of high density and low moisture content
12F-44		SILTY	94.1	8.4	
12D-200		CLAYEY	84.9	8.6	
14Z-478		SILTY	90.2	7.4	
12D-183		SILTY	84.2	4.5	
12F-143		SILTY	103.5	18.0	
14Z-526		CLAYEY	83.1	13.3	
12D-181		SILTY	79.1	8.2	Typical silty Loess of low density
14Z-527		SILTY	89.5	6.9	
14Z-476		SILTY	83.8	8.6	
13S-106		SILTY	89.0	6.0	
13S-111		SILTY	81.7	6.5	
13S-109		SILTY	83.8	7.3	
13S-112		SILTY	81.3	9.5	
14Z-524		SILTY	82.0	10.6	
12D-191		CLAYEY	78.6	20.3	
13S-105	PRE-WETTED	SILTY	81.1	29.3	
13S-111		SILTY	82.5	30.4	
14Z-476		SILTY	81.6	34.8	
14Z-521		SILTY	78.2	34.9	
14Z-524		SILTY	78.0	33.9	
13S-108		SILTY	78.4	28.9	

EXPLANATION

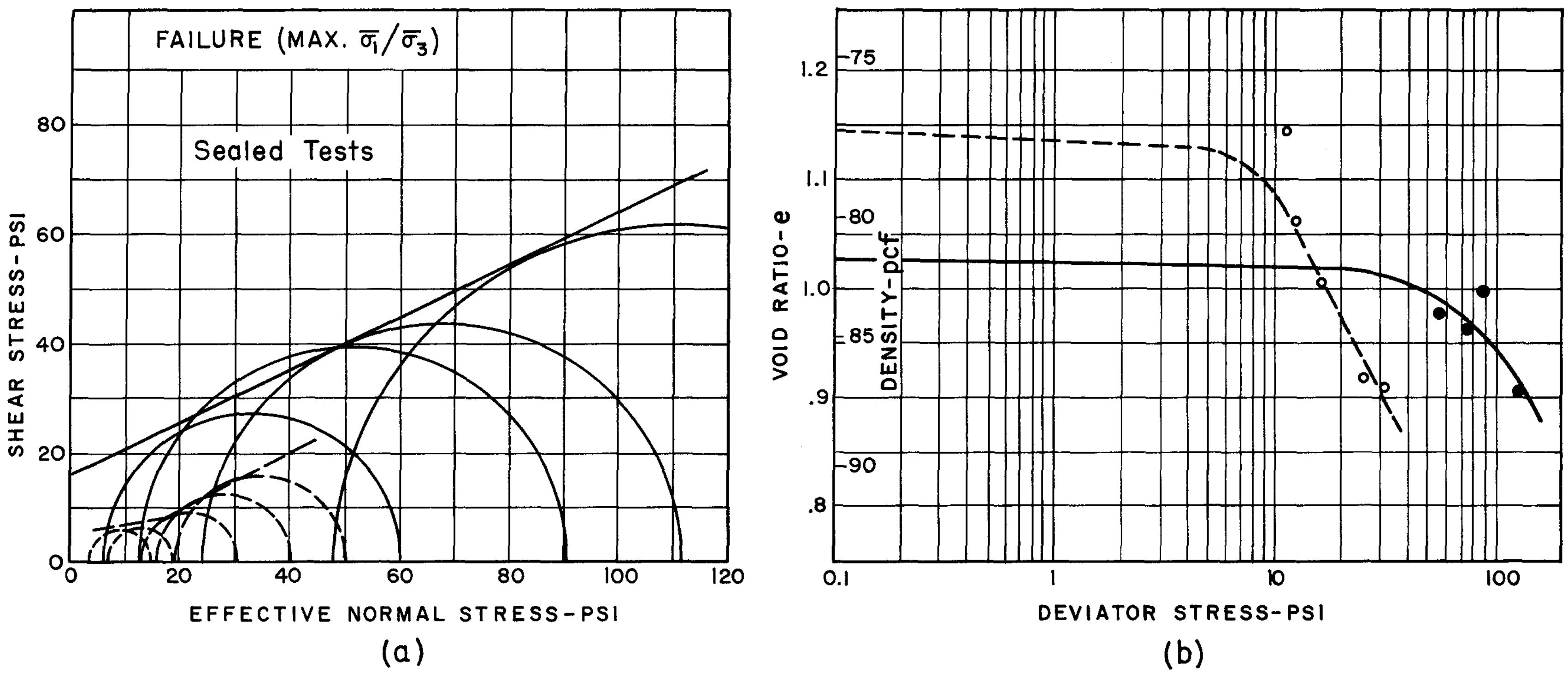
——— Tests at natural moisture condition

– – – Tests at wetted condition

SHEAR TESTS OF REPRESENTATIVE LOESSIAL SOILS

FIGURE 10

INITIAL CONDITIONS	NATURAL	PONDED
DRY DENSITY (pcf)	82.02	78.02
MOISTURE CONTENT (%)	10.57	33.96
DEGREE OF SATURATION (%)	27.50	80.23
SPECIFIC GRAVITY 2.660		



SHEAR AND VOLUME CHANGE CHARACTERISTICS OF DRY AND WET LOESS

FIGURE 11

Figure 11b shows the consolidation which occurred in the shear specimens. The dashed curves showed that wet loess consolidated under much lower stress conditions than the dry loess. The rise in shearing resistance under higher stresses is related to the greater consolidation which occurs in these specimens. It is interesting to note that wetting has caused expansion in the loess since the initial density of the wetter loess is considerably less than the initial density of the dry loess.

RESEARCH FINDINGS FOR LOESS

Several research studies, both in the laboratory and in the field, were conducted to clarify specific problems related to the use of loess as a foundation and construction material.

Results of Plate Load Tests on Loess

To demonstrate the settlement and bearing capacity of spread footings on loess, a series of plate load tests were conducted in a typical low density loess near Ashton, Nebraska 1/.

The settlement characteristics of this soil are shown by the laboratory consolidation curves marked 14Z-521 and 524 in Figure 8a. The field tests involved the loading of square plates of three sizes: (1) 1 by 1 foot, (2) 3 by 3 feet, and (3) 5 by 5 feet. Each plate was placed at a depth of 5 feet in holes equal to the plate size so that the full effect of surcharge existed.

The results of the tests are shown in Figure 12. Settlements are shown in relation to the pressure. The results of each loading test are indicated for two sets of plates: for the loess at natural moisture content, and for loess which was prewetted. In addition, the theoretically computed settlements, obtained from the consolidation tests in Figure 8, are shown for the 3- by 3-foot and the 5- by 5-foot plates. (Computing settlement for the 1- by 1-foot plate was not practical because of its small size.)

The results show that this loess at a natural moisture content of about 10 to 12 percent is capable of supporting considerable load, about 5 tons per square foot, without serious settlement. When this loess was prewetted by ponding, considerable settlement occurred after loading. The settlements of the larger plates were greater because the distributions of pressure included greater depths of compressible loess than the smaller plates. Thus, these tests clearly show the error that could arise if the results of field load tests on small plates were used directly to estimate settlements of large footings.

The important observation is that the wetted material for footings of sizes 5 by 5 feet or larger showed increased settlement under loads as low as 0.8 ton per square foot. For safety reasons, this material would probably only permit loadings of about 500 pounds per square foot. In contrast, the dry (natural moisture content) material did not show excessive settlement under loadings as high as 5 tons per square foot.

The computed values of settlement checked the actual measured settlements fairly well for the large size plate. As the plates become smaller, computed estimates become less accurate. It is of interest to note that the curve computed from consolidation tests and the plate load test curve (for example, the 3- by 3-foot plate) have similar shapes for the beginning part, indicating that consolidation is the primary cause of settlement of the plate in that range of loading. For greater loadings, the plate load-test curve shows greater settlement and crosses the computed curve, indicating progressive settlement and greater effects of shear failure.

Results of Ponding Tests in Loess

Ponding of loess may in some cases be desirable to develop the weakest condition in the loess prior to construction. This is likely to be most important in hydraulic structures which will have their foundations thoroughly wetted by normal operation. Such ponding would permit settlements to take place before or during construction. If the foundations are of low density and susceptible to large settlement, ponding would be very desirable in preparing them for pile driving. This will be discussed further under pile driving and pile-load testing in loess. Also, ponding of foundations for earth embankments may be desirable so that settlement can take place as the embankments are constructed and thus reduce the possibility of the foundation slumping as saturation by the reservoir occurs.

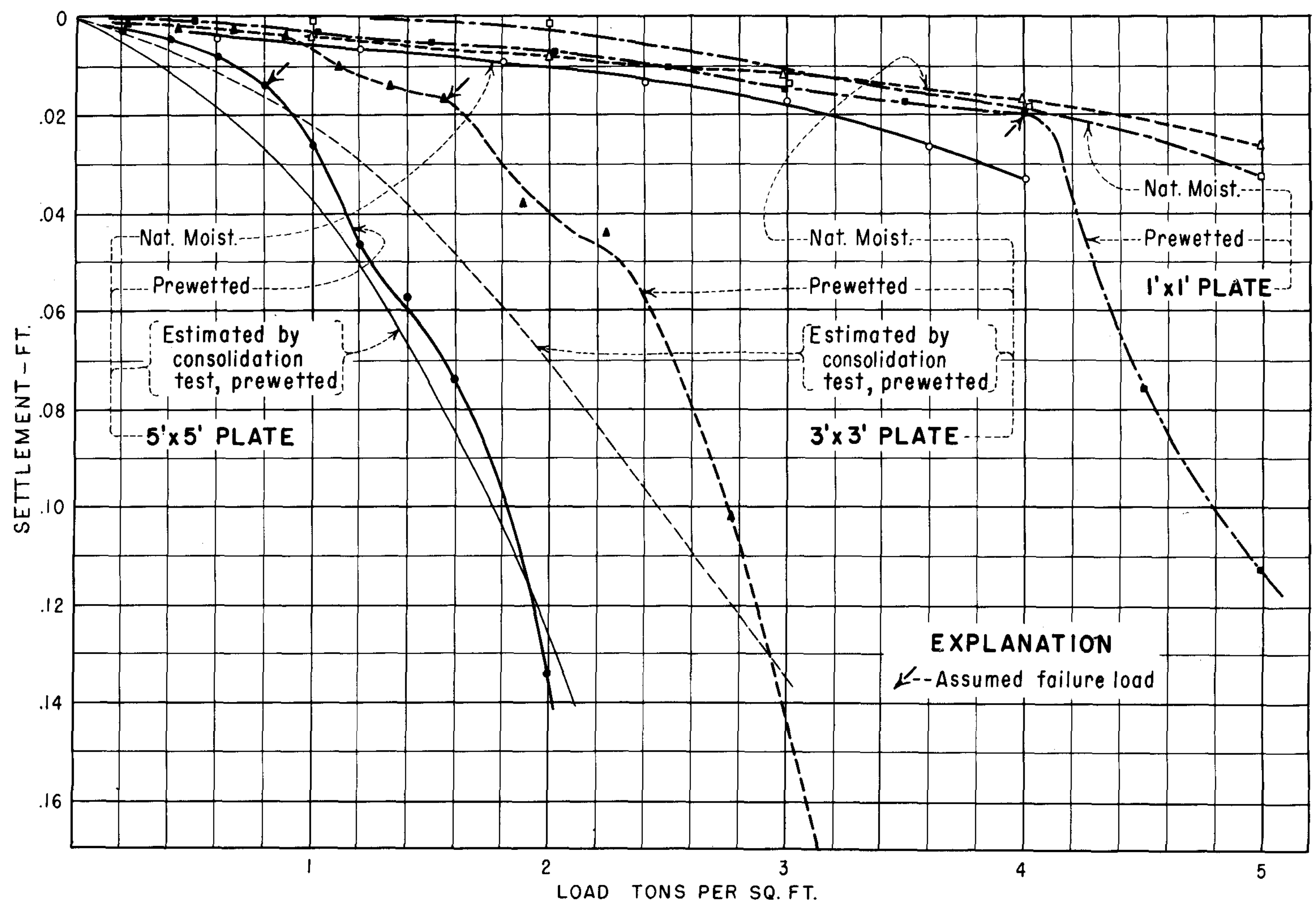


PLATE - LOAD TESTS FOR A TYPICAL LOESS DEPOSIT FOR COMPARISON OF MATERIAL AT NATURAL MOISTURE AND PREWETTED CONDITIONS

FIGURE 12

Figure 13 shows the results of surface ponding in typical loess of low density near Ashton, Nebraska. The two ponding experiments are identified in the figure as Site 1, where the loess was about 40 feet deep underlain by a medium to coarse sand, and Site 2, where the loess was in excess of 60 feet deep.

In Site 2, the soil was wetted to a depth of 60 to 70 feet. In Site 1, the loess was wetted to the top of the sand stratum at about 40 feet. The wetting was accomplished by continuously ponding 1 foot of water over the areas for a period of 6 to 9 weeks. After 2 weeks of ponding, it was decided that open drill holes should be made to expedite wetting so that it could be accomplished in the allotted time. These drill holes were made in the western one-half of Site 2 and around the edge of Site 1. The locations of moisture observation holes are shown in the plan views in Figure 13, and the depths of moisture penetration for various numbers of days of wetting are shown in the profiles. On Sections AA and BB, it may be seen that the open drill holes definitely assisted wetting. The wetting of Site 1 was somewhat slower than Site 2 because of greater densities. After ponding was stopped, Test Holes No. DHP-23 and -25 in Site 2, and DHP-26 in Site 1 showed that wetting was accomplished to the proposed depths. Forty days of ponding were required for Site 2 and 63 days for Site 1.

Example of Prewetting

The foundation of Medicine Creek Dam, Nebraska, was thoroughly wetted by ponding and sprinkling before embankment construction (described by Clevenger 8/). Figure 14 is a photograph of the dikes and the ponds. Moisture content of the loess was raised from about 12 to 28 percent in from 25 days to 2 months during which time 33 million gallons of water were used. Settlement measuring points were established throughout these ponded areas. No significant settlement occurred from saturation alone. Base plates for measuring the foundation settlement caused by fill construction were installed on top of the loess stratum in four locations, designated BP-1 through BP-4 in the plan shown in Figure 15.

Fill construction on the loess began about mid 1949 and was completed in late 1949. Base plate settlement measurements were made periodically from beginning of fill construction until July 1954. Three of the plates had settled from 0.8 to 1.0 foot, and the fourth settled a total of 2 feet by 1954, as shown in Figure 15. After the reservoir had been full for about 3 years, the settlement curves become flat, indicating that settlements virtually ceased. This example illustrates the use of prewetting to permit a large part of the settlement to take place during construction.

Behavior of Piles in Loess

Piles are sometimes used as a solution to the problem of large settlements of rigid irrigation structures such as powerplants, pumping plants, gate structures, bridges, and appurtenant canal structures. In attempting to visualize the suitability of piles, these questions were asked:

1. How must piles be placed since the loess is quite firm and sometimes hard when dry?

2. What happens to the pile-bearing strength when the loess becomes thoroughly wetted?

3. Can the natural structure of loess support friction piles or must there always be firm bearing?

4. What kind of piles are desirable?

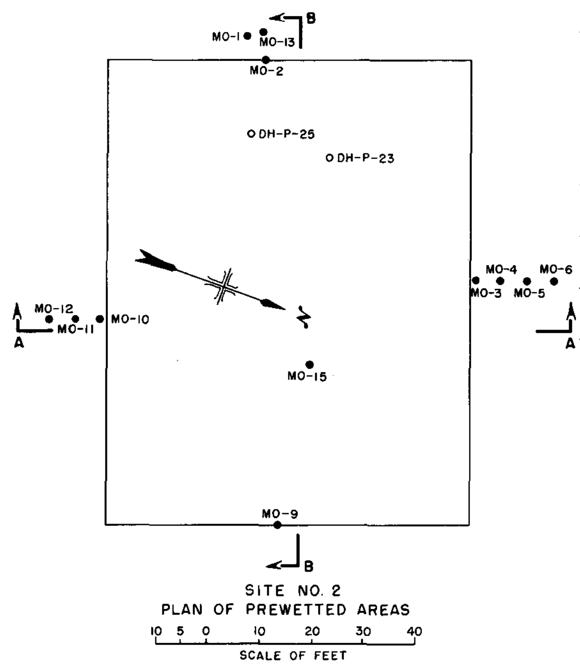
5. Will end bearing piles become overloaded as consolidation of surrounding loess takes place?

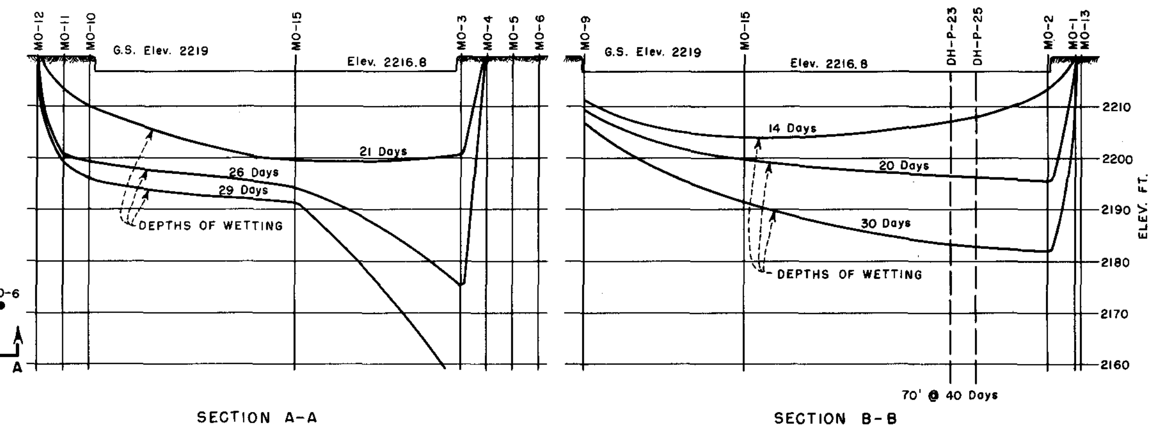
A research study, near Ashton, Nebraska, of full-scale pile tests was conducted to answer these questions. The test sites contain loess which is representative of that found at many proposed irrigation projects. Site 1 contained end-bearing piles resting in firm sand underlying shallow loess. Site 2 contained friction piles in loess greater than 60 feet deep. The loess at both sites was at a medium range of density, 80 to 90 pounds per cubic foot. The study included driving 44 piles and performing 28 pile-load tests. Two general types of piles were studied: nondisplacement (steel-H) piles and displacement (timber and concrete) piles. Each test site contained an area in which piles were placed in loess at a natural moisture content of about 11 percent and an area which was prewetted by surface ponding to a depth greater than the proposed pile length.

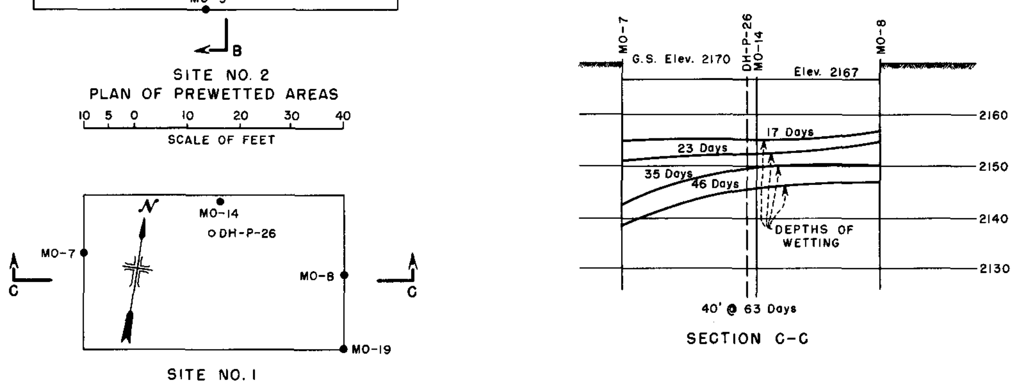
The natural moisture area of each site contained the following types of piles and placement methods:

Group (1)--3 timber piles placed by driving only or preboring if necessary

Group (2)--3 steel H-piles placed by driving only







NOTE

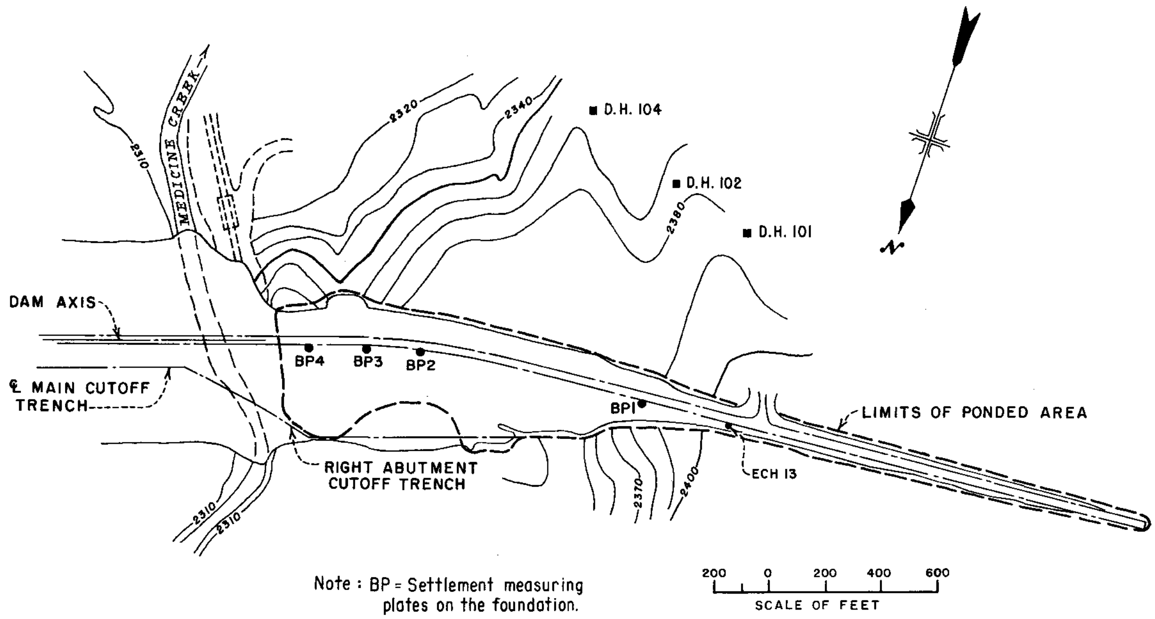
These profiles should only be considered approximate as they are based on observations at scattered time intervals. The observations were obtained from rapidly made drill holes. Penetration holes, DH-P-23, 25 and 26, made after ponding was stopped, are the best proof of wetting.

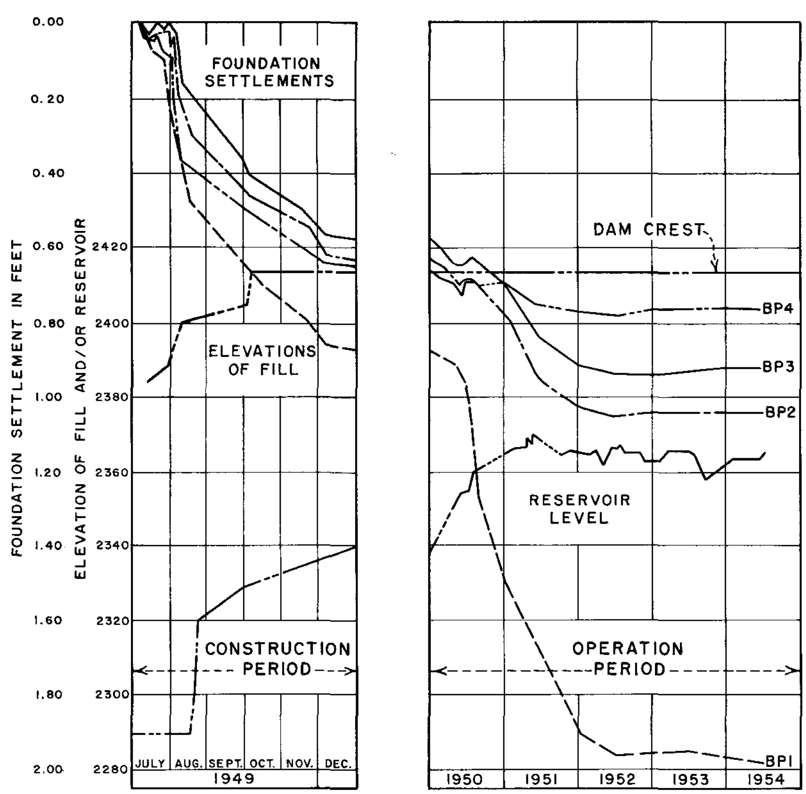
RECORDS OF PONDING EXPERIMENTS AT ASHTON PILE TEST AREAS

FIGURE 13

PREWETTING OF LOESS FOUNDATION BY PONDING AT MEDICINE CREEK DAM

FIGURE 14





MEDICINE CREEK DAM
FOUNDATION SETTLEMENT INSTALLATIONS

FIGURE 15

Group (3)--3 steel-shell, cast-in-place concrete piles placed by driving only or preboring if necessary

Group (4)--3 timber piles placed in jetted holes

The prewetted area of each site contained only displacement piles placed by driving only. At the friction pile site (Site 2), in addition to the single separated piles, a cluster of nine piles was driven to determine the consolidation effect of group pile driving.

Representative piles of each type and placement method were load tested. Piles which were placed in the natural moisture areas were load tested before and after wetting the areas.

One of the purposes for testing end-bearing piles was to study downward drag on the piles resulting from the upper loess settling when wetted. However, this part of the study did not materialize because the loess at this site did not settle as a result of wetting alone.

Soil profiles and plans of the two test sites are shown in Figure 16. In Site 1, Figure 16a, the loess was from 35 to 40 feet deep. The Grand Island sand formation, was considered the bearing material, was at about 45-foot depth. Between the loess and the Grand Island sand was a transition zone of sand with silt. The loess varied in density from 84 pounds per cubic foot near the surface to 90 pounds per cubic foot at lower depths. The Grand Island sand was quite dense, having a density of 112 pounds per cubic foot.

In Site 2, Figure 16b, the loess was of considerably greater depth than the proposed pile length of 55 feet. The loess from 0 to 40 feet was of relatively low density, 80 to 85 pounds per cubic foot. This was underlain by a somewhat clayey, old soil horizon, 1 to 2 feet in thickness. Below this old soil horizon, to 62-foot depth, the loess was slightly more sandy and denser, being at 85 to 95 pounds per cubic foot.

The loess in this study was described as "silty loess" and the physical properties were similar, in respect to gradation, plasticity, and mineral contents, to other loess in the Kansas-Nebraska area. Typical gradation curves are shown in Figure 17.

The equipment used for pile driving was a single-acting steam hammer which was particularly suitable in a research study of this kind because the energy of the blows could easily be interpreted and maintained constant for comparing the driving of one pile to another. The 5,000-pound driving hammer was dropped 36 inches and was operated at 55 to 60 blows per minute.

The preboring of dry holes was done by driving an open end pipe into the ground for about 4 feet, pulling it out, and blowing the soil plug from the pipe with steam. The process was repeated until the desired depth was reached.

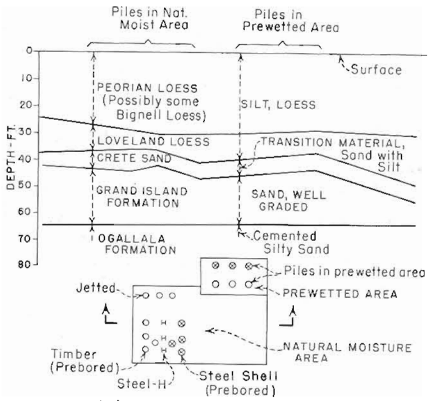
The jetted holes were made by ejecting a straight stream of water at 100- to 120-psi pressure from a 1-1/2-inch-diameter jet pipe into the ground using a long vertical pipe guided by the leads of the pile driver. The jet pipe was worked up and down with short strokes and followed the hole down as it was made. The finished hole was somewhat irregular in shape, varying from 7 to 12 inches in diameter.

Load tests were made by stacking standard railroad rails on a loading frame above the pile to be tested. A hydraulic jack between the loading frame and the pile permitted the application of the load in controlled amounts. The method of load testing is shown in Figure 18.

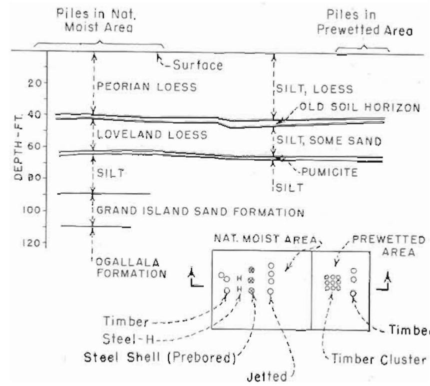
Results of Pile Driving Studies

The principal results of driving studies are presented here by means of three graphs, Figures 19a, b, and c. These graphs display the record of a representative pile of each of the general conditions.

Figure 19a represents the driving records of the displacement piles placed by various methods in deep loess at Site 2, the friction pile site. The solid line curve is the driving record of a timber pile placed by driving only in thoroughly prewetted loess. Such a pile drove rather easily and gradually developed resistance of about 36 blows per foot. It was apparent that the denser and more sandy loess below the old soil horizon caused resistance to increase more rapidly. The Engineering News formula indicated a safe load of 35 tons for this pile. A similar pile placed in dry loess, shown by a dash-dot line, indicates a distinct contrast in driving resistance. It was only possible to drive this pile 25 feet before refusal resistance was reached. The safe load of this pile after the soil is wetted should be that indicated by driving a pile in prewetted loess to a similar depth, and, in this case, by the Engineering News formula, would be about 9 tons. A safe load computed from the driving record in the dry loess was 90 tons, which shows that driving in dry loess, which

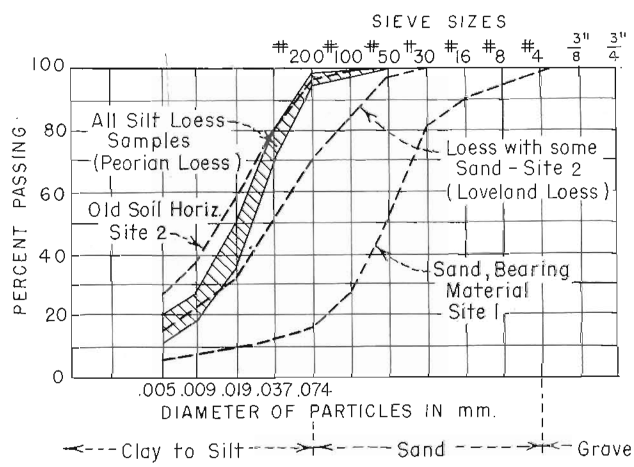


(a) PROFILE OF SITE NO. 1
(END-BEARING SITE)

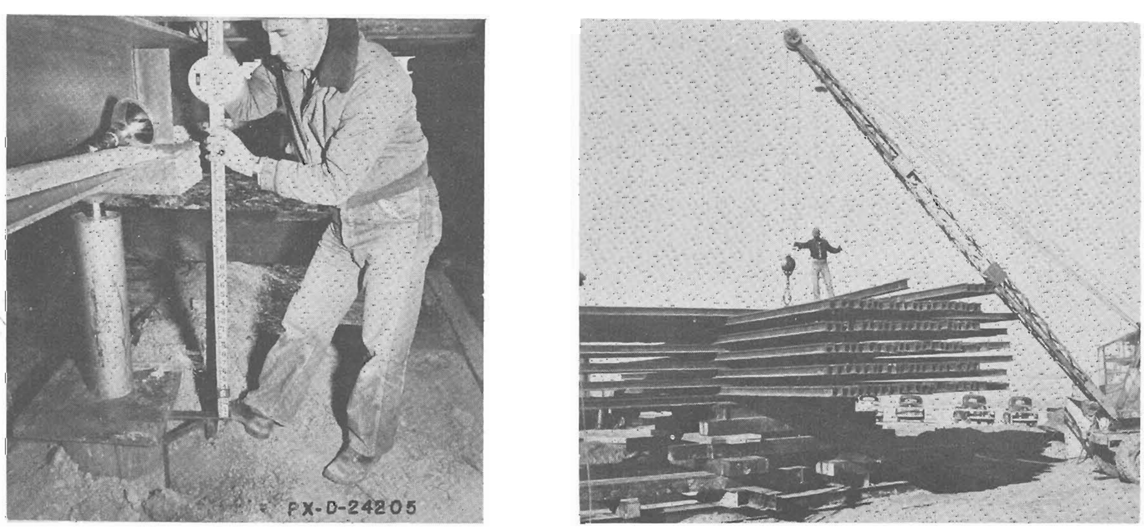


(b) PROFILE OF SITE NO. 2
(FRICTION PILES)

PROFILES AND PLANS OF TEST SITES
FIGURE 16



GRADATION TESTS
FIGURE 17



METHOD OF MAKING PILE LOAD TESTS
FIGURE 18

would be subsequently wetted, would give erroneous indications of strength.

It was evident that preexcavation was necessary to place a displacement pile in dry loess to the proposed depth. Further, it was found that to place a pile in a dry prebored hole, the hole had to be practically as large as the pile. A representative pile placed in a dry prebored hole, shown in Figure 19a by a dash-double dot line, dropped in the hole to 35 feet without resistance and rapidly picked up high resistance from there to the proposed depth of 55 feet. A pile in a jetted hole, shown by the dashed line, had gradually increasing resistance from a depth of 12 feet.

Of the three placement methods which permitted the piles to be placed to the proposed depth of 55 feet, the pile placed in the prewetted loess by driving only was considered to give highest strength because maximum consolidation of surrounding soil was obtained. Piles placed in jetted holes were considered to be the next best as the piles drove easily and some consolidation of adjacent wetted loess was obtained. A pile in a dry prebored hole was considered to give the least strength because practically no consolidation was obtained. Pile tests shown later support these opinions.

In Figure 19b, a similar comparison is made for piles placed in Site 1, the end-bearing site, where the loess was relatively shallow. In general, the driving resistance in the loess was similar to that of Figure 19a. The important consideration is that all piles which reached the firm Grand Island sand stratum increased in resistance almost immediately regardless of whether the pile was in a jetted hole, a prebored hole, or in prewetted material. Therefore, it appears that this sand will adequately support piles placed by any of these methods, provided they are snugly held in the upper loess for adequate lateral support. The loadings are discussed below.

Figure 19c shows the comparison of different types of piles, all of which were placed by driving only. The timber pile in prewetted material drove easiest. In dry materail, the nondisplacement steel H-pile drove easiest; however, the effect of greater clayeyness in the old soil horizon was particularly noticeable. Displacement piles, both timber and steel-shell piles, drove with much difficulty in dry loess and reached refusal values at relatively shallow depths.

Results of Pile-load Tests

Figure 20a, b, c, and d show the results of load tests on various representative piles in deep loess at Site 2, the friction-pile site. Figure 20a is a load test for a displacement pile, driven in prewetted loess to a depth of 55 feet. This pile was tested in two series of loadings. The second series was carried to complete failure at 170 tons. However, the curve indicates beginning failure at 120 tons. This curve is used as a measure of comparison for the other piles. Figure 20b shows the test of a displacement pile in a jetted hole. The pile was tested before wetting the area and showed similar strength to that of the pile in the prewetted area. However, after the area was wetted, greater movements may be seen and failure occurred at a somewhat lower load.

Figure 20c shows the test of a displacement pile in a prebored hole. Although the strength of this pile was fair under dry conditions with an indication of beginning failure at 60 tons, the pile was considerably weaker when the area was wetted. The test indicates great movement under very light loads, particularly when compared to the pile driven in the prewetted area. Figure 20d shows a test for a pile placed by hard driving to only a shallow depth in dry loess. This pile showed high strength with only slight movement under dry conditions, but after wetting the area, complete failure was obtained under 60 tons. In summary, these tests show that great loss of strength can be anticipated if friction piles are driven in dry loess or placed in prebored holes in dry loess which is subsequently wetted.

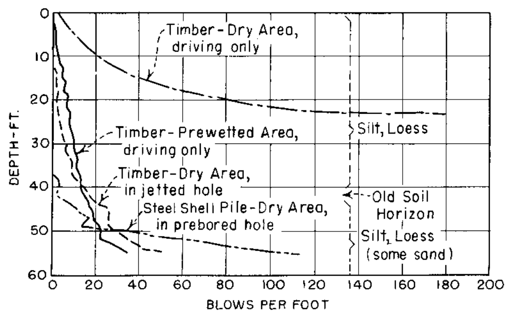
Load tests in Site 1, the end-bearing site, were all of high strength, indicating that firm bearing on the sand was entirely satisfactory for all placement methods. Nondisplacement steel H-piles in this area were found to be satisfactory, when embedded 5 feet into the bearing sand. Since it was possible to drive steel H-piles in dry loess and not displacement piles, a nondisplacement pile was considered the only type which was practical to place in dry loess by driving only.

Summary--Study of Piles in Loess

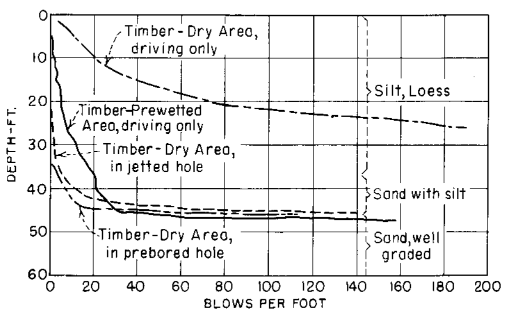
1. From this overall study, opinions of general requirements for piles and pile driving in loess have been summarized in Figures 21 and 22 on the basis of moisture content and density of the natural loess.

2. Friction piles in deep loess had considerable difference in load-carrying capacity, depending on their placement method.

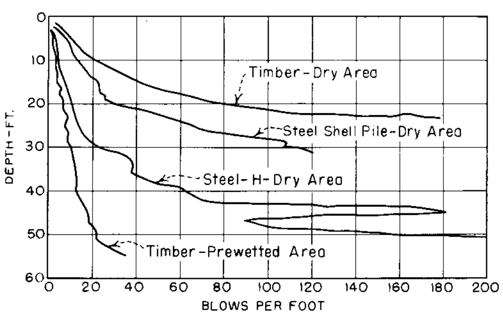
a. For displacement piles in loess which will be wetted in the future, pre-



(a) Driving records of displacement piles in Site 2, the friction pile site



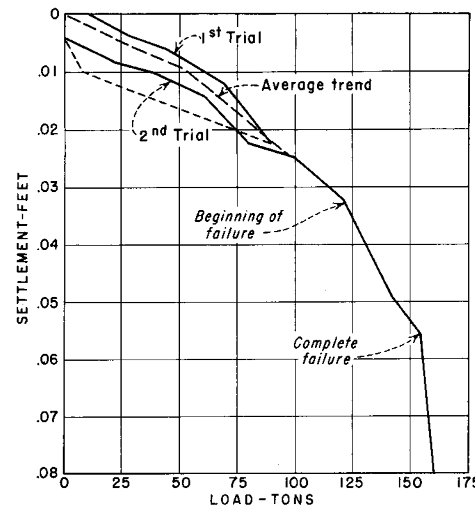
(b) Driving record of displacement piles in Site 1, the end-bearing site



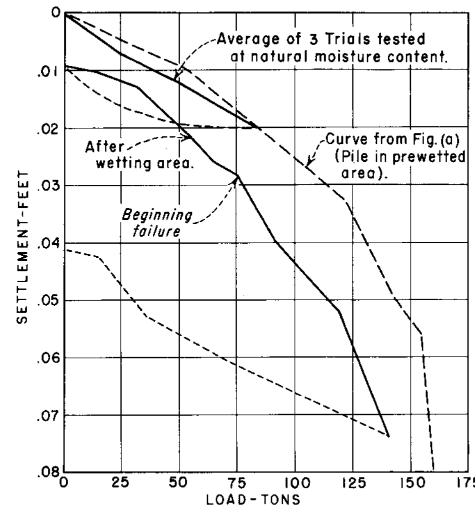
(c) Comparison of piles of different types placed by driving only in deep loess

DRIVING RECORDS

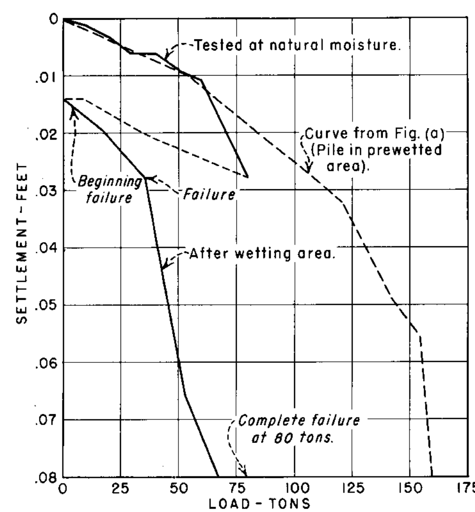
FIGURE 19



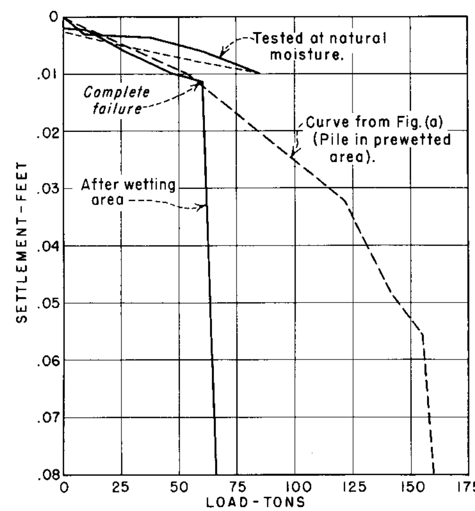
(a) Pile driven in prewetted area.



(b) Pile placed in jetted hole.



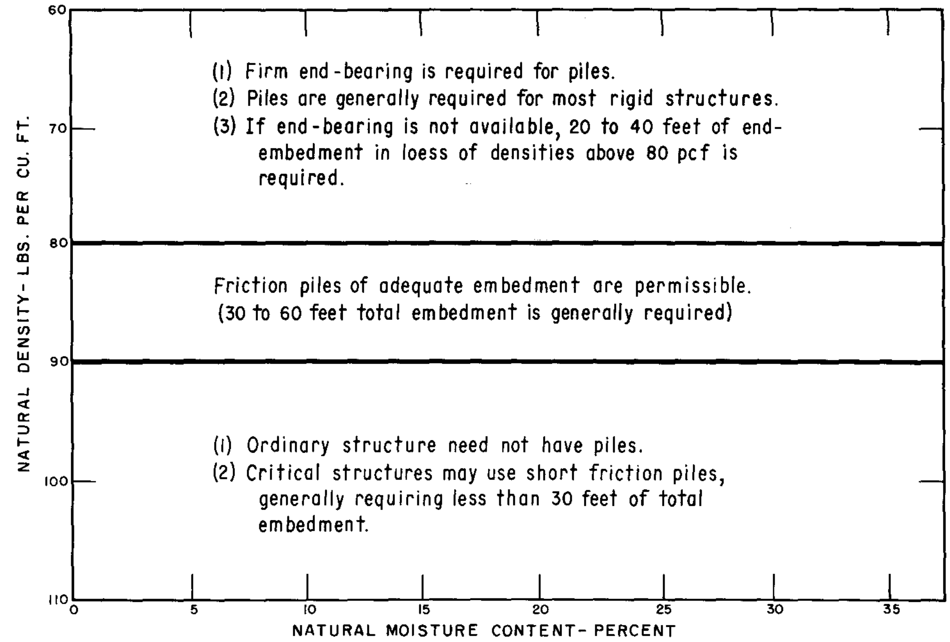
(c) Pile placed in dry prebored hole.



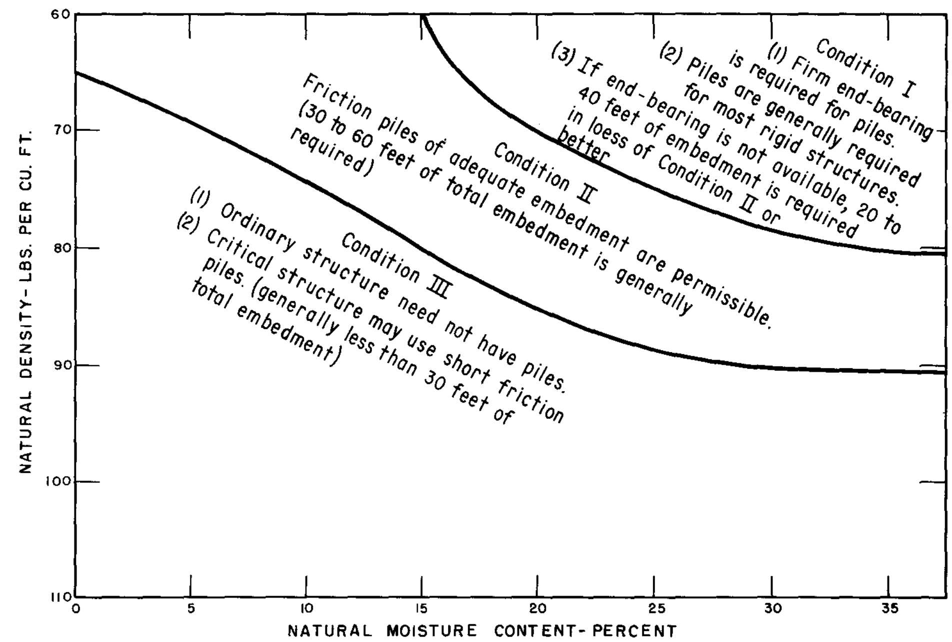
(d) Pile driven in dry natural material.

COMPARISON OF PILE LOAD TESTS FOR FRICTION PILES IN LOESS

FIGURE 20



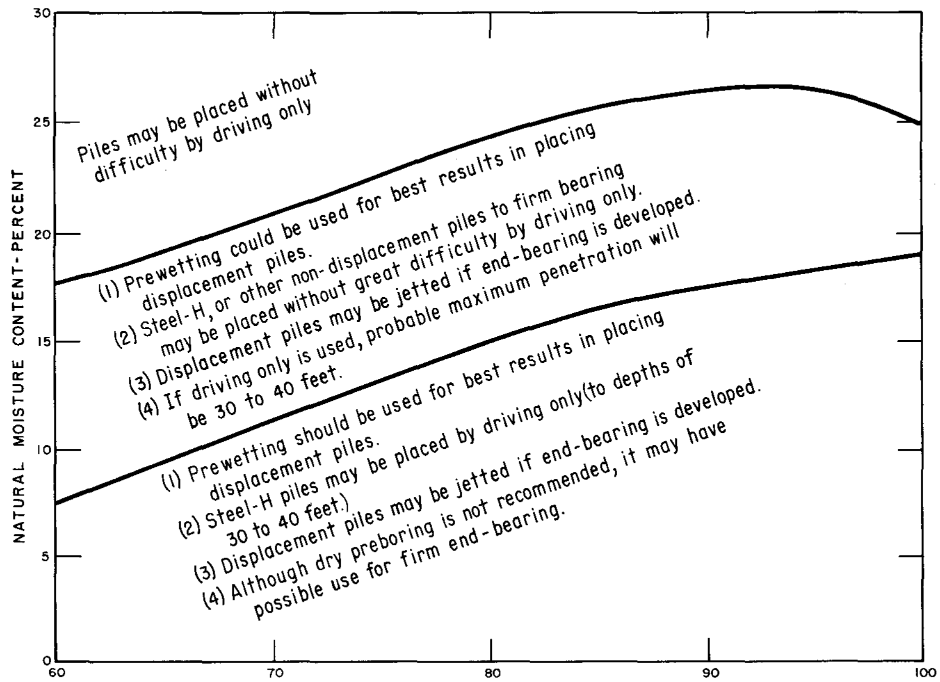
CASE 1. When higher moisture contents are anticipated.
(As in the case of hydraulic structures)



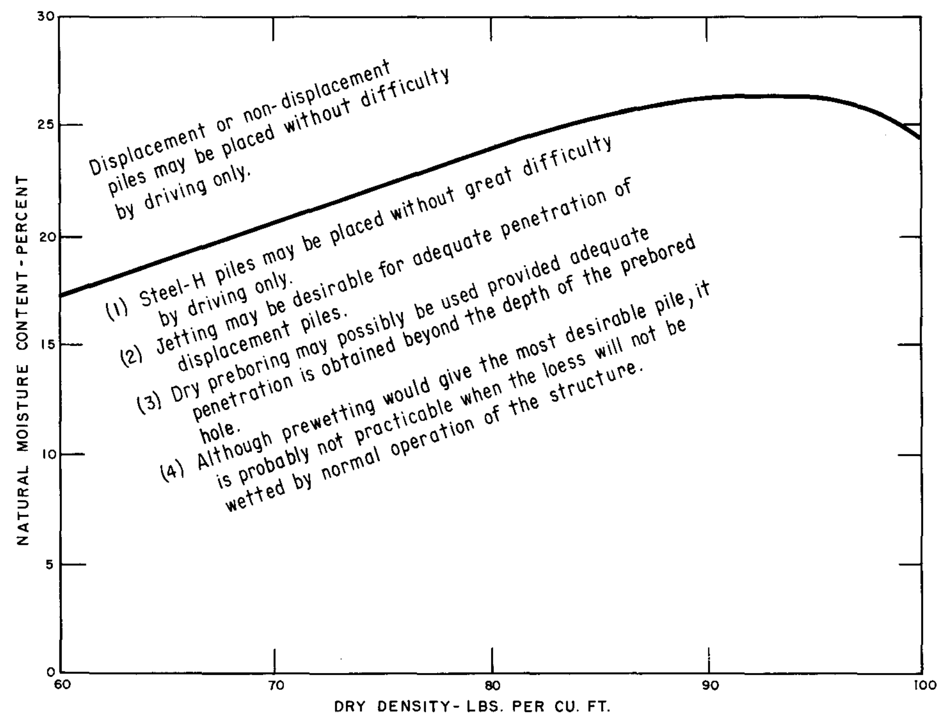
CASE 2. When natural moisture contents are not expected to increase.

REQUIREMENTS FOR ADEQUATE SUPPORTING CAPACITY OF PILES

FIGURE 21



CASE 1. When higher moisture contents are anticipated.
(As in the case of hydraulic structures)



CASE 2. When natural moisture contents are not expected to increase.

REQUIREMENTS FOR PRACTICAL PLACEMENT OF PILES

FIGURE 22

wetting the soil is recommended since highest strength will be obtained because of maximum consolidation of surrounding material.

b. Placing displacement piles in jetted holes may be possible in certain instances since holes smaller in diameter than the piles may be made and some wetting of the adjacent loess is obtained from the jet water.

c. Placing displacement piles in prebored holes in loess at low natural moisture content is not recommended since virtually no consolidation of surrounding material is obtained on driving, and in this case, after the foundation is wetted, a weak bond between the soil and the pile can be anticipated. In addition, considerable weakening of the loess surrounding the pile can be expected.

d. The use of displacement piles placed by driving alone in loess at low natural moisture content is not recommended, since driving is extremely difficult and adequate penetration cannot be obtained. Also, the load-bearing capacity after wetting the soil is low.

3. Nondisplacement steel H-piles can be driven in loess at low natural moisture content, but adequate embedment in permanently firm material is necessary since shearing resistance in loose wetted loess is quite low.

4. End-bearing piles resting on firm-bearing material such as dense sand were found to be satisfactory regardless of the placement method, provided they are snugly held for adequate lateral support.

5. Both types of displacement piles, timber and steel shell, had similar driving and loading characteristics. The strength limitations of the pile itself would mainly govern which pile would be desirable.

6. For piles placed in loess and assuming material underlying a pile foundation is competent, the following rules are recommended:

a. When loess is at densities below 80 pounds per cubic foot, piles must have firm end-bearing or a substantial amount of embedment of the ends in dense material of permanently high shearing resistance.

b. When loess is at densities from 80 to 90 pounds per cubic foot, friction piles will generally be satisfactorily supported only by adequate embedment in the loess, based on wetted conditions.

c. When loess is at densities greater than 90 pounds per cubic foot, moderately loaded structures may be supported without piles, and if piles are found necessary for critical structures, relatively short lengths may be used.

DENSITY OF LOESS AS A CRITERION OF SETTLEMENT

In the construction and operation of Bureau of Reclamation dams, reservoirs, and canals, the effects of saturation on the settlement of loess is of particular importance. A simple criterion for judging the susceptibility of loess to settlement is of value in predicting problem areas and the requirement for foundation treatment. Approximate limits of density have been used for the loess of the Nebraska-Kansas area, since other basic properties are generally similar. Extremely low-density loesses apparently subside under their own weight when they are subjected to saturation. Moderately low-density loess settles appreciably when subjected to loadings and saturation. These critical conditions of loess frequently occur because of low natural moisture contents and arid and semiarid climatic conditions.

Limiting values of density for various types of soil, which indicate the susceptibility of a soil to subsidence on saturation, can be defined using the following basic principles:

(1) The liquid limit represents the moisture content, based on a standard laboratory test, at which the soil is in a weak or approaching liquid condition.

(2) If the natural density of the soil is low enough that the porosity is more than that required for the liquid limit moisture content to saturate the soil, it is logical that the soil could develop this weakened condition and could be susceptible to subsidence as added moisture approached this amount.

(3) On the other hand, if the porosity of the natural soil is less than that required for the liquid limit moisture content, such as for a dense condition, it is logical that the soil could become saturated and still be in a plastic state and thus not subside unless loadings are great enough to compress it. (It may even expand if it contains expanding-type clay minerals.)

(4) Denisov, 9/, an investigator and author of publications on loessial soils in Soviet Russia, has used an equation which may be applicable in correlating density and liquid limit:

$$K_d = \frac{\text{Porosity at liquid limit}}{\text{Porosity at natural density}}$$

When the ratio, K_d, is less than 1, the soil has possibilities of subsiding on saturation.

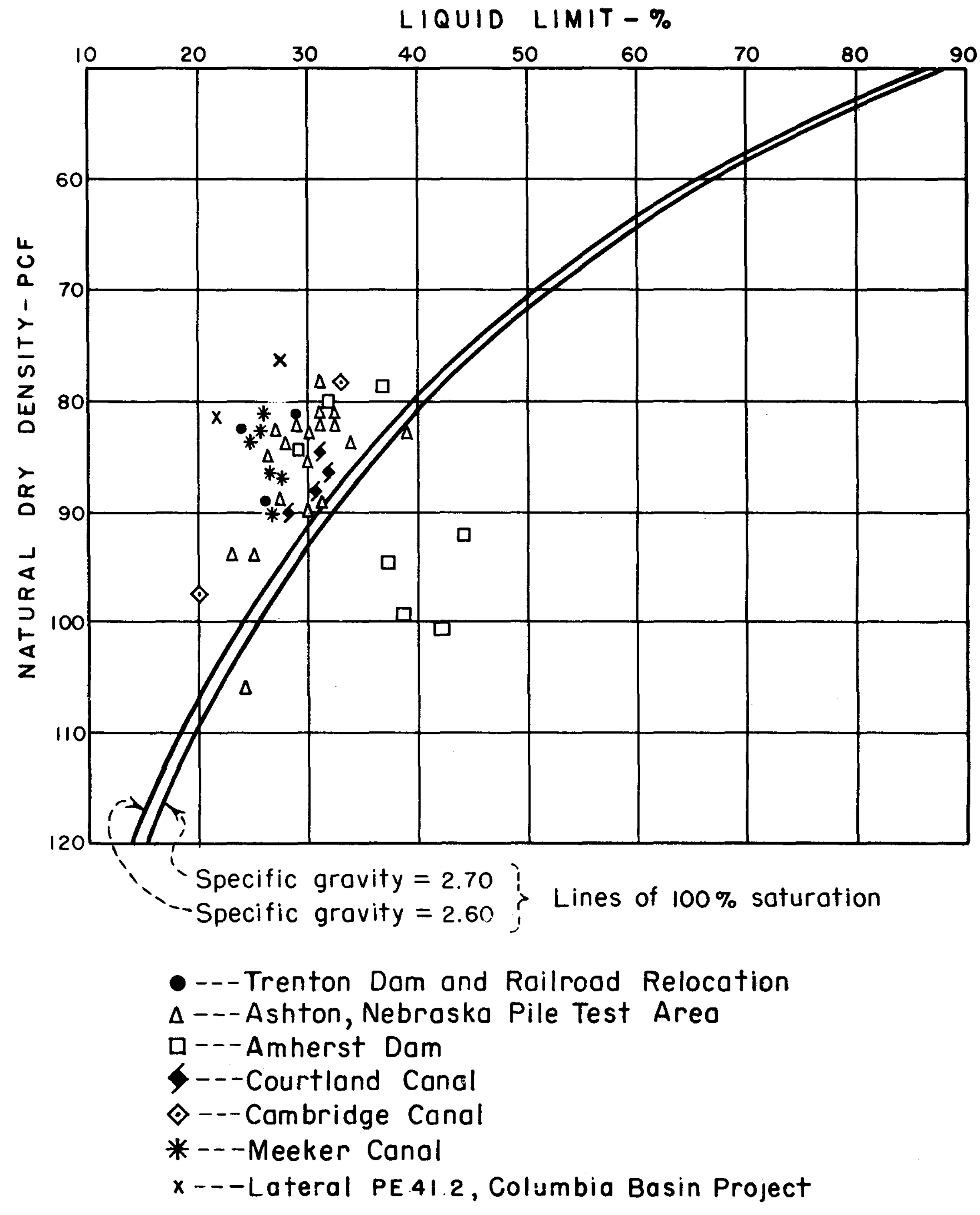
Based on the above principles, a chart or graph can be drawn with dry density versus liquid limit moisture content, as shown in Figure 23. The curves on this graph, as shown in the figure, represents the condition at which the porosity for a particular dry density equals the porosity at the liquid limit. For practical purposes the curves are considered as a single line, because the position of this line varies only slightly according to the specific gravity of the soil. Points above this line represent conditions easily susceptible to subsidence upon wetting, and the further the points are above the line, the more susceptible the soil is to subsidence. Soil with points below the line are not susceptible to subsidence unless loadings are applied to compress the soil.

In Figure 23, liquid limit data from Figure 6 are plotted for samples having natural density determinations. These data show that most natural density values of loessial soils fall above the dividing line. Also, as mentioned previously in regard to Figure 6, most liquid limit values of loessial soils fall between 25 and 35 percent.

On the basis of previous observations by Holtz and Gibbs 1/, without regard to the density-liquid limit relationship, it was concluded that the probability of extreme settlements of loessial soils was not great for densities above 90 pcf. In viewing the plot in Figure 23 for values of liquid limit between 25 and 35 percent, this conclusion is considered reasonable. Later experiments in ponding and field plate-load testing, Figures 13 and 12, respectively, indicated that loessial soils having densities between 80 and 90 pcf were weak and suceptible to appreciable settlement under loading, but they did not subside by wetting alone. It should be remembered, however, that this ponding may not have fully developed saturation that would occur in extended canal and reservoir operation. Such prewetting sufficiently weakens the soil to permit settlement to take place as relatively small structural loads are applied, as shown in Figure 12. Pile driving for pile foundations can easily be accomplished under such conditions. It has further been observed that loess with densities below 80 pcf is extremely susceptible to settlement upon saturation.

Subsidence has been observed on some canals in loessial soils. Figure 24 is a photograph of some subsidence that has occurred at a canal lateral on the Columbia Basin Project in Washington. The density and liquid-limit were determined on undisturbed samples in nonsubsided soil next to the subsidence that has occurred. These data are plotted in Figure 23 by x-points. Also shown in Figure 23 are data from Meeker Canal in Nebraska (asterisk points) where similar subsidence has occurred. The data fall well above the dividing line; three points were near the value of 80 pcf density, and all points were below 90 pcf. These soils are relatively low in liquid limit, having values from 22.0 to 27.5 percent which cause a density of 80 pcf, as shown in Figure 23 to be critical in respect to the average loessial soils.

It has been observed that the natural loesses of the Nebraska-Kansas area frequently have moisture contents below 10 percent. Pile tests and plate-load tests have shown that such loess resist very large loads without appreciable settlement. Ponding tests in the field and wetting of consolidation test specimens in the laboratory indicated that when moisture contents were raised to above 20 percent, appreciable settlements could easily take place under loading. However, as can be seen in Figure 23 about 35 percent moisture content or greater is needed to saturate low density loess. Therefore, increased moisture content is an important characteristic for permitting settlement to take place, but density is the primary feature which governs the susceptibility to settlement. The critical ranges of density values are governed by the type of soil which is indicated by the liquid limit.



NATURAL DENSITY VS. LIQUID LIMIT RELATIONSHIP FOR LOESSIAL SOILS

FIGURE 23

AN EXAMPLE OF SUBSIDENCE OF LOW-DENSITY SOIL AFTER SATURATION FROM CANAL OPERATION

FIGURE 24

CONCLUSIONS

Certain features which govern the soil mechanics and foundation properties of loess have been established in this monograph.

The basic properties of loess in the Nebraska-Kansas area are similar. This similarity has been noted in other locations. However, some trends of changing characteristics have been observed in relation to the distances of deposits from their probable source and in relation to climatic environments which prevail. The loess of the Nebraska-Kansas area is predominately silty (75 percent of all samples tested). There are some instances of more sandy loess and, on the other hand, some clayey loess. From a general soil mechanics viewpoint, loess appears to have rather uniform characteristics of gradation and plasticity.

Figure 23 is a chart on which natural density and liquid limit values can be plotted to aid in evaluating the susceptibility of a soil to settlement on saturation. The higher the plotted points are above the lines shown the more susceptible the soils are to subsidence on saturation. The critical values of density will vary according to the plasticity of the soil. However, silty loess is similar in its plasticity characteristics and the liquid limit values range from 25 to 35 percent. Because of this similarity in basic properties along with consolidation and strength studies, it is concluded that initial (in place) density is a good criterion for indicating the probability of settlement for structures. The following are recommendations of logical boundary values for density of silty loess. More sandy material will be somewhat more critical.

a. Silty loess having densities of less than 80 pounds per cubic foot is considered loose and highly susceptible to settlement upon wetting.

b. Silty loess having densities from 80 to 90 pounds per cubic foot is moderately loose to medium dense and is moderately susceptible to settlement, particularly for critical or heavily loaded structures. Extreme saturation may result in subsidence.

c. Silty loess having densities of above 90 pounds per cubic foot is somewhat dense and may be capable of supporting ordinary structures without serious settlement. Settlement will be of normal characteristics with loading.

d. A more general criterion has been used for earth dams in which 85 pounds per cubic foot is used as the division between low and high density loess or the division where special foundation treatment is required for lower densities.

Because loess is predominately a silty soil and has at least a small amount of clay, there is pronounced adjustment in particle-to-particle strength as a result of adjustment in moisture content. In the Nebraska-Kansas area, natural moisture contents are frequently below 10 percent, and the natural loess is frequently capable of supporting very large loads. However, when moisture contents are raised due to wetting, as in foundations of hydraulic structures, the minimum shear-strength conditions and full settlement with load should be expected. The following are recommendations of boundary values for moisture content:

a. Moisture contents below 10 percent are considered very dry and maximum dry strength and high resistance to settlement should be expected.

b. Moisture contents from 10 to 15 percent are considered somewhat dry, giving moderately high strength.

c. Moisture contents from 15 to 20 percent are approaching moist conditions.

d. Moisture contents above 20 percent are considered somewhat wet to moist, and will generally permit full consolidation to occur under load.

e. Experience has shown that moisture contents of near 25 to 28 percent can easily be obtained by surface ponding, and about 35 percent moisture (depending on density) is required for complete saturation.

Certain shear characteristics have been established:

a. Dry loess at natural moisture contents of less than 10 percent generally has inherent shear strengths resembling cohesion which permit natural loess to stand on very steep slopes for considerable heights, although it may be of low density. This cohesive strength is apparently due to the small amount of clay which gives the loess a particle-to-particle bond. This cohesive strength has been observed to be as much as 15 psi. Generally, it is about 5 to 10 psi for the Nebraska-Kansas loess. The slope of the shear resistance curve (tan ϕ) is about 0.60 to 0.65. Such values of cohesion and tan ϕ permit loess to stand on steep (or nearly vertical) slopes 50 to 80 feet high.

b. Wetted loess is greatly reduced in strength. Experience shows that cohesion is generally reduced to less than 1 psi when the loess is wetted and even for initially dense loess, it becomes less than 4 psi. An important finding in these studies is that high pore pressure develops in wetted loess as consolidation takes place, and therefore the development of the additional shear resistance resulting from friction may be restricted until drainage takes place. Drainage may be sufficiently slow to cause lateral movement of embankment foundations during normal construction periods.

Acknowledgment

Much of the petrographic and geologic narrative was written from original notes and work compiled by members of the Petrographic Laboratory Section, in particular the late M. E. King.

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