1985

Liquid silts - their occurrence and distribution in loess

Robert Odell Lamb
Iowa State University

Recommended Citation

Lamb, Robert Odell, "Liquid silts - their occurrence and distribution in loess " (1985). *Retrospective Theses and Dissertations*. 7866.
https://lib.dr.iastate.edu/rtd/7866

INFORMATION TO USERS

This reproduction was made from a copy of a document sent to us for microfilming. While the most advanced technology has been used to photograph and reproduce this document, the quality of the reproduction is heavily dependent upon the quality of the material submitted.

The following explanation of techniques is provided to help clarify markings or notations which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting through an image and duplicating adjacent pages to assure complete continuity.
2. When an image on the film is obliterated with a round black mark, it is an indication of either blurred copy because of movement during exposure, duplicate copy, or copyrighted materials that should not have been filmed. For blurred pages, a good image of the page can be found in the adjacent frame. If copyrighted materials were deleted, a target note will appear listing the pages in the adjacent frame.
3. When a map, drawing or chart, etc., is part of the material being photographed, a definite method of "sectioning" the material has been followed. It is customary to begin filming at the upper left hand corner of a large sheet and to continue from left to right in equal sections with small overlaps. If necessary, sectioning is continued again—beginning below the first row and continuing on until complete.
4. For illustrations that cannot be satisfactorily reproduced by xerographic means, photographic prints can be purchased at additional cost and inserted into your xerographic copy. These prints are available upon request from the Dissertations Customer Services Department.
5. Some pages in any document may have indistinct print. In all cases the best available copy has been filmed.

University
Microfilms
International

300 N. Zeeb Road
Ann Arbor, MI 48106

8514418

Lamb, Robert Odell

LIQUID SILTS - THEIR OCCURRENCE AND DISTRIBUTION IN LOESS

Iowa State University PH.D. 1985

University
Microfilms
International 300 N. Zeeb Road, Ann Arbor, MI 48106

Liquid silts - their occurrence and distribution in loess

by

Robert Odell Lamb

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

Department: Civil Engineering
Major: Geotechnical Engineering

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major Department

Signature was redacted for privacy.

For the Graduate College

Iowa State University
Ames, Iowa
1985

TABLE OF CONTENTS

INTRODUCTION

General

Soils believed to be of aeolian origin and composed predominantly of particles classified as silts (0.074 to 0.002 mm grain size) are designated "loess". Loess deposits are found in regions throughout the world, one major region being in the midwestern United States. Loess is the surficial sediment covering approximately 66% of the state of Iowa. These soils are best known to engineers for their ability to remain stable in high, near-vertical cuts and for their tendency to exhibit rapid reduction in volume upon saturation. These characteristics are not typical of all loessial soils, but have prompted much of the research on loess. Little attention has been given to other aspects of loessial soil behavior, including the potential for expansion upon wetting of some of these soils. It is not surprising, then, that discovery of a "mushy" sometimes flowing, soil at depth in unsupported boreholes in loess deposits would attract the attention of researchers.

The term "loess mush" has been given to this soft, sticky, high water content soil that on occasion has squeezed into boreholes, inhibiting sampling. There are few published accounts of soils like this being encountered in boreholes in loess, which would imply either that the condition is not widespread, or that it has been encountered but not reported. There is also the possibility that the condition is related to seasonal water table fluctuations so that it does not always exist at a given site.

The significance of the behavior of such a soil from an engineering standpoint is in the considerably reduced undrained shear strength and increased compressibility that it is likely to exhibit. This is of particular importance if the "mush" condition is of a transient or seasonal nature where it might not be discovered during a site investigation but may appear later after some alteration of stresses has occurred as a result of construction. The soil might also exhibit a tendency to liquify when subjected to dynamic loads, making the condition of paramount concern in earthquake-prone regions where loess soils predominate.

The term "loess mush" is very descriptive. However, Handy [13] has suggested that "liquid silt", being more general, would be the preferred appellation since mush-like conditions no doubt occur in other silty soils. There are, for instance, soft, silty clays belonging to the general category of soils called soft clays. These soils are known to have formed in fluvial, lacustrine, glacio-lacustrine, and deltaic environments; and in bays, lagoons, tidal flats and marshes. The liquid silts discussed herein occur in a geologic setting that is much different from those of the other soft soils: the liquid silts have been found in relatively uniform loess deposits occupying upland positions.

Previous Investigations

Hallberg et al. [12] appear to be the first to report having encountered "loess mush". They describe the material, hypothesize in regard to its consolidation state, and present quantitative data regarding the soil index properties. Their soil profile with supporting engineering data is shown in Figure 1. They describe the liquid silt as being of a consistency "...somewhere between play-dough and thick gravy." They suggest the liquid silt is underconsolidated and note that the natural water content is in excess of the liquid limit water content.

Lutenegger [21] reports "mush" and "semi-mush" conditions in soils sampled at 12 different sites in east-central Iowa and northern Missouri. A summary of data from all previously reported "semi-mush" and "mush" soils is provided in Table 1, and the general locations of all sites known to exhibit these conditions is shown in Figure 2.

Ruhland [27] created a "mush" condition artificially in the laboratory by placing air-dry loess in a vertical plastic tube with the lower portion immersed in water. The model was designed to simulate a 5.49 m (18.0 ft) thick loess deposit with a perched water table at its base related to a stiff, impermeable substrata. A drawing of the apparatus is shown in Figure 3, with test results given in Figure 4. He concluded that the conditions necessary for development of "loess mush" are

(i) Maximum in-situ dry unit weight of 14.61 kN/m^3 (93 lb/ft^3),

(ii) Minimum loess thickness of 2.44 m (8.0 ft), and

(iii) Presence of perched water table at the base of the loess.

With these conditions being met, "loess mush" will occur, according to Ruhland, if the water content is at or above the soil liquid limit water content.

By comparing in-place water content to liquid limit water content as a criterion for identifying the liquid silt condition, one can see in Figure 4 that a broad zone of the material developed in the lower portion of the capillary fringe, extending below the water table.

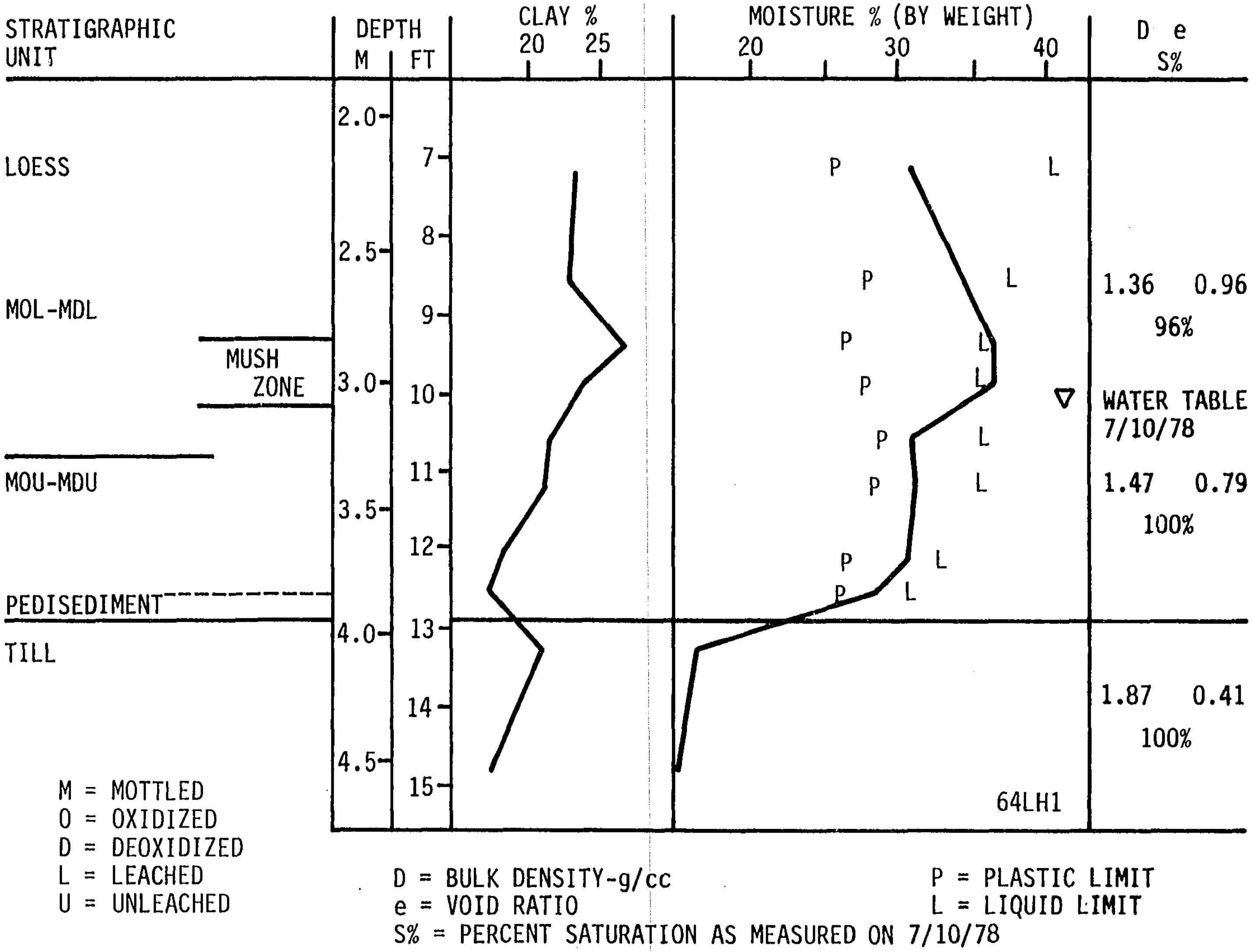


Figure 1. Geotechnical data from site 64-LH1 (from Hallberg et al.[12])

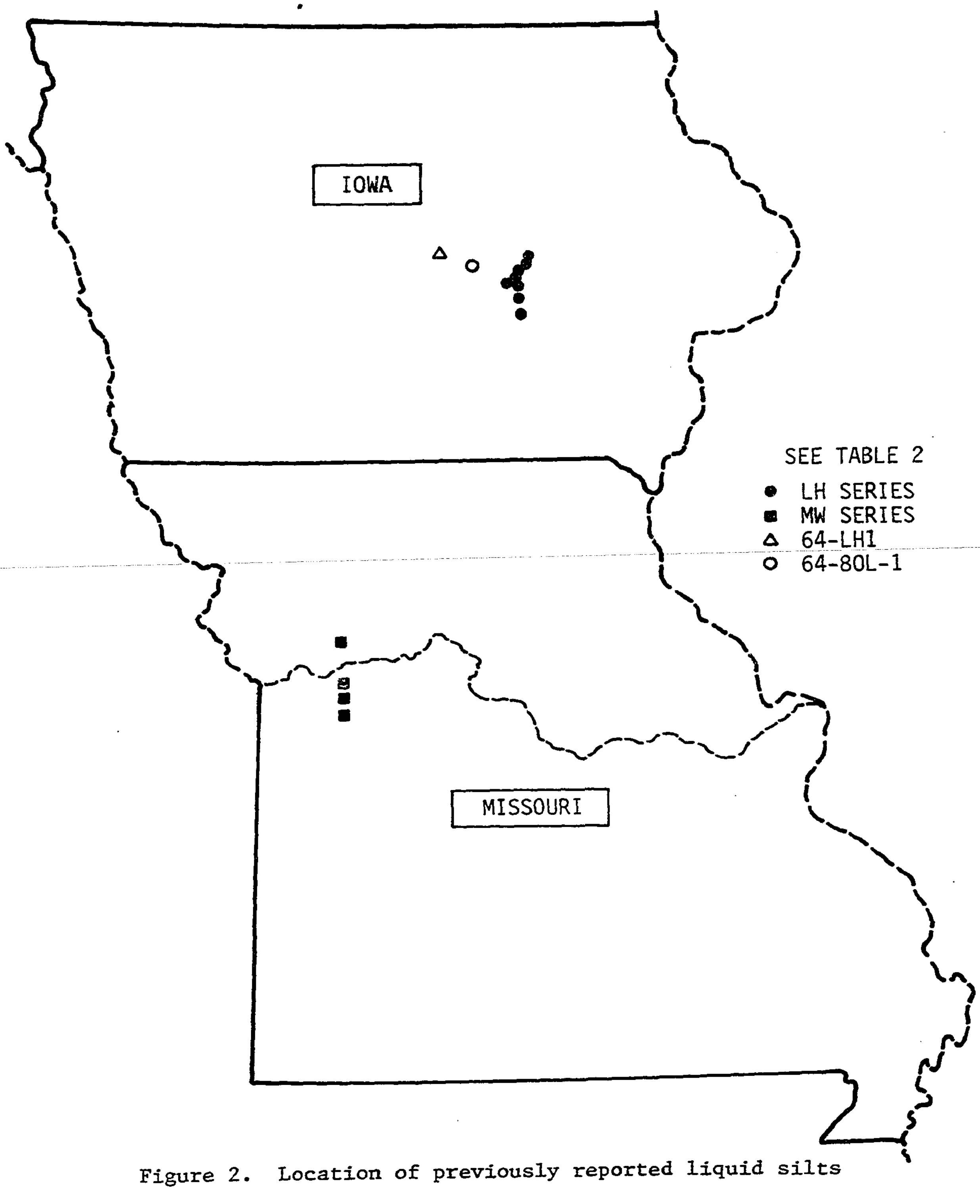


Figure 2. Location of previously reported liquid silts

Table 1. Summary of properties of liquid silts from previous investigations

Site	Depth m	Weathering Zone	Water Content %	Dry Density kg/m^3	Solids Specific Gravity	Void Ratio e
1LH	3.30-3.76	MDU	---	---	---	---
2LH	5.56	OU	28.1	1500	---	0.805
3LH	2.94-3.05	MOU	25.0^a 22.1^a	1390^a 1400^a	---	---
5LH	2.69-2.74	OL	29.6^a	1420^a	---	---
6LH	3.86-4.17	MOL	---	---	---	---
7LH	2.64-2.72	MDU	25.9^a 26.3^a	1550^a 1550^a	--- ---	--- ---
10LH	3.05-4.17	OL	---	---	---	---
12LH	2.24-2.79	MDL	32.5	1400	---	---
2MW	5.18-5.46	DL	26.1^a 23.2^a	1550^a 1550^a	--- ---	--- ---
7MW	2.54-2.62	MOL	27.7^a	1500^a	---	---
8MW	2.11-3.68	OL	27.5^a	1510^a	---	---
8MW	4.95-5.03	OL	---	---	---	---
9MW	1.82-1.85	MOL	29.1^a	1480^a	---	---
9MW	2.52-2.59	MOL	28.1^a	1500^a	---	---
64-LH1	2.8 3.0	MOL-MDL MOL-MDL	36 36	1360^a ---	--- ---	0.96^a ---

[a] Indicates values from closest sample above and/or below depth shown.

Saturation %	LL	PL	LI	Sand	Silt	2μm clay
---	---	---	---	0.4	79.3	20.3
94.5	---	---	---	0.4	80.3	19.3
72.1[a]	---	---	---	0.8[a]	79.1[a]	20.1[a]
64.4[a]	---	---	---	0.4[a]	79.4[a]	20.2[a]
88.6[a]	---	---	---	0.3[a]	75.0[a]	24.7[a]
				0.3[a]	76.2[a]	19.7[a]
---	---	---	---	1.2[a]	75.8[a]	24.7[a]
				1.4[a]	78.9[a]	19.7[a]
93.9[a]	---	---	---	0.4[a]	76.5[a]	23.1[a]
96.3[a]	---	---	---			
---	---	---	---	1.3	76.1	22.6
95.5	---	---	---	1.3	76.8	21.9
93.9	---	---	---	0.8[a]	81.4[a]	17.8[a]
84.5[a]	---	---	---	0.6[a]	81.5[a]	17.9[a]
92.3[a]	---	---	---	1.8	81.9	16.3
95.3[a]	---	---	---	0.3	80.5	19.2
---	---	---	---	0.8[a]	82.5[a]	16.7[a]
				1.1[a]	79.4[a]	19.5[a]
95.2[a]	---	---	---	0.7[a]	72.3[a]	27.0[a]
94.5[a]	---	---	---	10.4[a]	69.5[a]	20.1[a]
96[a]	36	26	1.0	2.0	72	26
---	36	28	1.0	2.0	74	24

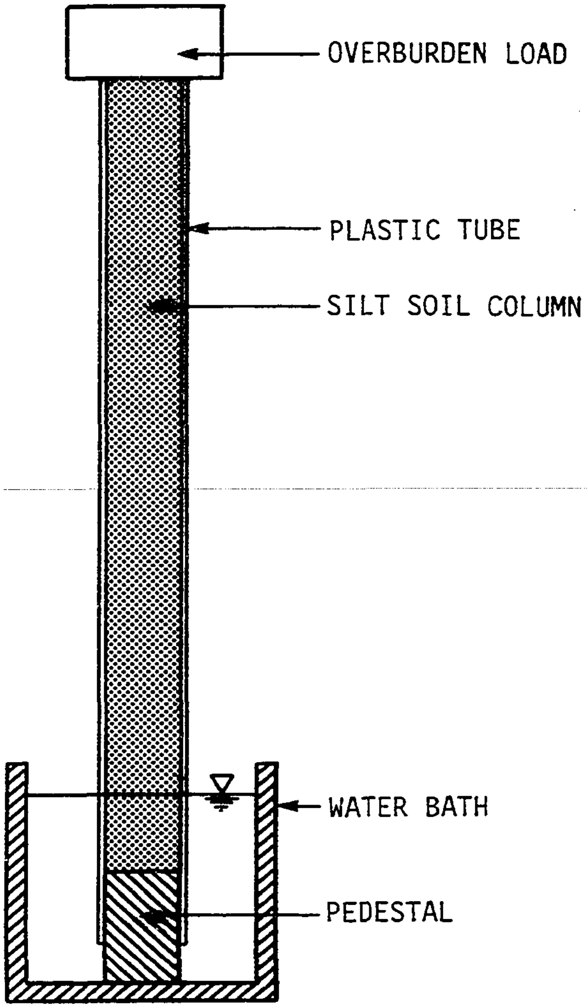


Figure 3. Silt column apparatus (from Ruhland [27])

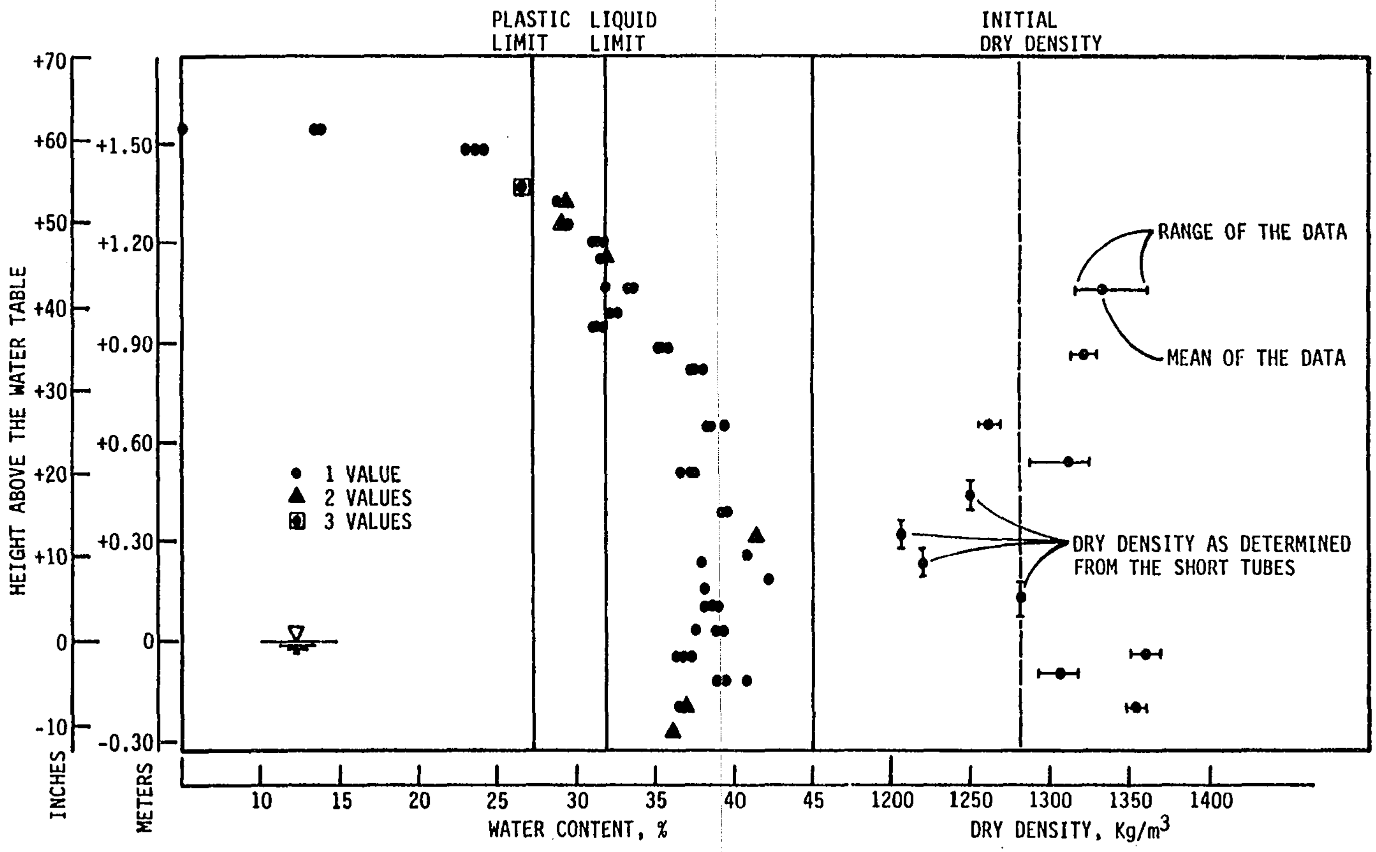


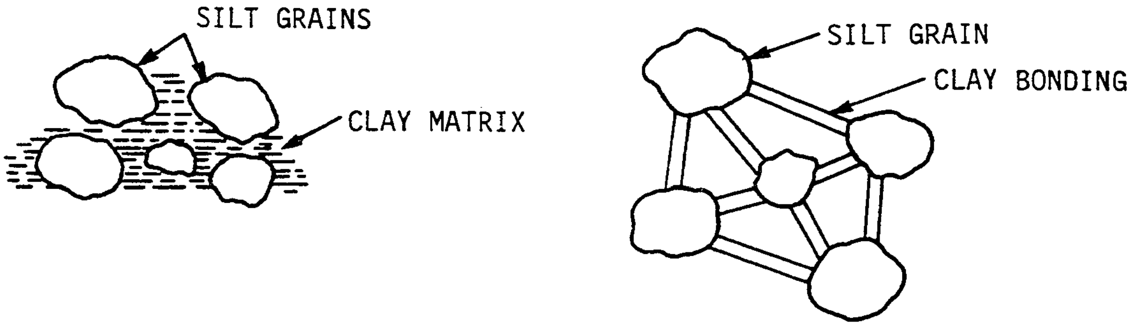
Figure 4. Geotechnical data from laboratory model (after Ruhland [27])

Perez [25] believes that this condition results from expansion of clay minerals upon wetting, giving a saturated, low-density, honeycombed soil fabric as shown in Figure 5. Her interpretation is based on Ruhland's density data (see Figure 4) that show a decrease in dry density after capillary saturation occurred.

Perez was concerned with the consolidation state of the liquid silt because it has properties very similar to loess that is known to be collapsible. Specifically, the clay content, consistency limits, and dry density of the liquid silt are of the same magnitude as those of medium-density collapsible loess. She was interested in showing whether the liquid silt would collapse since such a tendency would indicate the existence of some mechanism capable of sustaining, even after saturation, the metastable soil fabric responsible for the collapse phenomena. Numerous one-dimensional consolidation tests were conducted on undisturbed liquid silt specimens, and there was no evidence of collapse.

Lobdell [19] performed similar tests on loess from the state of Washington, called Palouse loess, believed initially to be collapsible. He found that this soil, with a dry unit weight ranging from 14.61 to 14.50 kN/m^3 (93 to 98 lb/ft^3) and degree of saturation of 85% to 96%, was not collapsible.

The fact that neither of these loessial soils is collapsible is perhaps directly related to findings of Leonards and Altshaeffl [18] as summarized by Altshaeffl [1], who notes that "any clayey soil can collapse under load when wetted if it is partly-saturated at the time of wetting." Collapse potential is therefore related to degree of



A) AIR DRY SILT AND CLAY DURING DEPOSITION

B) SATURATED EXPANDED SILT-CLAY

Figure 5. Mechanism of formation of liquid silt structure (from Perez [25])

saturation -- clayey soils that are at or near saturation under existing loads will not collapse under additional loads.

Summary

The occurrence of zones of liquid silt within loess deposits is relatively wide-spread as shown by Lutenegger's work [21]. Liquid silt and semi-liquid silts were found in east-central Iowa and northern Missouri. Ruhland [27] compiled data from the sites as found by Lutenegger [21] and Hallberg et al. [12] and suggested that liquid silts could be found in loess deposits of 2.44 m (8.0 ft) or greater thickness overlying impermeable glacial tills or paleosols, provided the dry unit weight of the loess is less than 14.61 kN/m^3 (93 lb/ft^3) and the natural water content is at or greater than the liquid limit water content. Perez [25] showed that the liquid silts are not collapsible and suggested that expansive clay minerals play a key role in their formation.

PRESENT INVESTIGATION

Objectives and Scope

At present, only qualitative information is available for identifying liquid soils. As a result, the exact same soil might be identified as a liquid silt by one investigator and a semi-liquid silt by another. Therefore, one objective of the present work is to develop guidelines for the identification and classification of liquid silts. The primary objective, however, is to gain sufficient understanding of the conditions leading to their occurrence so that their distribution may be predicted with some degree of certainty.

This research has been limited to soils in Iowa, where intensive sampling has been performed at sites known to exhibit liquid silts. Results of detailed laboratory testing on specimens obtained from these samples have enabled predictions to be made of the area in Iowa most likely to exhibit this condition. A proof of the hypothesized distribution would be provided by sampling soils elsewhere within the projected area to confirm the existence of liquid silts, but this work has not been done as a part of this research.

General Procedures

Samples were obtained at four sites. As noted earlier, these sites had been reported to have semi-liquid or liquid silt conditions. Sampling was performed in a manner to give a continuous vertical column of soil representing the entire profile from just below the solum to well below the zones of liquid silt. A piezometer was installed at each site to monitor ground water elevations over the period during which sampling occurred (See Appendix D). The effect of fluctuating ground water on the liquid silt formation at each site was studied by obtaining soil samples when the water table was at its highest and lowest recorded levels.

Standard laboratory tests were performed on specimens obtained from these samples. The tests included particle size distribution, consistency limits, specific gravity, water content, bulk density, and one-dimensional consolidation. Numerous specimens were tested so that characteristics and properties of the liquid silt could be identified.

Site Descriptions

The general locations of the four sampling sites are shown in Figure 6, and details of each of the sites are given in Appendix A. Three of these sites are ones previously described by Hallberg et al. [12] or Lutenegger [21]. The fourth site, described by Kemmis et al. [16] had been reported informally to have a liquid silt zone. The general location of these sites and their correspondence to those reported by others are indicated in Table 2. The sites are similar in that each has Wisconsin-age loess overlying glacial till.

State Center

This site, described by Kemmis et al. [16], is near the terminus of the Des Moines lobe formed during Wisconsin-age continental glaciation. Loess here is 7.41 m (24.3 ft) thick over a paleosol formed in older glacial till. The water table, perched above the paleosol, fluctuated from a depth of 1.65 to 2.90 m (5.4 to 9.5 ft) during the 12-month

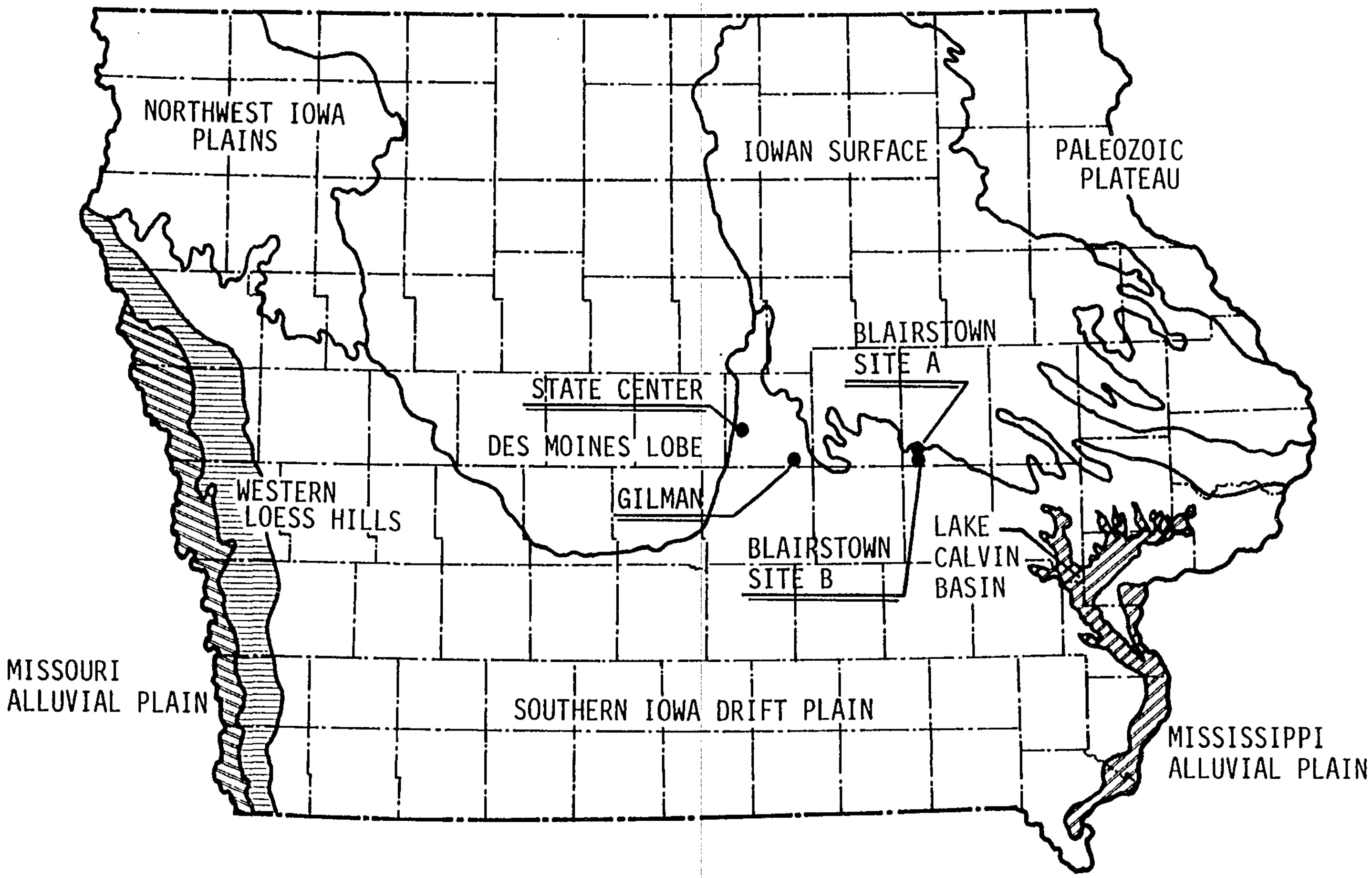


Figure 6. Location of study sites

Table 2. Reported Liquid Silt Sites

Site	Location		Reference	Corresponds to Site
	County	State		
1LH	Benton	Iowa	[21]	Blairstown Site B
2LH	Iowa	Iowa	[21]	
3LH	Iowa	Iowa	[21]	
5LH	Iowa	Iowa	[21]	
6LH	Iowa	Iowa	[21]	
7LH	Keokuk	Iowa	[21]	
10LH	Benton	Iowa	[21]	Blairstown Site A
12LH	Iowa	Iowa	[21]	
2MW	Carroll	Missouri	[21]	
7MW	Lafayette	Missouri	[21]	
8MW	Lafayette	Missouri	[21]	
9MW	Lafayette	Missouri	[21]	
64-80L-1	Marshall	Iowa	[16]	
64-LH1	Marshall	Iowa	[12]	
Blairstown A	Benton	Iowa		10LH
Blairstown B	Benton	Iowa		12LH
Gilman	Marshall	Iowa		64-LH1
State Center	Marshall	Iowa		64-80L-1

period of observation. A zone of liquid silt was found at a depth of between 1.83 to 2.59 m (6.0 to 8.5 ft).

Gilman

This is the site that Hallberg et al. [12] first reported as having "loess mush." It has 3.90 m (12.8 ft) of loess over an eroded till plain, known regionally as the Iowan erosion surface. A zone of semi-liquid silt was found here at a depth of between 3.35 and 3.96 m (11.0 to 13.0 ft). The water table fluctuated from a depth of 3.66 to 5.79 m (12.0 to 19.0 ft).

Blairstown Site A

This site is on a loess-mantled upland immediately adjacent to and rising abruptly above the "classic" Iowan erosion surface. Depth of the loess here is reported by Lutenegger [21] to be in excess of 8.69 m (28.5 ft). Liquid silt exists from a depth of 2.59 to 3.51 m (8.5 to 11.5 ft). The water table fluctuated considerably, varying from a minimum depth of 1.98 m (6.5 ft) to a maximum depth of 5.12 m (16.8 ft).

Blairstown Site B

Blairstown Site A and the "classic" Iowan erosion surface are located only 3.22 km (2.0 mi) directly north of this site which, according to Lutenegger [21], has 5.27 m (17.3 ft) of loess over a paleosol formed in glacial till. Depth to the water table varied from 2.44 to 4.60 m (8.0 to 15.1 ft), meaning it fluctuated from above to below the semi-liquid silt zone, which was found at a depth of 2.74 to 3.51 m (9.0 to 11.5 ft).

Sampling

Undisturbed samples were obtained in accordance with the American Society for Testing and Materials (ASTM) designation D 1587 [2] using an hydraulically advanced open-tube sampler fitted with a 76.2 mm (3.00 in) diameter thin-walled sample tube. Immediately after being withdrawn from the borehole, each sample tube was removed from the sampler and sealed at both ends. Samples were retained in the tube for transport from the field to the laboratory, where they were extruded within 24 hours of sampling and sealed in two layers each of plastic film and heavy duty aluminum foil. They were then stored in a room maintained at 100 percent relative humidity until removed for testing purposes.

Testing

Index properties and characterization

As the samples were extruded from the sampling tubes, they were tested for carbonate content by placing droplets of dilute hydrochloric acid at intervals along the sample length. Effervescence was deemed to indicate the presence of carbonates.

Discs of soil were carefully cut from the cylindrical samples at regular intervals using a sharp, clean stainless steel ring of known dimensions. The masses of these soil discs were determined before and after the discs were dried to constant weight in an oven maintained at 105°C (220°F). Wet, total, or bulk density and natural moisture content were computed from these volumetric and gravimetric measurements.

Consistency limits and specific gravity of the soil solids were determined from trimmings made while cutting the soil discs. These tests were in accordance with ASTM designations D 854, D 423, and D 424 [2].

Soil particle size distribution was determined using the pipette method described by Lutenegger [21] and Walter et al. [34].

Pertinent soil properties and related characteristics determined from results of these tests are contained in Appendix B.

One-dimensional consolidation

Oedometer tests were performed to determine the loading history and confined compression behavior as aids in interpreting the formation of liquid silts. Perez [25] performed one-dimensional consolidation tests on soil specimens from State Center and Blairstown Site A, and additional tests were performed as a part of the present research. Results of relevant tests performed by Perez are included herein.

The procedures outlined in ASTM designation D 2435 [2] were followed for these tests with the exception that seating pressures smaller than those recommended by ASTM were found necessary. This is because the material was so soft that it tended to squeeze from around the upper porous stone when the initial loads in the series suggested in ASTM D 2435 were applied. Specimens of 63.5 mm (2.50 in) diameter and approximately 19.1 mm (0.75 in) thickness were tested in a fixed-ring consolidometer. Plots of void ratio versus common logarithm of pressure for the series of tests obtained at various depths from borehole 5 at Blairstown Site A are given in Figure 7. Additional data are provided in Appendix C.

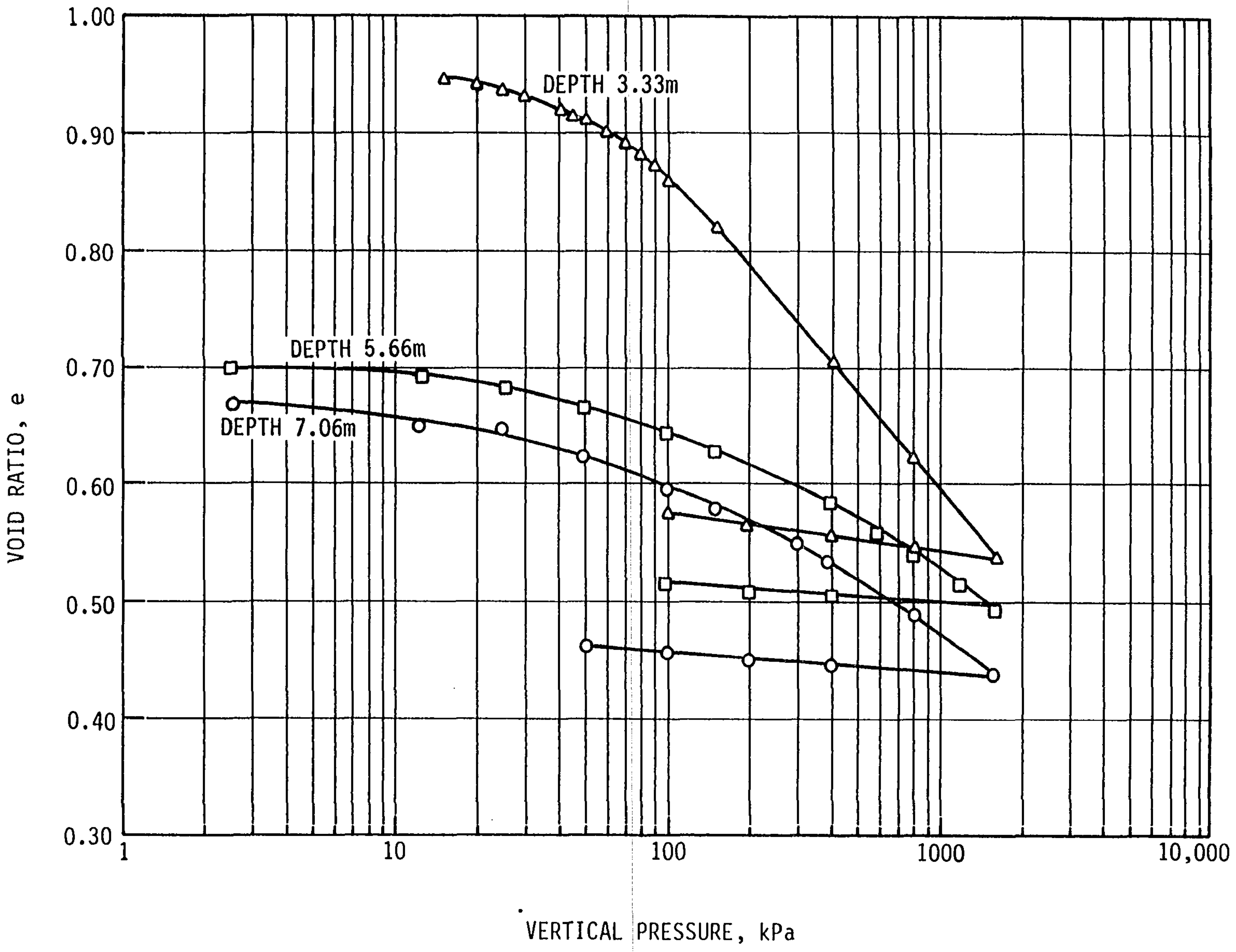


Figure 7. One-dimensional consolidation test results for borehole 5 at Blairstown Site A

Pre-consolidation pressures were estimated using both Casagrande's [6] and Schmertmann's [28] techniques. All specimens were found to be normally consolidated.

X-ray diffraction

As will be discussed later, a significant increase in void ratio or increase in unit weight, occurs immediately below the liquid silt zone at all four sites sampled. X-ray diffraction analyses were used to determine whether the clay mineralogy changes at this point, with the liquid silts perhaps having higher expansive clay mineral contents than the underlying soils. Particle size analysis revealed that there is only a nominal 5 percent change in total clay content (see Appendix B).

X-ray diffraction patterns for samples obtained at depths of 2.59, 3.00, 3.26, and 4.85 m (8.5, 9.8, 10.7, and 15.9 ft) from borehole 5 at Blairstown Site A are shown in Figure 8. These plots show peak intensity versus diffraction angle for fractionated soil samples, both air-dry and glycolated. Specimens were prepared using the procedure suggested by Carroll [5]. Fractionation was achieved using a sedimentation process whereby a dispersed sample of soil was allowed to settle for a specified time in a distilled water sedimentation column. A slurry was obtained by concentrating in a centrifuge the soil-water solution decanted from the sedimentation column. Droplets of the slurry were allowed to air dry on a glass slide to create a specimen for X-ray diffraction analysis. A vapor pressure glycolation process was employed.

The X-ray diffraction data show that the clay minerals montmorillite, illite, and kaolinite are present in all the samples. A qualitative

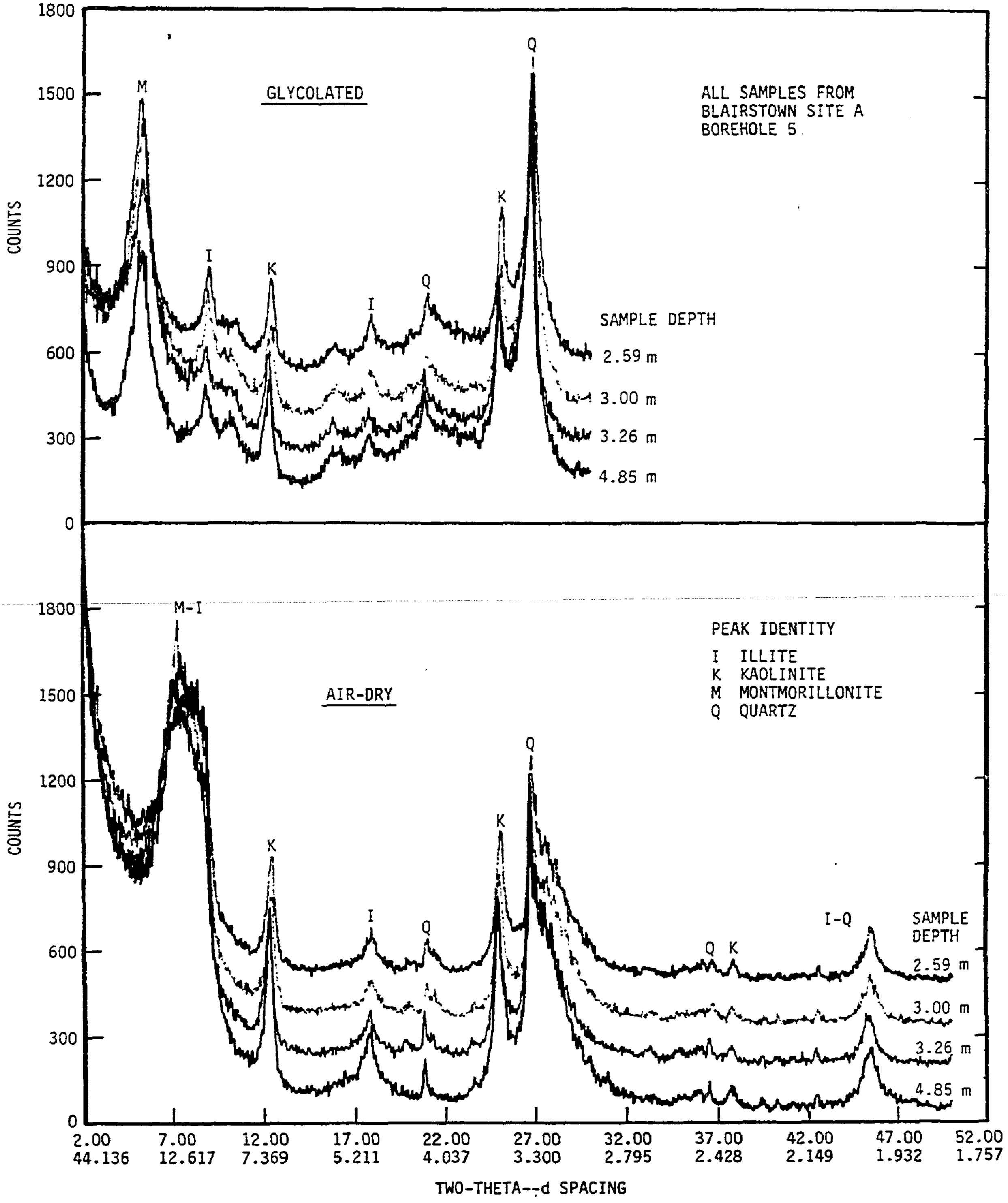


Figure 8. X-ray diffraction patterns

estimate of the relative amount of each of the minerals, based on peak intensities of the diffraction patterns, reveals that montmorillonite is probably the most abundant clay mineral.

Thermogravimetry

Liquid silts were found to be associated with loess soils that have been leached of carbonates. The usual method of determining whether soils are leached or unleached gives only qualitative results, which suffices for identifying the extent of soil weathering as it is affected by leaching. But more precise measures of carbonate content are necessary to determine the degree to which carbonates have been removed. Thermogravimetric analysis was used for this purpose.

Differential thermographs and simultaneously recorded thermogravimetric data for three samples from borehole 5 Blairstown Site A are shown in Figure 9. The presence of carbonate is indicated by the simultaneous change in mass and temperature that occurs between approximately 675–825°C. These changes in both mass and temperature result from formation of calcium oxide and evolution of carbon dioxide. The sample from 2.99 m (9.5 ft) depth did not contain any measurable carbonate whereas the samples from depths of 3.90 m (12.8 ft) and 4.85 m (15.9 ft) contained 6.9% and 10.7%, respectively.

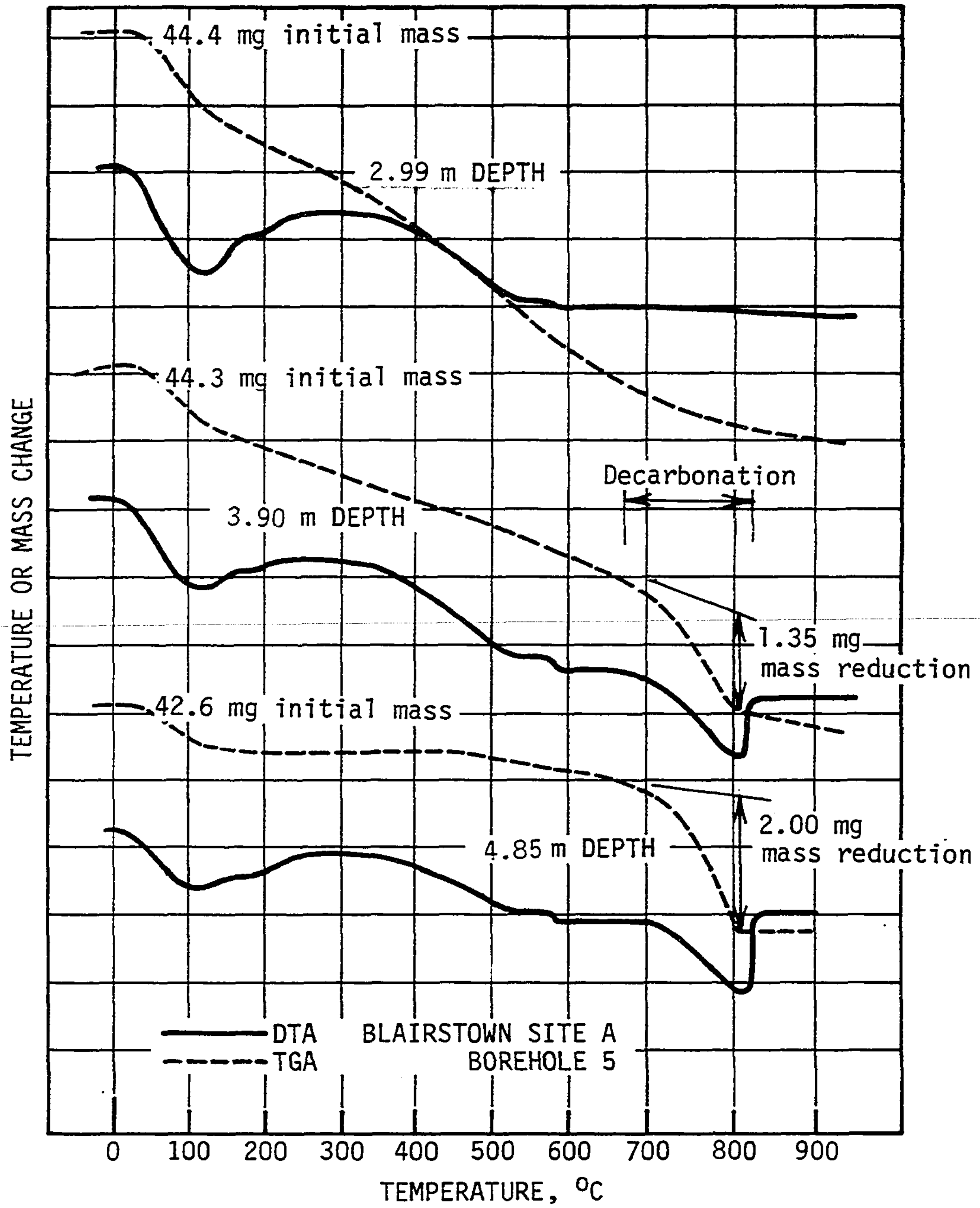


Figure 9. Differential thermal analysis/thermogravimetric analysis results

LIQUID SILT

Identification and Classification

There are no specific criteria as to what constitutes liquid silt. Silts are known for their tendency to become "quick" when saturated; that is, they behave like a viscous liquid and actually flow if disturbed. This aspect of their behavior is emphasized by the U.S. Bureau of Reclamation [33] in describing characteristics of silts for identification purposes. Some clays also exhibit this same tendency and are called quick clays. Thus it is not surprising to find that Hallberg's et al. [12] description of the consistency of liquid silt is very similar to a description of quick clay given in a Swedish calendar of 1767 as being "A soil consisting of a fine, sandy clay which when saturated forms a dough-like, almost flowing mass" (cited in Flodin and Broms [10]). Quick clays belong to the category of soils called soft clays.

The literature on soft clays serves as a source of criteria for establishing guidelines for identification and classification of liquid silts. Brenner et al. [4] consider soft clays to be any clayey soils with undrained shear strengths of less than 40 kPa (836 lb/ft^2). The liquid silts found in Iowa have clay contents (based on clay-size particles being finer than 0.002 mm) of approximately 20% by weight, a sufficient amount for them to be considered clayey soils. In addition, their undrained shear strengths may be as low as 2.5 kPa (50 lb/ft^2) according to Ruhland [27], making it appear that liquid silts can be categorized as soft clays.

Bjerrum [3], however, defines soft clays as clays that were originally deposited with a loose, flocculated structure. But he fails to define which soils he considers to be clays, so there is some doubt as to whether liquid silts would be considered soft clays according to his definition.

Liquid silts and soft clays appear to have similar consistencies and undrained shear strengths. Because the present soft clay identification criteria are somewhat vague, it is not possible to state whether liquid silts may be included in the soft clay category. Even if this determination were possible, the criteria are so general that identification of liquid silts, per se, could not be made. Therefore, it seems appropriate to develop specific criteria for identification and classification of liquid silts.

Undrained shear strength is of obvious significance in any such criteria. Since undrained strength of a saturated soil is primarily a function of soil dry density or void ratio, either of these parameters would served in identifying or classifying liquid silts. Selection of the appropriate values for these parameters which would allow categorizing soils according to their liquid silt condition would be, by necessity, arbitrary. It will be shown later that there is no one single value of void ratio that defines the liquid silt condition, but, rather, that each soil has a value that is a function of clay content and type.

A convenient way of relating soil consistency, or firmness, to the natural water content is by use of the liquidity index, LI, defined as

$$LI = \frac{w_n - w_p}{w_L - w_p} \qquad (1)$$

where

w_n = natural water content,

w_L = liquid limit water content, and

w_p = plastic limit water content.

At $LI \geq 1$, the soil, if disturbed, would behave in a manner approaching that of a liquid. At $LI = 0$, the same soil would behave like a friable or brittle material. The transition between the two conditions is gradual, which accounts for the introduction of such terms as "semi-mush."

Test data from 70 specimens representative of the four sites investigated in Iowa (see Appendix B) were compared to descriptions made during sample extrusion that gave qualitative estimates of the soil consistency. Data reflecting the properties and characteristics of all specimens identified as liquid and semi-liquid silts based on this comparison are shown in Table 3. When these data are combined with those in Table 1, the following observation can be made concerning the liquid and semi-liquid silts:

(i) Liquidity index, $LI > 0.61$

(ii) Degree of saturation, $S > 93\%$

(iii) $0.805 <$ void ratio, $e < 0.994$

(iv) 2 μm clay content varies from 15.7 to 26.4%.

Table 3. Summary of properties of liquid silts from present investigation

Site/ Bore-hole	Depth m	Weathering Zone	Water Content %	Dry Density kg/m^3	Solids Specific Gravity	Void Ratio e
Blairstown						
1A	3.41	MOL	31.1	1450	2.72	0.876
2A	3.22	MOL	33.0	1420	2.72	0.920
3A	3.15	MOL	33.3	1390	2.73	0.957
4A	2.87	MOL	32.7	1410	2.72	0.933
5A	3.00	MOL	34.3	1390	2.71	0.946
5A	3.25	MOL	34.1	1380	2.71	0.958
6A	3.45	MOL	32.9	1400	2.72	0.942
7A	3.60	MOL	30.0	1490	2.71	0.823
8A	3.23	MOL	31.3	1450	2.71	0.862
9A	2.54	MOL	35.5	1360	2.70	0.993
Blairstown						
2B	2.79	MOL	33.0	1390	2.73	0.971
2B	3.45	MOL	32.6	1420	2.72	0.914
3B	2.28	MOL	33.3	1380	2.72	0.968
Gilman No. 1						
	3.30	MOL	33.5	1410	2.71	0.924
	3.45	MOL	34.6	1390	2.72	0.957
State Center No. 2						
	2.29	MOL	34.9	1370	2.73	0.994

Saturation %	LL	PL	LI	Sand	Silt	2μm clay
96.6	32.8	11.3	0.85	0.1	84.2	15.7
97.5	37.8	18.2	0.74	0.2	77.4	22.4
94.9	37.3	16.7	0.76	0.1	79.8	20.1
95.3	35.2	13.7	0.82	0.1	81.3	18.6
98.2	36.4	15.1	0.86	0.3	78.0	21.7
96.5	35.6	15.0	0.90	0.5	78.7	20.8
94.8	36.3	15.6	0.78	0.2	79.3	20.5
99.0	32.5	11.3	0.78	0.2	82.3	17.5
98.2	33.1	11.9	0.85	0.3	81.7	18.0
96.7	36.1	15.8	0.96	0.0	80.3	19.7
93.0	41.7	22.4	0.61	0.0	75.3	24.7
96.9	38.5	18.1	0.67	0.2	78.4	21.4
93.6	37.9	19.6	0.73	0.0	78.7	21.3
98.3	40.9	19.9	0.63	0.0	73.6	26.4
98.2	39.9	19.6	0.73	0.0	74.2	25.8
95.9	38.9	18.6	0.79	0.0	76.7	23.3

Also note that, with the exception of four specimens, all are totally leached of carbonates. If the specific gravity of solids, G, is assumed to be 2.70, the minimum void ratio recorded for these soils converts to a maximum dry unit weight of 14.61 kN/m^3 (93 lb/ft^3), which is practically the same value suggested by Ruhland [27] as being the maximum dry weight that will give a liquid silt condition. This seemingly unique value comes about because there is little difference in clay content and specific gravity between the soil tested by Ruhland and the soil sample having the lowest void ratio in Table 3.

One-dimensional consolidation tests were performed on undisturbed samples of liquid silts as a part of this investigation and the one by Perez [25]. Particular attention was given to Blairstown Site A. Comparison of preconsolidation stresses determined from these tests with existing overburden stresses reveals that these soils are normally consolidated. The geostatic stress profile and preconsolidation stress data are shown in Figure 10.

In summary, semi-liquid and liquid silts from the sites investigated can be classified as normally consolidated soils. They are identified as being near saturation with a minimum void ratio of 0.805 and a minimum liquidity index of 0.61. The conditions of near-saturation and minimum liquidity index could possibly be adopted as general criteria for identification of liquid silts, with some refinement being given to the liquidity index to separate semi-liquid from liquid silts. By comparison, the "threshold" void ratio given is for these specific soils and could not be included as part of some general criteria since it will vary with soil type.

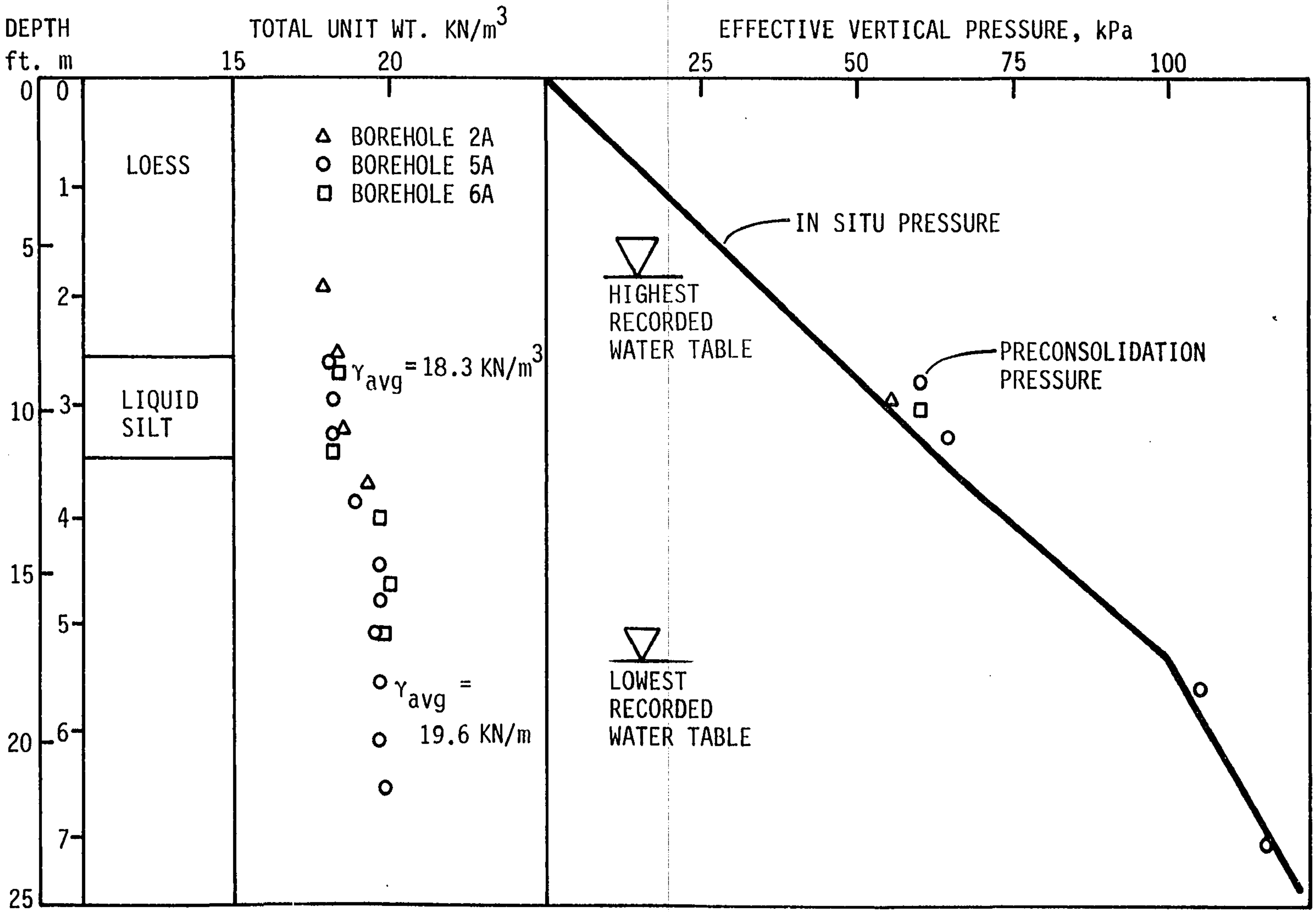


Figure 10. Geostatic stress profile for Blairstown Site A

Occurrence

Development of the liquid silt condition is dependent upon the in situ void ratio being sufficient to accommodate a water content at saturation that is near the soil liquid limit water content. Clay content and type of clay mineral play a major role in this relationship because they affect the liquid limit water content and thus the stage at which a liquid consistence would develop if the soil were disturbed. In addition, clay type and amount are largely responsible for the consolidation characteristic of clayey sediments because clay-size particles, with high specific surface, exert a dominant influence on soil behavior [22].

Skempton [30] compiled data on the gravitational (self-weight) consolidation behavior of clay deposits from throughout the world and presented it in the form of the two graphs shown in Figures 11 and 12. He included, under the general heading of clays, soils with clay contents ranging from less than 10% to more than 70%, and with liquid limits of from 20 to more than 140. The unique relationship that exists between void ratio and effective overburden pressure for each saturated, normally consolidated clayey soil of a given liquid limit is clearly shown in Figure 11. These same data when plotted in the form of liquidity index versus effective overburden pressure as in Figure 12, provide an insight into the occurrence of liquid silts in normally consolidated soils. For instance, if the lower limiting value of liquidity index used to define liquid silts is arbitrarily chosen to be 0.75, one can determine from Figure 12 that the corresponding maximum overburden pressure would range from approximately 20 to 120 kPa

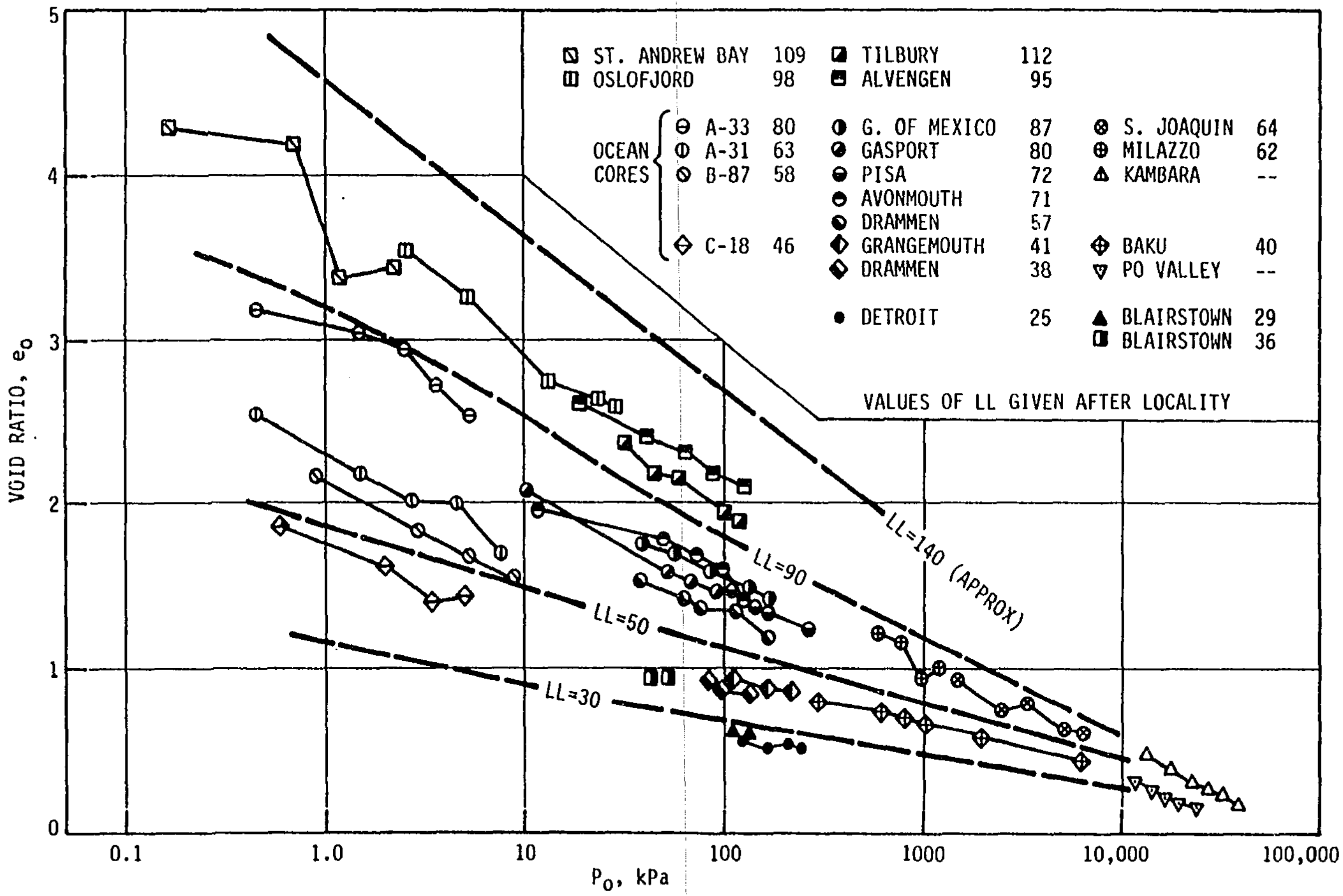


Figure 11. Sedimentation compression curves (from Skempton [30])

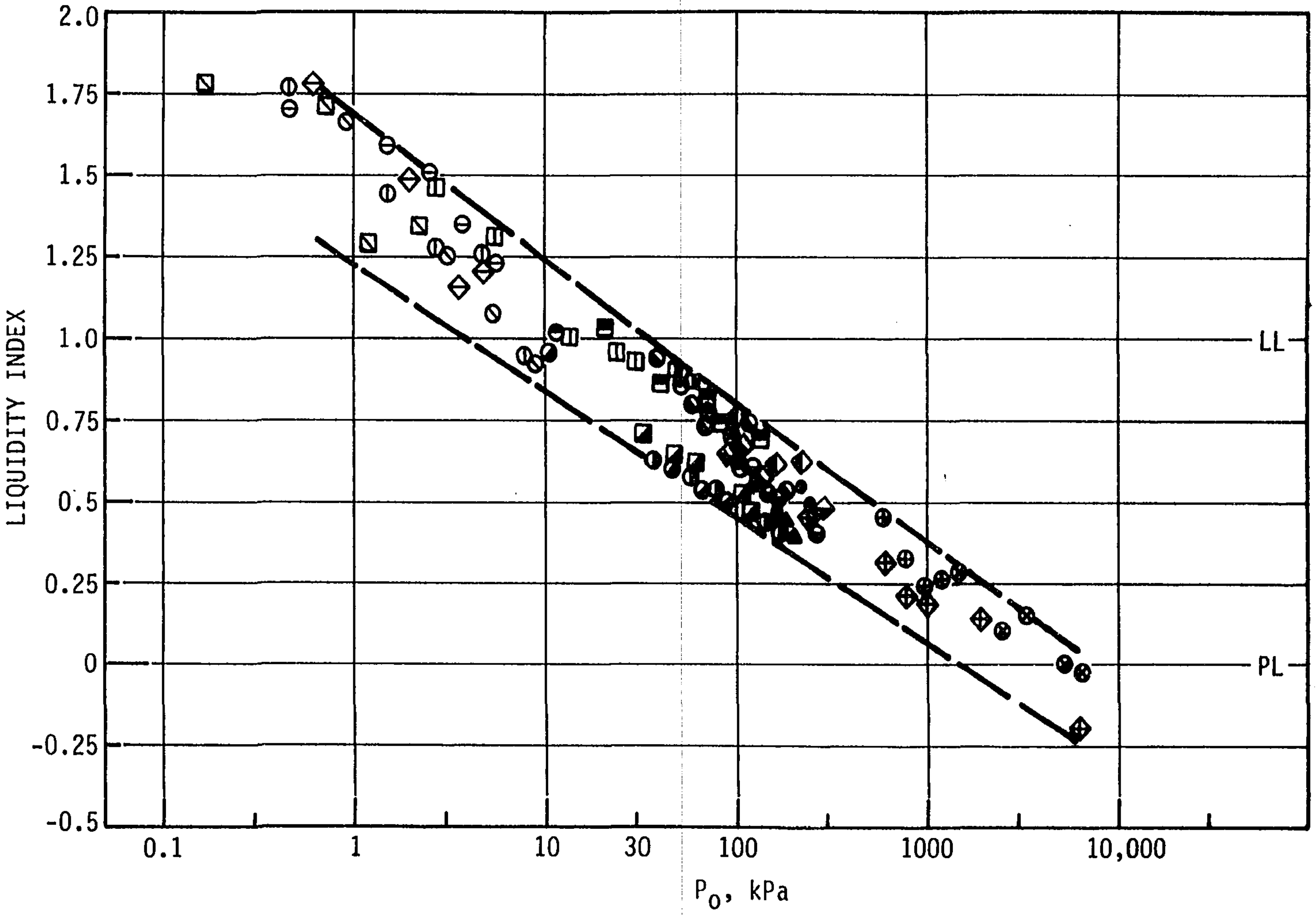


Figure 12. Relation between liquidity index and effective overburden pressure (from Skempton [30])

(420 to 2500 lb/ft^2) depending on the consistency limits of the soil. Based on soil having a total unit weight of 17.33 kN/m^3 (110 lb/ft^3), these pressures are equivalent to maximum overburden depths of from 1.15 to 6.92 m (3.8 to 22.7 ft). Thus under no circumstances would liquid silts be encountered below depths of approximately 6.92 m (22.7 ft) in saturated, normally consolidated deposits.

The above analysis still leaves the question as to why liquid silts have not been found at depths of less than 1.15 m (3.8 ft). This is no doubt related to environmental effects such as wetting and drying, introduction of organic matter, translocation of clays and all other pedogenic processes and mechanisms that alter the upper soils to the extent that the set of conditions necessary for liquid silt development are never realized.

Data from Blairstown Site A plots close to the appropriate curves in Figure 11, confirming the similarity of behavior between the liquid silts and the leaner clayey sediments reported by Skempton [30].

The liquid silt condition and its upper and lower boundaries appear to be unaffected by location of the water table as long as near-saturation conditions are maintained within the liquid silt zone. At Blairstown Site A, for example, the water table fluctuated from 0.76 m (2.5 ft) above to 1.83 m (6.0 ft) below the liquid silt zone. Samples obtained when the water table was at these two extremes showed the liquid silts were sustained at the same depth regardless of the water table elevation. This indicates, first of all, that changes in void ratio accompanying changes in effective stress as the water table

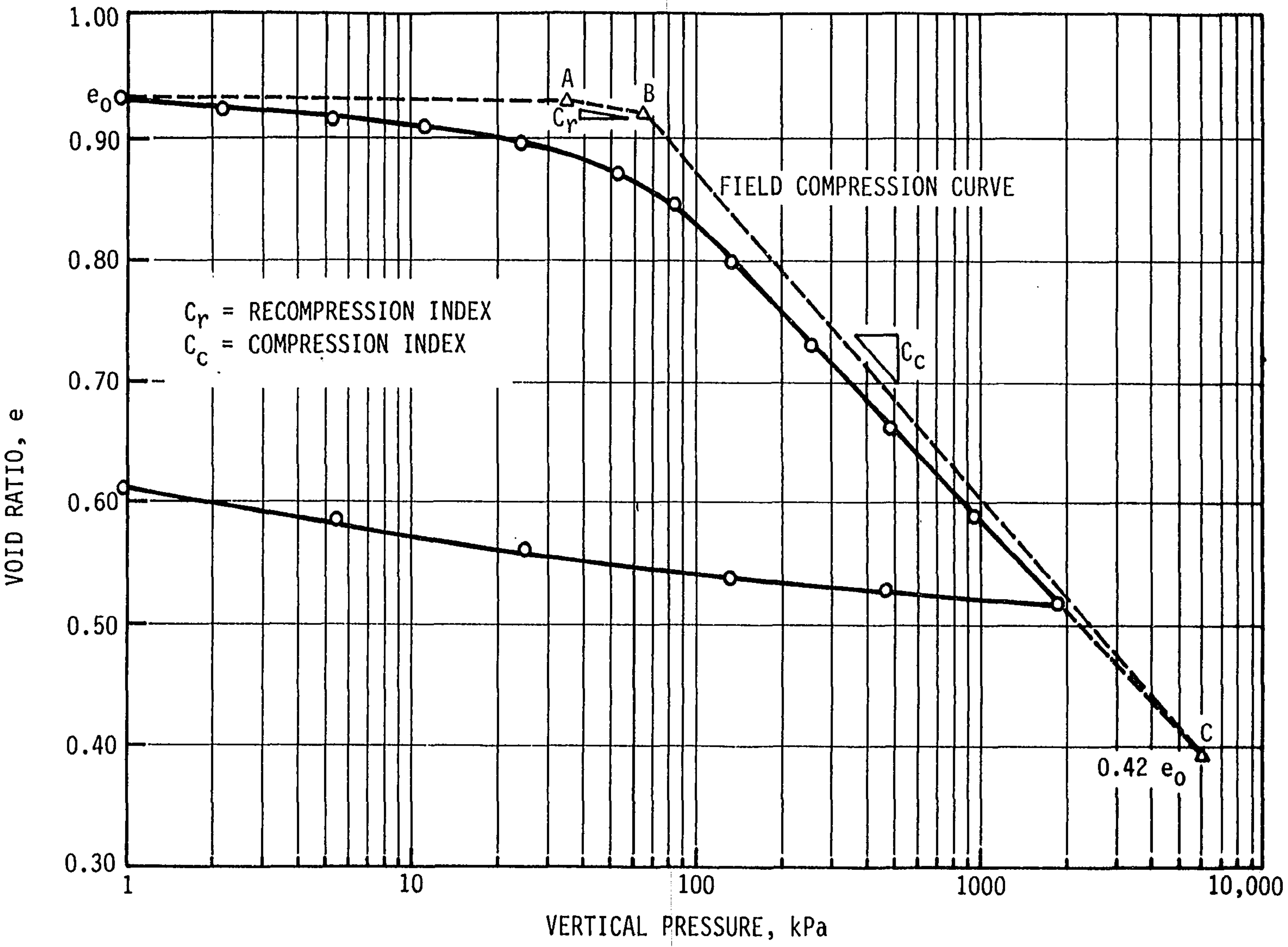


Figure 13. One-dimensional consolidation test results from a liquid silt

fluctuates are relatively small over the range of stresses involved. For example, the consolidation curve for a liquid silt sample from a depth of 2.77 m (9.1 ft) is shown in Figure 13. The field compression curve, reconstructed using Schmertmann's [28] technique, is designated by line ABC. Point A represents the void ratio when the sample is submerged and point B, the void ratio when the water table has dropped well below the sample elevation. Void ratio change resulting from the maximum water table drop is only 0.003, which is reflected in the extremely low value for recompression index, C_r, of 0.02.

Conditions of near saturation, even with the water table at considerable depth, also indicate that the soil pore structure does not permit free gravity drainage, at least during the four months required for the water table to drop from its highest to lowest level at this site. If saturation is maintained solely by capillary rise above the water table, negative pore pressures of approximately 26.91 kPa (562 lb/ft^2) would result. This corresponds to a 2.74 m (9.0 ft) capillary rise, which is the distance from the lowest recorded water level to the top of the liquid silt zone. Negative pore water pressures of this magnitude would certainly tend to produce a preconsolidation effect in the soil, but this was not observed. A possible explanation for this is suggested by the relatively subtle decrease in degree of saturation in the liquid silt -- from 97.5 to 94.5% -- that accompanies the drop in water table level. The somewhat lower degree of saturation may reflect the development of discontinuous water columns at some distance above the water table. This would mean that pore water pressures in these upper regions are not a function of capillary rise and that pressures of a much lower magnitude than given above would be realized.

To summarize, the conditions leading to the formation of liquid silts at the sites investigated can be explained in terms of the observed behavior of saturated, normally consolidated clayey sediments. The primary factors that are involved are the overburden pressure, which affects void ratio, and the clay content and type of clay mineral, which determine the liquid limit water content. The liquid silt condition is dependent upon availability of water to the extent that the soil is essentially saturated at all times.

Distribution

Liquid silts have been encountered at various sites representative of the loess found throughout the upper midwestern United States. There is nothing at this point to suggest that liquid silts could not occur in all loess deposits. The purpose of this section is to take the concepts just presented on the occurrence of liquid silts and to apply them to Iowa loess on a state-wide basis in an attempt to predict the distribution of liquid silts within the state.

There is a large body of information on Iowa loess. Of primary interest is the liquid limit since it is a key to consolidation behavior of the soil. Davidson and Handy [8], Handy [14], and Sheeler [29] have shown that the liquid limit and plastic limit of loess are both primarily dependent upon clay content. These index properties,

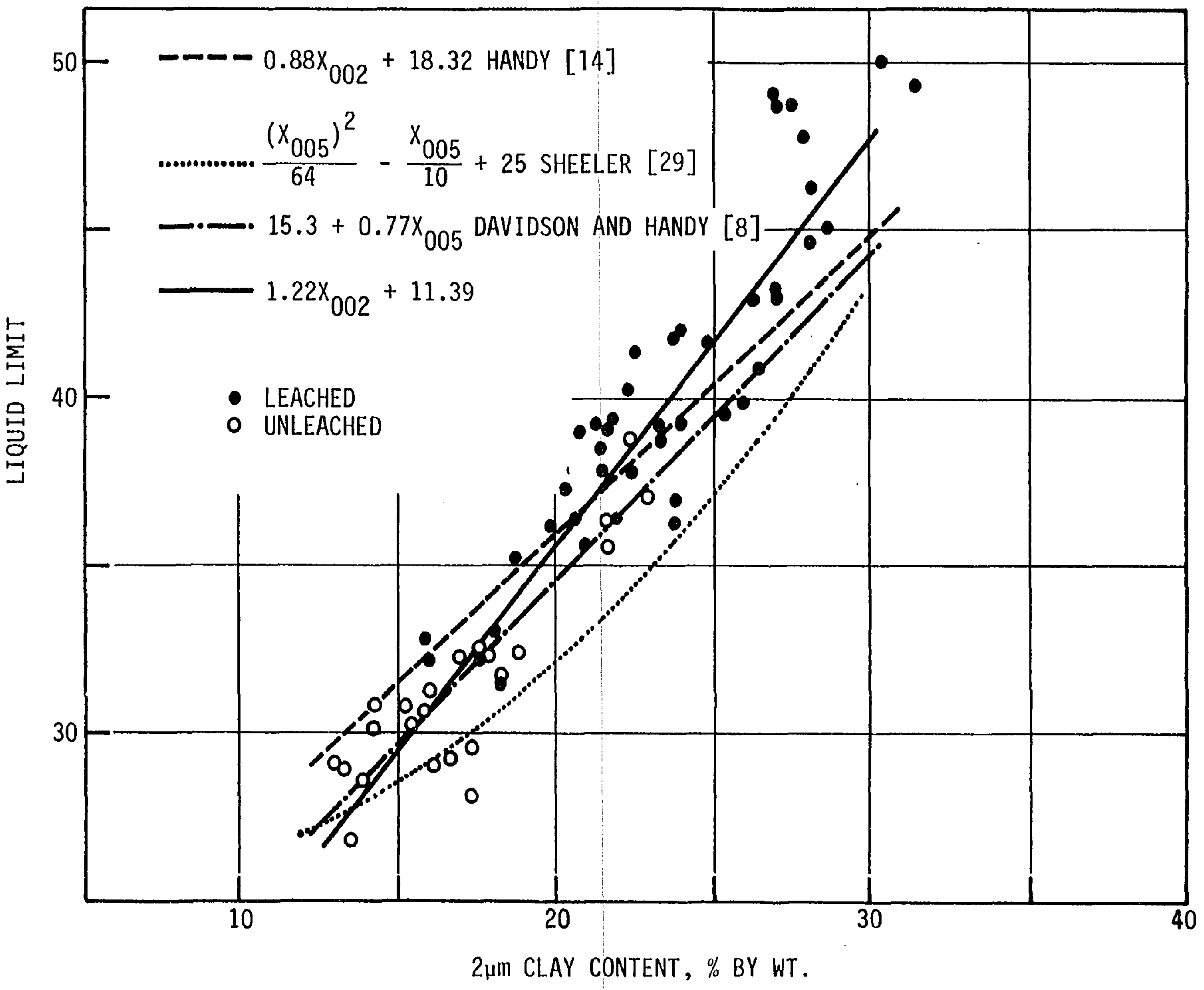


Figure 14. Relation between liquid limit and clay content

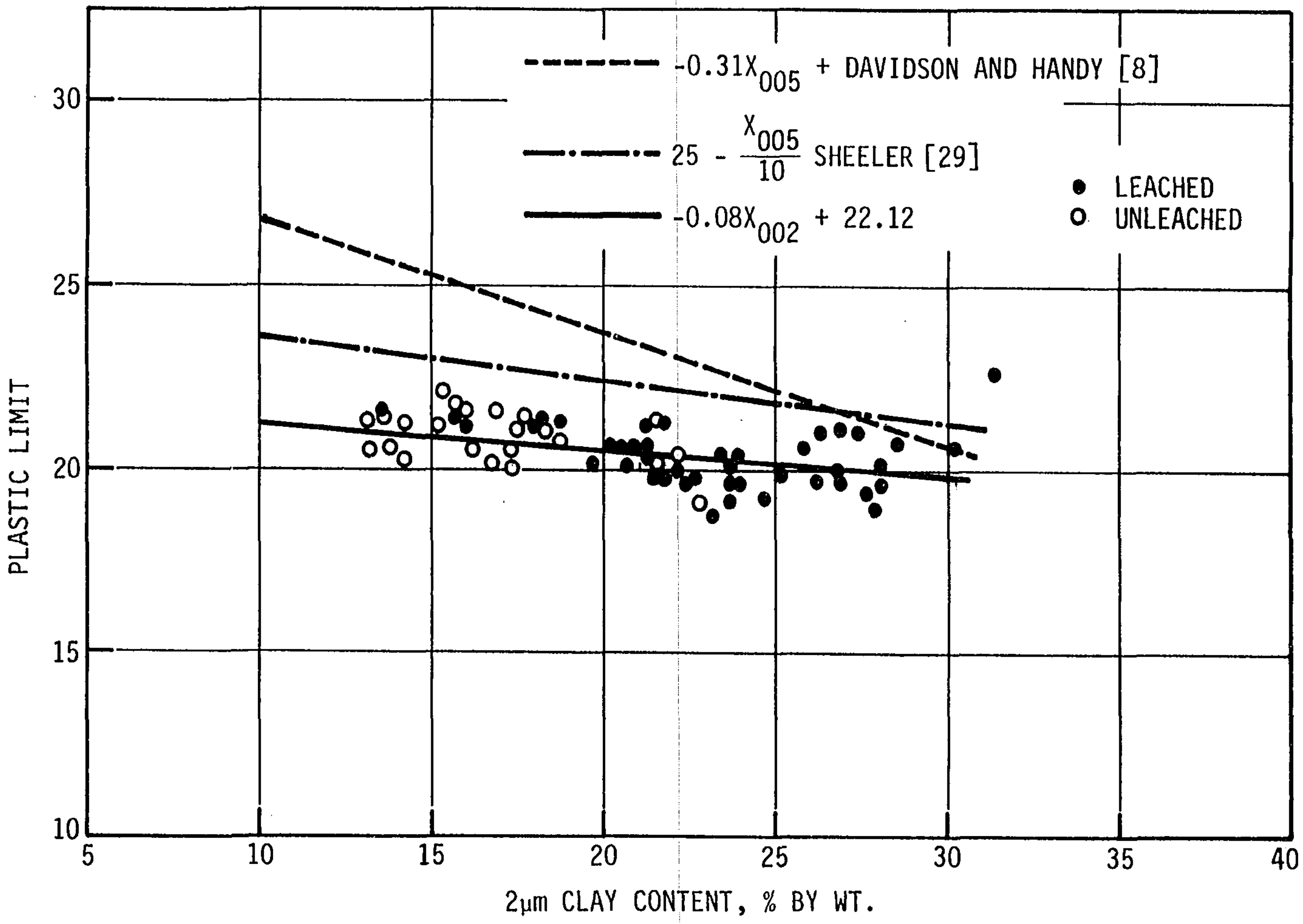


Figure 15. Relation between plastic limit and clay content

as a function of 2 μm clay content, for the sites investigated as a part of this research are shown in Figures 14 and 15. Plots of the mathematical expressions developed by Handy and Sheeler are also shown in these figures. Two of these expressions in their original form are in terms of 5 μm clay content; conversion to 2 μm clay content was made by using the relationship suggested by Handy [14],

$$x_{002} = 0.8\ x_{005} \qquad (2)$$

where

x_{002} = 2 μm clay content, and

x_{005} = 5 μm clay content.

It is obvious that these functions do not adequately define the correspondence between either the liquid limit or plastic limit and the clay content for the soils presently investigated. Linear regression of the data from this investigation gives the following expressions

$$w_L = 1.22\ x_{002} + 11.39 \qquad r^2 = 0.89 \qquad (3)$$

$$w_p = -0.08\ x_{002} + 22.12 \qquad r^2 = 0.18 \qquad (4)$$

where

w_L = liquid limit, and

w_p = plastic limit.

The compression curves presented by Skempton [30] and shown in Figure 11 are essentially linear over the range of stresses of interest -- 10 to 1000 kPa (210 to 20900 lb/ft^2). These curves have been redrawn in Figure 16, and the virgin compression curves for selected specimens

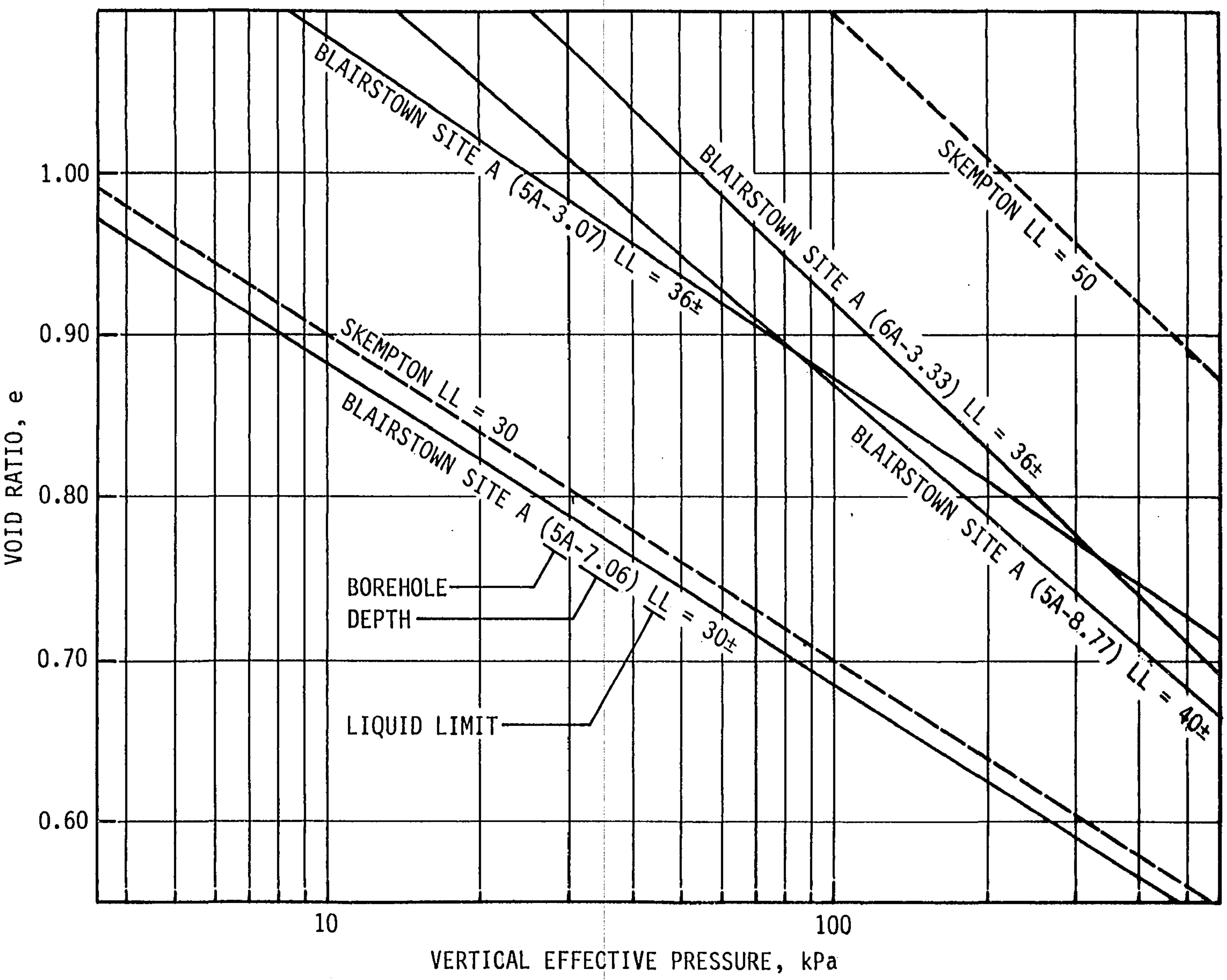


Figure 16. Sedimentation compression curves

from Blairstown Site A have been added to the graph to show how well Skempton's generalized curves predict the actual behavior of the loessial soils.

The general equation for Skempton's curves shown in Figure 11 for liquid limits varying from approximately 30 to 50 is

$$e = -0.005\ (w_L + 10)\ \log \sigma_v + 0.03w_L + 0.20 \qquad (5)$$

where

e = void ratio,

w_L = liquid limit, and

σ_v = effective vertical pressure (kPa).

This can be put into terms of clay content by substituting equation (3) into equation (5) to give

$$\begin{aligned} e = &-(0.006x_{002} + 1.07)\ \log \sigma_v \\ &+ 0.037x_{002} + 0.54 \qquad (6) \end{aligned}$$

which has been plotted in Figure 17. Furthermore, the relationship

$$Se = wG \qquad (7)$$

where

S = degree of saturation,

e = void ratio,

w = water content, and

G = specific gravity,

can be combined with equation (1) to yield

$$e = \frac{G}{S}\ [w_L\ LI + w_p\ (1 - LI)]. \qquad (8)$$

This can be put in terms of clay content by substituting equations (3) and (4) for the liquid limit and plastic limit, respectively, to give

$$e = [1.30x_{002}\ LI - 10.73LI - 0.08x_{002} + 22.12]\ \frac{G}{S} \qquad (9)$$

Equating this to equation (6) and rearranging terms will result in

$$LI = [(0.107 - 0.006x_{002})\ \log \sigma_v + 0.037x_{002} + 0.54$$
$$+ (0.08x_{002} + 22.12)\ \frac{G}{S}]\ /\ (1.30x_{002} - 10.73)\ \frac{G}{S} \qquad (10)$$

Curves for LI = 1.00, 0.75, and 0.50 based on G = 2.70 and S = 100% are plotted in Figure 17. The graph can be interpreted as follows:

> Consider a saturated deposit having a specific gravity of 2.70 and 2 μm clay content of 20%. If liquid silt conditions (arbitrarily established as being when $LI \geq 0.75$) are to exist, the void ratio must be greater than approximately 0.86. In a normally consolidated deposit, this void ratio would occur at a depth of approximately 2.7 to 3.4 m (9 to 11 ft), depending upon the soil unit weight. The soil does not have to be normally consolidated to exhibit the liquid silt conditions; however, it is possible to predict where liquid silts will occur only in normally consolidated deposits.

Note in Figure 17 that for overburden pressures of from 45 to 75 kPa (940 to 1560 lb/ft^2) the liquid silt condition is not particularly sensitive to clay content. Notice, however, that a very substantial difference in void ratio may result from only a 10 percent change in clay content.

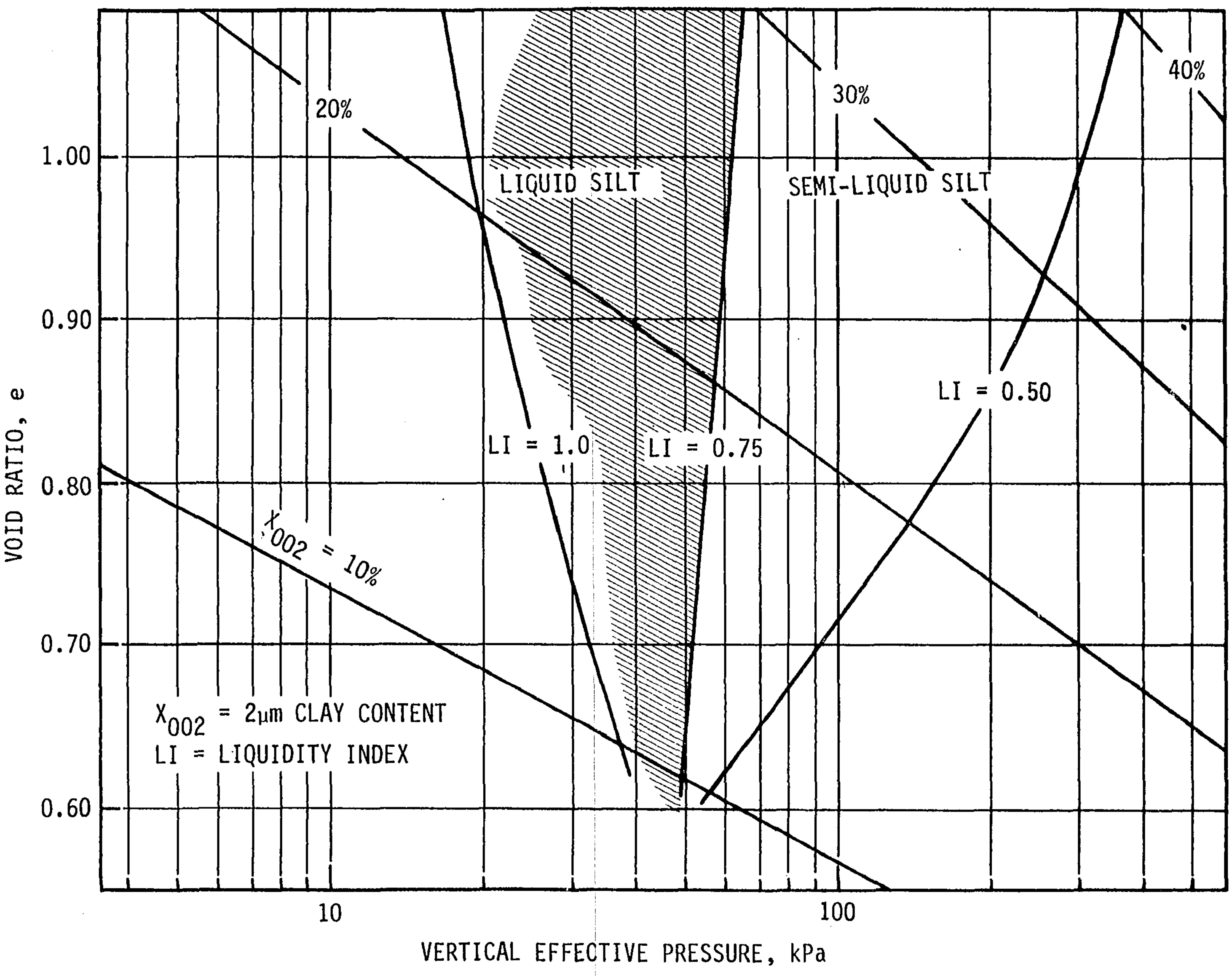


Figure 17. Sedimentation compression curve in terms of clay content

Figure 17, or variations of it, could be used to predict the depth of occurrence of liquid silt knowing only the 2 μm clay content, specific gravity of solids, and the applicable relationship between clay content and the liquid and plastic limits. The only one of these variables that changes significantly on a state-wide basis is the clay content, and this has been mapped as shown in Figure 18.

Although the procedure just described seems relatively simple, it must be remembered that Figure 17 is based on the assumption that the soil is saturated, but it is obvious that not all loess is saturated. Furthermore, clay content is rarely constant with the depth as is implied in the map. These conditions present major problems in making predictions of the distribution of liquid silts.

Soil color and color patterns are indicators of soil moisture conditions [7]. Constant submergence with a total absence of available oxygen will lead to dark gray, blue and green soils. Saturation with water of limited oxygen supply results in gray soils in which secondary iron compounds may segregate into concretions or tubules. Soils which have an abundant supply of oxygen under conditions of good drainage will be reddish-brown, yellowish-brown, or olive brown. If drainage is imperfect, causing occasional-to-frequent saturation or near-saturation, the soils will exhibit the same colors as those with good drainage except that gray mottles will be apparent.

All reported liquid silts, with the exception of those at four sites, have occurred in soils whose colors are indicative of either continual or frequent saturation. These exceptions were found in

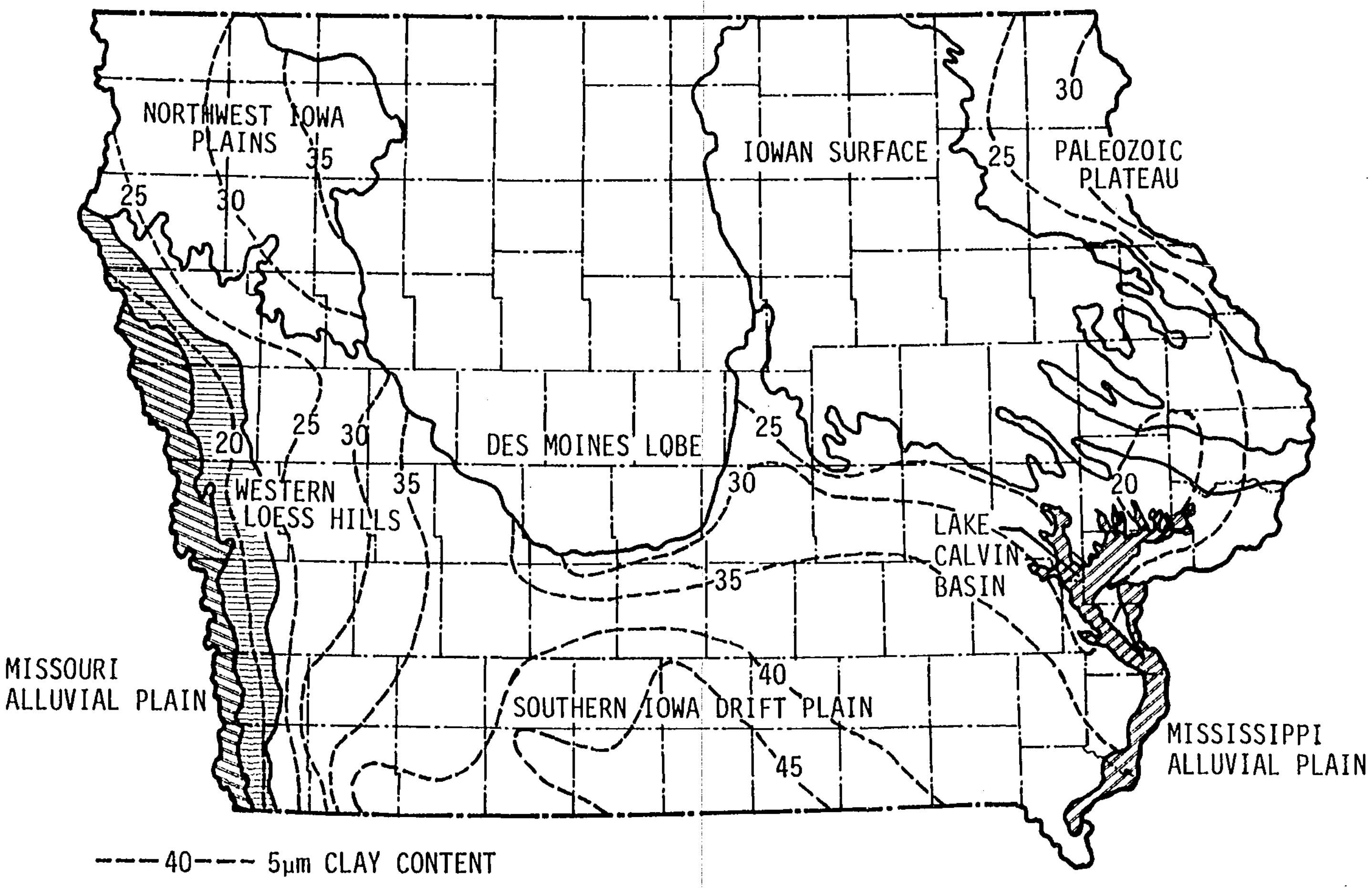


Figure 18. Variation of clay content in Iowa loess (after Hansen et al.[15])

soils that are apparently free-draining, which illustrates the possible transitory nature of some liquid silts; that is, at these sites, liquid silts would not normally exist because, if they did, the soil would show evidence of frequent saturation. Trying to predict the distribution of soils in which liquid silts exist so infrequently may be difficult.

Soil color data, particularly the occurrence of mottling, from the reports of Lutenegger [21], Hallberg et al. [12], Kemmis et al. [16], and Davidson et al. [9] were combined with comparable data from this investigation and used to define, in a general manner, the zone of saturation in Iowa loess. In order to do this, the height of mottling above the base of the loess was plotted against loess thickness, as shown in Figure 19. A wide range of values is apparent.

The lower boundary of Figure 19 reflects groundwater conditions in the loess of southwestern Iowa as defined by the Redfield, Red Oak, and Harlan data. The upper boundary is similarly dependent on conditions in east-central Iowa. This suggests that the observed variations in height of mottling for a given loess thickness may be related to geographic factors, with topography and precipitation being two of these factors.

Total annual precipitation decreases progressively across the state in a northwesterly direction [24]. The difference in height of mottling between the Harlan site, in southwest Iowa, and Blairstown Site A, in east-central Iowa, can possibly be explained on the basis of dissimilar climate since Harlan receives approximately 150 mm (6.0 in) less preciptiation than does Blairstown. However, the Redfield and

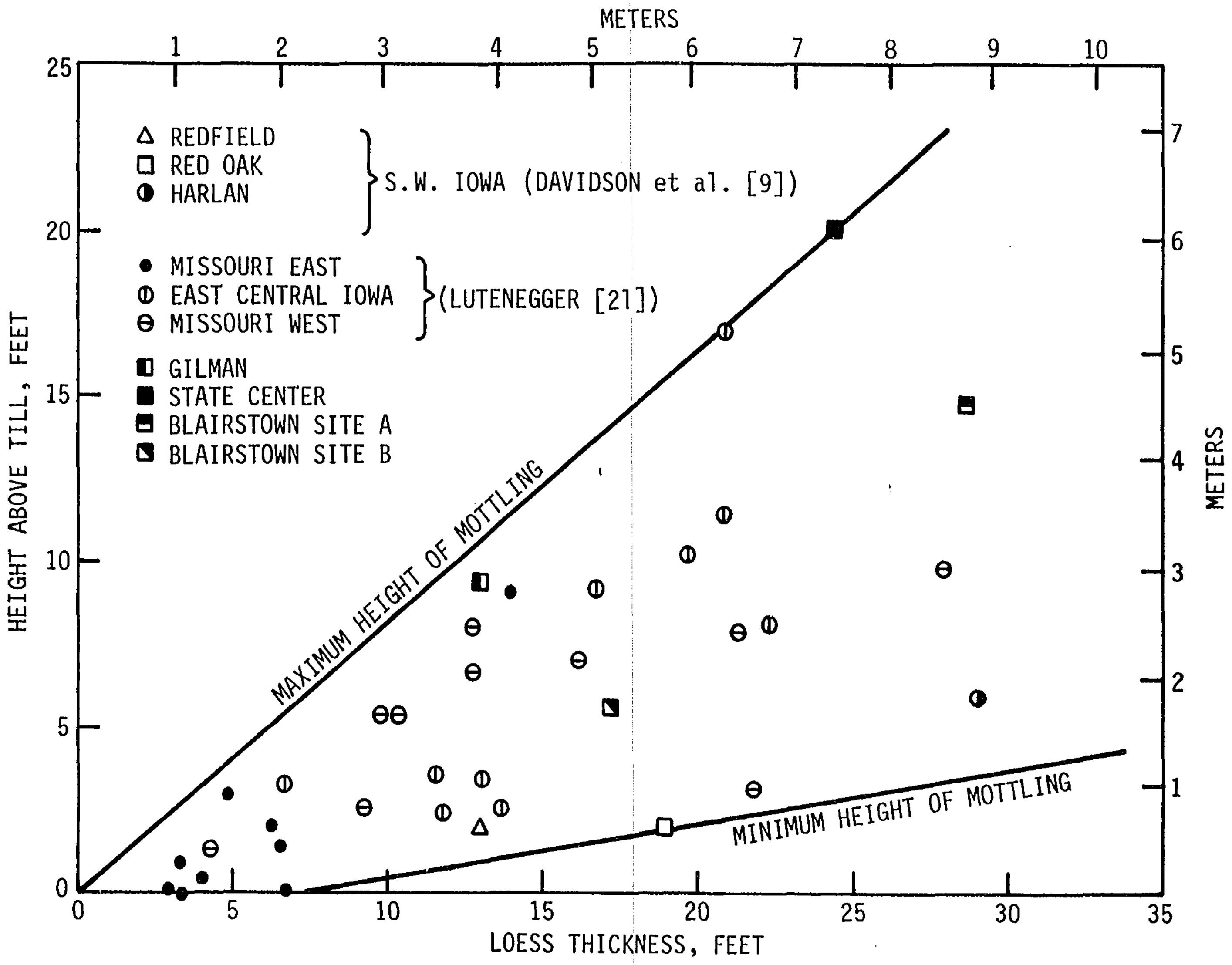


Figure 19. Height of mottling above base of loess

Gilman sites receive the same annual precipitation, but have significantly different mottling heights.

Consideration of topographic effects does not resolve the contradictory observations just made since, for each of the cases cited, the terrain is perceived as being very similar. Determination of the factors that influence height of mottling at these diverse sites is beyond the scope of this study.

The data of Figure 19 are of importance, however, because they allow for establishing the probable extremes in extent of saturation by perched groundwater in loess typified by the various sites. Since saturation is a prerequisite for development of liquid silts, the limits thus defined also define the range in depth over which liquid silts could be encountered. The influence this has on their occurrence can be seen by comparing the liquid silt zones shown in Figures 20 and 21.

Saturation is not the only factor controlling development of liquid silts. In a given deposit the maximum depth below the ground surface at which liquid silt would be expected to occur is a function of the soil unit weight and the resulting overburden pressure. This depth is called the "lower boundary of potential liquid silt" in Figures 20 and 21. This so-called boundary is the level at which a transition from liquid to semi-liquid consistency would theoretically take place as a consequence of increasing overburden pressure. Liquid conditions would exist above this level; semi-liquid conditions, below. Its location, for a soil of given clay content, is obtained from Figure 17 by determining the overburden pressure at which LI = 0.75. For a

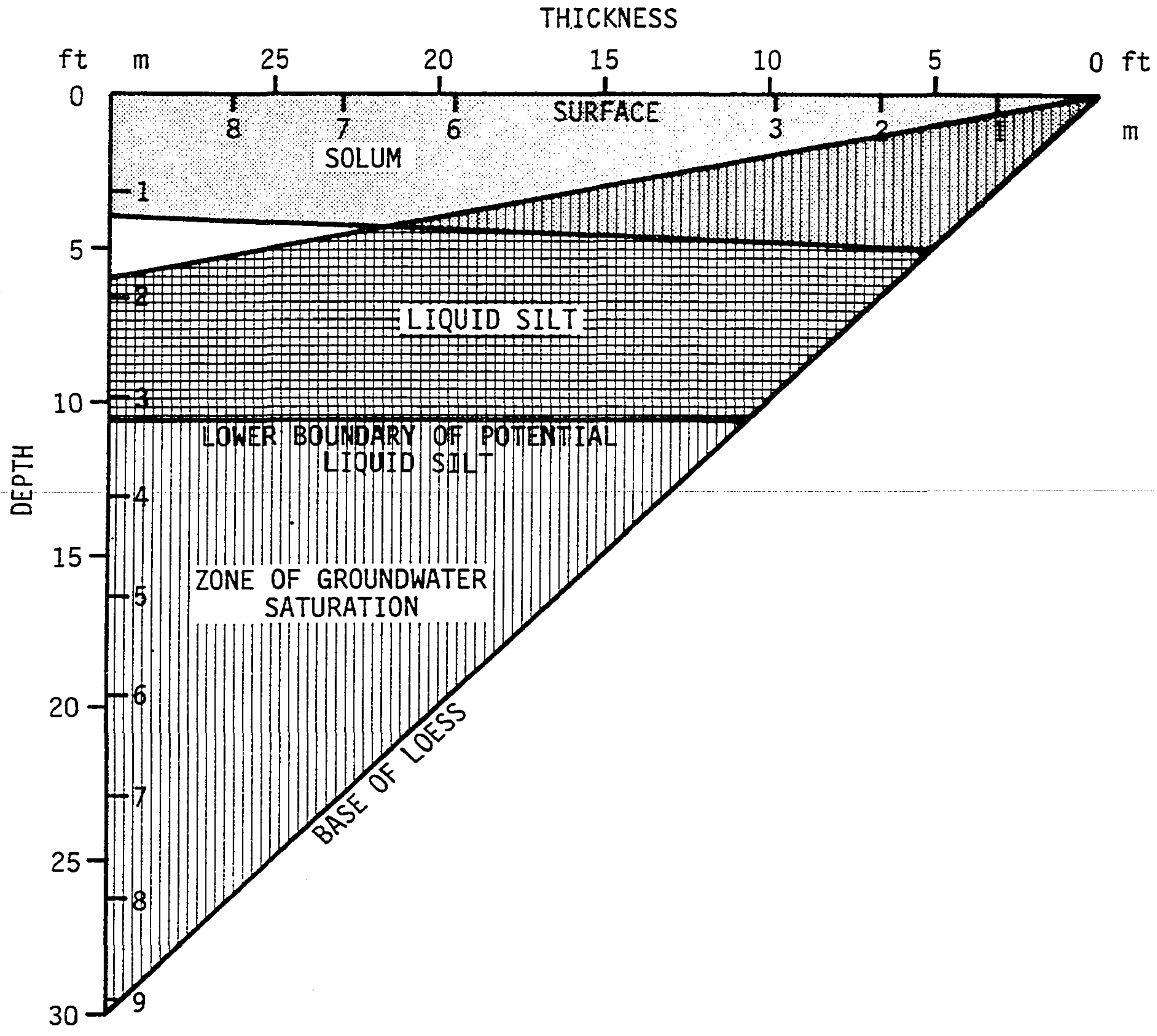


Figure 20. Maximum extent of liquid silt in loess typical of east-central Iowa

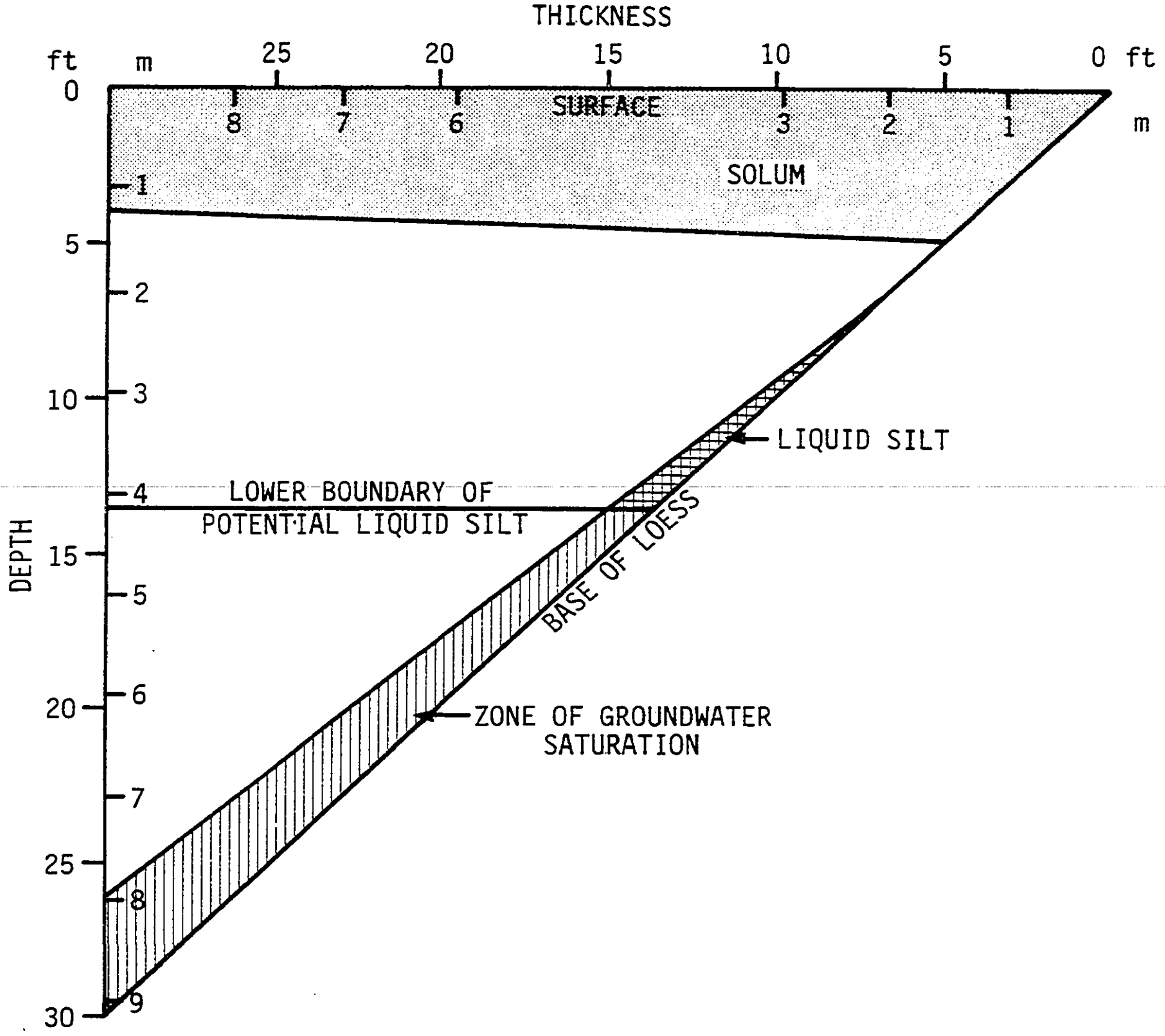


Figure 21. Minimum extent of liquid silt in loess typical of western Iowa

soil with 20% clay content and 18.0 kN/m^3 (115 lb/ft^3) total unit weight, which represents the sites in east-central Iowa, the boundary is at a depth of approximately 3.23 m (10.6 ft). This is shown in Figure 20.

Conditions depicted in Figure 21 differ in two respects from those in Figure 20. First, the zone of saturation in Figure 21 is far less extensive, and, second, the lower boundary of potential liquid silt in Figure 21 is based on a soil of lower unit weight. The situation thus created is representative of loess in western Iowa. For a soil with 20% clay content and 14.0 kN/m^3 (89 lb/ft^3) total unit weight, the lower boundary is located at a depth of 4.15 m (13.6 ft).

Weathering processes, both physical and chemical, alter the uppermost soils in a typical loess deposit to the extent that liquid silts will probably not be found at shallow depths (where overburden pressures are minimum) even though the soil may be saturated. This was pointed out earlier and is accounted for in Figures 20 and 21 by showing the upper portion of the loess to be composed of a solum. The base of the solum is the minimum depth at which liquid silts would form. The solum is assumed to be of variable thickness because it is recognized that as loess becomes progressively thicker, the associated land surfaces generally become steeper, in which case thinner sola generally result [24, 26].

The shaded areas in Figures 20 and 21 show where the concurrent requirements for saturation and for overburden pressure being less than some threshold value are both satisfied. This defines the zone of potential liquid silt. The solum may drastically reduce the extent of this zone in thin deposits as is evident in Figure 20. These two figures can be interpreted as follows:

(i) Liquid silts will not occur in loess that is less than approximately 1.5 m (5 ft) thick as shown in Figure 20.

(ii) Under conditions of maximum extent of saturation, liquid silts are limited to depths of from 1.37 m (4.5 ft) to 3.23 m (10.6 ft) as shown in Figure 20. In thin loess, the liquid silt zone is bounded on the top by the solum and on the bottom by the underlying glacial till. As the loess thickens, overburden pressures limit downward progression of the lower boundary to depths no greater than 3.23 m (10.6 ft), and the upper boundary becomes a function of the height to which saturation exists.

(iii) Under conditions of minimum depth of saturation, liquid silts would not be found at any location where loess thickness is greater than 4.6 m (15 ft) as shown in Figure 21. For loess between 1.5 m (5 ft) and 4.6 m (15 ft) thickness, the liquid silt would exist as a thin layer at the base of the loess.

Thickness of loess in Iowa has been mapped and is shown in Figure 22. Using the interpretation made above and assuming the loess

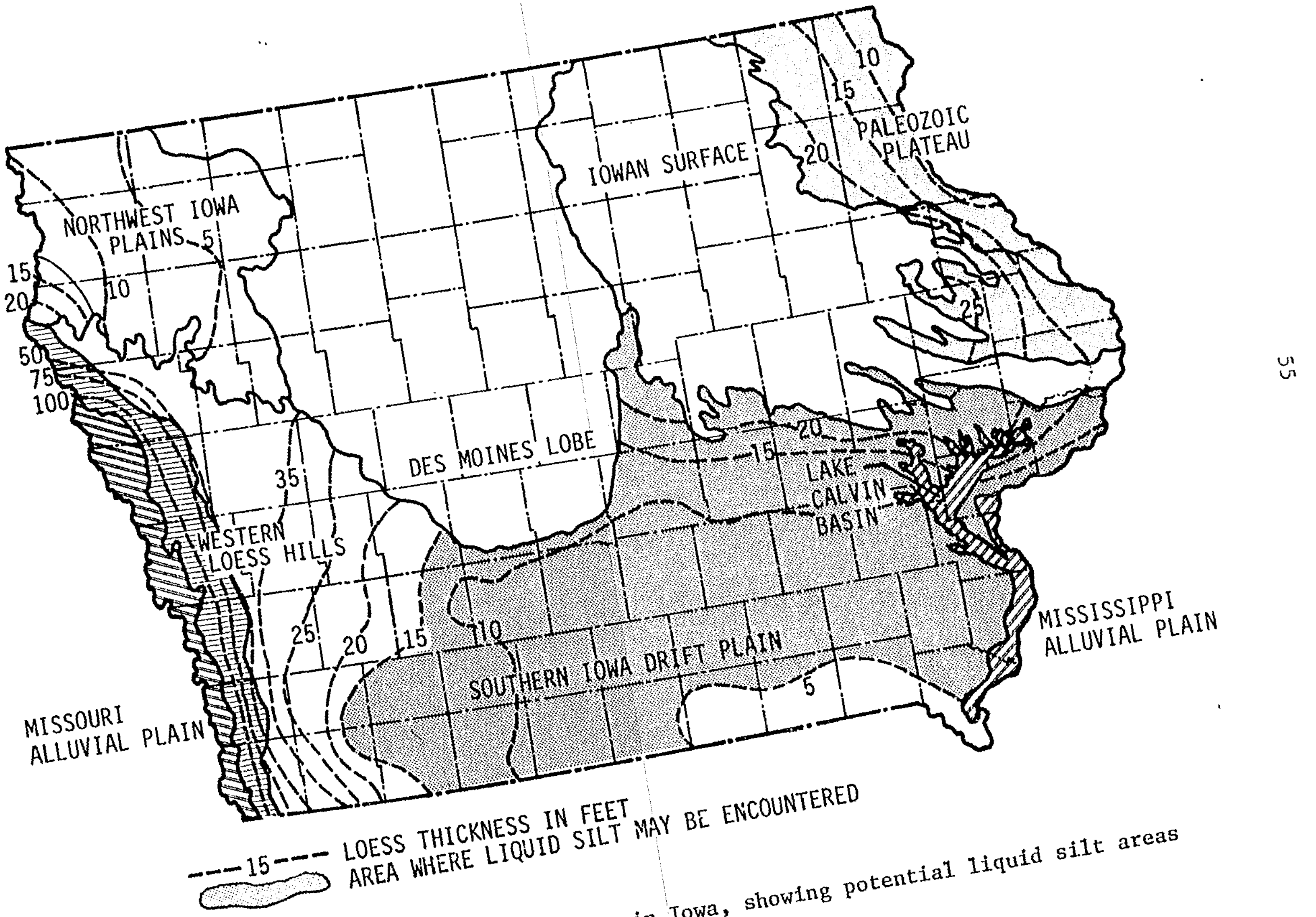


Figure 22. Variation of loess thickness in Iowa, showing potential liquid silt areas

in western Iowa has a minimal zone of saturation, one can conclude that the shaded portion of Figure 22 represents the area in which liquid silts may be encountered under existing conditions. This projected area is tentative and is, of course, affected by the several assumptions that have gone into the development of Figures 20 and 21. All the soils in this area are not loess: loess generally occupies only the upland positions. But all the loess in the area should be considered to have conditions favoring existence of liquid silt. The possibility of creating liquid silts artificially in areas where they do not exist naturally must not be overlooked. The loess of western Iowa would be particularly susceptible to this if water were made available through crop or lawn irrigation or water impoundment.

Origin

All liquid and semi-liquid silts that have been reported, including those investigated as a part of this study, have occurred as relatively distinct zones in loess deposits. All but three of the 14 separate sites involved have had these soft layers confined to the leached portion of the soil profile. Since the test method employed for determining the extent of carbonate leaching was a simple qualitative procedure measuring only a reaction to dilute hydrochloric acid, there is no way of knowing the degree to which leaching may have actually progressed. In other words, even the soils designated as unleached may have been partially leached, but not to the point that a reaction with acid could not be observed. The sites having the liquid silts in unleached soils were sampled by others so further tests could not be performed as a part of the present investigation without obtaining additional samples; this was not done.

The fact that carbonate leaching is prevalent in the soils which have liquid silts suggests that removal of carbonate in situ may be a mechanism promoting formation of the liquid silt condition. The process is envisioned as one in which calcium and magnesium carbonate, occurring as silt-size particles, and as coatings on other particles [29], react chemically with weak carbonic acid formed when gaseous carbon dioxide from the atmosphere dissolves in water. The reaction involving calcium carbonate [17] is

$$\begin{array}{c} H_2O + CO_2 \\ \uparrow\downarrow \\ CaCO_3 + H_2\,CO_3 \rightleftarrows Ca^{++} + 2HCO_3^-. \end{array}$$

If there is a net movement of groundwater through the soil as with a fluctuating water table, the dissolved carbonate is leached.

Since leaching removes soil solids, it is expected, first of all, that the particle size distribution would be altered to show an increase in clay content and, secondly, that the remaining soil particles would experience some relative movement or deformation, similar to that observed in secondary compression, simply resulting from increased contact stresses as the number of interparticle contacts is decreased. This would have an effect similar to aging, or delayed compression, as explained by Bjerrum [3] whereby void ratio decreases under constant applied stresses. This is depicted in Figure 23. It

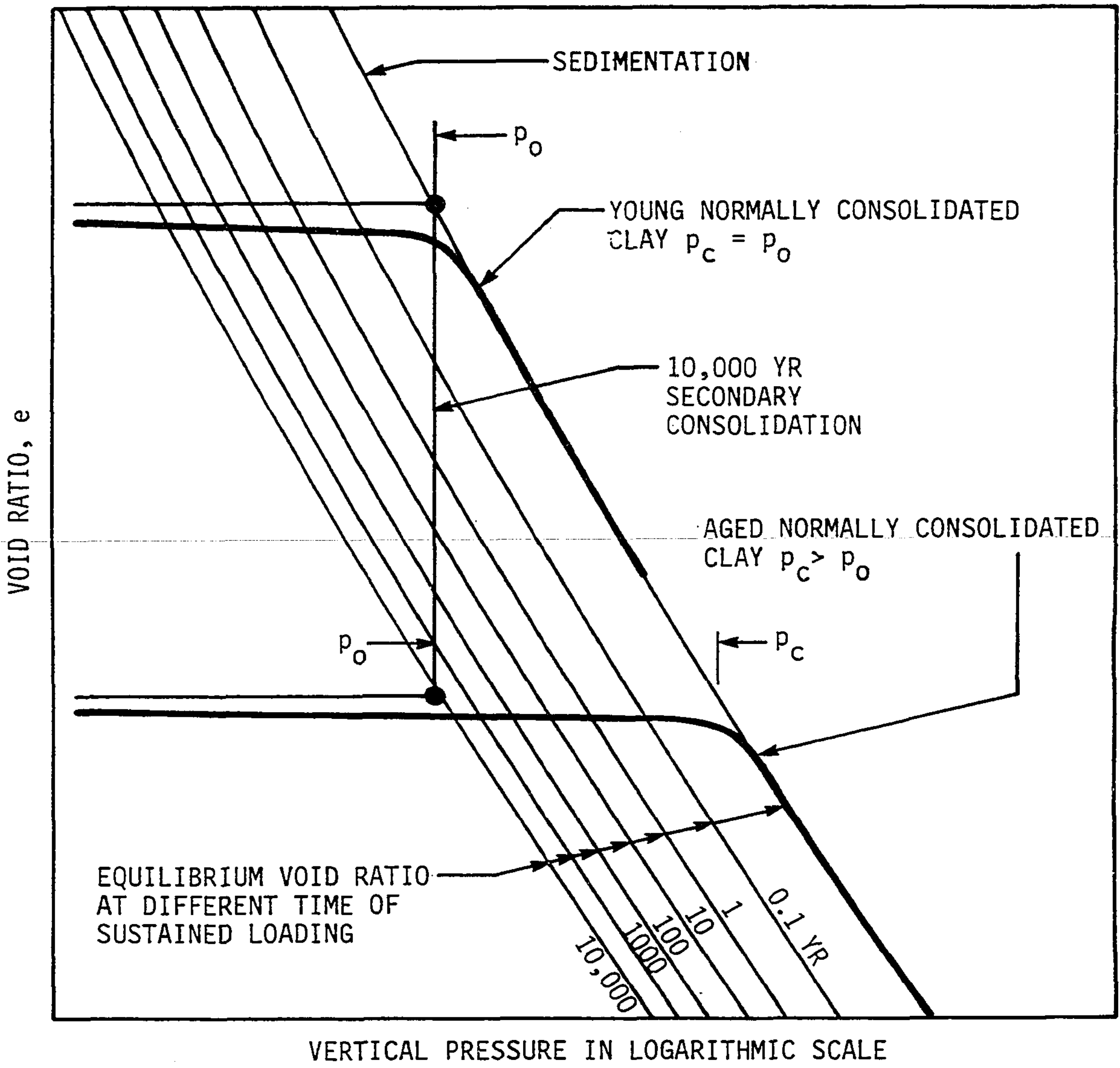


Figure 23. Effect of geological history on the compressibility of normally consolidated clays (from Bjerrum [3])

must be remembered, however, that without the structural rearrangements, leaching itself would have the opposite effect because it brings about an increase in void ratio.

The net change in void ratio that occurs as a result of these two phenomena is no doubt a function of carbonate content and overburden stress, among other things. At low stress levels the delayed compression should be minimal, making the change in void ratio directly related to carbonate content. Overburden stresses at depths where liquid silts have been encountered are all considered low, being less than 100 kPa (2100 lb/ft^2).

Also of significance with respect to low stress levels is the increase in void ratio associated with expansive clay minerals as compared to less expansive clays at the same stress level. X-ray diffraction (see Figure 8) revealed that montmorillonite was the predominant clay mineral in the liquid silt at Blairstown Site A.

The hypothetical model for in situ formation of liquid silt in loess, which has been arrived at after considering all of these factors, comprises a material that is

(i) initially calcareous,
(ii) composed of silts and clays, with the predominant clay minerals being expansive,
(iii) frequently saturated either by submergence or capillary rise, and
(iv) subjected to overburden stresses of less than 100 kPa (2100 lb/ft^3);

and a process that involves

- (i) collapse of the loess if it was initially susceptible to self-weight collapse,
- (ii) expansion of clay minerals, and
- (iii) leaching of carbonates,

which results in

- (i) consolidation behavior typical of normally consolidating saturated clayey sediments, and
- (ii) a low density, high water content soil that, if disturbed, develops a consistency similar to that at the soil liquid limit.

This model reflects an analysis of the combined data from all sites, but the detailed study performed on samples from Blairstown Site A are the most informative. A review of these findings follows.

Figures 7 and 13 contain one-dimensional consolidation test results from specimens located at various depths throughout the soil profile. From these test results and the vertical effective stress profile of Figure 10, it was determined that the soils here are normally consolidated.

Weathering zones and variations with depth of clay content, natural water content, dry density, void ratio, and degree of saturation for this site are shown in Figure 24. The liquid silt zone is identified in this figure, and it can be seen that immediately below this zone the clay content, liquidity index, and void ratio all decrease. It is also at this depth that unleached soil was first encountered.

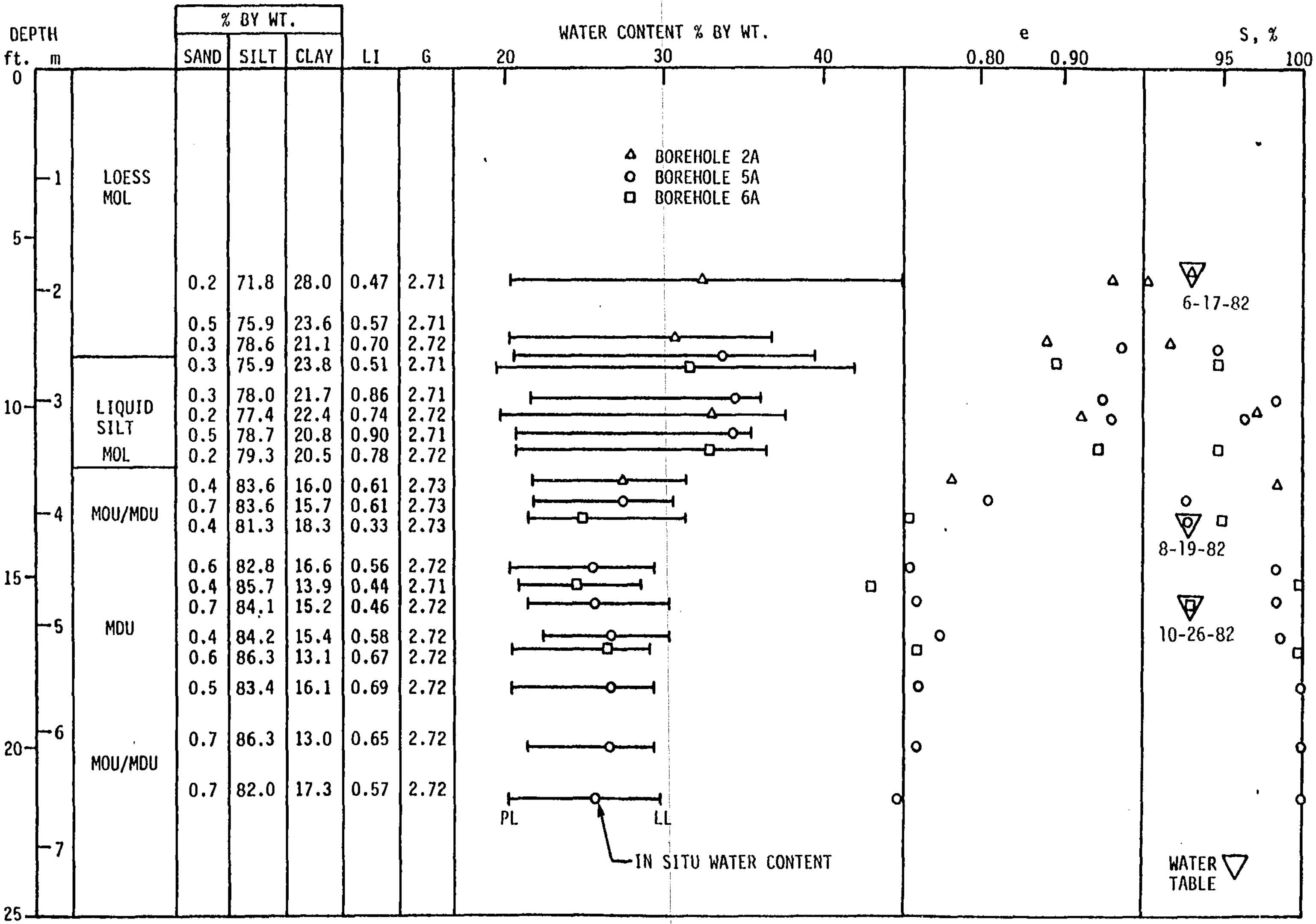


Figure 24. Geotechnical data for Blairstown Site A

It is entirely possible that these changes reflect two separate loessial soils, differing perhaps because of changes in characteristics of the source material or because of alterations to the lower soil after its deposition. Results of X-ray diffraction studies show that clay mineralogy does not change with depth. The diffraction patterns are shown in Figure 8 for specimens taken from throughout the soil profile. If there are two separate deposits, their clay mineralogy is so similar as to make them indistinguishable. To reiterate, montmorillonite is the predominant clay mineral.

It is also possible that the entire deposit was initially relatively uniform, and that the changes are a result of the effects of weathering, particularly leaching, within the upper portion. In a situation like this, the assumption is often made that the lower soil reflects the properties and characteristics of the "unaltered" soil.

Based on this assumption, it was possible to approximate the variation of void ratio with depth for the "original" calcareous deposit by using the average of the field compression portions of the e versus log σ_v curves for samples 5A-5.66 and 7.06, which are representative of the lower soil. Overburden pressures at various depths were obtained from Figure 10. (Variation of void ratio with depth may also be determined from the appropriate curve in Figure 17.) The void ratio-depth relationship based on field compression curves is shown in Figure 25.

The same procedure was used to obtain the void ratio-depth relationship representative of the upper leached soil. This is also shown in

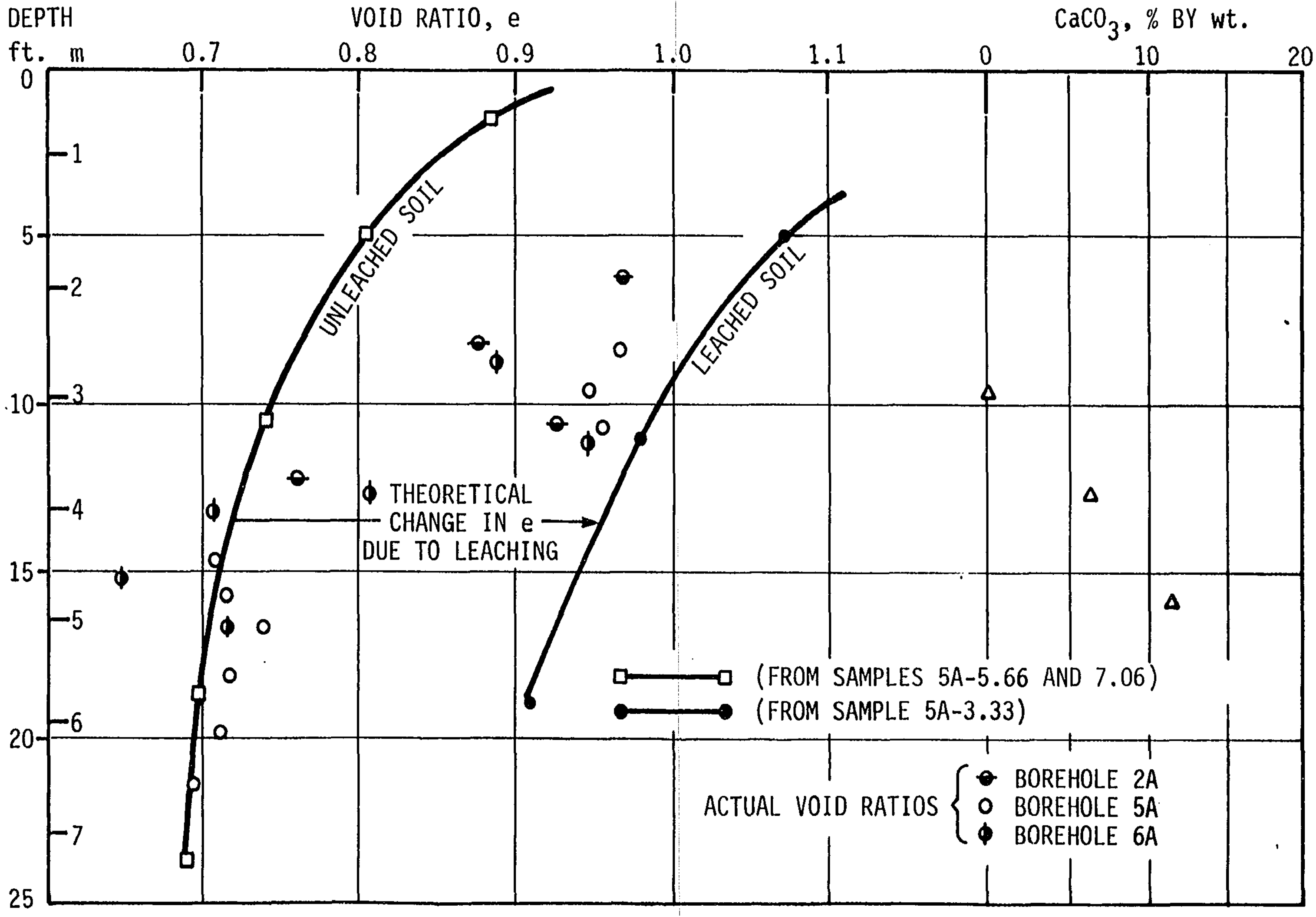


Figure 25. Variation of void ratio and $CaCO_3$ with depth

Figure 25. In this case, the field compression curve for sample 5A-3.33 was used. These two curves represent the difference in consolidation behavior between typical unleached and leached loess soils. More precisely, the contrast in behavior reflects the difference in clay contents.

Actual in situ void ratios from specimens throughout the profile were plotted to show if the theorized behavior models the actual behavior, and it can be seen that this data supports the assumption of an initial uniform deposit of calcareous loess which has subsequently been leached in the upper portion.

Notice in Figure 25 that the transition between the two zones is relatively gradual and occurs over a distance of approximately 1.5 m (5 ft).

Thermogravimetric analyses were performed on specimens at three different depths in this portion of the soil profile to determine carbonate content and its variation with depth. Results of these tests are shown in Figure 9, and the data have been plotted in Figure 25 to clearly show the relationship.

By using these values and by assuming the carbonate content of the specimen from the greatest depth is representative of the initial carbonate content, one can compute changes in void ratio that result from leaching. Furthermore, it is possible then to predict the void ratios of leached soil at selected depths by simply adjusting the initial (unleached) void ratios by the computed changes. For instance, there is a decrease in carbonate content from 10.7 to 6.9% between the specimens at 4.85 m (15.9 ft) and at 3.90 m (12.8 ft), respectively. In 1.0 m^3 of soil, this represents a decrease of 0.58 kN of solids or a corresponding decrease in solids volume of 0.02 m^3, using G = 2.70. At the 3.90 m (12.8 ft) depth, this decrease in solids volume would give a void ratio increase of 0.06, which, when added to the initial (unleached) void ratio of 0.73, gives a void ratio of 0.79 for the leached condition. The actual in situ void ratio was 0.80.

Similarly, at 2.99 m (9.5 ft) depth the increase in void ratio above the theoretical value representing unleached conditions is 0.21, or an increase from 0.75 to 0.96, which compares to the actual in situ value of 0.95.

This provides very strong supporting evidence that the deposit was initially relatively uniform and has subsequently been leached of carbonates in the upper portion, resulting in an increase in void ratio and a corresponding increase in saturation water content to the extent that the liquid limit of the leached soil has been approached.

The difference in clay content between the leached and unleached soils also can be explained on the basis of carbonate leaching. The average particle size distribution of the unleached loess, which contains 10.7% $CaCO_3$ by weight, is 15.6% clay, 83.8% silt, and 0.6% sand. For the carbonate-free loess, the distribution is 21.2% clay, 78.4% silt, and 0.4% sand. If the carbonates exist only as silt-size particles, the clay content increase as a result of leaching is 2.1%, which is less than one-half the observed change. If, however, the carbonates exist both as individual grains and as part of a calciteclay mixture that coats other grains as noted by Sheeler [29], then leaching would not only remove carbonate, it would free clay-size particles previously cemented in the mixture. Furthermore, the individual carbonate particles are likely to contain some clay-size mineral "impurities" that would contribute to an increase in clay content upon removal of the host carbonate. Inclusion of non-carbonate particles would be expected whether the carbonates are secondary precipitates formed in situ or fragments of the original carbonate rock. Lohnes [20] found that carbonate concretions formed in loess contain up to 34% insoluble residue, and Goudge [11] reports that limestone bedrock in Canada, a possible source of carbonates found in Iowa soils that are either direct or indirect products of continental glaciation, may contain up to 50% non-carbonate minerals.

Whatever mechanisms are involved, complete leaching of carbonates from these loess soils would lead to an increase in both clay content and void ratio. An increase in clay content gives an increase in liquid limit (see Figure 14); consequently, the changes in void ratio that accompany leaching must be large enough to give a saturation water content approaching the liquid limit; otherwise, a liquid silt will not develop.

SUMMARY AND CONCLUSIONS

The terms "liquid silt" and "loess mush" have been used herein to designate low density, high water content soils encountered in loess deposits in Iowa and Missouri. Undisturbed samples of these soils are very soft; disturbed samples may actually flow. This behavior is a consequence of the void volume, which is a function of overburden pressure and the amount and type of clay, being sufficient to accommodate a saturation water content that is at or near the soil liquid limit. Because of the combination of high void volume and high water content, these soils presumably will have low undrained shear strengths.

The liquidity index is used to quantify the consistency of liquid silts and thus is a convenient parameter for their identification. The maximum reported value for liquid silts is 1.0. A value of 0.75 is suggested as the minimum liquidity index for liquid silts in order to separate them from the somewhat stiffer semi-liquid silts. Liquidity index is a laboratory criterion based on a property of disturbed soil. There is a need to develop similar criteria based on in situ shear strength values so that objective field identification is possible.

It has been shown that the liquid silts at the sites investigated occur in saturated, normally consolidated sediments, the consolidation behavior of which is known to be strongly influenced by clay type and amount. It is possible to predict the occurrence of liquid silts in similar normally consolidated loess deposits elsewhere in Iowa. This has been done, and the predictions have served as a basis for mapping the distribution of loessial soils in Iowa that may exhibit liquid silts.

Liquid silts may also exist in loess deposits that are not normally consolidated, but the distribution of these soils has not been determined as a part of this study.

The requirement for saturation appears to be a major factor limiting the areal distribution of liquid silts because there may not be many loess deposits that are saturated even occasionally at levels in the soil profile where overburden pressures are conducive to liquid silt formation. Because groundwater plays such an important role in development of liquid silts and because its location is also highly unpredictable on an area-wide basis, the proposed distribution of liquid silts must be considered as being suggestive of where liquid silts may occur, not where they are likely to occur.

Liquid silts appear most frequently in leached loessial soils. Leaching is not a necessary requirement, however, since even calcareous loess would exhibit liquid silt conditions at the appropriate overburden stress levels. But leaching can cause a significant increase in void ratio under constant stress conditions, leading to in situ formation of liquid silts under circumstances where they would not otherwise occur.

Consolidation states of loess may vary significantly within a given deposit depending on the deposit thickness. This is shown in Figure 26, which reflects the findings of this investigation concerning saturated, normally consolidated loess and the findings of Olson [23] concerning previously unsaturated, collapsible low-density loess. The consolidation state of the solum was inferred from soil survey information

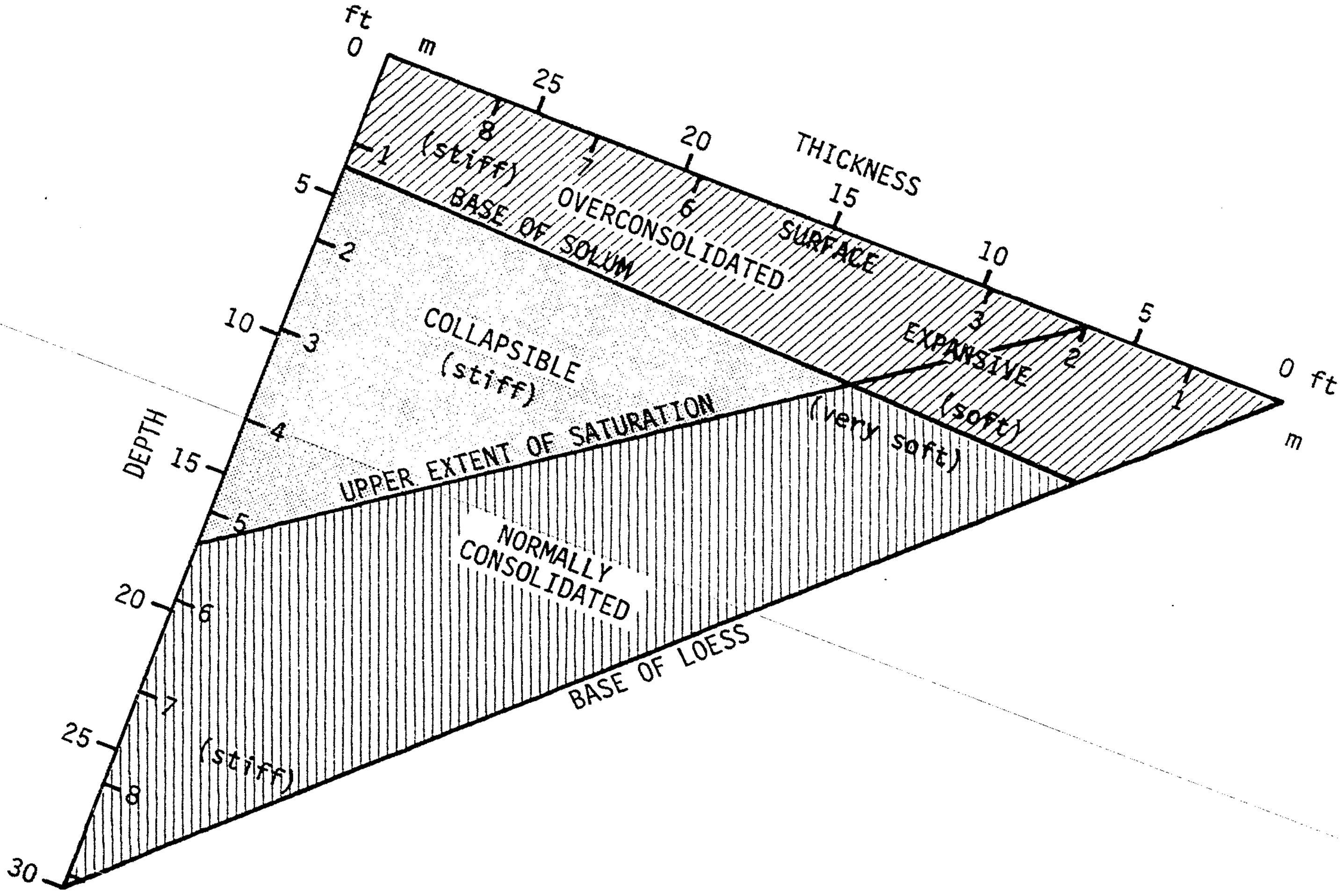


Figure 26. Consolidation states and consistence of loess

provided by the U.S. Department of Agriculture [32] by noting that the B-horizons, in general, have a high shrink-swell potential, indicating the presence of expansive clay minerals. Furthermore, the B-horizons have a blocky structure, which can be attributed to repeated cycles of wetting and drying [31]. Drying shrinkage would normally cause overconsolidation in clayey soils.

At some sites, depending on the extent of saturation, there is the potential for soils from different levels in the deposit to exhibit very different volume change behaviors. For a given applied load, these can range from relatively little volume change in stiff, normally consolidated or overconsolidated soils to significant volume change in soft, normally consolidated or collapsible soils.

BIBLIOGRAPHY

1. Altschaeffl, A. G. Discussion of "Design Consideration for Collapsible Soils." J. Geotech. Engr. Div., Proc. ASCE, 108, No. GT.4 (1982), 674-676.

2. American Society for Testing and Materials. Annual Book of ASTM Standards. Part 19. Philadelphia: ASTM, 1982.

3. Bjerrum, L. "Embankments on Soft Ground." In Performance of Earth and Earth-Supported Structures, Vol. 2. New York, ASCE, 1972, pp. 1-54.

4. Brenner, R. P., P. Nutalaya, G. V. Chilingarian and J. O. Robertson, Jr. "Engineering Geology of Soft Clay." In Soft Clay Engineering. Ed. E. W. Brand and R. P. Brenner. Amsterdam: Elsevier Publ. Co., 1918, pp. 159-238.

5. Carroll, D. "Clay Minerals: A Guide to Their X-ray Identification." The Geological Society of America, Special Paper 126, 1970.

6. Casagrande, A. "The Determination of the Pre-consolidation Load and its Practical Significance." Proc. 1st Int'l. Conf. on Soil Mech. and Found. Engr., Cambridge, 3 (1936), 60-64.

7. Daniels, R. B., G. H. Simonson, and R. L. Handy. "Ferrous Iron Content and Color of Sediments." Soil Sci., 91, No. 6, (1961), 378-382.

8. Davidson, D. T. and R. L. Handy. "Studies of the Clay Fraction of Southwestern Iowa Loess." Proc. 2nd Nat'l. Conf. on Clays and Clay Minerals, (1953), 190-208.

9. Davidson, D. T., R. L. Handy, and T. Y. Chu. "Depth Studies of the Wisconsin Loess in Southwestern Iowa: I. Particle-size and In-place Density." Proc. Iowa Academy of Science, 60 (1953), 333-353.

10. Flodin, N. and B. Broms. "Historical Development of Civil Engineering in Soft Clay." In Soft Clay Engineering. Ed. E. W. Brand and R. P. Brenner. Amsterdam: Elsevier Publ. Co., 1981, pp. 27-156.

11. Goudge, M. F. Limestones of Canada, Their Occurrence and Characteristics, Part IV, Ontario. Ottawa: Canada Department of Mines and Resources.

12. Hallberg, G. R., T. E. Fenton, G. A. Miller, and A. J. Lutenegger. "The Iowan Erosion Surface: An Old Story, an Important Lesson, and Some New Wrinkles." In 42nd Annual Tri-State Geological Field Cnference Guidebook. Iowa City, Iowa: Iowa Geological Survey, 1978, pp. 2-2 to 2-94.

13. Handy, R. L. "Mechanics and Distribution of Liquid Silt." Nat'l. Sci. Found., Proposal under contract. Civil Engineering Department, Iowa State University, Ames, Iowa, Sept. 1, 1980.

14. Handy, R. L. "Collapsible Loess in Iowa." Soil Sci. Soc. Am. Proc., 37, No. 2 (1973), 281-284.

15. Hansen, J. A., A. R. Dahl, and D. T. Davidson. "Further Studies of Loess in Iowa: Thickness, Clay Content, and Engineering Classification." Proc. Iowa Academy of Science, 65 (1958), 317-322.

16. Kemmis, T. J., G. R. Hallberg, and A. J. Lutenegger. "Depositional Environments of Glacial Sediments and Landforms on the Des Moines Lobe, Iowa." Iowa Geological Survey Guidebook Series No. 6. Iowa City, Iowa: Iowa Geological Survey, 1981.

17. Krauskopf, K. B. Introduction to Geochemistry. New York: McGraw-Hill, Inc., 1967.

18. Leonards, G. A. and A. G. Altschaeffl. Discussion of "Review of Collapsing Soils." J. Soil Mech. Found. Div., Proc. ASCE, 97, No. SM1 (1971), 269-271.

19. Lobdell, G. T. "Hydroconsolidation Potential of Palouse Loess." J. Geotech. Engr. Div., Proc. ASCE, 107, No. GT.6 (1981), 733-742.

20. Lohnes, R. A. "Petrography of Quaternary Concretions from Western Iowa." M.S. Thesis. Iowa State University, Ames, Iowa, 1961.

21. Lutenegger, A. J. "Random-Walk Variable Wind Model for Loess Deposits." Ph.D. Dissertation. Iowa State University, Ames, Iowa, 1979.

22. Mitchell, J. K. Fundamentals of Soil Behavior. New York: John Wiley and Sons, Inc., 1976.

23. Olson, G. R. "Direct Shear and Consolidation Tests of Undisturbed Loess." M.S. Thesis. Iowa State University, Ames, Iowa, 1958.

24. Oschwald, W. R., F. F. Reicken, R. I. Dideriksen, W. H. Scholtes, and F. W. Schaller. "Principal Soils of Iowa." Iowa State University Cooperative Extension Service, Ames, Iowa, Special Report 42, 1965.

25. Perez, E. C. "Consolidation State of Some Loessial Soils in Central Iowa." M.S. Thesis. Iowa State University, Ames, Iowa, 1983.

26. Ruhe, R. V. Quaternary Landscapes in Iowa. Ames: Iowa State University Press, 1969.

27. Ruhland, R. R. "Shear Strength of a Silt Column as Affected by Capillary Rise." M.S. Thesis. Iowa State University, Ames, Iowa, 1980.

28. Schmertmann, J. H. "The Undisturbed Consolidation Behavior of Clay." Trans. ASCE, 120 (1955), 1201-1227.

29. Sheeler, J. B. "Summarization and Comparison of Engineering Properties of Loess in the United States." Highway Research Board Record, No. 212 (1968), 1-9.

30. Skempton, A. W. "The Consolidation of Clays by Gravitational Compaction." Q. J. Geol. Soc. London, 125 (1970), 373-411.

31. Spangler, M. G. and Handy, R. L. Soil Engineering. 4th ed. New York: Harper and Row, Inc., 1982.

32. U.S. Department of Agriculture. Soil Conservation Service. Soil Survey, Wayne County, Iowa. Washington: GPO, 1971.

33. U.S. Department of Interior. Bureau of Reclamation. Earth Manual. 2nd ed. Washington: GPO, 1974.

34. Walter, N. F., G. R. Hallberg, and T. F. Fenton. "Particle-size Analysis by the Iowa State University Soil Survey Laboratory." In Standard Procedures for Evaluation of Quaternary Materials in Iowa. Iowa Geological Survey Tech. Info. Series., No. 8. Iowa City, Iowa: Iowa Geological Survey, 1978, pp. 61-74.

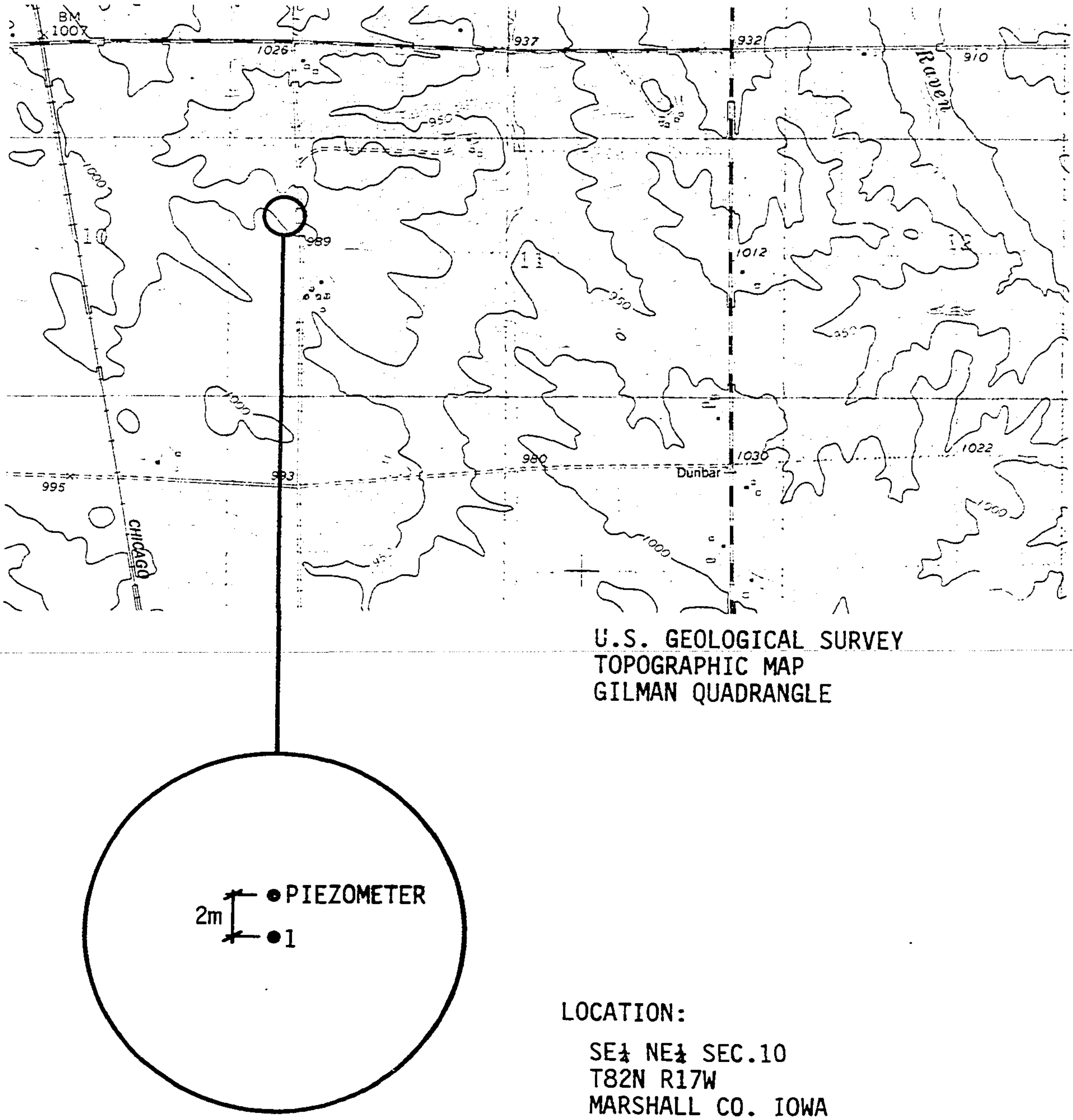
ACKNOWLEDGEMENTS

This work was funded by the National Science Foundation under Contract CEE-8020345: Mechanics and Distribution of Liquid Silt, and was performed at the Geotechnical Research Laboratory, Engineering Research Institute, Iowa State University.

Sampling was performed with the assistance of Njoroge Wainaina, Mark Pabst, Rodney Hoffman, and Brett Gunnink. Scott Deetz assisted with both field and laboratory work. Laboratory test data provided by Eglis Perez was of particular importance in the completion of this investigation. The contribution of these individuals is appreciated.

The author is grateful to Dr. Richard Handy for his assistance, support, and advice throughout the period required for this work. Dr. Altay Birand was very helpful in interpreting the initial laboratory test data. Drs. Turgut Demirel and Robert Lohnes provided both encouragement and valuable suggestions at very crucial times; their contribution is especially appreciated. And Dr. Carl Ekberg provided support, without which the author would never have been able to complete this work.

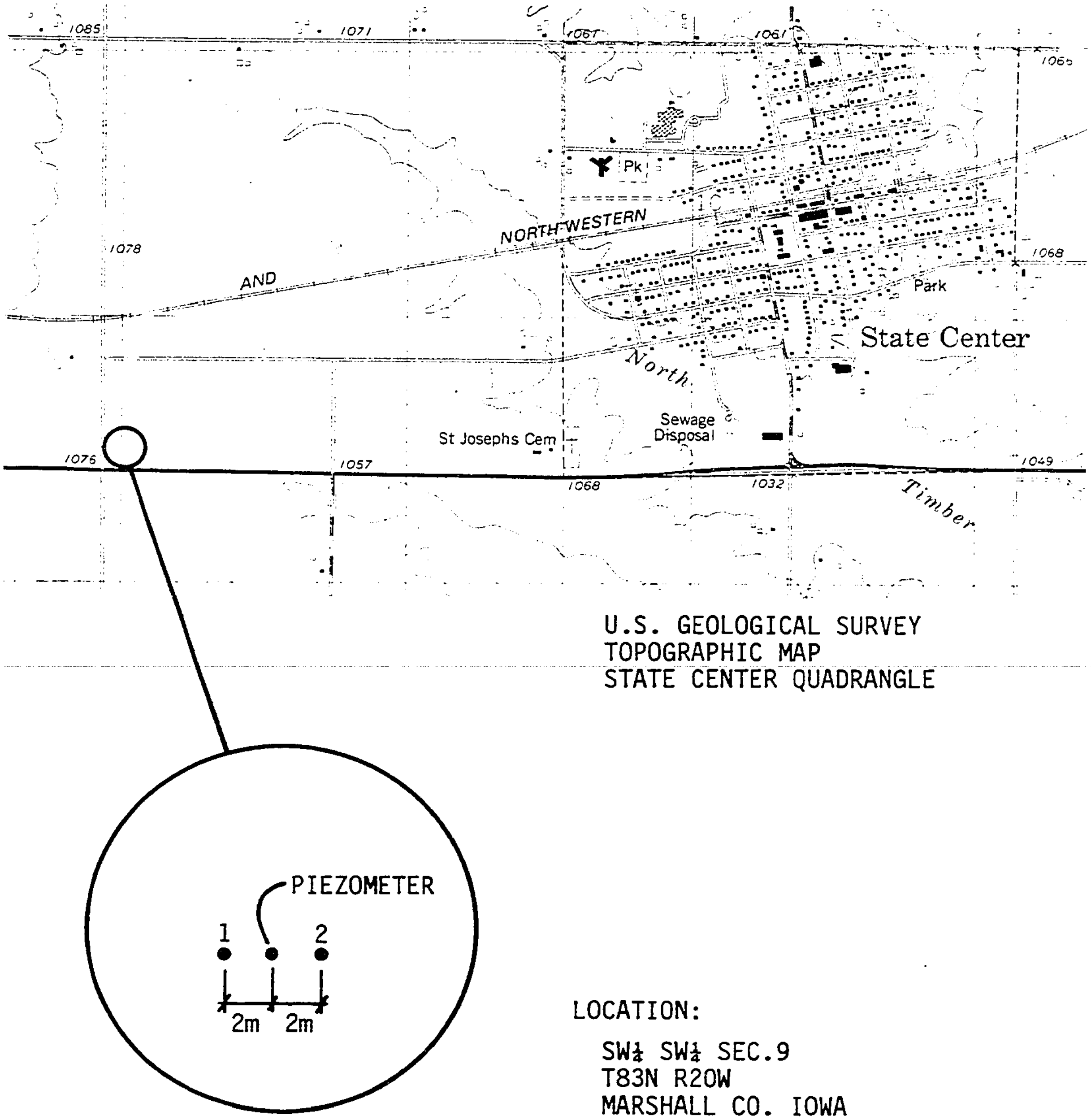
APPENDIX A: SAMPLING LOCATIONS



U.S. GEOLOGICAL SURVEY
TOPOGRAPHIC MAP
GILMAN QUADRANGLE

LOCATION:
SE¼ NE¼ SEC.10
T82N R17W
MARSHALL CO. IOWA

Figure A1. Gilman

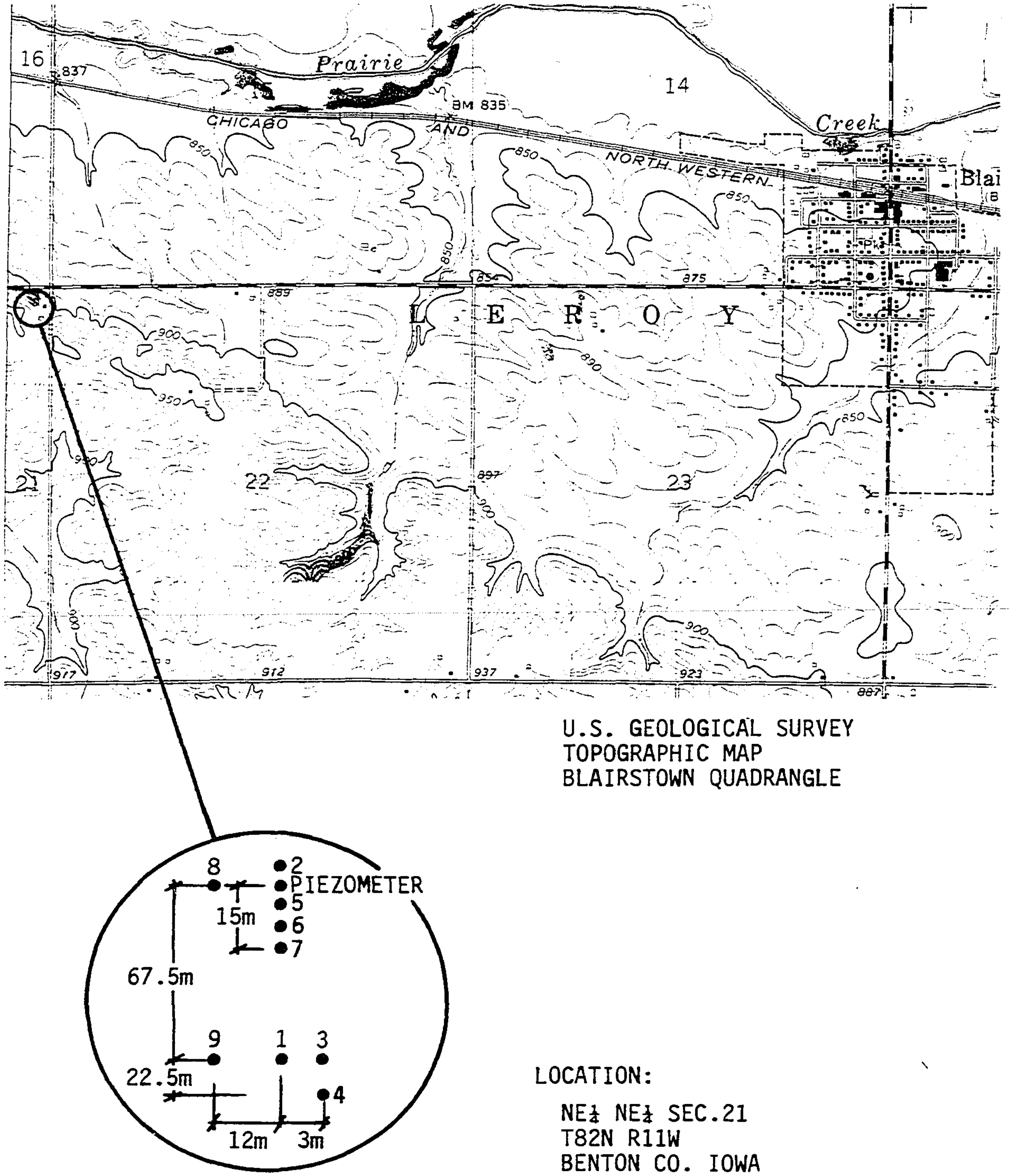


U.S. GEOLOGICAL SURVEY
TOPOGRAPHIC MAP
STATE CENTER QUADRANGLE

LOCATION:

SW¼ SW¼ SEC.9
T83N R20W
MARSHALL CO. IOWA

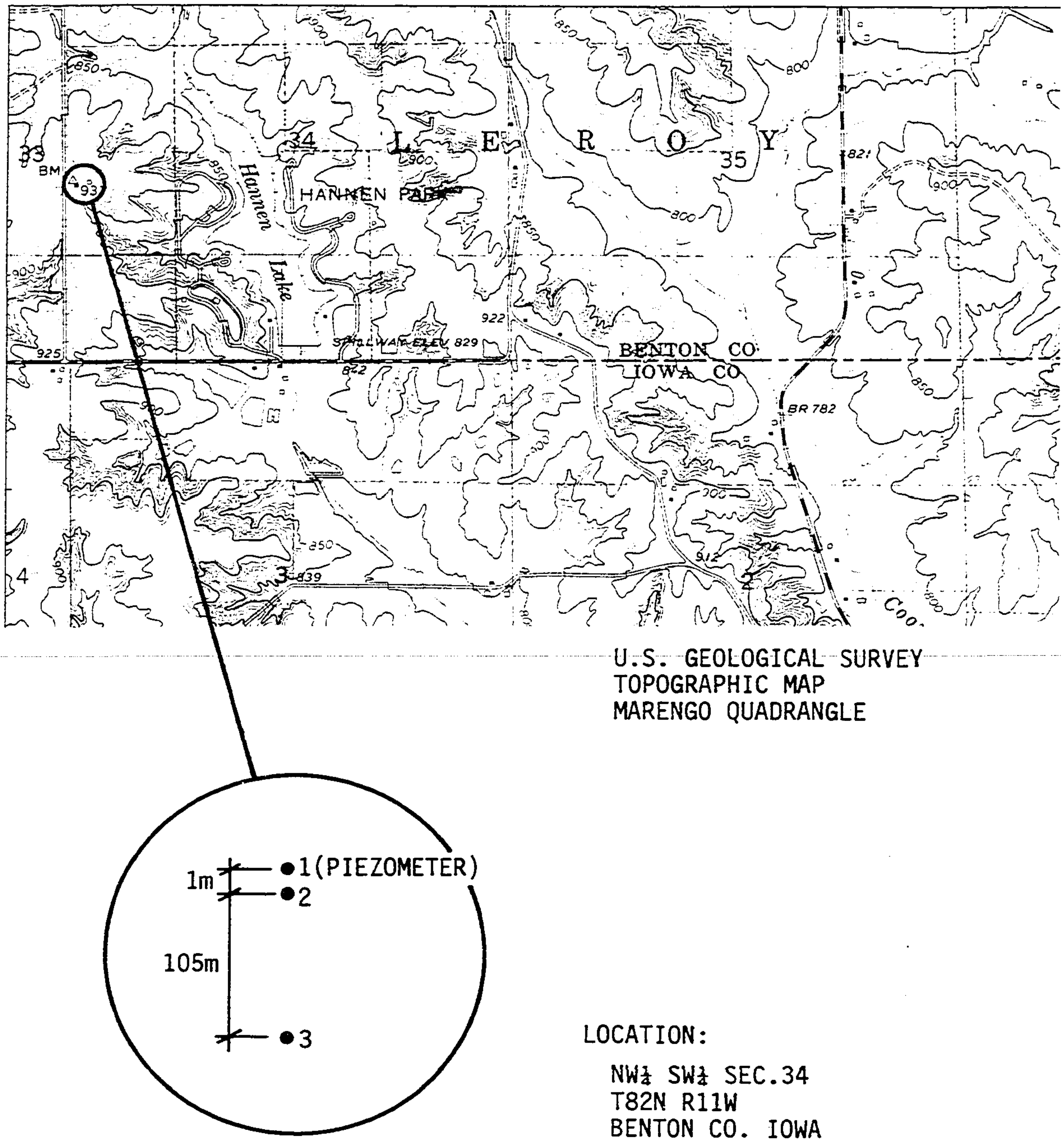
Figure A2. State Center



U.S. GEOLOGICAL SURVEY
TOPOGRAPHIC MAP
BLAIRSTOWN QUADRANGLE

LOCATION:
NE¼ NE¼ SEC.21
T82N R11W
BENTON CO. IOWA

Figure A3. Blairstown Site A



U.S. GEOLOGICAL SURVEY
TOPOGRAPHIC MAP
MARENGO QUADRANGLE

LOCATION:
NW¼ SW¼ SEC.34
T82N R11W
BENTON CO. IOWA

Figure A4. Blairstown Site B

APPENDIX B: SOIL INDEX PROPERTIES

Table B1. Index properties of soils investigated

Site/ Bore- hole	Depth m	Weathering Zone	Water Content %	Dry Density kg/m^3	Solids Specific Gravity	Void Ratio e
Blairstown 1A						
	2.29	MOL	31.6	1383	2.72	0.966
	2.82	MOL	30.9	1457	2.72	0.869
	3.41	MOL	31.1	1452	2.72	0.876
	3.94	MOU	27.7	1537	2.73	0.778
	4.27	MOU	27.0	1566	2.73	0.743
	4.78	MDU	25.5	---	---	---
	4.93	MDU	26.5	1582	2.72	0.722
Blairstown 2A						
	1.88	MOL	32.3	1378	2.71	0.963
	2.54	MOL	29.6	1445	2.71	0.877
	3.22	MOL	33.0	1416	2.72	0.920
	3.73	MOU	27.4	1551	2.73	0.760
Blairstown 3A						
	1.91	MOL	29.7	1409	2.72	0.932
	2.52	MOL	31.3	1449	2.72	0.880
	3.15	MOL	33.3	1394	2.73	0.957
	3.81	MOL	30.1	1489	2.73	0.830
Blairstown 4A						
	1.63	MOL	32.8	1389	2.72	0.956
	2.57	MOL	32.2	1447	2.72	0.878
	2.87	MOL	32.7	1407	2.72	0.933
	3.53	MOU	29.2	1513	2.73	0.803
	3.96	UU	26.0	1590	2.72	0.933
Blairstown 5A						
	2.59	MOL	33.6	1383	2.72	0.965
	3.00	MOL	34.3	1393	2.71	0.946
	3.25	MOL	34.1	1384	2.71	0.958
	3.91	MDU	27.2	1513	2.73	0.802
	4.52	MDU	25.2	1600	2.71	0.946
	4.85	MDU	25.8	1585	2.72	0.714
	5.13	MDU-MOU	26.9	1563	2.72	0.742
	5.56	MDU	26.5	1583	2.72	0.715
	6.10	MDU-MOU	26.4	1590	2.72	0.712
	6.55	MDU-MOU	25.6	1608	2.72	0.691

Saturation %	LL	PL	LI	Sand	Silt	2μm clay
89.0	43.2	18.9	0.52	0.1	72.0	27.9
96.8	39.0	20.0	0.57	0.1	78.4	21.5
96.6	32.8	21.5	0.85	0.1	84.2	15.7
97.3	30.8	20.4	0.70	1.5	84.3	14.2
99.3	30.1	21.2	0.65	0.5	85.3	14.2
---	---	---	---	---	---	---
99.9	28.4	20.6	0.75	0.1	82.5	17.4
90.9	46.3	20.1	0.47	0.2	71.8	28.0
91.7	36.8	20.1	0.57	0.5	75.9	23.6
97.5	37.8	19.6	0.74	0.2	77.4	22.4
98.6	31.2	21.6	0.61	0.4	83.6	16.0
86.7	38.7	21.2	0.31	0.2	72.9	26.9
97.0	41.4	19.7	0.54	0.2	77.4	22.4
94.9	37.3	20.6	0.76	0.1	79.8	20.1
98.8	32.2	21.1	0.81	0.3	83.7	16.0
93.1	48.6	21.0	0.43	0.0	92.7	27.3
99.5	39.1	20.4	0.63	0.1	76.0	23.9
95.3	35.2	21.5	0.82	0.1	81.3	18.6
99.1	32.4	21.7	0.70	0.1	82.6	16.9
99.7	32.6	21.3	0.42	0.5	81.8	17.7
94.7	39.3	20.7	0.70	0.3	78.6	21.1
98.2	36.4	21.3	0.86	0.3	78.0	21.7
96.5	35.6	20.6	0.90	0.5	78.7	20.8
92.6	30.7	21.8	0.61	0.7	83.6	15.7
98.2	36.4	20.2	0.56	0.6	82.8	16.6
98.0	30.9	21.4	0.46	0.7	84.1	15.2
98.5	30.3	22.0	0.58	0.4	84.2	15.4
100.0	29.2	20.5	0.69	0.5	83.4	16.1
100.0	29.1	21.3	0.65	0.7	86.3	13.0
100.0	29.8	20.1	0.57	0.7	82.0	17.3

Table B1. (Continued)

Site/ Bore- hole	Depth m	Weathering Zone	Water Content %	Dry Density kg/m^3	Solids Specific Gravity	Void Ratio e
Blairstown 6A						
	2.64	MOL	31.0	1435	2.71	0.888
	3.45	MOL	32.9	1398	2.72	0.942
	4.06	MOU	24.6	1602	2.73	0.706
	4.62	MOU	24.2	1638	2.71	0.653
	5.13	MDU	26.2	1587	2.72	0.713
Blairstown 7A						
	1.72	MOL	29.1	1409	2.71	0.924
	2.18	MOL	30.5	1433	2.72	0.897
	2.87	MOL	30.8	1443	2.71	0.884
	3.60	MOU	30.0	1489	2.71	0.823
Blairstown 8A						
	1.27	MOL	27.2	1451	2.71	0.864
	2.18	MOL	28.9	1458	2.70	0.855
	2.49	MOL	29.4	1469	2.69	0.832
	3.23	MOL	31.3	1452	2.71	0.862
Blairstown 9A						
	1.30	MOL	26.0	1427	2.71	0.895
	2.11	MOL	32.7	1403	2.70	0.927
	2.54	MOL	35.5	1356	2.70	0.993
	3.15	MOL	29.0	1484	2.73	0.840
Blairstown 2B						
	2.18	MOL	30.4	1428	2.72	0.907
	2.79	MOL	33.0	1386	2.73	0.971
	3.45	MOL	32.6	1425	2.72	0.914
	4.01	MOU	27.8	1518	2.72	0.794
	4.62	MDU	23.3	1635	---	---
	5.23	MDU	25.1	1585	2.73	0.725
Blairstown 3B						
	1.67	MOL	29.8	1456	2.72	0.870
	2.28	MOL	33.3	1381	2.72	0.968
	2.89	MOU	29.2	1479	2.73	0.844
	3.48	MDU	27.5	1525	2.73	0.788
	4.11	MDU	25.2	1562	2.71	0.736
	4.72	MDU-MDL	26.8	1488	2.72	0.825

Saturation %	LL	PL	LI	Sand	Silt	2μm clay
94.6	42.0	19.6	0.51	0.3	75.9	23.8
94.8	36.3	20.7	0.78	0.2	79.3	20.5
95.1	31.8	21.1	0.33	0.4	81.3	18.3
100.0	28.6	20.7	0.44	0.4	85.7	13.9
100.0	29.0	20.5	0.67	0.6	86.3	13.1
85.4	47.8	19.5	0.34	0.6	71.8	27.6
92.5	42.0	19.0	0.50	0.1	76.3	23.6
94.8	40.4	20.0	0.53	0.3	77.6	22.1
99.0	32.5	21.2	0.78	0.2	82.3	17.5
85.3	50.2	20.4	0.23	0.1	69.8	30.1
91.3	39.1	19.6	0.48	0.2	78.2	21.6
95.1	39.2	18.9	0.52	0.3	76.5	23.2
98.2	33.1	21.2	0.85	0.3	81.7	18.0
78.6	49.1	19.8	0.21	0.0	73.2	26.8
95.4	39.0	20.1	0.67	0.1	79.3	20.6
96.7	36.1	20.3	0.96	0.2	78.4	21.4
94.3	31.6	21.3	0.75	0.1	81.7	18.2
91.3	42.9	19.7	0.46	0.4	73.5	26.1
93.0	41.7	19.3	0.61	0.4	74.9	24.7
96.9	38.5	20.4	0.67	0.2	78.4	21.4
95.2	32.5	20.8	0.60	0.2	81.2	18.6
94.7	35.6	21.3	0.27	0.1	78.4	21.5
93.2	39.5	19.6	0.51	0.1	74.8	25.1
93.6	37.9	21.2	0.73	0.0	78.7	21.3
94.3	32.0	22.4	0.70	---	---	---
95.2	34.6	21.4	0.46	---	---	---
92.6	33.6	21.3	0.31	---	---	---
88.2	36.3	19.9	0.42	---	---	---

Table B1. (Continued)

Site/ Bore- hole	Depth m	Weathering Zone	Water Content %	Dry Density kg/m^3	Solids Specific Gravity	Void Ratio e
Gilman No. 1						
	2.56	MOL	31.6	1437	2.72	0.891
	2.84	MOL	31.9	1459	2.71	0.855
	3.30	MOL	33.5	1409	2.71	0.924
	3.45	MOL	34.6	1388	2.72	0.957
	4.03	MOL	31.7	1467	2.71	0.847
State Center No. 2						
	0.97	MOL	25.8	1287	2.72	1.113
	1.63	MOL	30.5	1439	2.72	0.894
	2.29	MOL	34.9	1368	2.73	0.994
	3.00	MOU	30.7	1442	2.73	0.896
	3.45	MDU	29.1	1493	2.73	0.828
	4.06	MDU	29.0	1495	2.74	0.836

Saturation %	LL	PL	LI	Sand	Silt	2µm clay
96.4	43.0	20.0	0.51	0.0	73.2	26.8
100.0	44.6	19.6	0.49	0.1	71.9	28.0
98.3	40.9	21.0	0.63	0.0	73.6	26.4
98.2	39.9	20.3	0.73	0.0	74.2	25.8
100.0	36.2	19.7	0.73	1.7	74.6	23.7
63.0	49.3	22.7	0.12	0.0	68.7	31.3
93.1	45.0	20.6	0.41	0.1	71.4	28.5
95.9	38.9	20.4	0.79	0.0	76.7	23.3
93.6	36.3	20.0	0.66	0.3	78.2	21.5
96.0	37.0	19.0	0.56	0.0	77.2	22.8
95.2	38.7	20.5	0.47	0.3	77.5	22.2

APPENDIX C: ONE-DIMENSIONAL CONSOLIDATION TEST RESULTS

Table C1. One-dimensional consolidation test sample properties

Site	Sample Borehole	Depth m	Initial Void Ratio e_o	Initial Water Content w,%	Solids Specific Gravity
Blairstown A	1	5.11	0.730	25.8	2.71
	2	2.97	0.901	29.2	2.71
	3	2.72	0.882	30.4	2.72
	3	3.33	0.970	33.0	2.73
	5	2.77	0.930	36.4	2.72
	5	3.33	0.978	31.5	2.71
	5	5.66	0.708	26.1	2.72
	5	7.06	0.670	25.7	2.72
	6	3.07	0.920	32.7	2.72
State Center	2	1.91	0.959	32.9	2.72
	2	4.24	0.795	27.0	2.74

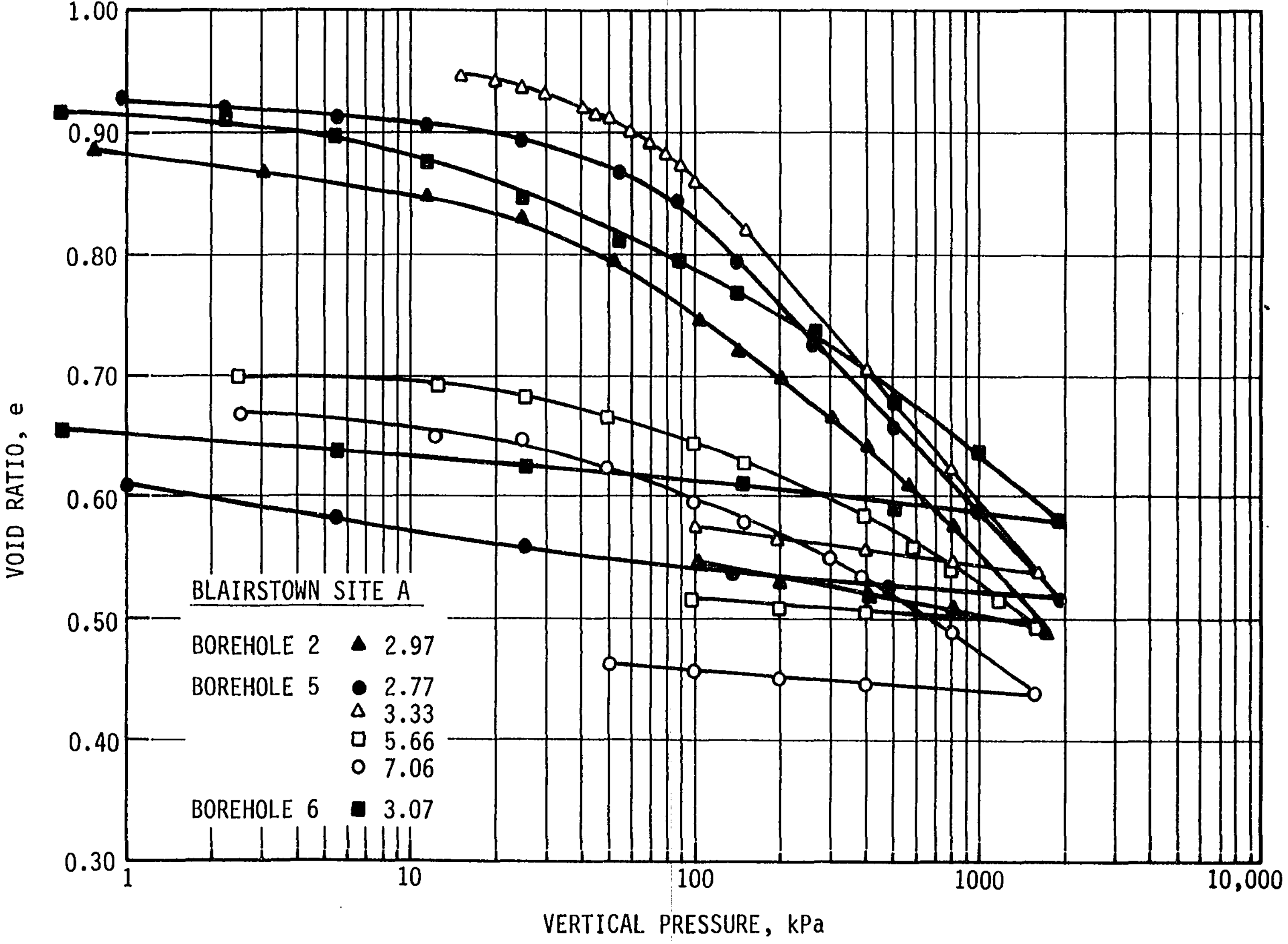


Figure C1. One-dimensional consolidation test results

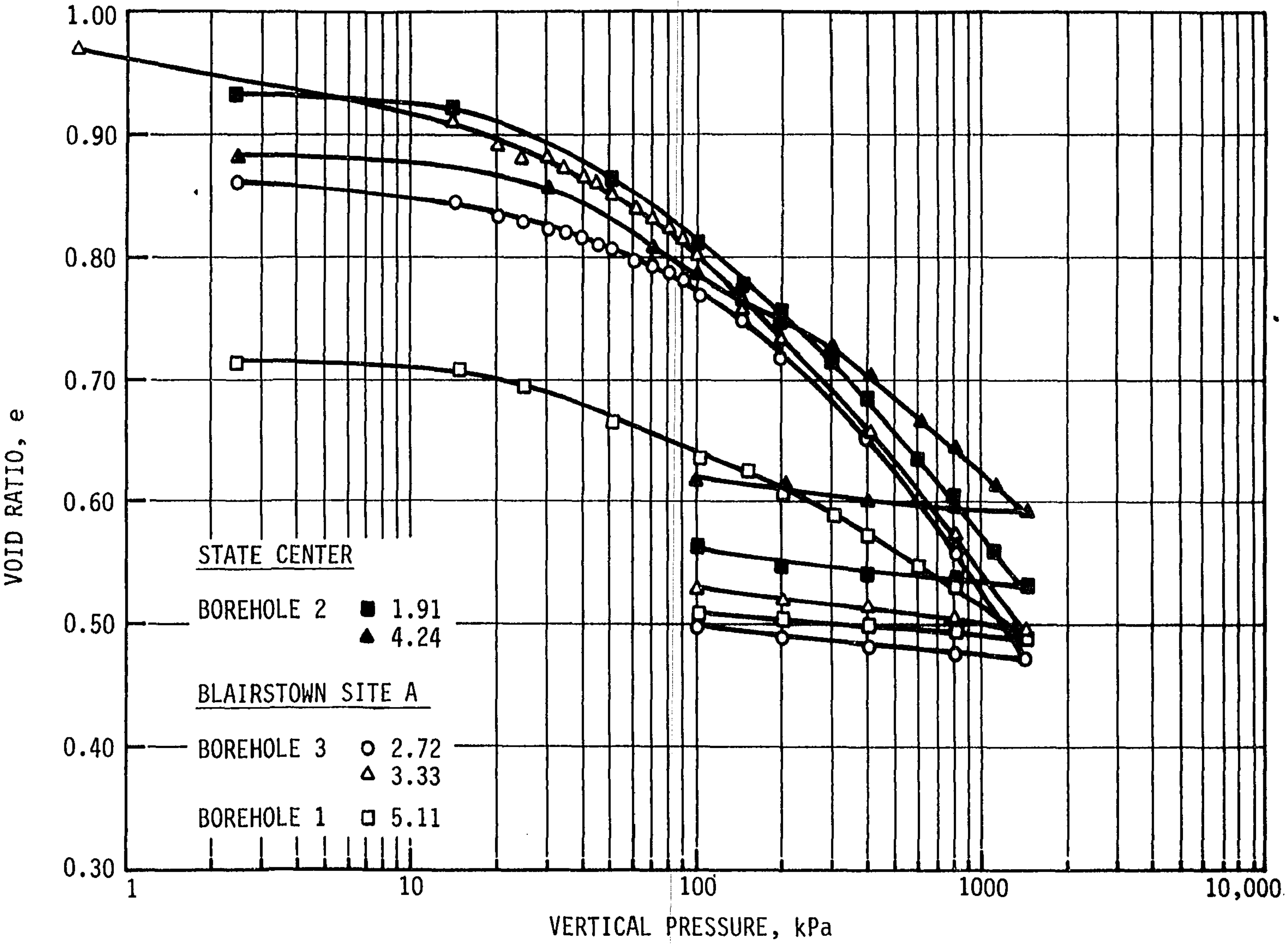
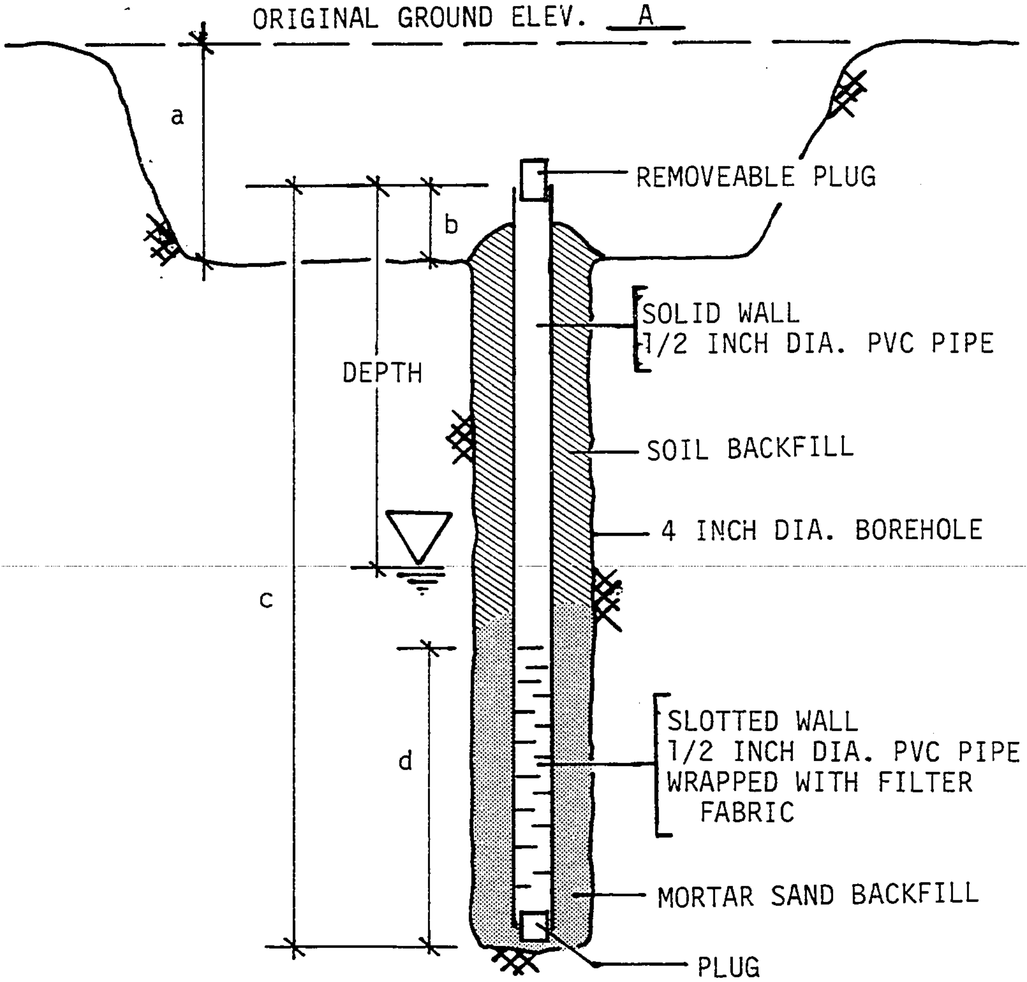


Figure C2. One-dimensional consolidation test results

APPENDIX D: PIEZOMETER DATA



Dimensions are given in Table D1.

Figure D1. Piezometer construction details

Table D1. Piezometer installation details

Site	Elevation A m (ft)	Distance m (ft)				Date of Installation
		a	b	c	d	
Gilman	304.8 (1000)	0.91 (3.0)	0.15 (0.5)	6.40 (21.0)	3.05 (10.0)	6-3-82
State Center	326.1 (1070)	0.0 (0.0)	0.15 (0.5)	9.91 (32.5)	4.57 (15.0)	6-1-82
Blairstown Site A	289.6 (950)	1.37 (4.5)	0.15 (0.5)	8.08 (26.5)	3.05 (10.0)	6-14-82
Blairstown Site B	285.6 (937)	0.91 (3.0)	0.15 (0.5)	8.38 (27.5)	3.05 (10.0)	8-19-82

Table D2. Piezometer data

Date	Depth m (ft)	Date	Depth m (ft)
	Gilman		Blairstown Site A (heavy rainfall 6-14)
6-3-82	3.47 (11.4)	6-16-82	0.76 (2.5)
6-4	3.57 (11.7)	6-17	0.46 (1.5)
6-7	3.57 (11.7)	7-23	2.35 (7.7)
6-10	3.60 (11.8)	8-12	2.80 (9.2)
6-16	3.51 (11.5)	8-16	3.08 (10.1)
7-23	3.41 (11.2)	9-15	3.26 (10.7)
8-12	3.96 (13.0)	10-26	3.90 (12.8)
9-15	4.27 (14.0)	11-28	2.83 (9.3)
10-26	4.88 (16.0)	12-23	2.10 (6.9)
11-28	4.75 (15.6)	1-20-83	2.44 (8.0)
12-23	4.42 (14.5)	2-24	2.13 (7.0)
1-20-83	4.21 (13.8)	3-23	3.02 (9.9)
2-24	4.18 (13.7)	4-26	0.64 (2.1)
4-26	2.74 (9.0)	6-28	2.07 (6.8)
6-28	3.96 (13.0)	8-4	2.74 (9.0)

Date	Depth m (ft)	Date	Depth m (ft)
	State Center		Blairstown Site B
6-1-82	2.32 (7.6)	8-24-82	3.35 (11.0)
6-2	2.04 (6.7)	9-15	3.60 (11.8)
6-16	1.65 (5.4)	10-26	3.69 (12.1)
6-18	1.92 (6.3)	11-28	2.77 (9.1)
7-23	2.35 (7.7)	12-23	2.41 (7.9)
8-12	2.68 (8.8)	1-20-83	2.74 (9.0)
9-15	2.87 (9.4)	2-24	2.07 (6.8)
10-26	2.90 (9.5)	3-23	2.68 (8.8)
11-28	2.59 (8.5)	4-26	1.52 (5.0)
12-23	2.53 (8.3)	6-28	3.05 (10.0)
1-20-83	2.62 (8.6)		
2-24	2.26 (7.4)		
3-23	2.47 (8.1)		
4-26	2.35 (7.7)		
6-28	2.59 (8.5)		