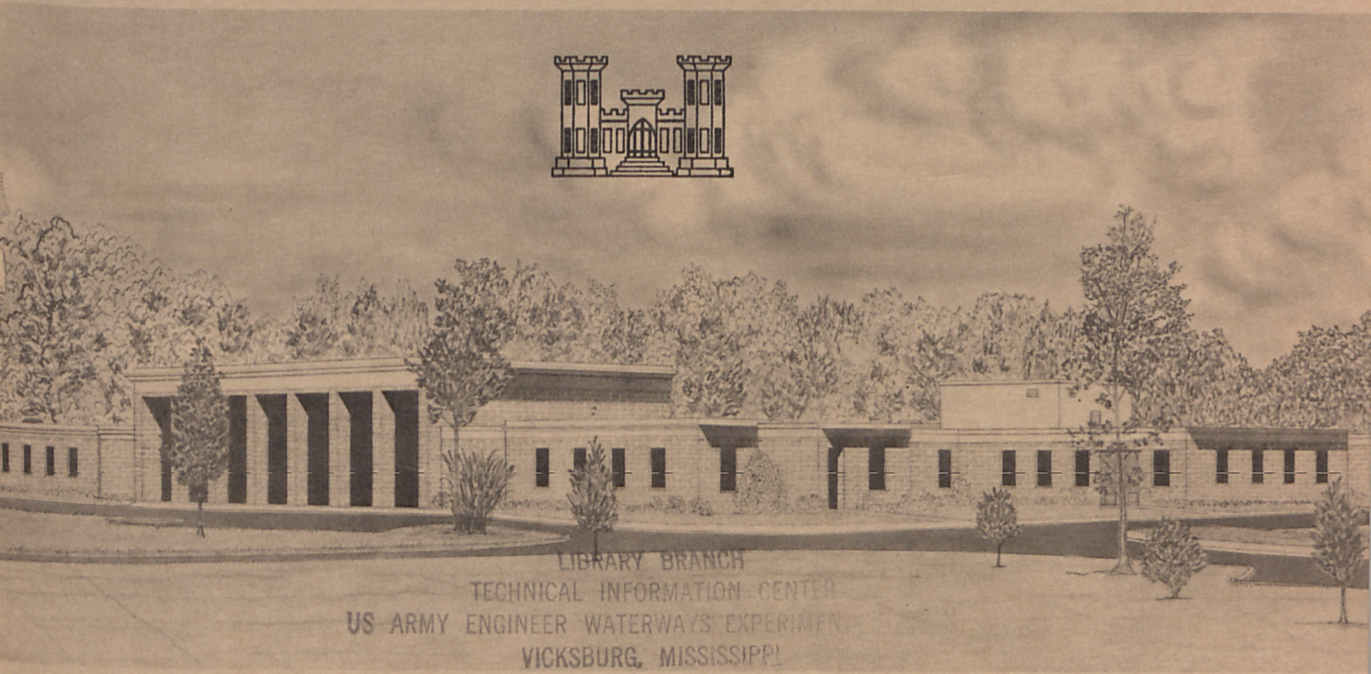
MISCELLANEOUS PAPER S-73-49

EFFECT OF VARIATION IN CONVENTIONAL SOIL PROPERTIES ON DYNAMIC CONSTRAINED MODULUS FOR SEVERAL GLACIAL TILLS

by

H. M. Taylor, Jr.



June 1973

Sponsored by Office, Chief of Engineers, U. S. Army

Conducted by U. S. Army Engineer Waterways Experiment Station
Soils and Pavements Laboratory
Vicksburg, Mississippi

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ARMY-MRC VICKSBURG, MISS.

FOREWORD

The work reported herein was conducted in the Soils and Pavements Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES) during the period July 1970-November 1972. It was sponsored by the Office, Chief of Engineers, Nuclear Construction and Engineering, under Task 08, "Ground Shock and Dynamic Earth Pressure Effects."

This report is essentially a thesis submitted by Mr. H. M. Taylor, Jr., of the Soil Dynamics Division, WES, to Mississippi State University in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering. Suggestions offered by Mr. J. E. Windham relevant to the correlations and analyses presented herein are gratefully acknowledged. The work was conducted under the immediate supervision of Dr. J. G. Jackson, Jr., Chief, Soil Dynamics Division. Messrs. J. P. Sale and R. G. Ahlvin were Chief and Assistant Chief, respectively, of the Soils and Pavements Laboratory during the preparation and publication of this report.

COL Ernest D. Peixotto, CE, was Director of the WES during the investigation and preparation of this report. Mr. F. R. Brown was Technical Director.

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CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
inches	2.54	centimeters
feet	0.3048	meters
miles (U. S. statute)	1.609344	kilometers
pounds (force) per square inch	0.6894757	newtons per square centimeter
kips (force) per square foot	47.8803	newtons per square meter
pounds (mass) per cubic foot	16.0185	kilograms per cubic meter
inches per second	2.54	centimeters per second
feet per second	0.3048	meters per second

SUMMARY

This report presents the results of an effort to analyze and correlate data from tills to determine if the dynamic constitutive relations needed for ground shock code input are predictable from simple index and seismic tests.

Data from glacial tills at seven sites in the northern United States were used successfully to correlate secant constrained moduli with percent saturation and percent air in a unit volume of soil. These correlations indicated trends distinctive enough to use either of the correlations to approximately predict, for a till, the loading portion of the UX stress-strain curve to a stress of about 500 psi. Predictions using these correlations should be made with due consideration of the validity and amount of saturation and percent air data. In addition, some qualitative consideration should be given to the unit weight and seismic velocity data, the depth of weathering, and the location of the groundwater table.

For the tills investigated in this study, dry density, UU strength, and Young's modulus taken from the static UU stress-strain curve cannot generally be used to predict the secant constrained moduli to the stress levels of interest.

CHAPTER I

INTRODUCTION

Background

The development of nuclear explosives has resulted in an intensified effort to understand the propagation and attenuation of explosively induced waves through the earth, the transformation of earth under the influence of such waves, and the effect of these waves on buried protective structures.

With the development of offensive and defensive missle systems hardened for survival in the event of a nuclear attack and with the conduct of large-scale, high-explosive field tests, an urgent need has been demonstrated for preliminary estimates of the soil constitutive relations, or stress-strain properties, that are used in calculating earth motions resulting from such explosions. Among the most useful stress-strain relations currently being generated are those from controlled impulsive stresses applied to an undisturbed soil specimen confined to deform in a state of uniaxial strain (UX test).[1]

Since 1968, the U. S. Army Engineer Waterways Experiment Station (WES) has conducted undisturbed sampling programs and detailed dynamic soil property investigations for a number of sites in the United States and Canada. The purpose of these investigations was to determine dynamic stress-strain properties for use as input to computer code calculations of ground motion due to either a nuclear or high-explosive detonation.

As a result of these site investigations, a great amount of constitutive and index property data as well as field seismic data is available for several geographic locations with various geologic profiles. The sites investigated are in the northern part of the United States in areas that have been modified by significant glaciation, as shown in figure 1.

Several of the sites shown in figure 1 were found to contain one or more strata of glacial till in the soil profile. Till, which is possibly the most variable earth material identified by a single name, is commonly defined as nonstratified sediment carried or deposited by a glacier. It may consist principally of clay particles or large boulders or of any combination of these, including intermediate sizes. The tills tested to provide the data for this study contained grain sizes no larger than coarse gravel (3 in.*). By far, most of the grain-size data indicated that 80 percent by weight of the soil particles were finer than the No. 40 sieve and that 55 percent of the soil particles were finer than the No. 200 sieve. Hence, most of the tills considered in this study were some combination of clay, fine sand, and silt-size material, with some gravel. The Atterberg limits of the minus No. 40 fraction place these soils above the A-Line on the plasticity chart. The soils were classified as CL or CH in the Unified Soil Classification System.[2] An example of the variation in texture of till encountered in samples from a single boring is shown in figure 2.

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* A table of factors for converting British units of measurement to metric units is presented on page xi.

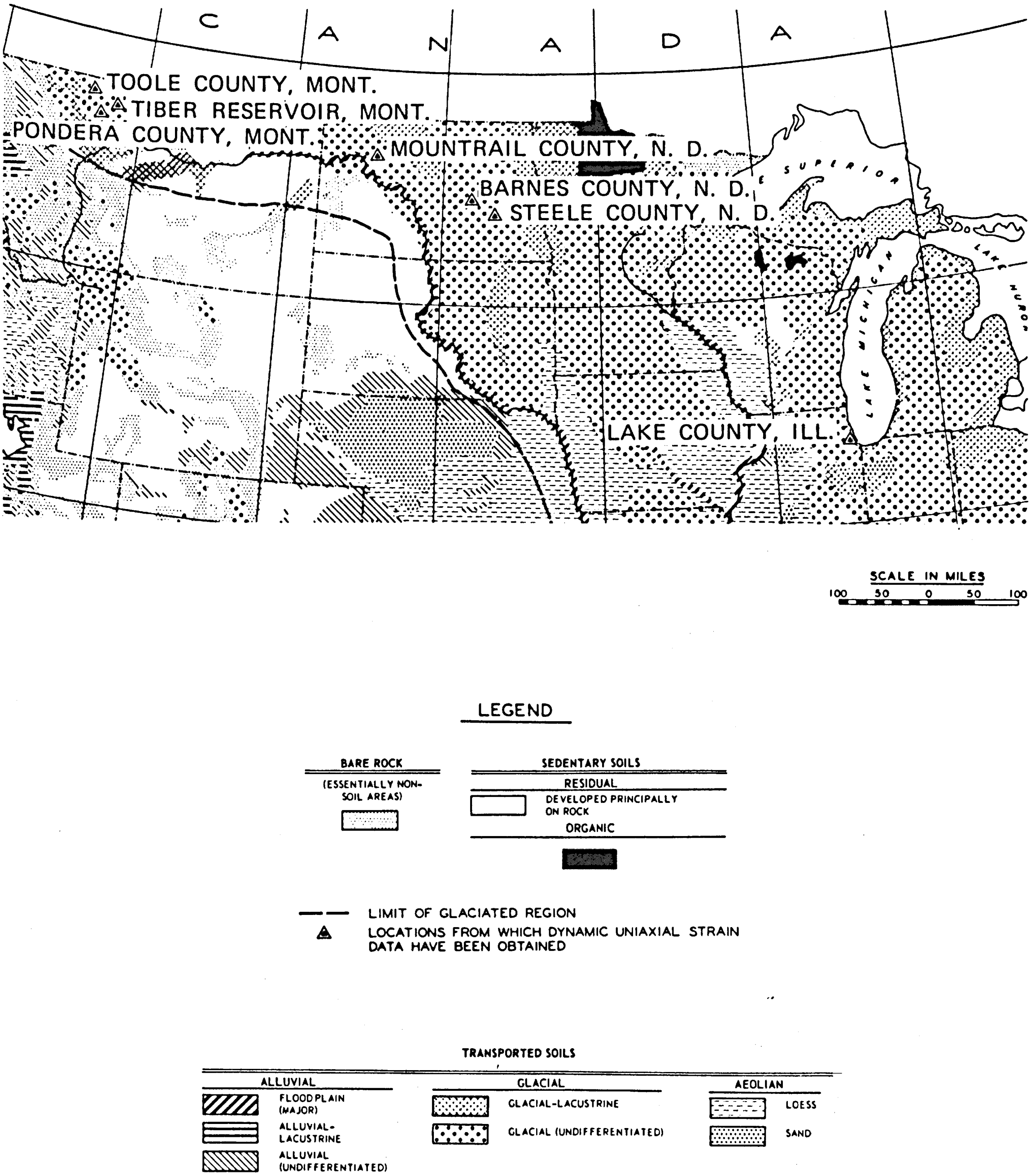
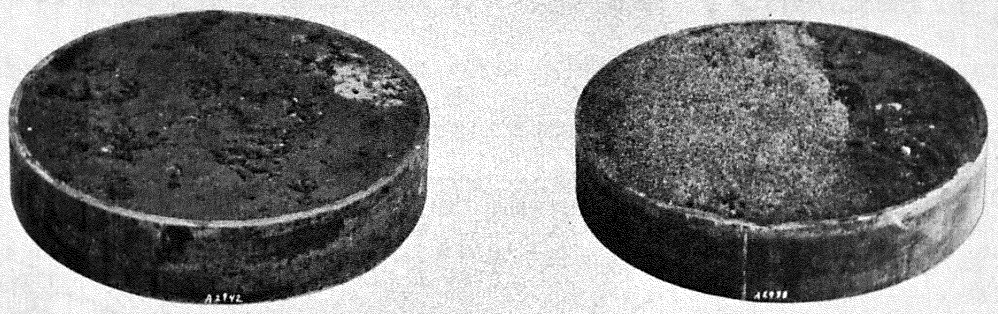


Figure 1 Locations of seven sites founded in till that were considered in this study



EL 987.7

Oxidized Sandy Clay

EL 935.5

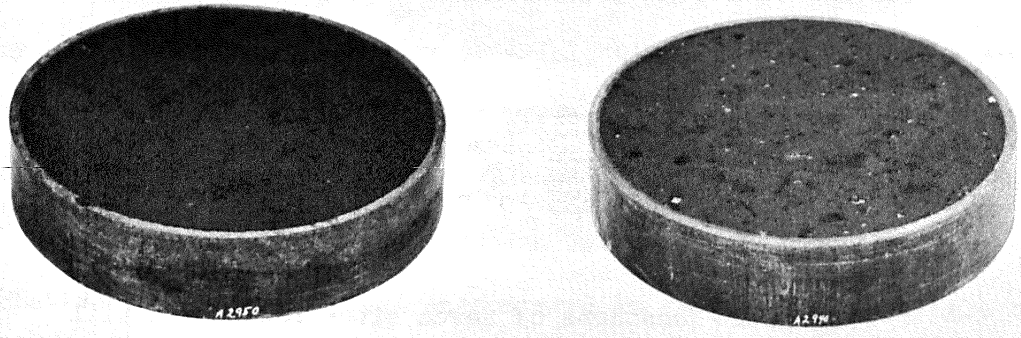
Sand Pocket

EL 987.6

Trace of Gravel

EL 909.7

Sandy Clay



EL 977.9

Unoxidized Sandy Clay

EL 895.9

Sandy Clay

Figure 2 Variation of grain size for material from a single boring in till

A parameter that can be used to describe variations in the material stress-strain curve from the dynamic* UX test is the secant slope from zero live stress to some particular stress level of interest on the loading portion of the soil stress-strain curve. In this study, 50-, 100-, 250-, and 500-psi stress levels were used. This parameter is called the secant constrained modulus, and it is with this parameter that correlations were attempted in this study. The secant constrained modulus has direct application in the prediction of airblast-induced vertical ground motion.[3-6]

Previous research on the composition,[7,8] the effect of freeze-thaw cycling on stress-strain characteristics,[9] and the effect of organic topsoil content on stress-strain characteristics[10] of tills are mentioned only as literature considered in this study. The results of additional investigations of tills and the determination of relations between simple soil properties and unconfined compressive strengths for certain tills are discussed in references 11 and 12. Since references 7-12 are concerned with the static properties of tills, none of the data reported therein are presented in this investigation.

Purpose

The objective of this study was to develop any correlation

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* In this case, the word "dynamic" is not meant to imply that significant inertia forces are present in the test. In fact, efforts are always undertaken to ensure that such forces are negligible. The term is meant to imply that the rise time to peak stress is on the order of a few milliseconds or, at most, a few tens of milliseconds.

possible between the dynamic secant constrained modulus M_c from the UX test and any conventional soil property and/or field seismic data. It is thought that such a correlation will allow preliminary prediction of M_c for glacial tills in cases in which only limited soil property data are available.

Scope

Correlations of M_c's to four different stress levels with elementary soil properties were attempted. The seven sites from which till data were available for this study are identified in figure 1 only by their general locations because of various restrictions placed upon the data by the agencies that sponsored the data collection. These sites are the (a) Toole County, Montana; (b) Pondera County, Montana; (c) Tiber Reservoir, Montana; (d) Mountrail County, North Dakota; (e) Barnes County, North Dakota; (f) Steele County, North Dakota; and (g) Lake County, Illinois, sites.

Attempts were made to correlate M_c with: (a) dry unit weight (defined as the weight of oven-dried soil solids per unit of total volume of soil mass and usually expressed in pounds per cubic foot); (b) volume of air voids expressed as a percentage of the total volume of soil; (c) saturation, i.e., volume of water expressed as a percentage of the total volume of voids; (d) unconsolidated-undrained (UU) shear strength $\left(\frac{\sigma_1 - \sigma_3}{2}\right)_{max}$ determined at a confining pressure equal to the overburden stress; and (e) the initial slope of the UU stress-strain curve mentioned above. In addition, the initial modulus M_i computed by multiplying the mass density ρ

and the square of the material's seismic P-wave velocity c_i was compared with the ratio of M_c/M_i, and a comparison of saturation versus M_c/M_i was also made. Attempts were also made to determine the relative effects on M_c of various weathering conditions, the groundwater level, and variations in the amount of the coarse fraction of the soil.

The individual site locations, geologies, and soil profiles are described in Part II; the correlations attempted are described and discussed in Part III; and conclusions resulting from these attempted correlations are presented in Part IV.

CHAPTER II

SOURCES OF SOIL PROPERTY DATA

Toole County, Montana, Site

The approximate location of the Toole County, Montana, site is shown in figure 1. This site is situated on a relatively flat field within a gently rolling to rough glacial till plain that extends from northern Canada into south-central Montana. The ground surface elevation* of the site is el 3405. The maximum relief in the vicinity of this site is about 250 ft. A 42.5-ft-thick mantle of till consisting of a silty, sandy, stiff, gray-to-tan clay overlies the bedrock at the site. Bedrock consists of shales of the Upper Cretaceous Colorado Group. The groundwater elevation remained fairly constant approximately at el 3380 during a 15-day observation period in September 1968. Weathering was evidenced to a depth of 72.5 ft by the presence of iron-oxide stains in fractures in the shale.

Pondera County, Montana, Site

The approximate location of the Pondera County, Montana, site is also shown in figure 1. The site lies on a broad, somewhat hummocky crest of an east-west trending glaciated ridge between Pondera and South Pondera Coulees approximately at el 3545. The immediate site area has a surface relief of about 55 ft. A mantle of glacial

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* All elevations (el) cited herein are in feet referred to mean sea level (msl).

till consisting of slightly weathered, stiff to hard, massive, pebbly, sandy clay extends from the surface to depths as great as 60 ft. On the ridge crest, the till is underlain by tertiary terrace deposits 4 to 15 ft thick that consist of sandy gravel with various amounts of silt and clay. Groundwater is present in the terrace gravels and in fractures in the underlying Cretaceous shales. The shale is part of the Kevin Member of the Marias River Formation, Colorado Group. The top of the essentially unweathered shale (not hand crushable) is approximately at el 3500.

Tiber Reservoir, Montana, Site

The approximate location of the Tiber Reservoir site is also shown in figure 1. The site area lies on the northeast flank of the South arch, the southern unit of the broad, north-plunging Sweetgrass arch, and partly in the trough of the Marias River syncline. Ground surface elevation in the immediate vicinity of the site is about el 3320. Topography in the site area is very gentle, with relief on the order of 20 ft. The site overburden consists of 40-65 ft of glacial deposits that overlie shale. The near-surface material is a massive-to-bedded sandy clay and clayey ablation till that overlies an upper lodgment till. Where the ablation till is massive, differentiation between it and the weathered lodgment till is difficult. The ablation till is generally thin but has a maximum thickness of 10 ft. The upper lodgment till is a stiff-to-hard massive sandy clay with gravel. The upper lodgment till forms a thin mantle over a series of stratified lake deposits. The lake deposits are composed of a series of cross-bedded clayey and silty sands intermingled with bedded clay and the beds of till-like sandy clay gravel. Where they exist, the lake-bed sediments vary in thickness from a few feet to nearly 50 ft. A 5- to 10-ft-thick sheet of till consisting of hard, massive, sandy clay with gravel immediately underlies the lake deposits. Where the lake deposits are absent, the contact between the two lodgment tills cannot readily be determined. As might be expected, an increase in shale particles is common in the basal portion of the lower till, and the material commonly grades into the underlying weathered shale surface. The bedrock consists of dark gray to brownish gray thinly bedded shale with occasional beds of sandy siltstone, calcareous shale, and bentonite, all of which are parts of the Ferdig Member of the Marias River Formation. The water table was not well defined in the investigation at this site but is assumed to exist approximately at the shale surface.

Mountrail County, North Dakota, Site

The Mountrail County, North Dakota, site is located as shown in figure 1. The area under study is located along the southern edge of the Missouri Coteau morainal hills within the Missouri Plateau, a part of the Great Plains physiographic province. The site itself lies on a gently rolling, uncultivated field having a maximum relief of about 7 ft. The ground surface elevation at the borehole from which undisturbed samples were taken is el 2249. A 60-ft-thick zone of glacial drift blankets the bedrock in the vicinity of the site.

Of interest in this study is the upper 26 ft of this drift, which is a till consisting of a heterogeneous mixture of weathered clay, silt, sand, and gravel. Beneath this to the 58-ft depth is a fairly clean, loose, fine- to medium-grained, micaceous silty sand. The water table is in this sand layer approximately at el 2204. A 2-ft-thick clay layer occurs at the base of the drift and overlies the bedrock sequence of soft to hard, interbedded, very silty clay shales, lignites, silts, and sands of the Fort Union Group.

Barnes County, North Dakota, Site

The location of the Barnes County, North Dakota, site is shown in figure 1. The area of interest lies within the Drift Prairie, a part of the Central Lowlands physiographic province. The site is approximately at el 1450 ± 50 ft. The relief in the area of the site is 15 to 20 ft. The site is situated on a gently rolling till plain underlain by 30 to 60 ft of weathered till and 160 to 190 ft of unweathered till. The grain-size distribution within the two till zones is approximately the same. The major difference between the two is that the upper zone is oxidized but the lower zone is not. In the upper zone, iron-oxide stain is dispersed throughout the clay and also occurs as coatings along fracture planes and on sand grains. The iron oxide also occurs as concretions or as a cementing agent binding small clusters of silt and fine sand grains. The tills in both zones are composed of angular to subangular fragments of gray shale, quartz, and limestone bound together in a montmorillonite clay matrix. The till, in turn, overlies about 8 ft of plastic clay shale, which marks the upper weathered zone of the Pierre shale. Saturated till was encountered at about the 15-ft depth during drilling at the site. Infiltration of water into the borehole was slow, however, due to the impervious nature of the till. When sand and gravel pockets or seams were encountered, a much freer flow of water resulted.

Steele County, North Dakota, Site

The approximate location of the Steele County, North Dakota, site is shown in figure 1. The site is approximately at el 1490 to 1500 and is situated on a flat to gently rolling, glacial till plain sloping to the east at 25 to 50 ft per mile. Maximum relief within the site area is approximately 10 ft. Glacial overburden extends to a depth of about 150 ft and overlies Pierre shale. The groundwater level ranges from a depth of 10 to 14 ft below the ground surface. The till overburden consists essentially of silty to sandy lean clay, which contains occasional clayey to silty fine sand and sandy silt units. The borehole lithology indicates that weathering extends to a depth of about 18 ft, the lower limit of iron-stained material.

Lake County, Illinois, Site

The approximate location of the Lake County, Illinois, site is shown in figure 1. Physiographically, the site is located in the Wheaton Morainal country of the Great Lakes Section, Central Lowland Province. The site is situated on the upland just west of the Des Plaines River Valley and is about 65 ft above the elevation of the river. The average site elevation is at about el 700, and the on-site relief is approximately 20 ft. The site consists of about 130 ft of glacial deposits overlying Niagaran dolomite. It is thought that the heterogeneous glacial materials were deposited during the Wisconsin stage (latest) of the Pleistocene period because none of the weathering characteristics usually associated with the earlier Illinoian stage deposits are evident. Boring log descriptions of the subsurface materials at the site indicate that the present overburden was deposited by three ice advances and corresponding retreats. The first of these advances deposited a gray-colored heterogeneous mixture of gravelly, sandy clay till containing cobbles and silty to sandy lenses on the bedrock. After this ice retreated, the meltwater deposited a material ranging in composition from silt to sandy gravel. The next ice advance and retreat resulted in deposits very similar in nature to those just described except that the meltwater was apparently swifter and washed away more of the fines, leaving a somewhat coarser grained outwash than the previous advance. The last ice advance again deposited a silty, sandy clay till containing gravel and occasional cobbles. This material has a brownish weathered color above the water table, which is located at a depth of about 16 ft, and is gray below the water table. Thus, there are three distinct tills at this site, only one of which is significantly weathered.

Summary of Available Data

In addition to the brief reference to lithology given above, a brief description of the soil profile for each site is given on the data summary sheets presented in plates 1-5. Also presented in plates 1-5 as a function of depth are the summarized in situ water content, wet unit weight, specific gravity, and saturation data taken from the UX test specimens. It should be noted that the saturations were determined for in situ overburden stress. That is, the saturation was determined for each specimen after the computed overburden total vertical stress had been reapplied under undrained conditions and some small change in volume had resulted from this reapplication. The water content, wet unit weight, specific gravity, and saturation data are also presented in tables 1-7 along with the dry unit weight, void ratio, percent air, and Atterberg limits. The results of the Atterberg limit tests are plotted on the plasticity chart shown in plate 6. Typical grain-size distribution curves for each site are shown in plates 7-13.

M_c's to stresses of 50, 100, 250, and 500 psi were plotted versus depth for each site when modulus data for each of these levels were available. These plots are presented in plates 14-19. The available moduli data are also presented for each site in tables 1-7. The recommended initial modulus M_i, computed from the product of a representative mass density ρ for the zone and the square of the seismic velocity c_i for the zone, is plotted as a dashed line in plates 14-19 for each site. M_i is normally an upper bound to M_c. For correlation purposes, M_i was calculated based on the mass density of each UX specimen, and the ratio M_c/M_i was computed for each UX test using M_c to the four stress levels. The seismic velocity, initial moduli, and the ratios M_{50}/M_i* , M_{100}/M_i , M_{250}/M_i and M_{500}/M_i are presented versus depth for each site in tables 8-14. The arithmetic mean and standard deviation of the ratios M_c/M_i for each site are included in tables 8-14 along with the mean and standard deviation of M_c/M_i for all the sites.

Data to determine soil strength were obtained from triaxial compression tests. For blast loading problems, a deformation controlled, unconsolidated-undrained (UU) test with a rise time to peak stress varying from 12 to 15 in./sec was used. But, in this study, correlations were sought with simple soil properties that would be most readily available for making preliminary judgments. Since many agencies are equipped with static test equipment and only a few have dynamic test equipment, the strength $\left(\frac{\sigma_1 - \sigma_3}{2}\right)_{max}$, determined at the overburden confining pressure, and the initial slope of the stress-strain curve (Young's modulus) E_i which were used in the correlations attempted were both determined from the static triaxial UU test data. Strength data are plotted versus depth in plates 1-5 for each site, and both strength and E_i data are presented in table 15. In addition to these data on tills, WES has on file a similar body of UX test data on clay shales from sites considered in this study and from other sites. Due to time and resource limitations, M_c correlations were not attempted with the shale data.

Correlations attempted with the data presented in this section are discussed in Part III.

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* The subscript number refers to the stress level at which the secant constrained modulus M_c was calculated.

CHAPTER III

CORRELATIONS ATTEMPTED WITH THE SECANT CONSTRAINED MODULUS

Dry Unit Weight

Results of attempts to correlate dry unit weight with M_c to 50-, 100-, 250-, and 500-psi stress levels are presented in plates 20-23. The first obvious conclusion that can be made from these plates is that there is no universal correlation of M_c with dry unit weight for these tills. Trends of generally increasing moduli with increasing dry unit weights were noted for individual sites, and the shapes of data bands for individual sites were roughly similar except for the Lake County, Illinois, site. Most of the UX specimens tested had dry unit weights ranging from 95 to 125 pcf. M_{50} generally ranged from 2,000 to 350,000 psi, M_{100} from 4,000 to 200,000 psi, M_{250} from 4,000 to 150,000 psi, and M_{500} from 4,000 to 150,000 psi. It can be concluded from the data presented in plates 20-23 that the dry unit weight of tills cannot generally be used to predict M_c to the stress levels investigated in this study.

Percent Saturation

Correlations of M_c to the 50-, 100-, 250-, and 500-psi stress levels with percent saturation are presented in plates 24-27. Considerable scatter in the data occurs, particularly in the correlation with M_{50}, M_{100}, and M_{250}, but trends are discernible in each of the four plots. M_c increased as saturation increased. These trends are indicated by the dashed lines in plates 24-27, which include nearly all of the data and are based on the best judgment of the author. As illustrated in Appendix A, an average curve estimated between the bounds of each curve presented in plates 24-27 could be used to approximately predict four points on the loading portion of the stress-strain curve for a 70 to 100 percent saturated till. The saturation correlations presented in plates 24-27 are among the best of the correlations attempted.

Unit Volume of Air

The unit volume of air is a more descriptive term to a ground shock calculator than percent saturation since it is the decimal strain at which the soil stress-strain curve locks up or the approximate point on the stress-strain curve where the loading constrained modulus exceeds about 300,000 psi. Since unit volume of air is closely related to saturation,* a good correlation with this parameter was also expected. Correlations of secant constrained modulus to the 50-, 100-, 250-, and 500-psi stress levels with the unit volume of air (the decimal fraction of air in a unit volume of soil determined for each undisturbed UX test specimen after it had been preloaded to the total vertical overburden stress) are presented in plates 28-31. Scatter is particularly evident in the lower stress level plots, but trends are apparent. The trend of increasing

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* The unit volume of air, v_a is equal to $v_a = (e/1+e)(1 - S)$, where e = the void ratio for the in situ condition, and S = the percent saturation ÷ 100 .

modulus with decreasing unit volume of air was bounded as shown by the dashed lines in plates 28-31. As illustrated in Appendix A, an average curve estimated between the bounds presented in the plates can also be used to approximately predict four points on the loading portion of the stress-strain curve for tills with a percent air ranging from 0 to about 15.

UU Strength

Plates 32-35 present the results of attempts to correlate M_c to the 50-, 100-, 250-, and 500-psi stress levels with static UU strength $\left(\frac{\sigma_1 - \sigma_3}{2}\right)_{max}$ determined for the overburden stress level. The UU strength data presented in these plates were taken from table 15, and the ranges of moduli were taken from tests on specimens from locations that were generally within ±2 ft and in some cases ±5 ft of the depth from which the strength data were obtained. As indicated in plates 32-35, trends are nonexistent; therefore, no further correlations were attempted with the UU strength.

Young's Modulus

Results of attempts to correlate M_c to the 50-, 100-, 250-, and 500-psi stress levels with Young's modulus E_i taken from the static UU stress-strain curve are presented in plates 36-39. The Young's moduli presented in these plates are also presented in table 15, and the ranges of M_c were determined for locations that were generally within ±2 ft and in some cases ±5 ft of the depth for which the Young's moduli were representative. As indicated in plates 36-39, no trends were apparent; hence, no further correlations were attempted with Young's moduli.

Ratio M_c/M_i

As stated earlier M_i is the product of the mass density ρ and the square of the field seismic P-wave velocity c_i from a refraction seismic investigation. Experience has indicated that M_i is a good indicator of the stiffness of a dry site and that it is an upper bound to M_c from a UX test. M_i is presented in plates 14-19 as dashed lines in the M_c versus depth plots for the seven sites considered in this study.

Since the seismic velocity can be determined at minimum expense and is a property of the soil acting as a mass (but at a very low stress level), several correlations were attempted with the ratio M_c/M_i .

The effects of the stress levels to which M_c was computed were investigated. The effect of stress level on the ratio M_c/M_i is presented in plate 40. As shown in the plate, the ratio M_c/M_i increases slightly with increasing stress level but is not greatly affected over the range of stress levels considered in this study. The range of 0.25-0.35 is typical of the averages for the various sites and stress levels considered. It is of interest to note that an M_c equal to 0.25-0.35 M_i yields a lower (and hence more conservative) estimate of M_c for stress levels from 50 to 500 psi than has been used in a number of cases in past engineering practice. In these cases, M_c was assumed to be about 1/2 M_i .

Attempts were made to correlate M_c/M_i with saturation. Results of these attempts are shown in plates 41-44 for the 50-, 100-, 250-, and 500-psi stress levels. The data in these plates do not show well-defined trends, but certain tendencies present in all four plates should be pointed out. For saturation values less than 90 percent, an M_c/M_i ratio of 0.25-0.35 bounds nearly all the data from above. For saturation values exceeding 90 percent, trends in the data indicate that M_c/M_i increases above the range of ratios. Above 90 percent saturation, the ratio of M_c/M_i varies widely, and more specific definition from this correlation is not warranted.

Effects of Weathering

As shown in table 16, the Toole County, Pondera County, Tiber Reservoir, and Mountrail County sites were weathered throughout the entire depth of the till. At the Barnes and Steele County, North Dakota, and Lake County, Illinois, sites, weathering extended only partially into the till. Hence, the evaluation of the effect of weathering is not as extensive as it might have been since test specimens from only three sites were unweathered.

Results of the effort to determine the effect of weathering on the correlations of M_c with dry unit weight are shown in plates 20 and 22. Lines across the data points in these plates indicate unweathered test specimens and test specimens from below the water table. Again, the only trends indicated are site-particular. As expected, the effect of weathering is generally to reduce the dry unit weight and M_c. Even after the effects of weathering were considered, general trends in correlations of M_c with dry unit weight were still not evident.

An effort to determine the effect of weathering on the correlation of M_c with percent saturation is best undertaken by considering the data in plates 20 and 22 in conjunction with the saturation data in tables 1-7. The saturation values in tables 1-7 show that the unweathered specimens (found only at the Barnes and Steele County, North Dakota, and Lake County, Illinois, sites) were from locations below the static water level and have values of saturation from 98 to 100 percent. The extreme scatter of the modulus data for the 100 percent saturated specimens is illustrated in plates 24-27 by the width of the band of plotted data at 100 percent saturation. The data in tables 1-7 indicate that the extremely low moduli at 100 percent saturation were taken from UX test results for specimens that were weathered. The moduli for weathered specimens generally scattered within the lower half of the range of the data for the 100 percent saturated specimens.

The effect of weathering on the correlation of M_c with the unit volume of air (decimal percent of air computed for each specimen) can be seen by considering the data in plates 28 and 29 for the unweathered specimens and the unit volume of air data in tables 1-7. All the unweathered specimens were from below the water table and had zero or very nearly zero percent air. The extreme scatter of data for zero percent air specimens is shown in plates 28-31 by the width of data scatter at zero percent air. The data in tables 1-7 indicate that the extremely low moduli at zero percent air were obtained only from the results of UX tests on weathered specimens. The moduli of weathered specimens generally scattered in the lower half of the range of the data for specimens with zero percent air. These trends are identical with the observations made in the prior discussion about saturation.

Effect of the Groundwater Level

The approximate depth of the groundwater level for each of the seven sites is presented in table 16. As indicated in the table, the groundwater level was found in the till at only four sites. The presence of groundwater in the weathered till caused specimens to approach 100 percent saturation (or zero percent air). Generally, for weathered till, percent saturation ranged from 95 percent near the water table to 100 percent at a depth of about 10 ft below the water table or at the depth of weathering, whichever came first. Generally, in the unweathered till below the water level, saturation values were 100 percent. At 100 percent saturation, the constrained moduli indicated by the dashed line in plates 24-27 are:

Live Stress Level psi	Constrained Modulus	
	Lower-Bound, psi	Upper-Bound, psi
50	20,000	120,000
100	15,000	270,000
250	24,000	200,000
500	42,000	200,000

In the past, it has been common practice to assign a constrained modulus of 100,000 psi or more to all materials below the groundwater table.[3,5] The data presented here do not support this practice. Certainly the data are in some error because of sampling disturbance and testing errors, and the lower bounds presented above are probably too conservative. However, an examination of plates 24-27 indicates that in each case, a vast majority of the tests on very nearly saturated specimens exhibited moduli less than 100,000 psi. In spite of the known sources of error in the data, it is felt that the data are sufficient to cast serious doubt on the assignment of a 100,000-psi minimum modulus for tills below the groundwater table.

Effect of the Coarse Fraction

Plates 7-13 present representative grain-size curves for the seven sites considered in this study. Five of these sites have 10 to 25 percent of sand-size particles, but two sites, Barnes and Steele Counties, North Dakota, have approximately 35 percent of particles coarser than the No. 200 sieve, and approximately 20 percent of the soil particles are coarser than fine sand. As shown in plates 20-23, these percentages of particles coarser than the No. 200 sieve have some significance since the till densities of the Barnes and Steele County sites were less than those of the other five sites in till. The difference in the specific gravity of the clay (2.68-2.72) and of the sand-size particles (2.62-2.66) would account for less than 3 percent of the decrease in dry unit weight. The angular shape of sand-size particles would tend to increase the void ratio, thus decreasing the dry unit weight. The latter hypothesis would seem to account for the 15- to 20-pcf difference in dry unit weight for the two sites mentioned. Not enough data were available to determine if the coarse fraction was the only cause of the lower density. As shown in plates 20-23, the moduli of the Barnes and Steele County sites fall within the range of moduli of the other sites although their densities are significantly lower. Thus, for the limited range of cases investigated, no trend in moduli with a change in the coarse fraction of tills could be determined.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Based on the results of this study, the following conclusions relative to determining the dynamic secant constrained modulus of till from conventional soil properties are believed warranted:

1. Dry unit weight of tills cannot generally be used to predict the M_c to the stress levels investigated in this study.

2. The bounds of the correlations of saturation with M_c to the 50-, 100-, 250-, and 500-psi stress levels presented in plates 24-27 can be used to predict four points on the loading portion of a stress-strain curve for a 70 to 98 percent saturated till. For the three sites considered, the predicted curves demonstrated in Appendix A compared favorably with the actual UX test data.

3. The bounds of the correlations of unit volume of air (decimal percent air in a unit volume of soil determined for each UX specimen) with M_c to the 50-, 100-, 250-, and 500-psi stress levels presented in plates 28-31, respectively, can also be used to predict four points on the loading portion of a stress-strain curve for till with a unit volume of air from about 0 percent to about 15 percent. For the three sites considered, the predicted curves demonstrated in Appendix A compared favorably with the actual UX test data.

4. Attempts to correlate M_c with static UU strength $\left(\frac{\sigma_1 - \sigma_3}{2}\right)_{max}$ and Young's modulus taken from the static UU stress-strain curve were not successful.

5. Based on the data presented in plate 40 and tables 8-14, 0.25 to $0.35M_i$ can be used as an approximate estimate of M_c for stress levels from 50 to 500 psi.

6. The correlation of the ratio M_c/M_i with saturation supports conclusion 5, but the correlation indicates that M_c/M_i for tills may increase with saturations greater than 90 percent.

7. As indicated in plates 20 and 22 and tables 1-7 for individual sites, weathering tends to reduce dry unit weight and M_c .

8. Generally, for weathered till, saturation ranged from 95 percent near the water table to 100 percent at a depth of about 10 ft below the water table or at the depth of weathering, whichever came first. Below the water table in the unweathered till, saturations were, for all practical purposes, 100 percent. The results of the analyses conducted do not appear to support the assignment of a 100,000-psi minimum modulus for tills from below the water table.

Recommendations

It is recommended that the saturation and unit volume of air correlations with M_c presented herein be used to make preliminary predictions of M_c . These predictions should, of course, be tempered by judgment based on the validity and amount of saturation and unit volume of air data. In some cases, it may be possible to use the dry unit weight and seismic velocity data, the degree of weathering, and the location of the water table as a basis for giving weight to the upper- or lower-bound correlations of saturation and unit volume of air with M_c .

It is further recommended that a correlation of conventional soil properties and field seismic P-wave velocity with M_c be attempted for clay shale data presently available in WES files. Even if few useful correlations result, the recommended work would consolidate the data into a form that can be more readily examined and used.

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Table 1

Soil Properties from Uniaxial Strain Tests, Toole County, Montana

UX Test No.	Depth ft	Water Content %	Dry Unit Weight pcf	Wet Unit Weight pcf	Specific Gravity	Void Ratio	Saturation %	Unit Volume of Air	Liquid Limit LL %	Plastic Limit PL %	Plastic Index PI %	Classification	M_c (Secant to 50 psi) psi	M_c (Secant to 100 psi) psi	M_c (Secant to 250 psi) psi	M_c (Secant to 500 psi) psi
2.1.4	1.0	13.0	113.5	128.2	2.67	0.468	74.4	0.082	22	19	3	CL	10,417	12,987	18,797	--
1.3.4	3.3	17.1	109.0	127.6	2.73	0.563	82.8	0.062	36	15	21	CL	2,326	3,333	--	--
1.3.1	4.1	16.2	112.9	131.1	2.73	0.508	87.1	0.044	35	15	20	CL	6,250	4,762	5,814	9,709
2.4.5	5.8	23.4	98.9	122.0	2.74	0.728	88.1	0.050	35	17	18	CL	4,762	5,128	6,757	11,574
1.4.3	5.9	14.4	115.2	131.7	2.70	0.462	84.3	0.050	35	16	19	CL	9,434	9,259	8,013	--
3.4.2	6.2	15.5	115.3	133.1	2.73	0.478	88.4	0.038	35	15	22	CL	3,521	4,545	--	--
3.4.1	6.5	17.0	109.9	128.5	2.71	0.539	85.6	0.050	35	15	20	CL	7,692	8,333	10,000	13,699
2.4.1	6.9	20.0	106.8	128.1	2.75	0.606	90.9	0.034	35	16	19	CL	10,204	11,494	14,451	19,920
4.6.5	13.2	15.1	115.0	132.3	2.74	0.487	85.1	0.049	35	15	20	CL	8,197	8,333	9,615	12,048
3.8.3	13.3	14.8	117.9	135.3	2.74	0.451	90.3	0.030	35	15	20	CL	16,667	16,129	15,060	19,380
3.8.2	13.6	16.3	114.1	132.6	2.74	0.498	89.9	0.034	37	16	21	CL	2,000	2,611	48,263	--
4.6.2	13.9	14.0	113.5	129.3	2.73	0.501	76.1	0.080	36	14	22	CL	9,091	7,407	6,024	6,964
2.8.2	15.6	13.3	115.7	131.0	2.72	0.467	77.2	0.073	33	15	18	CL	7,143	7,042	7,225	7,937
1.9.4	18.0	16.7	114.2	133.2	2.73	0.492	92.6	0.024	30	15	15	CL	10,000	10,870	14,881	22,936
3.11.2	18.0	14.9	110.1	126.5	2.74	0.552	73.8	0.093	35	15	20	CL	5,000	5,556	5,682	6,536
3.11.1	18.3	15.1	111.0	127.7	2.73	0.534	77.2	0.079	36	15	21	CL	6,250	5,405	3,676	4,926
4.8.2	18.5	15.1	102.2	117.6	2.73	0.666	61.8	0.153	38	15	23	CL	1,563	1,429	1,825	2,994
1.9.1	18.8	15.5	116.5	134.5	2.76	0.478	89.4	0.034	36	16	20	CL	3,290	3,802	5,938	10,060
4.8.1	18.8	14.9	104.9	120.5	2.74	0.630	64.6	0.137	37	16	21	CL	2,778	2,941	3,012	4,329
3.13.2	21.7	14.8	111.7	128.2	2.73	0.525	77.1	0.079	37	15	22	CL	5,882	5,587	4,902	--
1.11.4	24.0	13.6	121.6	138.1	2.74	0.406	91.5	0.025	39	16	23	CL	20,000	21,277	23,585	26,455
1.11.2	24.5	13.5	123.3	139.9	2.75	0.392	94.9	0.014	37	14	23	CL	27,778	18,868	16,892	--
2.13.2 ▽	24.5	14.8	119.9	137.6	2.73	0.421	95.9	0.012	38	16	22	CL	29,412	32,238	37,313	46,296
1.11.1 =	25.8	13.2	122.4	138.5	2.74	0.397	91.3	0.025	34	16	18	CL	32,258	29,851	34,965	--
4.12.2	25.9	14.0	107.4	122.4	2.74	0.592	65.0	0.130	36	15	21	CL	2,747	3,226	3,788	5,263
3.16.3	26.2	14.3	111.3	127.2	2.75	0.541	72.8	0.095	37	15	22	CL	1,613	1,471	--	--
3.16.2	26.5	14.5	112.7	129.0	2.72	0.507	77.8	0.075	36	16	20	CL	10,204	9,804	9,091	11,710
3.16.1	26.7	16.9	114.9	134.3	2.75	0.493	93.9	0.020	37	16	21	CL	27,700	25,641	31,250	40,000
4.15.3	27.9	15.7	118.3	136.8	2.74	0.445	96.9	0.010	39	15	24	CL	15,151	15,873	21,930	35,100
4.15.2	28.2	15.5	118.7	137.0	2.74	0.441	96.4	0.011	36	14	22	CL	45,455	47,619	52,083	61,000
1.13.4	30.5	14.4	119.7	136.9	2.71	0.413	94.5	0.016	37	15	22	CL	26,316	25,000	25,510	25,800
1.13.2	31.0	14.4	120.3	137.6	2.75	0.427	93.1	0.021	38	15	23	CL	15,625	17,241	21,186	--
1.13.1	31.3	14.6	118.8	136.1	2.76	0.449	89.5	0.032	38	17	21	CL	27,778	28,571	34,247	41,300
1.14.6	31.9	14.5	121.7	139.3	2.70	0.392	100.0	0.000	40	15	25	CL	5,102	7,194	13,228	--
1.14.4	32.4	15.2	120.3	138.5	2.75	0.427	98.2	0.005	37	16	21	CK	33,333	36,364	44,643	60,200
1.14.2	32.9	15.3	120.0	138.3	2.75	0.430	97.6	0.007	38	16	22	CL	15,385	19,231	32,468	52,600
1.14.1	33.0	15.3	120.0	138.3	2.75	0.431	97.5	0.007	37	15	22	CL	33,333	40,000	52,632	68,500
4.15.1	33.6	16.4	115.9	134.9	2.76	0.487	92.7	0.024	39	15	24	CL	14,706	15,873	22,321	36,200
2.18.5	35.5	15.1	118.8	136.7	2.75	0.445	93.4	0.020	38	14	24	CL	25,000	27,027	37,313	53,800
2.18.4	35.8	16.2	116.9	135.8	2.76	0.473	94.5	0.018	36	14	22	CL	15,625	15,152	18,116	29,600
1.16.3	37.4	14.8	120.9	138.7	2.76	0.425	96.1	0.012	37	14	23	CL	23,810	25,641	32,468	--
1.16.2	38.7	15.2	119.7	137.8	2.75	0.434	96.7	0.010	37	15	22	CL	27,778	30,303	34,722	44,400
1.16.1	39.0	15.9	120.7	139.8	2.74	0.416	100.0	0.000	36	15	21	CL	5,747	8,403	--	--
4.19.1	40.3	13.9	122.2	139.1	2.75	0.405	94.1	0.017	37	16	21	CL	83,333	83,333	78,125	72,500
1.18.4	48.3	14.0	123.3	140.6	2.76	0.396	97.3	0.008	40	18	22	CL	12,200	14,900	--	--
1.18.2	43.8	15.2	120.0	138.2	2.75	0.430	97.0	0.009	36	17	19	CL	17,900	19,200	28,400	44,600

Note: The static groundwater level was at a depth of 25 ft, as indicated by ▽. Weathering extended to a depth of about 73 ft.

Table 2

Soil Properties from Uniaxial Strain Tests, Pondera County, Montana

UX Test No.	Depth ft	Water Content %	Dry Unit Weight pcf	Wet Unit Weight pcf	Specific Gravity	Void Ratio	Saturation %	Unit Volume of Air	Liquid Limit LL %	Plastic Limit PL %	Plastic Index PI %	Classification	M_c (Secant to 50 psi) psi	M_c (Secant to 100 psi) psi	M_c (Secant to 250 psi) psi	M_c (Secant to 500 psi) psi
18.3.3	3.7	12.7	107.4	121.0	2.72	0.581	59.4	0.149	34	14	20	CL	2,380	--	--	--
33.3.3	3.8	11.3	106.4	118.6	2.70	0.584	52.3	0.176	39	15	24	CL	5,000	4,550	--	--
18.3.4	4.1	14.0	104.3	119.0	2.72	0.627	60.9	0.150	34	14	20	CL	2,500	--	--	--
33.3.4	4.2	12.6	108.5	122.1	2.71	0.558	61.2	0.139	40	13	27	CL	4,240	4,270	--	--
33.3.5	4.4	14.1	109.8	125.3	2.72	0.546	70.1	0.105	37	15	22	CL	4,630	--	--	--
18.6.2	8.2	15.9	111.2	129.0	2.73	0.533	81.6	0.064	40	14	26	CL	5,960	5,260	--	--
18.6.3	8.5	15.1	112.0	128.2	2.72	0.515	79.9	0.068	40	14	26	CL	5,000	3,580	--	--
18.6.4	8.8	15.4	113.0	130.5	2.75	0.519	81.6	0.063	36	15	21	CL	6,500	--	--	--
33.6.2	9.4	16.9	114.2	133.2	2.73	0.492	93.7	0.021	39	16	23	CL	9,440	9,350	--	--
33.6.3	9.7	16.7	113.4	132.0	2.74	0.508	90.2	0.033	40	14	26	CL	16,660	14,300	--	--
33.6.4	10.0	16.3	116.1	135.1	2.67	0.435	100.0	0.000	42	13	29	CL	9,620	--	--	--
33.9.2	14.0	23.4	100.8	136.8	2.73	0.690	92.3	0.031	50	14	36	CL	6,100	5,720	--	--
33.9.3	14.3	24.6	97.1	120.8	2.76	0.774	87.6	0.054	70	17	53	CH	6,180	5,650	--	--
33.9.4	14.7	14.1	114.5	130.4	2.74	0.494	78.4	0.072	33	13	20	CL	5,220	--	--	--
33.16.2	23.0	19.8	111.4	133.5	2.76	0.546	100.0	0.000	38	16	22	CL	6,800	10,300	--	--

Note: The static groundwater level was below the till. Weathering extended to a depth of about 50 ft.

Table 3

Soil Properties from Uniaxial Strain Tests, Tiber Reservoir, Montana

UX Test No.	Depth ft	Water Content %	Dry Unit Weight pcf	Wet Unit Weight pcf	Specific Gravity	Void Ratio	Saturation %	Unit Volume of Air	Liquid Limit LL %	Plastic Limit PL %	Plastic Index PI %	Classification	M_c (Secant to 50 psi) psi	M_c (Secant to 100 psi) psi	M_c (Secant to 250 psi) psi	M_c (Secant to 500 psi) psi
15.3.2	3.1	10.0	94.4	104.1	2.71	0.791	34.4	0.290	36	14	22	CL	9,090	8,264	--	--
15.3.3	3.6	10.8	97.1	107.0	2.73	0.754	36.8	0.272	36	13	23	CL	7,143	6,369	--	--
15.3.4	4.1	9.8	98.5	108.1	2.73	0.730	36.6	0.268	33	15	18	CL	7,742	--	--	--
15.6.1	7.7	14.5	120.7	138.0	2.77	0.432	92.7	0.022	38	14	24	CL	2,500	3,300	--	--
15.6.3	8.3	14.4	114.1	130.8	2.75	0.504	78.6	0.072	40	12	28	CL	7,050	5,950	--	--
15.6.4	8.6	14.8	113.3	130.0	2.71	0.493	81.6	0.061	38	17	21	CL	7,810	6,750	--	--
15.6.5	8.9	14.5	112.7	128.0	2.70	0.494	79.3	0.068	40	16	24	CL	7,810	--	--	--
15.7.2	9.7	12.9	116.5	131.5	2.65	0.441	79.0	0.064	35	13	22	CL	9,100	--	--	--
15.7.3	10.0	12.7	115.4	130.2	2.70	0.460	74.5	0.080	38	12	26	CL	6,600	6,670	--	--
15.10.2	17.8	12.2	117.1	131.5	2.74	0.460	72.7	0.086	43	14	29	CL	41,600	30,300	--	--
15.10.3	18.2	12.5	118.4	133.0	2.71	0.428	79.4	0.062	42	13	29	CL	52,700	--	--	--
15.10.4	18.6	17.1	108.4	129.5	2.69	0.549	83.6	0.058	64	22	42	CH	11,630	--	--	--
15.12.2A	22.8	17.4	111.7	131.0	2.75	0.536	89.5	0.037	41	13	28	CL	10,000	6,890	--	--
15.12.3	23.2	19.5	105.5	126.1	2.72	0.608	87.1	0.049	39	13	26	CL	4,170	4,780	--	--
15.12.4	23.6	17.0	112.7	131.9	2.74	0.517	80.0	0.034	40	16	24	CL	9,670	--	--	--
15.15.3	27.6	13.9	117.0	133.3	2.72	0.451	84.1	0.050	40	16	24	CL	4,000	21,053	--	--
15.15.4	28.0	12.0	120.9	135.5	2.72	0.404	81.4	0.053	40	13	27	CL	6,667	--	--	--
15.15.5	28.4	12.6	118.7	133.7	2.75	0.446	77.9	0.068	41	14	27	CL	3,401	--	--	--
15.20.2	35.0	12.2	114.8	128.8	2.71	0.473	70.0	0.096	30	14	16	CL	6,250	80,645	--	--
15.20.4	35.3	14.0	115.8	132.0	2.72	0.465	81.9	0.057	44	17	27	CL	4,386	--	--	--
15.20.5	35.6	14.4	116.0	132.7	2.70	0.450	86.6	0.041	39	16	23	CL	3,303	--	--	--
15.23.3	41.5	9.5	113.3	124.0	2.75	0.515	50.6	0.168	31	14	17	CL	2,273	15,625	--	--

Note: The static groundwater level was not well defined and was assumed to exist at the base of the till (59 ft). Weathering extended to a depth of 59 ft.

Table 4

Soil Properties from Uniaxial Strain Tests, Mountrail County, North Dakota

UX Test No.	Depth ft	Water Content %	Dry Unit Weight pcf	Wet Unit Weight pcf	Specific Gravity	Void Ratio	Saturation %	Unit Volume of Air	Liquid Limit LL %	Plastic Limit PL %	Plastic Index PI %	Classification	M_c (Secant to 50 psi) psi	M_c (Secant to 100 psi) psi	M_c (Secant to 250 psi) psi	M_c (Secant to 500 psi) psi
2.1.5	0.6	17.6	94.9	111.6	2.70	0.776	61.1	0.170	--	--	--	--	2,174	2,326	2,326	3,247
1.1.2	1.3	18.8	112.1	133.1	2.71	0.508	92.8	0.051	44	16	28	CL	5,263	5,000	4,951	7,463
2.1.2	1.4	15.4	107.4	123.9	2.74	0.592	71.2	0.107	38	15	23	CL	71,429	58,824	3,968	4,202
1.1.1	1.6	19.3	108.4	129.3	2.69	0.549	94.3	0.020	45	14	31	CL	14,286	9,804	10,965	17,123
3.3.3	3.7	14.6	107.8	123.5	2.74	0.587	68.2	0.118	43	11	32	CL	71,429	68,966	6,579	6,090
1.4.3	6.1	18.4	110.0	130.2	2.70	0.532	93.6	0.022	45	17	28	CL	12,500	10,870	11,013	17,007
1.4.2	6.4	18.4	110.0	130.2	2.70	0.532	93.5	0.022	44	16	28	CL	11,905	10,870	13,298	19,608
2.4.2	6.5	16.8	106.2	124.0	2.72	0.598	76.4	0.088	44	16	28	CL	4,545	4,444	4,310	5,682
1.4.1	6.7	18.5	110.8	131.2	2.72	0.532	94.5	0.019	43	16	27	CL	6,667	8,696	13,089	20,492
2.4.1	6.8	17.3	107.3	125.8	2.71	0.577	81.1	0.069	43	16	27	CL	6,579	6,061	4,808	6,410
3.6.3	8.5	17.1	111.0	129.9	2.72	0.530	88.0	0.042	46	18	28	CL	10,000	10,526	11,364	13,333
3.6.2	8.8	17.4	112.1	131.6	2.71	0.508	92.8	0.024	52	17	35	CH	18,519	14,925	11,905	14,925
3.6.1	9.1	17.1	112.0	131.1	2.70	0.505	91.5	0.029	45	17	28	CL	15,625	15,152	12,821	--
1.7.2	11.3	18.7	110.6	131.2	2.74	0.547	93.8	0.022	43	15	28	CL	13,158	12,658	14,124	22,422
1.7.1	11.5	19.2	110.5	131.7	2.73	0.543	96.8	0.011	47	15	32	CL	20,833	16,949	20,661	--
1.10.4	15.9	17.8	111.0	130.7	2.74	0.541	90.2	0.035	42	14	28	CL	11,905	11,111	10,246	14,368
1.10.1	16.8	18.3	111.0	131.3	2.74	0.541	92.6	0.026	44	16	28	CL	17,241	14,925	19,380	32,895
1.13.5	20.7	18.8	108.7	129.1	2.72	0.561	91.1	0.032	--	--	--	CL	13,158	12,500	11,521	16,447
1.13.2	21.5	17.4	110.9	130.1	2.72	0.531	89.1	0.038	40	14	26	CL	16,129	15,625	12,376	16,181
1.13.1	21.8	16.5	112.9	131.5	2.72	0.503	89.1	0.037	43	16	27	CL	13,514	11,765	9,328	12,853

Note: The static groundwater level was at a depth of 45 ft. Weathering extended to a depth of 26 ft.

Table 5

Soil Properties from Uniaxial Strain Tests, Barnes County, North Dakota

UX Test No.	Depth ft	Water Content %	Dry Unit Weight pcf	Wet Unit Weight pcf	Specific Gravity	Void Ratio	Saturation %	Unit Volume of Air	Liquid Limit LL %	Plastic Limit PL %	Plastic Index PI %	Classification	M_c (Secant to 50 psi) psi	M_c (Secant to 100 psi) psi	M_c (Secant to 250 psi) psi	M_c (Secant to 500 psi) psi
2.1.4	5.7	25.7	89.6	112.6	2.65	0.845	80.62	0.089	37	24	13	CL	3,846	3,922	4,878	6,711
2.1.3	6.1	22.4	96.7	118.3	2.66	0.717	83.21	0.070	38	24	14	CL	5,000	5,160	6,250	8,130
2.1.1	6.9	24.1	96.7	120.0	2.66	0.717	89.53	0.044	37	22	15	CL	3,968	4,396	5,882	9,050
1.5.4	10.8	26.5	94.8	120.0	2.64	0.738	94.85	0.022	35	24	11	CL	16,667	17,857	23,256	30,120
1.5.3	11.2	25.6	95.3	120.0	2.61	0.709	94.26	0.024	32	26	6	ML	6,897	8,621	12,821	18,939
1.5.1	12.0 ∇	25.1	96.6	121.0	2.62	0.693	94.99	0.020	35	26	9	ML	5,714	6,780	10,204	17,241
2.5.3	13.7	26.0	96.3	121.0	2.64	0.714	96.56	0.014	50	25	25	CL	33,333	28,571	30,864	37,313
2.5.2	14.1	26.7	96.0	122.0	2.63	0.709	98.91	0.005	42	23	19	CL	21,739	22,727	--	--
2.5.1	14.5	25.5	97.4	122.0	2.64	0.691	97.57	0.010	41	21	20	CL	10,000	11,364	20,161	36,765
2.6.4	15.9	25.3	97.7	122.0	2.66	0.699	96.26	0.016	44	22	22	CL	22,730	23,529	28,090	37,037
2.6.3	16.3	26.3	97.0	123.0	2.67	0.715	97.60	0.010	47	24	23	CL	18,519	21,277	29,412	45,872
2.6.2	16.7	25.9	96.9	122.0	2.66	0.715	96.40	0.015	42	23	19	CL	13,333	14,925	19,608	27,933
2.6.1	17.1	25.0	98.7	123.0	2.65	0.675	98.48	0.006	40	23	17	CL	33,333	37,037	49,020	75,758
1.9.4	20.8	24.9	98.3	123.0	2.66	0.688	96.39	0.015	41	24	17	CL	12,195	14,493	21,368	32,051
1.9.3	21.2	27.2	96.1	122.0	2.63	0.711	100.00	0.000	43	24	19	CL	27,778	34,483	52,083	71,429
1.9.2	21.6	28.1	94.3	121.0	2.65	0.752	99.14	0.004	43	23	20	CL	17,857	24,390	43,103	67,568
1.9.1	22.0	24.5	99.2	124.0	2.64	0.661	97.86	0.009	43	23	20	CL	9,615	13,699	23,256	39,370
2.8.3	26.3	27.3	94.7	121.0	2.66	0.752	96.44	0.015	38	22	16	CL	23,810	25,000	30,488	42,017
2.8.2	26.7	26.7	96.3	122.0	2.64	0.711	99.31	0.003	41	24	17	CL	38,462	37,037	43,103	--
2.12.3	33.5	26.8	96.5	122.0	2.64	0.707	100.00	0.000	42	23	19	CL	55,556	47,619	47,170	66,667
2.12.2	33.9	26.9	96.0	122.0	2.63	0.708	99.70	0.001	43	22	21	CL	22,222	30,303	48,077	--
2.13.4	35.8	24.3	99.9	124.0	2.65	0.656	98.09	0.008	33	20	13	CL	41,667	30,769	45,455	69,444
2.13.2	36.6	28.0	94.5	121.0	2.62	0.731	100.00	0.000	44	21	23	CL	20,000	23,810	39,683	64,516
2.13.1	37.0	28.9	93.9	121.0	2.63	0.750	100.00	0.000	45	22	23	CL	5,625	24,390	45,455	73,529
2.20.4	53.3	23.0	101.5	125.0	2.61	0.608	98.49	0.006	33	21	12	CL	71,429	58,824	86,207	119,048
2.20.3	53.7	23.3	101.0	124.0	2.61	0.613	99.19	0.003	34	21	13	CL	25,000	22,222	35,714	59,524
2.20.2	54.1	23.6	101.2	125.0	2.61	0.609	100.00	0.000	32	20	12	CL	55,556	51,282	69,444	101,010
2.20.1	54.5	23.6	101.2	125.0	2.60	0.604	100.00	0.000	34	23	11	CL	7,937	12,821	25,253	42,735
2.26.1	69.5	22.3	105.0	128.4	2.62	0.573	100.00	0.000	33	21	12	CL	16,129	25,641	50,000	81,967
2.26.4	73.3	22.0	107.0	130.8	2.60	0.555	100.00	0.000	34	22	12	CL	83,333	55,556	64,103	91,743
2.26.3	73.7	22.6	104.0	127.3	2.60	0.577	100.00	0.000	33	21	12	CL	23,810	28,571	42,373	64,935
2.26.2	74.1	21.7	104.0	127.1	2.60	0.555	100.00	0.000	34	20	14	CL	20,408	25,316	37,879	57,143
1.36.4	96.8	22.4	105.0	128.3	2.63	0.565	100.00	0.000	32	21	11	CL	76,923	74,074	111,111	101,010
1.36.3	97.2	22.7	102.0	125.3	2.61	0.594	99.70	0.001	34	22	12	CL	142,857	142,857	166,667	196,078
1.36.2	97.6	22.8	103.0	126.1	2.61	0.588	100.00	0.000	33	22	11	CL	34,483	44,444	67,568	101,010
1.36.1	98.0	22.1	103.0	125.8	2.60	0.574	100.00	0.000	33	22	11	CL	87,778	32,258	47,170	74,074
1.40.3	107.2	22.2	103.0	126.2	2.60	0.570	100.00	0.000	34	22	12	CL	100,000	90,909	100,000	121,951
1.40.2	107.6	22.3	103.0	126.1	2.58	0.561	100.00	0.000	35	20	15	CL	62,500	60,606	65,789	84,746
2.37.4	113.3	22.5	107.0	130.5	2.61	0.567	100.00	0.000	33	21	12	CL	142,857	125,000	92,593	125,000
2.37.3	113.7	23.2	102.0	125.8	2.62	0.601	100.00	0.000	34	22	12	CL	66,667	58,824	19,365	106,383
2.37.2	114.1	23.9	101.0	124.9	2.62	0.621	100.00	0.000	33	22	11	CL	55,556	60,606	78,125	108,696
2.37.1	114.5	23.1	102.0	125.2	2.62	0.606	100.00	0.000	33	22	11	CL	90,909	71,429	84,746	120,482
1.45.1	117.5	20.3	107.0	129.0	2.63	0.529	100.00	0.000	31	22	9	CL	71,429	64,516	63,291	90,909
1.47.4	121.8	23.1	104.0	127.5	2.60	0.566	100.00	0.000	35	25	10	ML	30,303	35,714	51,020	75,188
1.47.3	122.2	25.6	97.0	122.1	2.60	0.668	99.00	0.001	34	27	7	ML	50,000	40,000	45,045	62,500
1.47.2	122.6	26.1	97.0	121.9	2.58	0.664	100.00	0.000	34	26	8	ML	41,667	38,462	55,556	79,365
1.47.1	123.0	24.2	100.0	123.5	2.56	0.606	100.00	0.000	35	25	10	ML	76,923	52,632	78,125	119,048

Note: The static groundwater level was at a depth of 12 ft, as indicated by ∇ . Weathering extended to a depth of about 30 ft, as indicated by the dash-dot line.

Table 6

Soil Properties from Uniaxial Strain Tests, Steele County, North Dakota

UX Test No.	Depth ft	Water Content %	Dry Unit Weight pcf	Wet Unit Weight pcf	Specific Gravity	Void Ratio	Saturation %	Unit Volume of Air	Liquid Limit LL %	Plastic Limit PL %	Plastic Index PI %	Classification	M_c (Secant to 50 psi) psi	M_c (Secant to 100 psi) psi	M_c (Secant to 250 psi) psi	M_c (Secant to 500 psi) psi
2A.3.3	2.1	18.1	109.4	129.1	2.68	0.529	91.5	0.029	39	18	21	CL	13,158	12,048	9,804	--
5A.3.3	2.1	21.0	101.6	133.8	2.64	0.622	89.3	0.041	43	22	21	CL	7,143	6,579	7,143	--
2A.3.2	2.5	18.7	108.8	129.1	2.67	0.513	93.9	0.021	39	18	21	CL	12,820	13,698	15,823	--
6A.10.2	2.7	18.9	108.5	129.0	2.67	0.536	94.1	0.021	48	20	28	CL	16,666	13,889	13,966	--
2A.3.1	2.9	18.3	110.6	130.8	2.66	0.501	97.1	0.010	40	18	22	CL	17,904	12,048	14,706	--
4.1.4	3.1	22.3	102.2	125.0	2.66	0.624	95.0	0.019	34	20	14	CL	4,310	6,250	11,738	--
4.1.3	3.4	20.2	106.3	127.8	2.69	0.580	93.7	0.023	41	21	20	CL	6,944	9,615	17,123	--
3.1.3	3.4	21.1	103.3	125.1	2.65	0.600	97.7	0.009	31	17	14	CL	7,692	8,772	13,298	--
3.1.2	3.7	22.5	102.7	125.8	2.66	0.603	97.1	0.011	32	18	14	CL	6,944	8,696	12,500	--
3.2.3	6.1	23.2	102.1	125.8	2.65	0.620	99.3	0.003	32	18	14	CL	12,820	15,873	22,727	--
3.2.2 ∇	6.4	23.4	102.9	127.0	2.63	0.616	100.0	--	32	20	12	CL	12,500	15,385	22,522	--
5A.6.4	7.1	22.9	100.6	123.6	2.66	0.650	93.7	0.025	39	20	19	CL	9,615	10,526	12,195	--
5A.6.3	7.3	22.8	101.6	124.8	2.65	0.627	96.3	0.014	38	21	17	CL	16,667	16,667	21,739	--
6A.13.3	8.0	22.4	102.3	125.2	2.65	0.616	96.3	0.014	37	19	18	CL	10,000	10,526	14,620	--
6A.13.2	8.3	22.0	103.7	126.5	2.66	0.601	97.2	0.010	35	19	16	CL	16,667	14,706	18,116	--
4.4.4	8.4	22.8	103.7	127.3	2.70	0.625	98.5	0.006	32	18	14	CL	9,615	11,364	18,657	--
4.4.3	8.7	22.8	101.8	125.0	2.69	0.649	94.5	0.022	32	18	14	CL	9,615	11,494	17,241	--
4.7.4	15.8	21.0	105.2	127.3	2.63	0.561	98.5	0.005	40	20	20	CL	19,231	22,727	28,736	--
3.7.3	15.9	20.6	107.7	129.9	2.62	0.539	100.0	0.000	31	17	14	CL	38,760	51,020	81,967	--
4.7.3	16.1	21.6	104.9	127.6	2.67	0.587	98.2	0.007	36	19	17	CL	22,727	27,778	44,643	--
3.7.2	16.2	21.3	105.0	127.4	2.63	0.560	100.0	0.000	29	17	12	CL	28,409	37,879	67,568	--
3.13.3	27.6	22.0	104.1	127.0	2.64	0.580	100.0	0.000	37	19	18	CL	26,882	35,088	59,524	--
3.13.2	27.9	22.1	103.5	126.4	2.62	0.580	100.0	0.000	36	21	15	CL	45,454	55,866	86,800	--
4.12.3	28.8	22.2	104.0	127.1	2.64	0.585	100.0	0.000	35	19	16	CL	52,632	64,102	102,000	--
4.12.2	29.1	22.3	103.4	126.4	2.64	0.593	99.5	0.002	37	21	16	CL	35,714	43,478	69,250	--
5.15.3	33.0	28.8	92.3	118.9	2.59	0.749	99.6	0.002	38	27	11	ML	35,714	47,619	75,000	--
5.15.2A	33.3	28.8	93.0	119.8	2.59	0.745	100.0	0.000	40	26	14	ML	62,500	76,923	116,279	--
4.17.2	34.6	28.9	92.9	119.7	2.60	0.751	100.0	0.000	40	26	14	ML	66,667	81,967	112,108	--
2.12.3	38.2	28.5	91.2	117.2	2.59	0.773	95.4	0.020	37	25	12	ML	26,455	32,051	--	--
2.12.2	38.5	27.1	95.7	121.6	2.62	0.712	100.0	0.000	34	25	9	ML	66,600	76,900	--	--
3.20.1	51.1	20.6	107.8	130.0	2.63	0.541	100.0	0.000	49	21	28	CL	38,462	36,496	--	--
3.23.3	58.3	19.1	108.1	128.7	2.62	0.513	97.8	0.007	30	17	13	SC	22,727	16,667	--	--
3.23.2	58.6	19.0	110.4	131.4	2.67	0.511	99.7	0.001	38	19	19	CL	29,412	22,727	--	--
3.33.4	83.0	18.7	110.4	131.0	2.64	0.493	100.0	0.000	49	20	29	CL	23,810	21,739	--	--
3.33.3	83.3	18.6	110.9	131.5	2.65	0.493	100.0	0.000	42	19	23	CL	50,000	45,454	--	--
3.39.3	97.9	19.6	110.1	131.7	2.66	0.522	100.0	0.000	48	19	29	CL	83,333	68,493	--	--
3.39.2	98.2	19.6	108.8	130.1	2.65	0.520	100.0	0.000	47	19	28	CL	125,000	86,956	--	--
1.39.3	98.6	21.1	106.1	128.5	2.66	0.563	100.0	0.000	46	21	25	CL	71,478	74,074	--	--
1.39.2	98.8	20.4	107.3	129.2	2.64	0.538	100.0	0.000	48	19	29	CL	125,000	95,238	--	--

Note: The static groundwater level was at a depth of about 7 ft, as indicated by ∇ . Weathering extended to a depth of about 18 ft, as indicated by the dash-dot line.

Table 7

Soil Properties from Uniaxial Strain Tests, Lake County, Illinois

UX Test No.	Depth ft	Water Content %	Dry Unit Weight pcf	Wet Unit Weight pcf	Specific Gravity	Void Ratio	Saturation %	Unit Volume of Air	Liquid Limit LL %	Plastic Limit PL %	Plastic Index PI %	Classification	M_c (Secant to 50 psi) psi	M_c (Secant to 100 psi) psi	M_c (Secant to 250 psi) psi	M_c (Secant to 500 psi) psi
U1-1.1	12.0	15.9	117.5	136.2	2.73	0.450	96.5	0.011	31	15	16	CL	19,231	20,000	--	--
1.2	11.2 ∇	22.1	111.3	135.9	2.74	0.604	100.0	0.000	27	13	14	CL	17,857	17,094	--	--
5.1	27.5	17.0	116.4	136.2	2.74	0.469	99.3	0.002	32	15	17	CL	75,757	61,000	--	--
5.2	27.7	17.0	116.9	136.8	2.75	0.467	100.0	0.000	32	15	17	CL	55,555	45,000	--	--
5.3	27.3	16.3	118.0	137.2	2.75	0.454	98.7	0.004	33	15	18	CL	71,478	77,000	--	--
14.1	57.3	14.7	122.3	140.3	2.76	0.408	99.3	0.002	31	14	17	CL	238,095	142,857	--	--
14.2	57.9	15.8	121.5	140.7	2.76	0.431	100.0	0.000	32	15	17	CL	66,667	51,282	--	--
15.1	59.2	17.5	116.2	136.5	2.77	0.487	99.6	0.001	32	14	18	CL	181,818	--	--	--
15.2	59.6	17.8	114.3	134.6	2.77	0.513	96.2	0.013	33	15	18	CL	108,696	90,909	--	--
15.3	58.8	19.1	113.0	134.6	2.77	0.530	100.0	0.000	36	18	18	CL	208,333	147,059	--	--
38.1	115.5	18.7	112.5	133.5	2.74	0.519	98.7	0.005	23	16	7	CL-ML	156,250	--	--	--
38.2	116.9	14.7	122.8	140.9	2.75	0.398	100.0	0.000	21	16	5	CL-ML	200,000	188,679	--	--
39.1	118.8	10.3	135.9	149.9	2.77	0.280	100.0	0.000	24	12	12	CL	277,778	148,148	--	--
39.2	119.1	10.9	132.1	146.5	2.77	0.309	97.8	0.005	26	12	14	CL	172,414	--	--	--
42.1	125.3	12.6	127.9	144.0	2.79	0.361	97.5	0.007	26	12	14	CL	208,333	147,059	--	--

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Note: The static groundwater level was at a depth of about 16 ft, as indicated by ∇ . Weathering extended to a depth of about 16 ft, as indicated by the dash-dot line.

Table 8

Seismic Velocities, Initial Moduli, and the Ratios M_c/M_i

for the Toole County, Montana, Site

Depth ft	Seismic Velocity ft/sec	Initial Modulus M_i psi	Modulus Ratio M_{50}/M_i psi	Modulus Ratio M_{100}/M_i psi	Modulus Ratio M_{250}/M_i psi	Modulus Ratio M_{500}/M_i psi
1.0	1200	39,800	0.261	0.326	0.472	--
3.3	1200	39,600	0.059	0.084	--	--
4.1	1200	40,704	0.154	0.117	0.143	0.238
5.8	1200	37,900	0.126	0.135	0.178	0.305
5.9	1200	40,900	0.231	0.226	0.196	--
6.2	1200	41,300	0.085	0.110	--	--
6.5	1200	39,900	0.193	0.209	0.251	0.343
6.9	1200	39,800	0.256	0.289	0.363	0.478
13.2	1200	41,100	0.200	0.203	0.234	0.293
13.3	1200	42,000	0.397	0.384	0.358	0.461
13.6	1200	41,200	0.049	0.063	1.172	--
13.9	1200	40,200	0.236	0.184	0.150	0.173
15.6	1200	40,700	0.176	0.173	0.178	0.195
18.0	1200	41,400	0.242	0.263	0.360	0.554
18.0	1200	39,300	0.127	0.141	0.145	0.166
18.3	1200	39,700	0.158	0.136	0.093	0.124
18.5	1200	36,500	0.043	0.039	0.050	0.082
18.8	1200	41,800	0.079	0.091	0.142	0.239
18.8	1200	37,400	0.074	0.079	0.081	0.116
21.7	1200	39,800	0.148	0.140	0.123	--
24.0	1200	42,900	0.466	0.496	0.550	0.617
24.5	1200	43,400	0.639	0.434	0.389	--
24.5	1200	42,700	0.688	0.754	0.873	1.083
25.8	1200	43,000	0.750	0.694	0.813	--
25.9	1200	38,000	0.072	0.085	0.099	0.138
26.2	1200	39,500	0.041	0.037	--	--
26.5	1200	40,100	0.255	0.249	0.227	0.292
26.7	1200	41,700	0.545	0.615	0.749	0.959
27.9	1200	42,500	0.357	0.374	0.516	--
28.2	1200	42,500	1.068	1.119	1.224	--
30.5	1200	42,500	0.619	0.588	0.600	--
31.0	1200	42,700	0.366	0.403	0.496	--
31.3	1200	42,300	0.657	0.676	0.810	--
31.9	1200	43,300	0.118	0.166	0.306	--
32.4	1200	43,000	0.775	0.845	1.038	--
32.9	1200	43,000	0.358	0.448	0.758	--
33.0	1200	43,000	0.776	0.931	1.225	--
33.6	1200	41,900	0.351	0.379	0.533	--
35.5	1200	42,500	0.589	0.637	0.879	--
35.8	1200	42,200	0.370	0.359	0.430	--
37.4	1200	43,100	0.553	0.595	0.754	--
38.7	1200	42,800	0.649	0.708	0.811	--
39.0	1200	43,400	0.123	0.194	--	--
40.3	1200	43,200	1.929	1.929	1.809	--

Arithmetic Mean and Standard Deviation of M_c/M_i Values					All Sites
Mean	0.35	0.36	0.48	0.36	0.27
Standard Deviation	0.27	0.27	0.32	0.26	0.27

Table 9

Seismic Velocities, Initial Moduli, and the Ratios M_c/M_i for the Pondera County, Montana, Site

Depth ft	Seismic Velocity ft/sec	Initial Modulus M_i psi	Modulus Ratio M_{50}/M_i psi	Modulus Ratio M_{100}/M_i psi	Modulus Ratio M_{250}/M_i psi	Modulus Ratio M_{500}/M_i psi
3.7	1500	58,700	0.041	--	--	--
3.8	1500	47,600	0.087	0.079	--	--
4.1	1500	57,700	0.043	--	--	--
4.2	1500	59,200	0.072	0.072	--	--
4.4	1500	60,800	0.076	--	--	--
8.2	1500	62,600	0.095	0.084	--	--
8.5	1500	62,200	0.080	0.058	--	--
8.8	1500	63,300	0.103	--	--	--
9.4	1500	64,600	0.146	0.145	--	--
9.7	1500	64,100	0.260	0.223	--	--
10.0	1500	65,600	0.147	--	--	--
14.0	1500	66,400	0.092	0.086	--	--
14.3	1500	58,600	0.105	0.096	--	--
14.7	1500	63,300	0.083	--	--	--

Arithmetic Mean and Standard Deviation of M_c/M_i Values					All Sites
Mean	0.10	0.11	--	--	0.27
Standard Deviation	0.05	0.05	--	--	0.27

Table 10

Seismic Velocities, Initial Moduli, and the Ratios M_c/M_i for the Tiber Reservoir, Montana, Site

Depth ft	Seismic Velocity ft/sec	Initial Modulus M_i psi	Modulus Ratio M_{50}/M_i psi	Modulus Ratio M_{100}/M_i psi	Modulus Ratio M_{250}/M_i psi	Modulus Ratio M_{500}/M_i psi
3.1	1000	22,500	0.405	0.368	--	--
3.6	1000	23,100	0.310	0.276	--	--
4.1	1000	23,300	0.332	--	--	--
7.7	1000	29,800	0.084	0.111	--	--
8.3	1000	28,200	0.250	0.211	--	--
8.6	1000	28,000	0.278	0.241	--	--
8.9	1000	27,600	0.289	--	--	--
9.7	1000	28,400	0.321	--	--	--
10.0	1000	28,100	0.235	0.238	--	--
17.8	1000	28,400	1.467	1.068	--	--
18.2	1000	28,700	1.837	--	--	--
18.6	1000	27,900	0.416	--	--	--
22.8	1000	28,300	0.354	0.244	--	--
23.2	5200	735,400	0.006	0.007	--	--
23.6	5200	769,200	0.013	--	--	--
27.6	5200	777,400	0.005	0.027	--	--
28.0	5200	790,200	0.008	--	--	--
28.4	5200	779,700	0.004	--	--	--
35.0	5200	751,100	0.008	0.107	--	--
35.3	5200	769,800	0.006	--	--	--
35.6	5200	773,900	0.004	--	--	--
41.5	5200	423,100	0.003	0.022	--	--
42.1	5200	781,400	0.007	0.046	--	--
44.3	5200	748,200	0.002	0.014	--	--
45.0	5200	733,000	0.003	--	--	--

Arithmetic Mean and Standard Deviation of M_c/M_i Values					All Sites
Mean	0.21	0.21	--	--	0.27
Standard Deviation	0.28	0.25	--	--	0.27

Table 11

Seismic Velocities, Initial Moduli, and the Ratios M_c/M_i for the Mountrail County, North Dakota, Site

Depth ft	Seismic Velocity ft/sec	Initial Modulus M_i psi	Modulus Ratio M_{50}/M_i psi	Modulus Ratio M_{100}/M_i psi	Modulus Ratio M_{250}/M_i psi	Modulus Ratio M_{500}/M_i psi
0.6	1400	47,200	0.046	0.049	0.049	0.069
1.3	1400	56,300	0.094	0.089	0.088	0.133
1.4	1400	52,400	1.364	1.123	0.076	0.080
1.6	1400	54,700	0.261	0.179	0.201	0.313
3.7	1400	52,200	1.368	1.321	0.126	0.117
6.1	1400	55,000	0.227	0.197	0.200	0.309
6.4	1400	55,000	0.216	0.197	0.242	0.356
6.5	1400	52,400	0.087	0.085	0.082	0.108
6.7	1400	55,500	0.120	0.157	0.236	0.369
6.8	1400	53,200	0.124	0.114	0.090	0.120
8.5	1400	54,900	0.182	0.192	0.207	0.243
8.8	1400	55,600	0.333	0.268	0.214	0.268
9.1	1400	55,400	0.282	0.273	0.231	--
11.3	1400	55,500	0.237	0.228	0.255	0.404
11.5	1400	55,700	0.374	0.304	0.371	--
15.9	1400	55,200	0.215	0.201	0.185	0.260
16.8	1400	55,500	0.311	0.269	0.349	0.593
20.7	1400	54,600	0.241	0.229	0.211	0.301
21.5	1400	55,000	0.293	0.284	0.225	0.294
21.8	1400	55,600	0.243	0.212	0.168	0.231

Arithmetic Mean and Standard Deviation of M_c/M_i Values					All Sites
Mean	0.29	0.28	0.19	0.25	0.27
Standard Deviation	0.25	0.25	0.08	0.13	0.27

Table 12

Seismic Velocities, Initial Moduli, and the Ratios M_c/M_i

for the Barnes County, North Dakota, Site

Depth ft	Seismic Velocity ft/sec	Initial Modulus M_i psi	Modulus Ratio M_{50}/M_i psi	Modulus Ratio M_{100}/M_i psi	Modulus Ratio M_{250}/M_i psi	Modulus Ratio M_{500}/M_i psi
5.7	1100	29,400	0.131	0.133	0.166	0.228
6.1	1100	30,900	0.162	0.167	0.202	0.263
6.9	1100	31,300	0.127	0.140	0.188	0.289
10.8	1100	31,300	0.532	0.570	0.743	0.962
11.2	1100	31,300	0.220	0.275	0.409	0.605
12.0	1100	31,600	0.181	0.215	0.323	0.546
13.7	1100	31,600	1.056	0.905	0.977	1.182
14.1	1100	31,800	0.683	0.714	--	--
14.5	1100	31,800	0.314	0.357	0.633	1.159
15.9	1100	31,800	0.714	0.731	0.882	1.163
16.3	1100	32,100	0.577	0.663	0.916	1.429
16.7	1100	31,800	0.419	0.469	0.616	0.877
17.1	1100	31,100	1.038	1.154	1.527	2.360
20.8	1100	32,100	0.380	0.452	0.666	0.998
21.2	1100	31,800	0.872	1.082	1.636	2.244
21.6	1100	31,600	0.566	0.772	1.365	2.140
22.0	5250	737,100	0.013	0.019	0.032	0.053
26.3	5250	719,300	0.033	0.035	0.042	0.058
26.7	5250	725,200	0.053	0.051	0.059	--
33.5	5250	725,200	0.077	0.066	0.065	0.092
33.9	5250	725,200	0.031	0.042	0.066	--
35.8	5250	737,100	0.057	0.042	0.062	0.094
36.6	5250	719,300	0.028	0.033	0.055	0.090
37.0	5250	719,300	0.008	0.034	0.063	0.102
53.3	5250	743,100	0.096	0.079	0.116	0.160
53.7	5250	737,100	0.034	0.030	0.048	0.081
54.1	5250	743,000	0.075	0.069	0.093	0.136
54.5	5250	743,000	0.011	0.017	0.034	0.058
69.5	5250	763,200	0.021	0.034	0.066	0.107
73.3	5250	777,500	0.107	0.071	0.082	0.118
73.7	5250	756,700	0.032	0.038	0.056	0.085
74.1	5250	755,500	0.027	0.034	0.050	0.058
96.8	5250	762,700	0.101	0.097	0.146	0.132
97.2	5250	744,800	0.192	0.192	0.224	0.263
97.6	5250	749,600	0.046	0.059	0.090	0.135
98.0	5250	747,800	0.037	0.043	0.063	0.099
107.2	5250	750,200	0.133	0.121	0.133	0.162
107.6	5250	749,600	0.083	0.081	0.088	0.113
113.3	5250	775,700	0.184	0.161	0.119	0.161
113.7	5250	747,800	0.089	0.079	0.026	0.142
114.1	5250	742,400	0.075	0.082	0.105	0.146
114.5	5250	744,200	0.122	0.096	0.114	0.162
117.5	5250	766,800	0.093	0.084	0.083	0.118
121.8	5250	757,900	0.040	0.047	0.067	0.099
122.2	5250	725,800	0.069	0.055	0.062	0.086
126.6	5250	724,600	0.058	0.053	0.077	0.110
123.0	5250	734,100	0.105	0.072	0.106	0.162

Arithmetic Mean and Standard Deviation of M_c/M_i Values					All Sites
Mean	0.21	0.23	0.27	0.34	0.27
Standard Deviation	0.27	0.28	0.32	0.36	0.27

Table 13

Seismic Velocities, Initial Moduli, and the Ratios M_c/M_i for the Steele County, North Dakota, Site

Depth ft	Seismic Velocity ft/sec	Initial Modulus M_i psi	Modulus Ratio M_{50}/M_i psi	Modulus Ratio M_{100}/M_i psi	Modulus Ratio M_{250}/M_i psi	Modulus Ratio M_{500}/M_i psi
2.1	1300	47,100	0.280	0.256	0.208	--
2.1	1300	48,800	0.146	0.135	0.146	--
2.5	1300	47,100	0.272	0.291	0.336	--
2.7	1300	47,000	0.354	0.295	0.297	--
2.9	1300	47,700	0.376	0.253	0.308	--
3.1	1300	45,600	0.095	0.137	0.258	--
3.4	1300	46,600	0.149	0.206	0.368	--
3.4	1300	45,600	0.169	0.192	0.292	--
3.7	1300	45,900	0.151	0.190	0.273	--
6.1	1300	45,900	0.280	0.346	0.496	--
6.4	1300	46,300	0.270	0.332	0.486	--
7.1	1300	45,000	0.213	0.234	0.271	--
7.3	1300	45,500	0.366	0.366	0.478	--
8.0	1300	45,600	0.219	0.231	0.320	--
8.3	1300	46,100	0.361	0.319	0.393	--
8.4	1300	46,400	0.207	0.245	0.402	--
8.7	1300	45,600	0.211	0.252	0.378	--
15.8	1300	46,400	0.414	0.490	0.619	--
15.9	1300	47,300	0.819	1.078	1.731	--
16.1	1300	46,500	0.489	0.597	0.960	--
16.2	1300	46,400	0.612	0.816	1.455	--
27.6	5600	858,900	0.031	0.041	0.069	--
27.9	5600	854,900	0.053	0.065	0.102	--
28.8	5600	859,600	0.061	0.075	0.119	--
29.1	5600	854,900	0.042	0.051	0.081	--
33.0	5600	804,200	0.044	0.059	0.093	--
33.3	5600	810,200	0.077	0.095	0.144	--
34.6	5600	809,600	0.082	0.101	0.138	--
38.2	5600	792,700	0.033	0.040	--	--
38.5	5600	822,400	0.081	0.094	--	--
51.1	5600	879,200	0.044	0.042	--	--
58.3	5600	870,400	0.026	0.019	--	--
58.6	5600	888,700	0.033	0.026	--	--
83.0	5600	886,000	0.027	0.025	--	--
83.3	5600	889,400	0.056	0.051	--	--
97.9	5600	890,700	0.094	0.077	--	--
98.2	5600	879,900	0.142	0.099	--	--
98.6	5600	869,100	0.082	0.085	--	--
98.8	5600	873,800	0.143	0.109	--	--

Arithmetic Mean and Standard Deviation of M_c/M_i Values					All Sites
Mean	0.19	0.21	0.36	--	0.27
Standard Deviation	0.17	0.21	0.26	--	0.27

Table 14

Seismic Velocities, Initial Moduli, and the Ratios M_c/M_i for the Lake County, Illinois, Site

Depth ft	Seismic Velocity ft/sec	Initial Modulus M_i psi	Modulus Ratio M_{50}/M_i psi	Modulus Ratio M_{100}/M_i psi	Modulus Ratio M_{250}/M_i psi	Modulus Ratio M_{500}/M_i psi
12.0	2400	169,200	0.114	0.122	--	--
11.2	2400	168,800	0.106	0.101	--	--
11.2	2400	168,900	0.185	--	--	--
11.2	2400	168,900	0.191	0.201	--	--
27.5	5800	988,100	0.077	0.062	--	--
27.7	5800	992,500	0.056	0.045	--	--
27.3	5800	995,400	0.072	0.077	--	--
57.3	5800	1,017,900	0.234	0.140	--	--
57.9	5800	1,020,800	0.065	0.050	--	--
59.2	5800	990,300	0.184	--	--	--
59.2	5800	992,500	0.186	0.160	--	--
59.6	5800	976,500	0.111	0.093	--	--
58.8	5800	976,500	0.213	0.150	--	--
115.5	5800	968,500	0.161	--	--	--
116.5	5800	971,400	0.132	--	--	--
116.9	5800	1,022,200	0.196	0.184	--	--
~~116.9~~	~~5800~~	~~1,029,500~~	~~0.270~~	~~0.243~~	--	--
116.9	5800	1,041,100	0.267	0.223	--	--
116.9	5800	1,038,900	0.344	0.332	--	--
118.8	5800	1,087,500	0.259	0.136	--	--
118.8	5800	1,090,900	0.184	0.136	--	--
118.8	5800	1,092,600	0.183	--	--	--
118.8	5800	1,094,100	0.190	0.152	--	--
119.1	5800	1,062,900	0.162	--	--	--
125.3	5800	1,044,700	0.199	0.141	--	--

Arithmetic Mean and Standard Deviation of M_c/M_i Values					All Sites
Mean	0.17	0.14	--	--	0.27
Standard Deviation	0.07	0.07	--	--	0.27

Table 15

Initial Slopes of Stress-Strain Curves and Strengths $\left(\frac{\sigma_1 - \sigma_3}{2}\right)_{max}$ at the Overburden Confining Pressure from Static UU Tests

Depth ft	Initial Slope of Curve (Young's Modulus E_i) psi	Strength $\left(\frac{\sigma_1 - \sigma_3}{2}\right)_{max}$ kips/sq ft
	Toole County Site	
2.6	2,000	3.6
4.4	1,064	0.7
8.1	5,000	8.6
16.0	3,330	4.3
33.4	909	5.9
41.2	1,111	6.3
	Pondera County Site	
5.5	4,000	1.6
5.6	3,125	2.6
7.1	6,660	--
11.1	3,330	2.9
12.3	1,430	2.5
21.4	1,720	7.9
	Barnes County Site	
3.0	1,250	1.3
8.4	4,000	3.3
13.4	3,330	4.3
14.0	--	5.5
28.0	10,000	3.7
29.6	2,500	2.9
48.3	909	2.7
47.6	5,000	2.6
49.0	10,000	2.0
69.7	2,500	3.2
81.5	2,000	2.6
88.0	4,000	4.6
99.3	4,000	3.9
115.2	4,000	5.5

Depth ft	Initial Slope of Curve (Young's Modulus E_i) psi	Strength $\left(\frac{\sigma_1 - \sigma_3}{2}\right)_{max}$ kips/sq ft
	Tiber Reservoir Site	
5.5	5,000	3.9
15.6	5,560	11.5
25.2	20,000	8.6
33.0	6,670	6.9
52.0	12,500	1.0
58.4	5,000	1.0
	Mountrail County Site	
0.4	5,000	3.6
4.0	4,000	3.0
13.9	4,000	3.9
15.3	12,500	4.6
	Steele County Site	
9.9	3,330	8.0
17.4	5,000	17.5
31.2	6,670	13.0
33.3	1,180	15.0
41.1	2,500	6.5
53.4	5,000	34.0
	Lake County Site	
	No static data available	

Table 16

Depths of Till, Weathering, and Groundwater

Site	Approximate Depth to Till Base ft	Depth of Weathering ft	Approximate Depth of Groundwater ft
Toole County, Montana	42.5	72.5	25
Pondera County, Montana	23.0	52.0	--
Tiber Reservoir, Montana	60.0	60.0	60*
Mountrail County, North Dakota	26.0	26.0	45
Barnes County, North Dakota	130.0+	30.0	12
Steele County, North Dakota	130.0+	18.0	7
Lake County, Illinois	66.0	16.0	16

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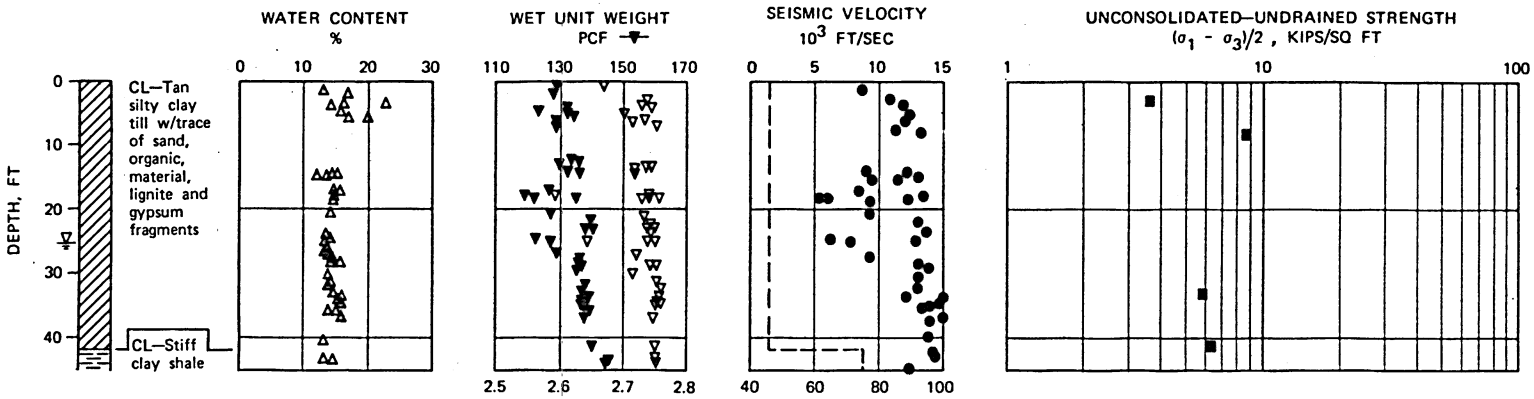
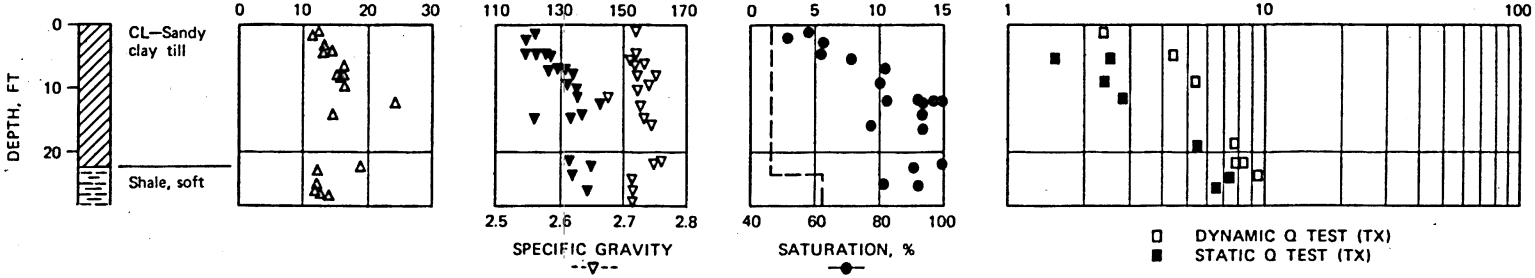
* Assumed.



a. TOOLE COUNTY

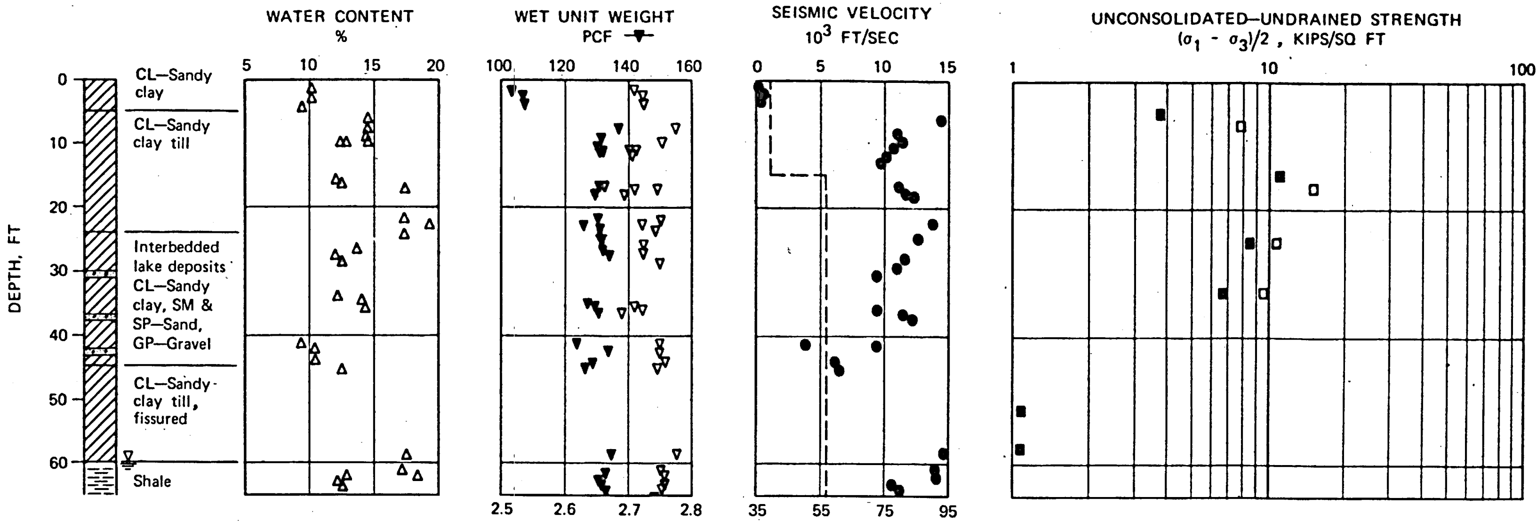


b. PONDERA COUNTY

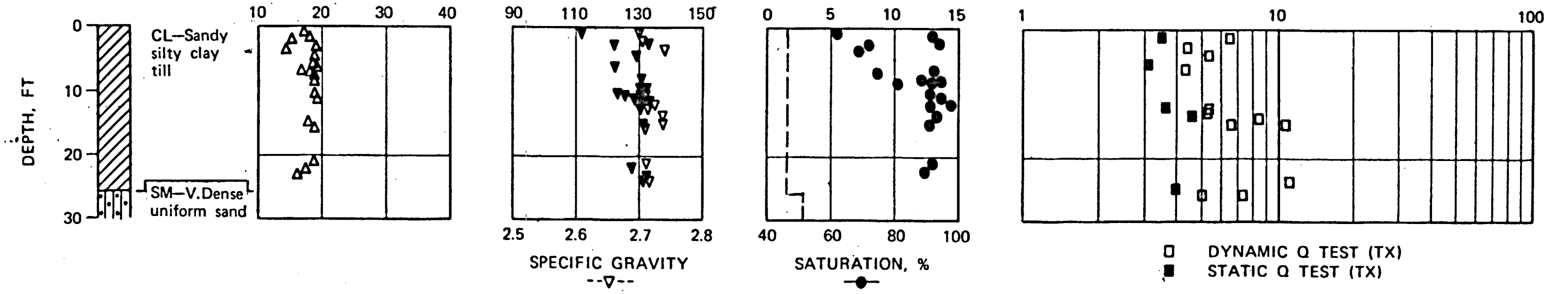
SOIL PROFILE DATA
TOOLE AND PONDERA COUNTY, MONTANA, SITES

PLATE 1

PLATE 2



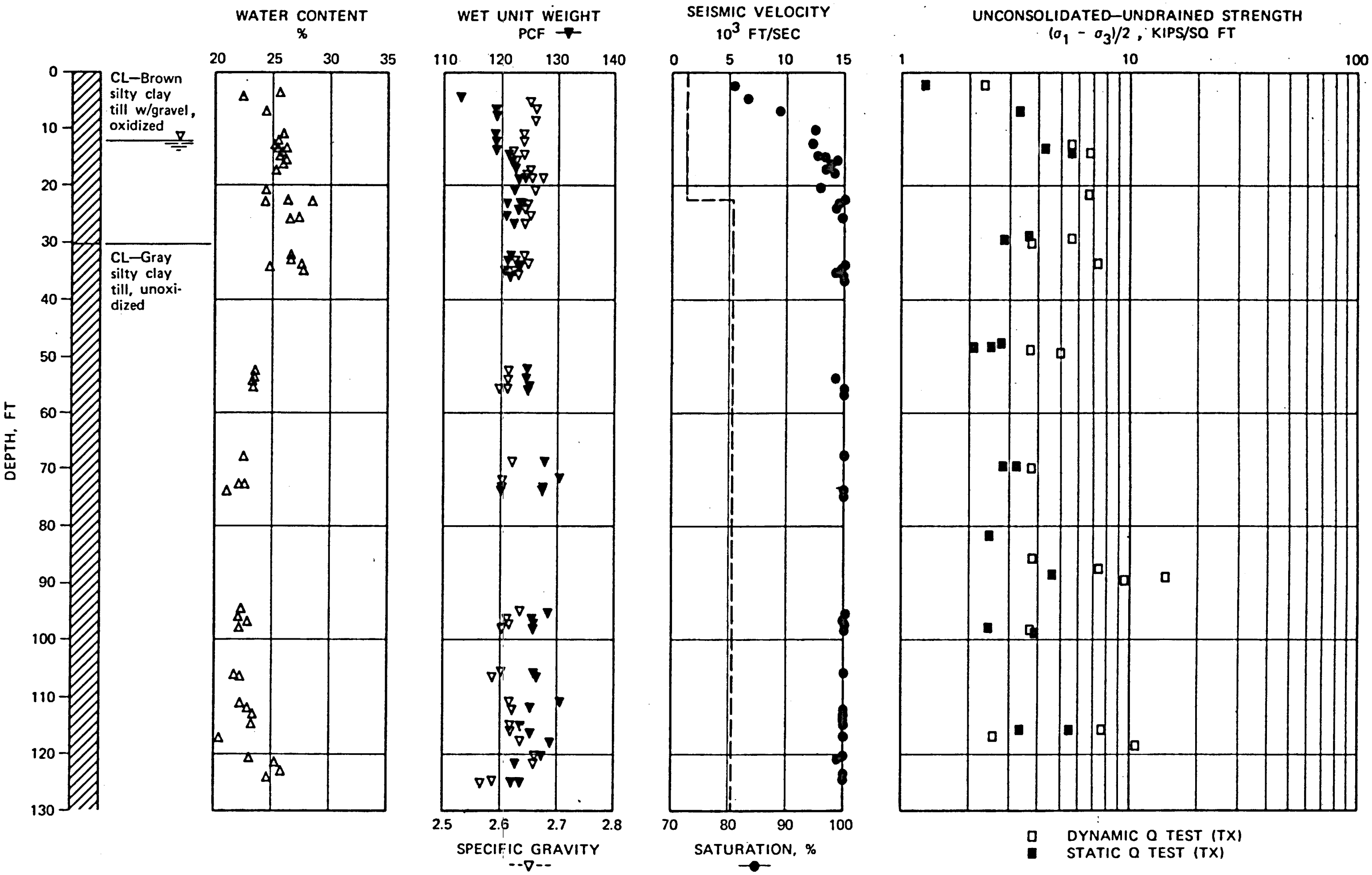
a. TIBER RESERVOIR



b. MOUNTRAIL COUNTY

SOIL PROFILE DATA

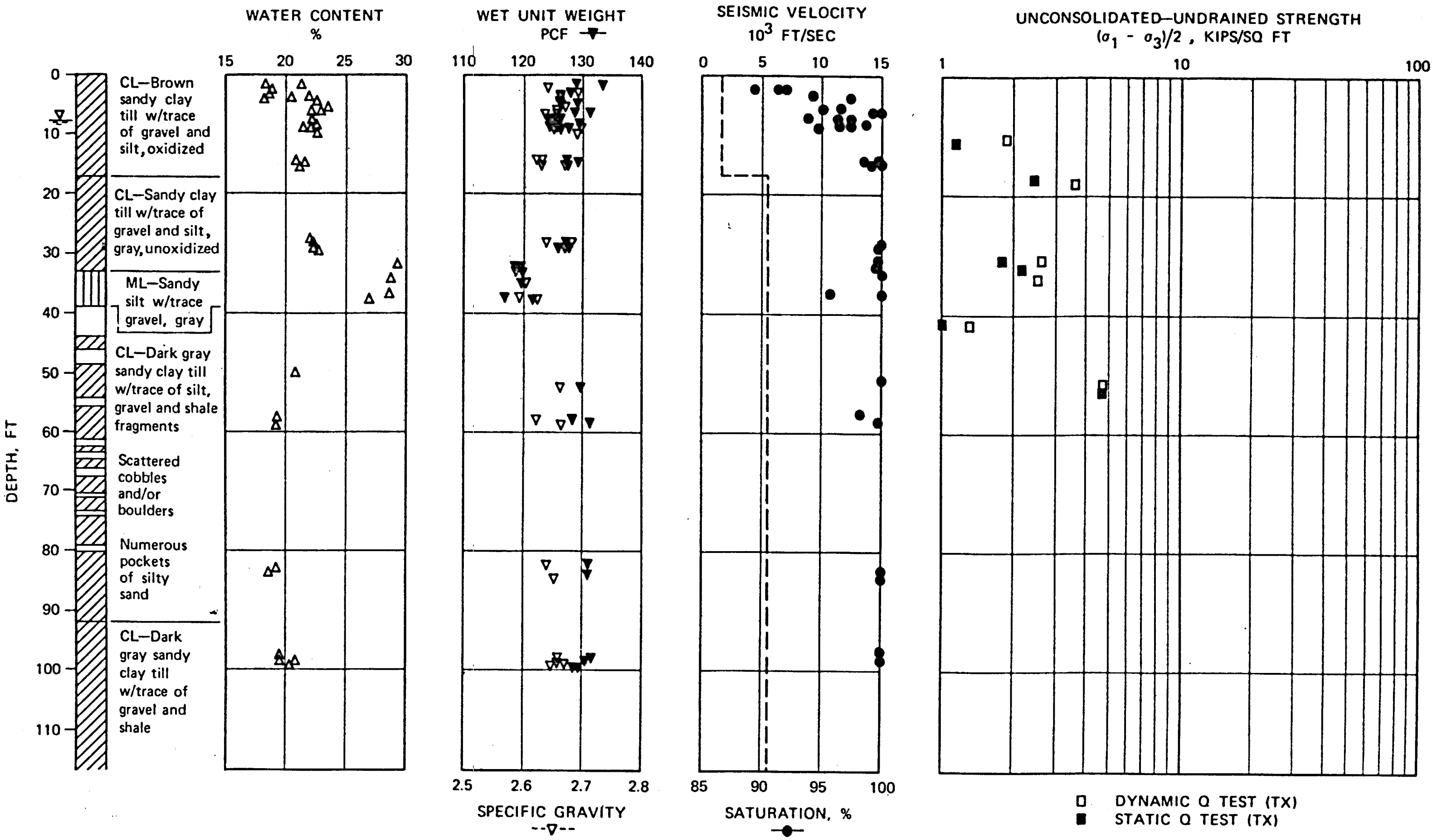
TIBER RESERVOIR, MONTANA,
AND MOUNTRAIL COUNTY,
NORTH DAKOTA, SITES



SOIL PROFILE DATA
BARNES COUNTY,
NORTH DAKOTA, SITE

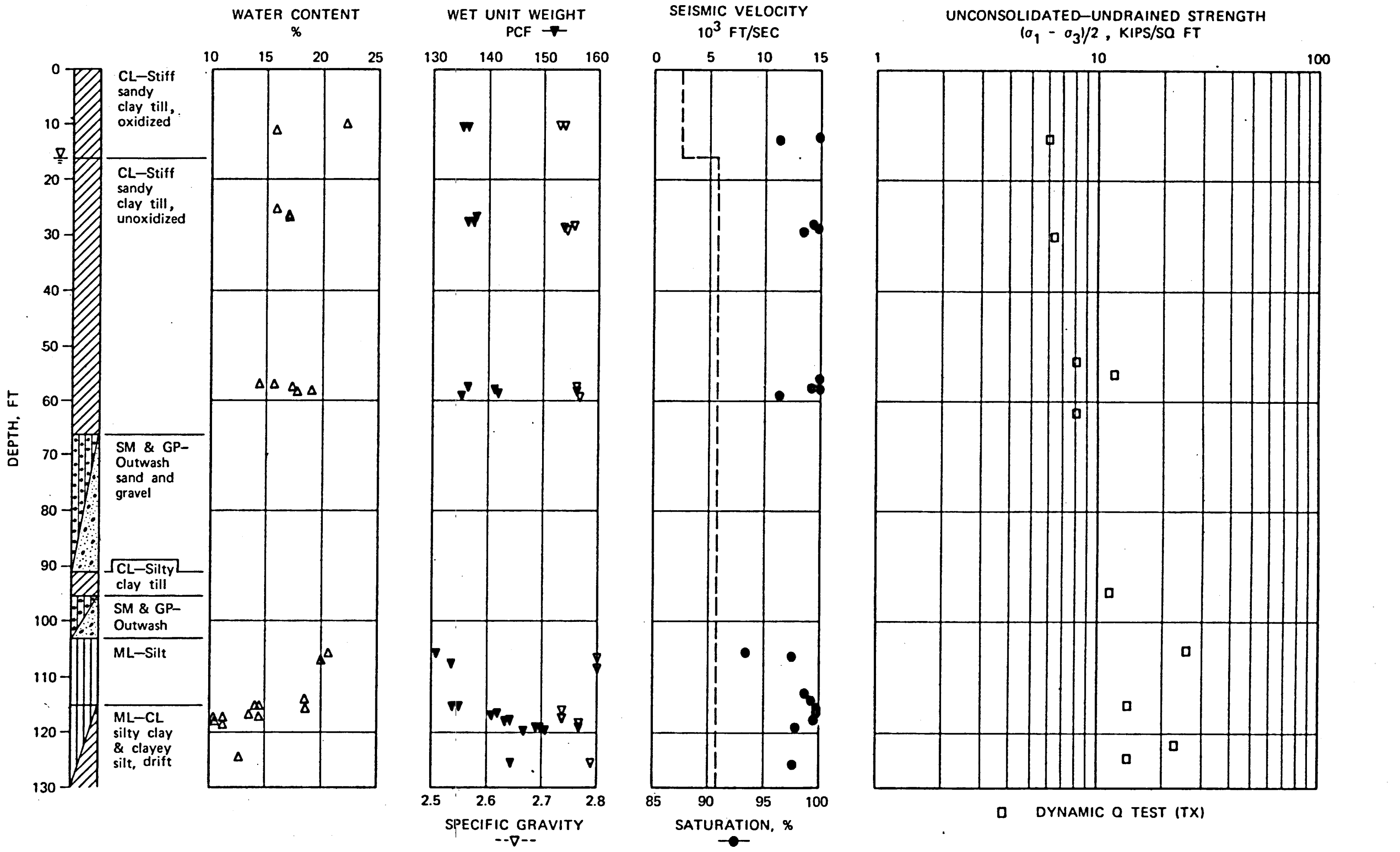
PLATE 3

PLATE 4



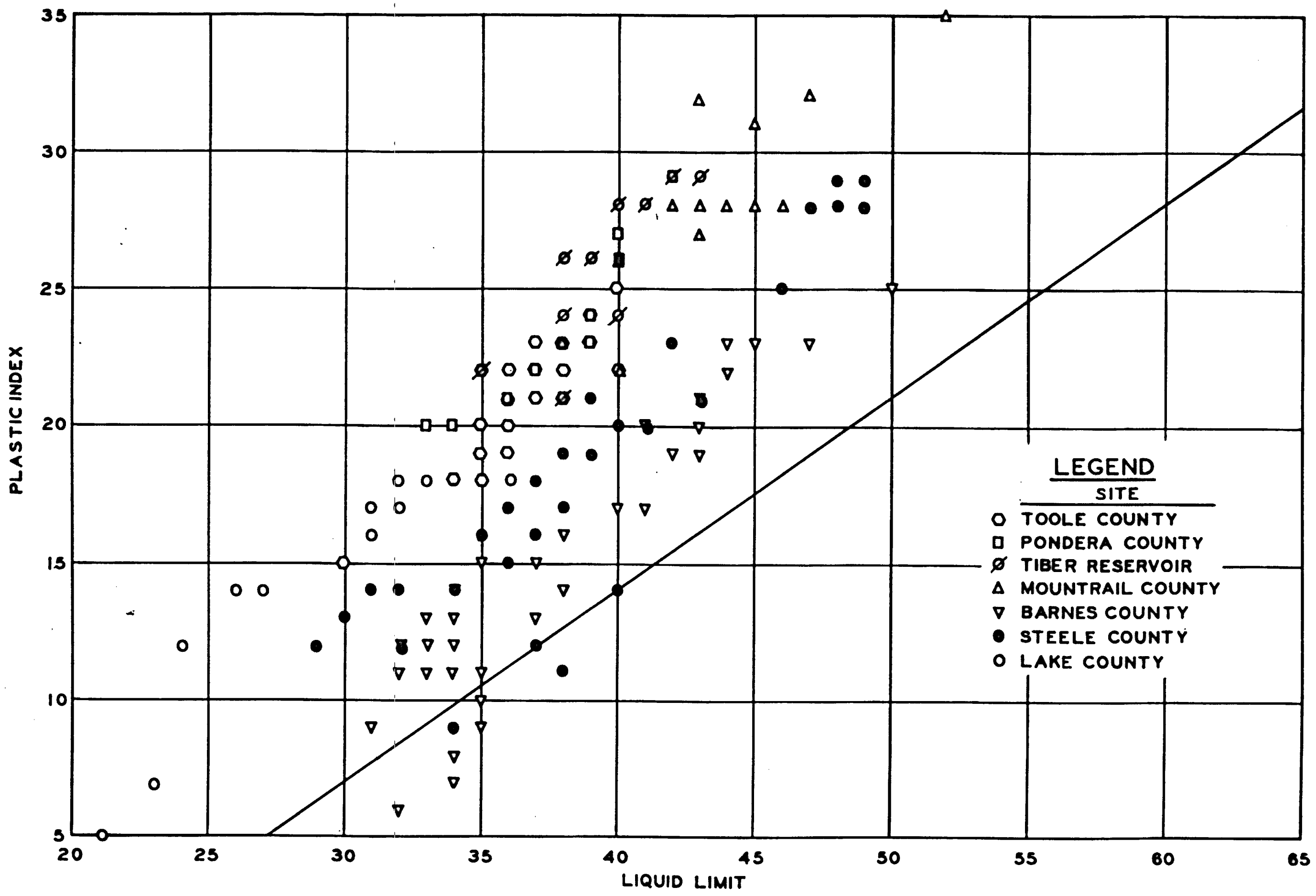
SOIL PROFILE DATA
STEELE COUNTY,
NORTH DAKOTA, SITE

PLATE 5

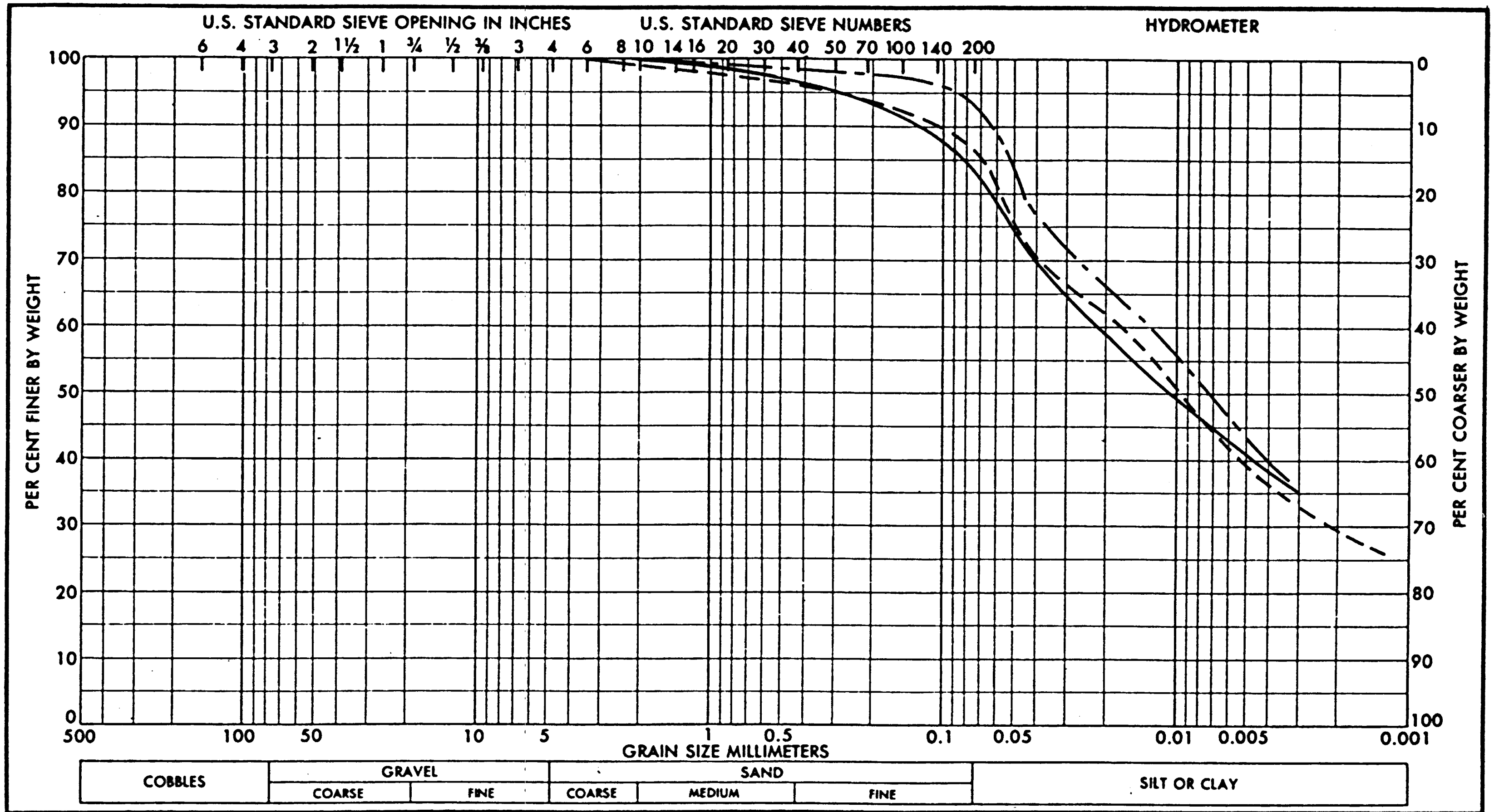


SOIL PROFILE DATA
LAKE COUNTY, ILLINOIS, SITE

PLATE 6



**ATTERBERG LIMIT
TEST RESULTS**

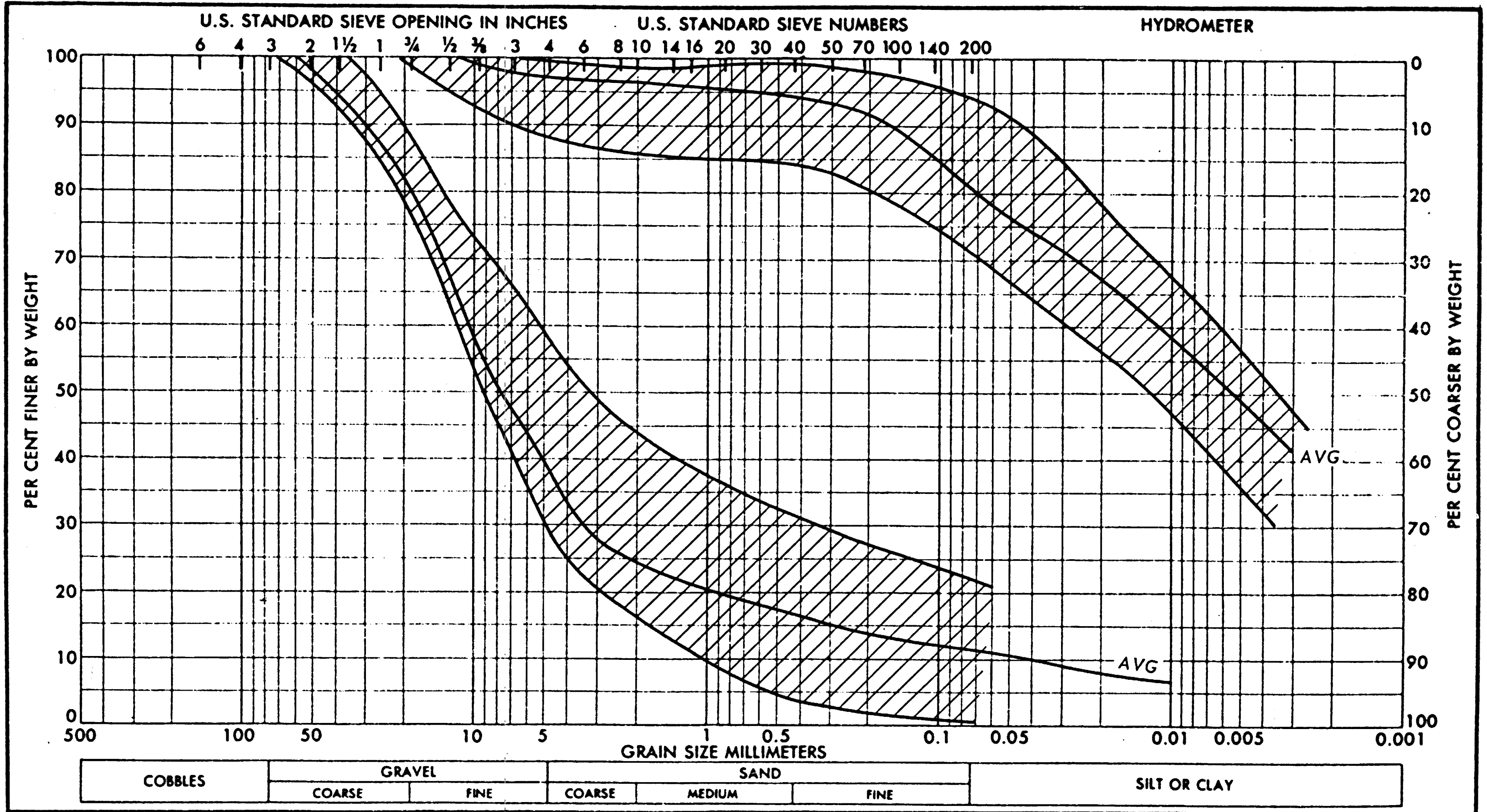


SAMPLE NO.	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
6	3363-3405	SILTY CLAY (CL)	2.72	36	14	22
10X	3363-3405	SILTY CLAY (CL)	2.75	39	17	22
20	3359-3363	SILTY CLAY (CL)	2.75	39	17	22

GRAIN-SIZE DISTRIBUTION CURVES
TOOLE COUNTY, MONTANA, SITE

PLATE 7

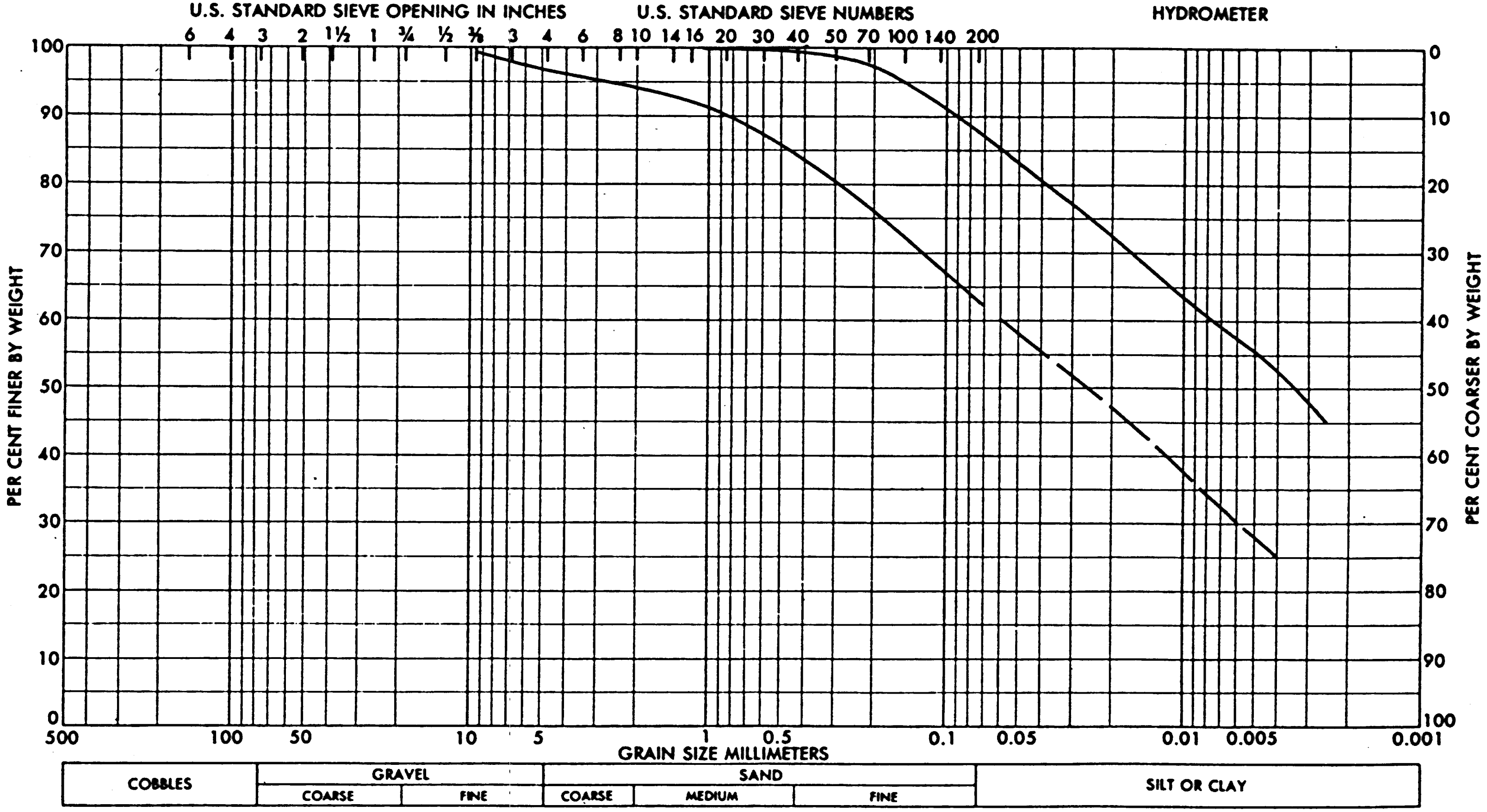
PLATE 8



SAMPLE NO.	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI

RANGE OF GRAIN-SIZE DISTRIBUTION CURVES

PONDERA COUNTY, MONTANA, SITE



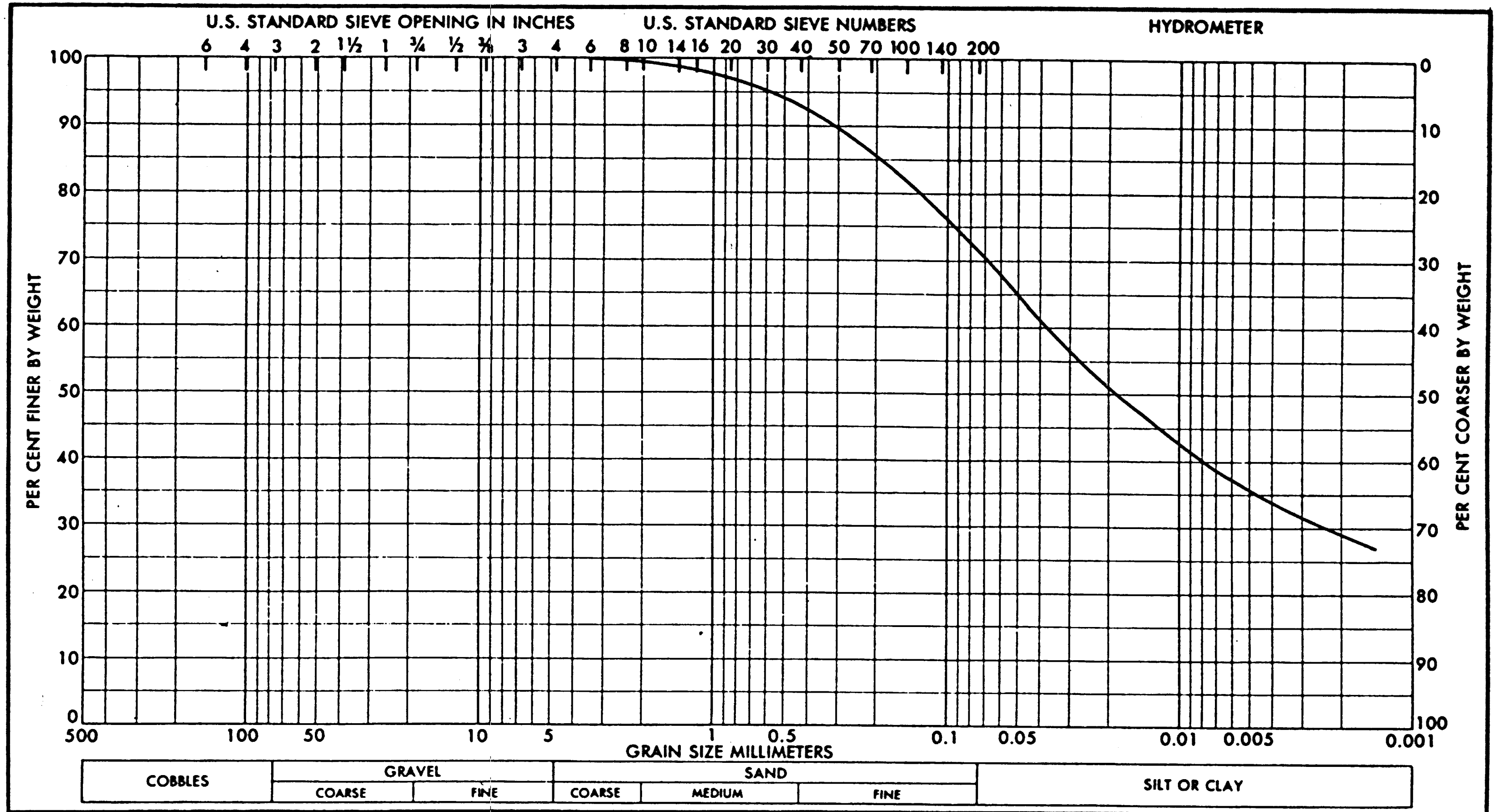
SAMPLE NO.	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI

RANGE OF GRAIN-SIZE DISTRIBUTION CURVES

TIBER RESERVOIR, MONTANA, SITE

PLATE 9

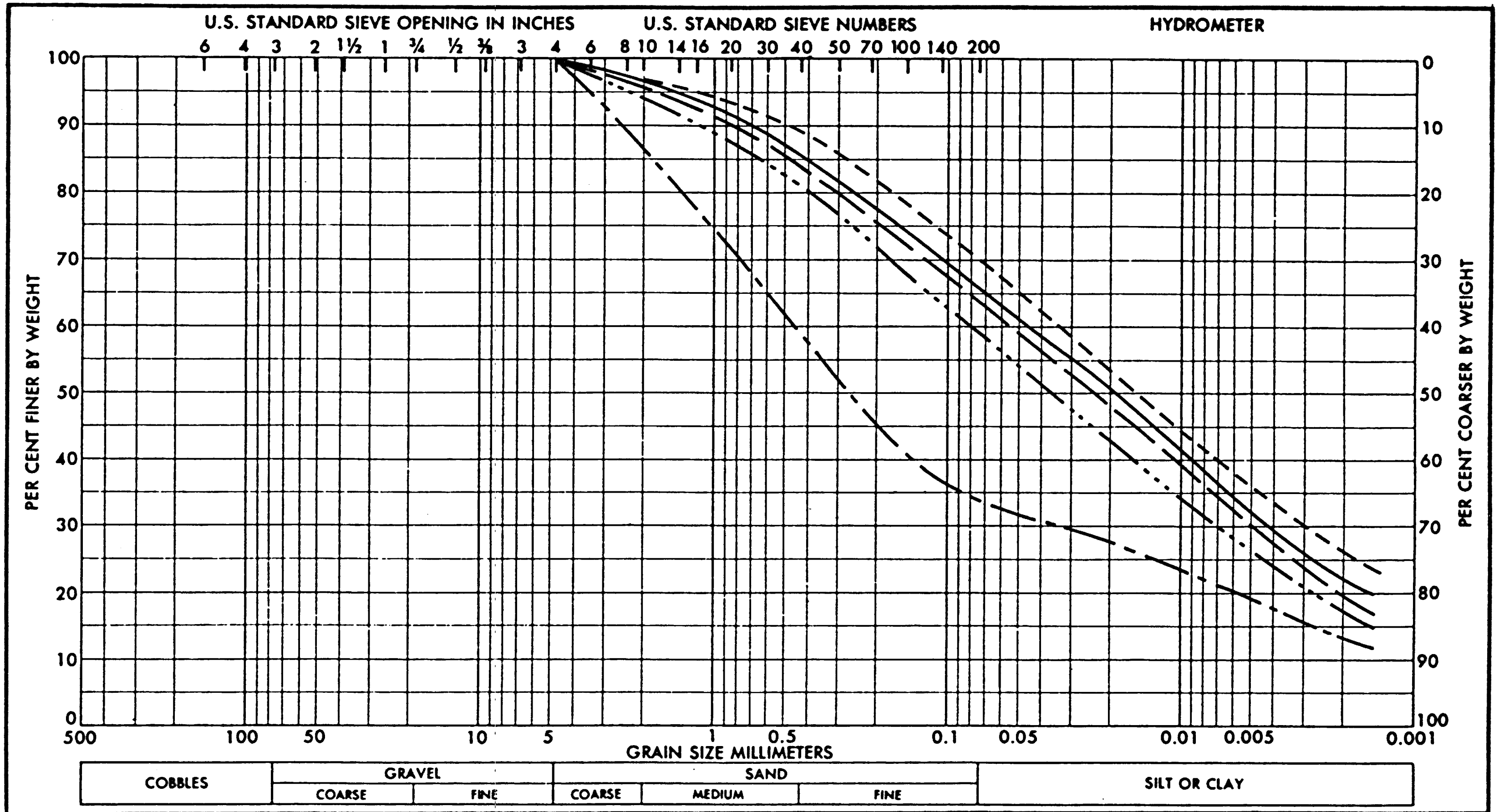
PLATE 10



SAMPLE NO.	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI
3.6.2	2222-2249	SANDY CLAY (CH)	2.71	52	17	35

TYPICAL GRAIN-SIZE DISTRIBUTION CURVE

MOUNTRAIL COUNTY,
NORTH DAKOTA, SITE

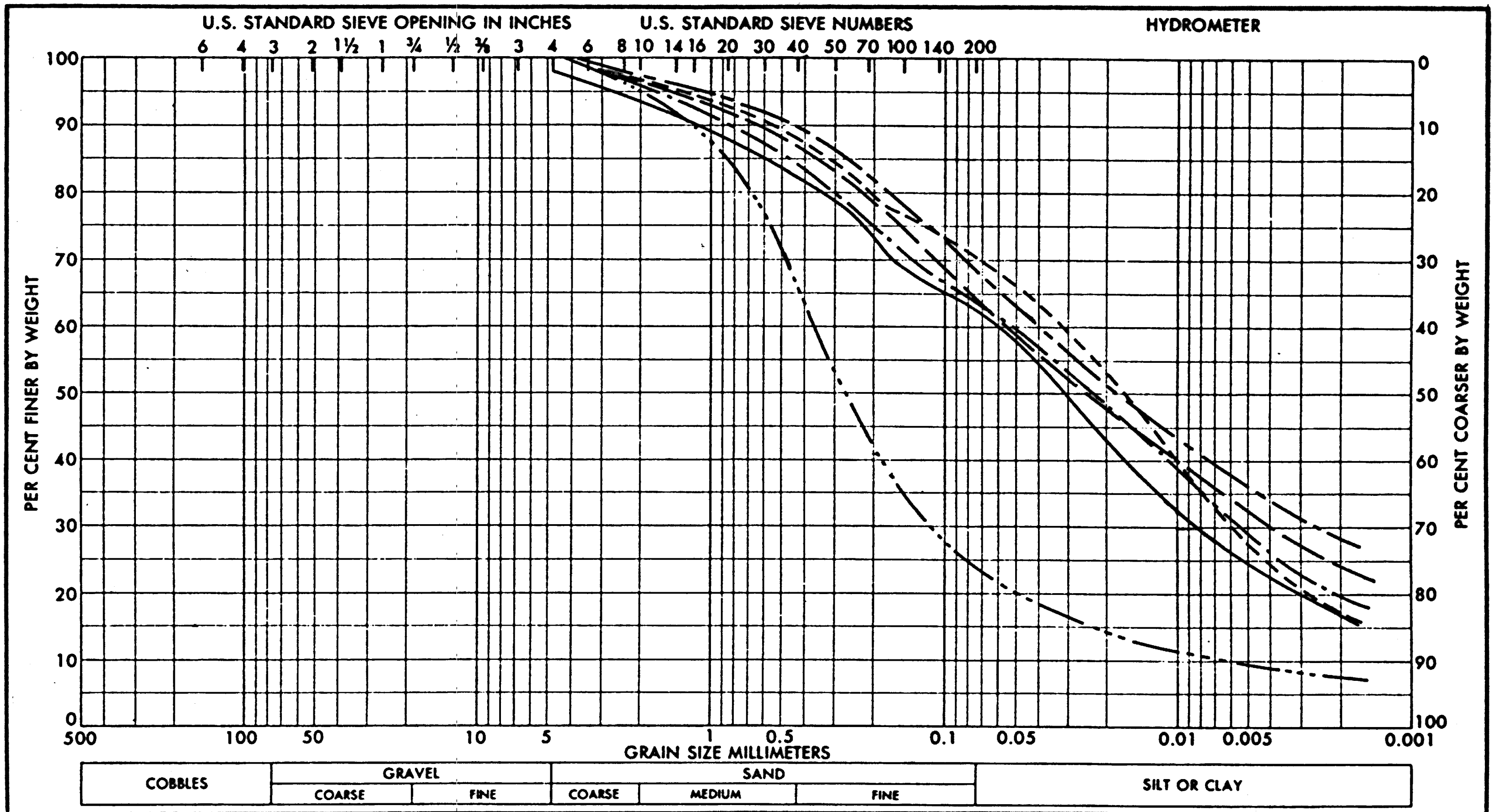


SAMPLE NO.	ELEV OR DEPTH	Symbol	CLASSIFICATION	NAT W%	LL	PL	PI
1	997-977	————	SANDY CLAY (CL)	2.65	40	23	17
2	977-947	— — — —	SANDY CLAY (CL)	2.65	40	23	17
2	977-947	—·—·—	CLAYEY SAND (SC)	2.66	31	19	12
3	947-907	—···—	SANDY CLAY (CL)	2.61	34	22	12
4	907-777	— — —	SANDY CLAY (CL)	2.62	34	23	11

GRAIN-SIZE DISTRIBUTION CURVES
BARNES COUNTY, NORTH DAKOTA, SITE

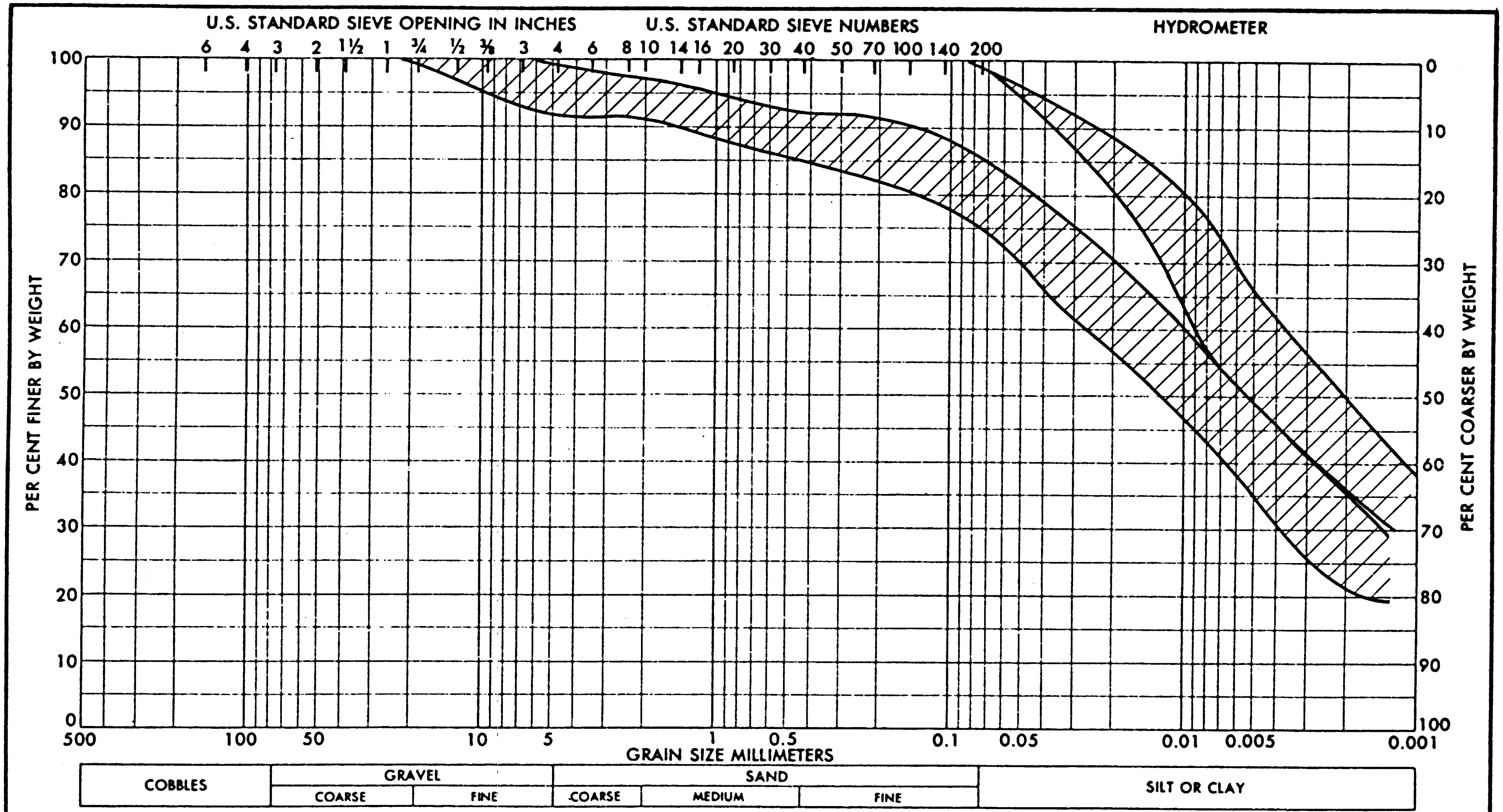
PLATE 11

PLATE 12



SAMPLE NO.	ELEV OR DEPTH	Symbol	CLASSIFICATION	NAT W%	LL	PL	PI
2 & 3	995-980	——·——	SANDY CLAY (CL)	2.66	35	19	16
4	980-964	————	SANDY CLAY (CL)	2.64	33	19	14
5	964-957	- - - - -	SANDY SILT (ML)	2.59	39	26	13
6	957-905	—···—	SILTY SAND (SM)	2.64	40	26	14
6	957-905	— — —	SANDY CLAY (CL)	2.65	40	19	21
7	905-757	— - —	SANDY CLAY (CL)	2.66	42	19	23

GRAIN-SIZE DISTRIBUTION CURVES
STEELE COUNTY, NORTH DAKOTA, SITE

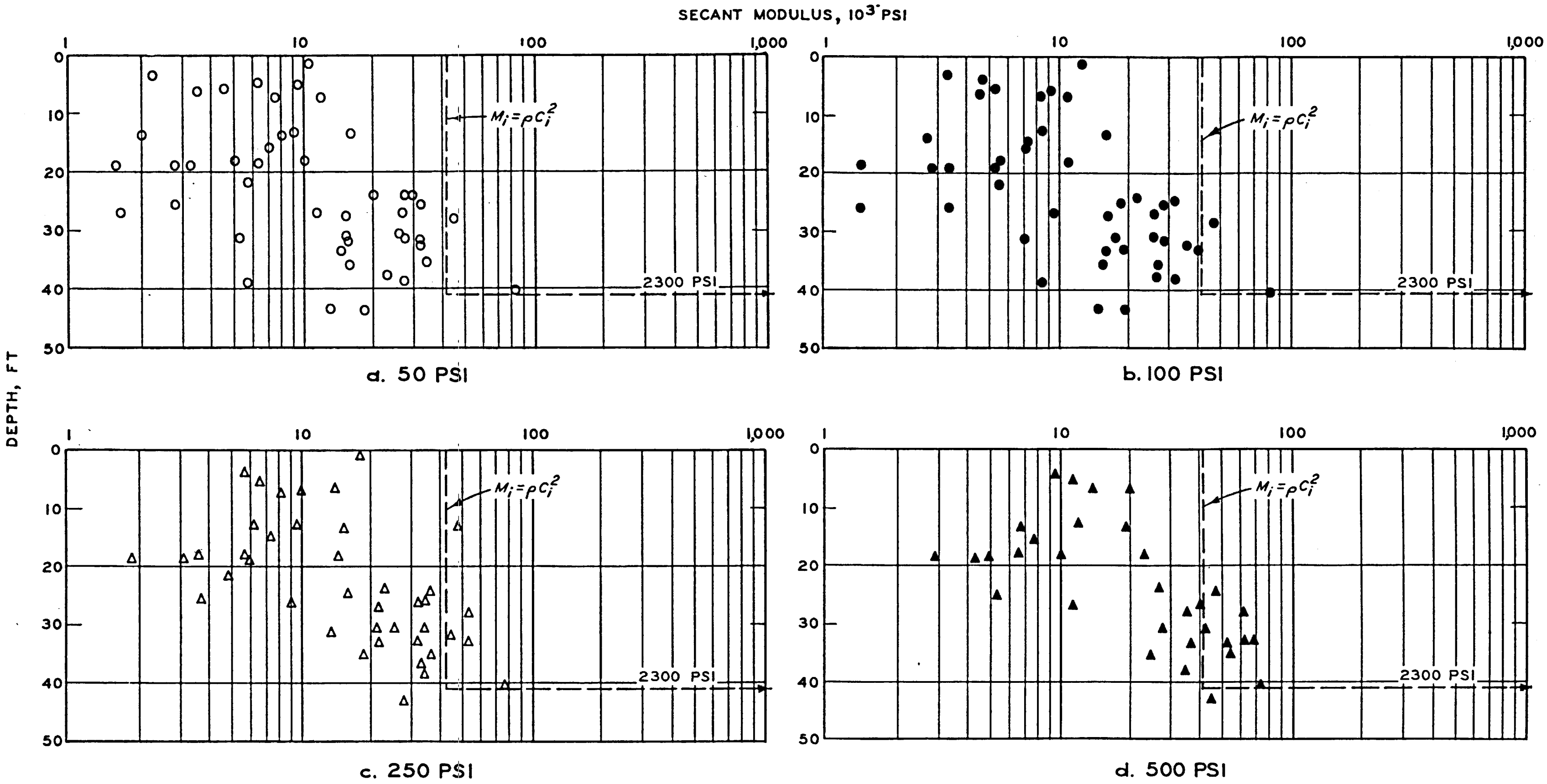


SAMPLE NO.	ELEV OR DEPTH	CLASSIFICATION	NAT W%	LL	PL	PI

RANGE OF GRAIN-SIZE
DISTRIBUTION CURVES
LAKE COUNTY, ILLINOIS, SITE

PLATE 13

PLATE 14



a. 50 PSI

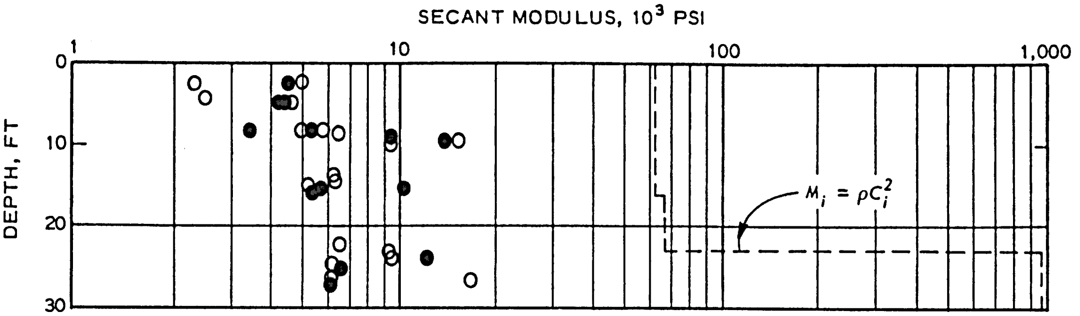
b. 100 PSI

c. 250 PSI

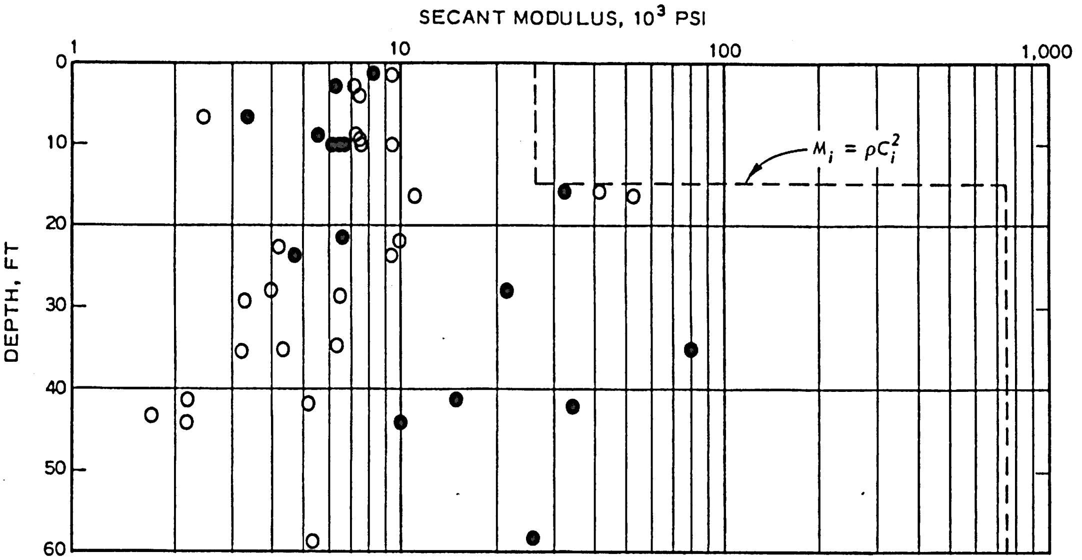
d. 500 PSI

SECANT CONSTRAINED MODULUS TO VARIOUS STRESS LEVELS VS DEPTH

TOOLE COUNTY, MONTANA, SITE



a. PONDERA COUNTY SITE



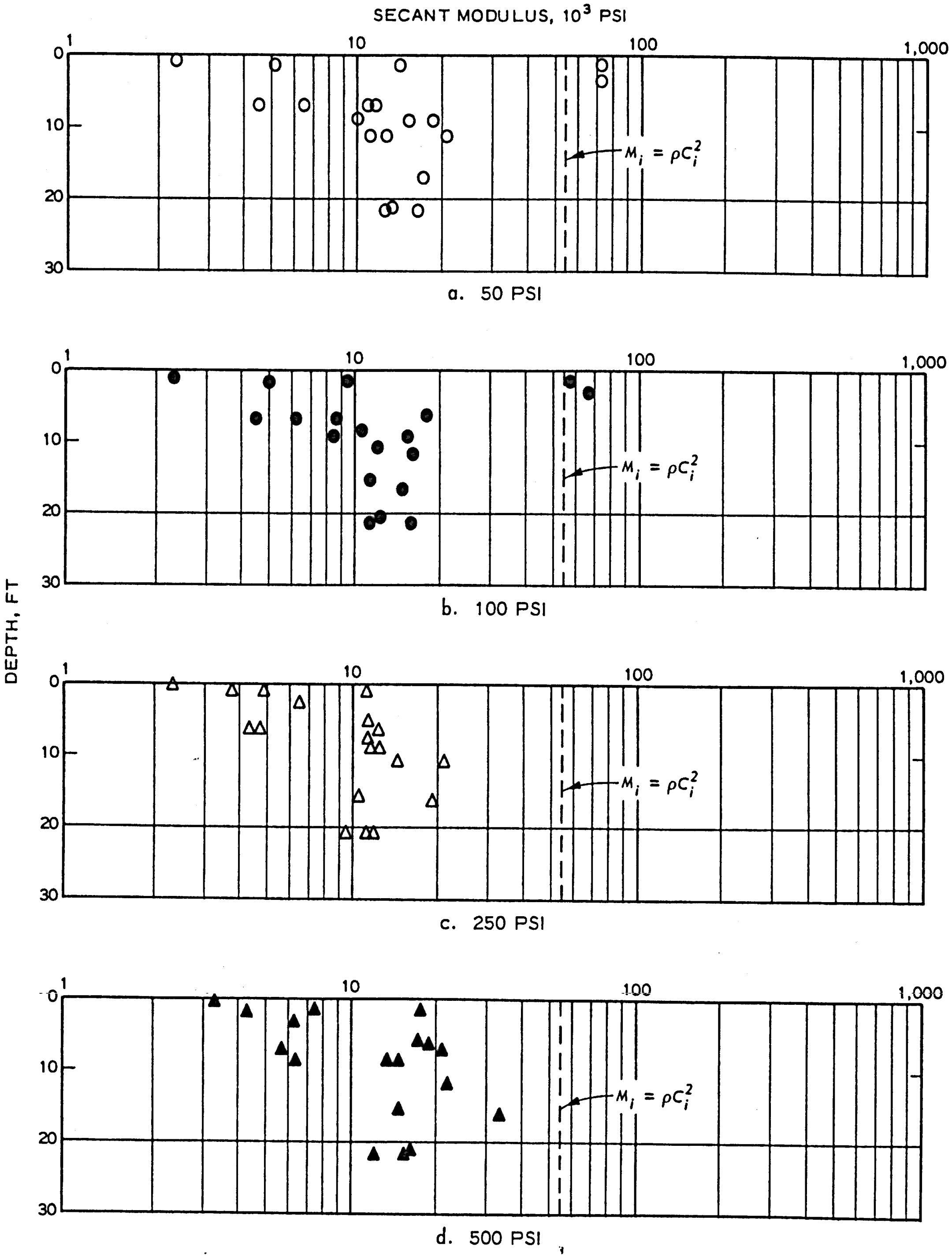
b. TIBER RESERVOIR SITE

LEGEND

SYMBOL	MODULUS
○	M_{50}
●	M_{100}

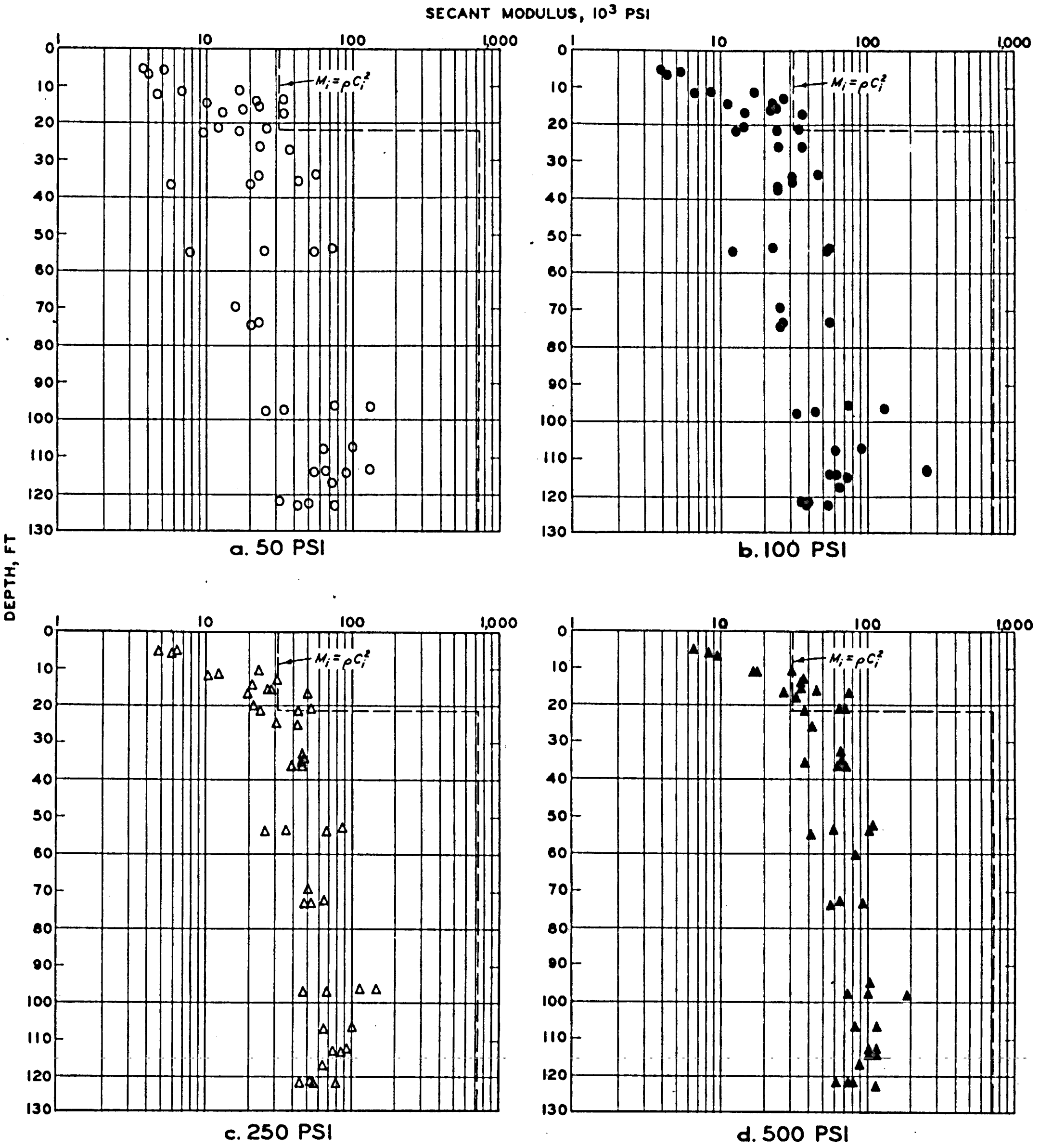
SECANT CONSTRAINED MODULUS TO 50- AND 100-PSI STRESS LEVELS VS DEPTH

PONDERA COUNTY AND
TIBER RESERVOIR, MONTANA, SITES



SECANT CONSTRAINED MODULUS
TO VARIOUS STRESS LEVELS
VS DEPTH
MOUNTRAIL COUNTY,
NORTH DAKOTA, SITE

PLATE 16



a. 50 PSI

b. 100 PSI

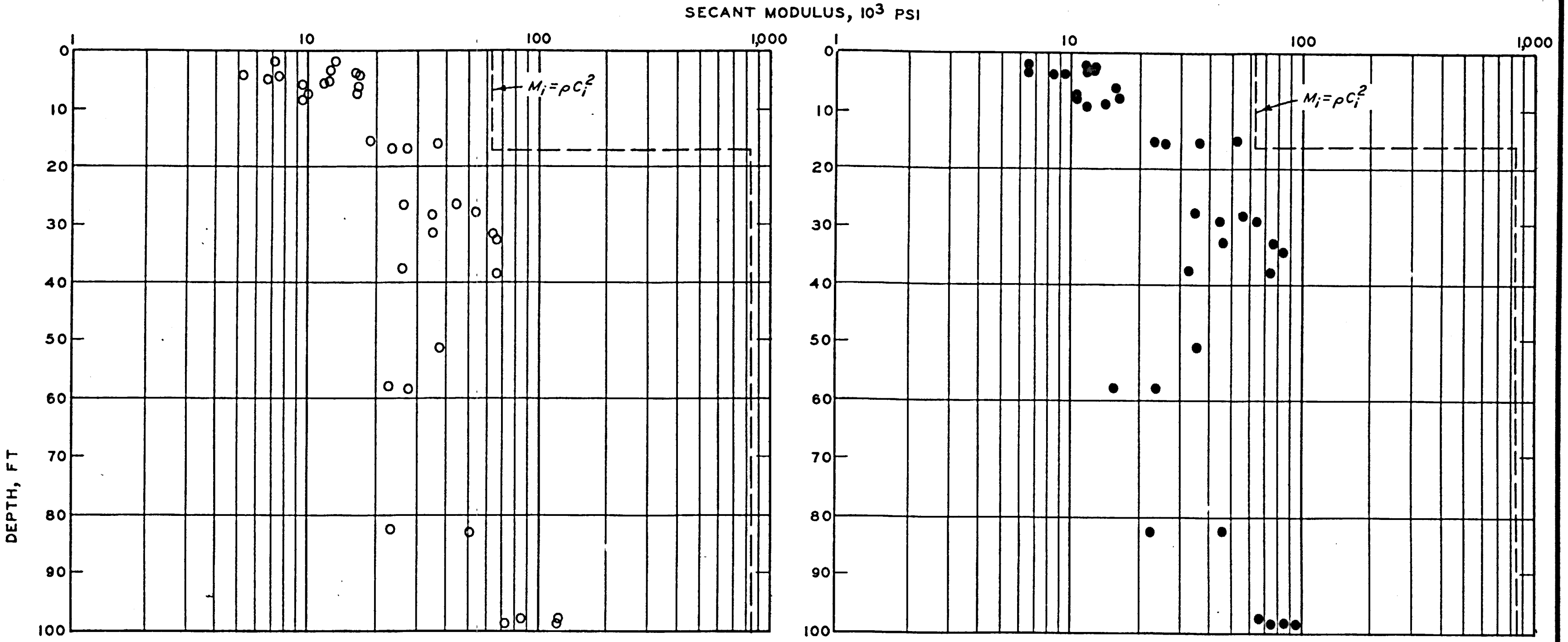
c. 250 PSI

d. 500 PSI

SECANT CONSTRAINED
MODULUS TO VARIOUS
STRESS LEVELS VS DEPTH

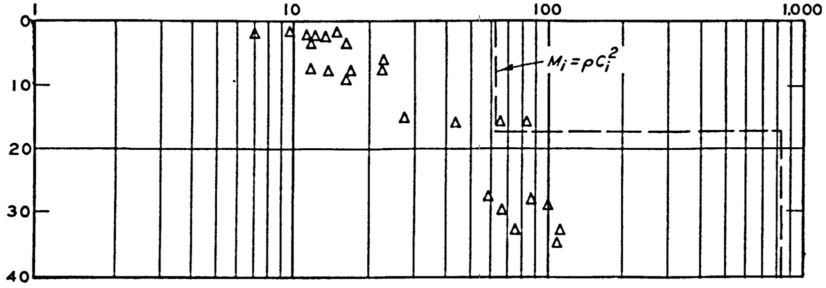
BARNES COUNTY,
NORTH DAKOTA, SITE

PLATE 18



a. 50 PSI

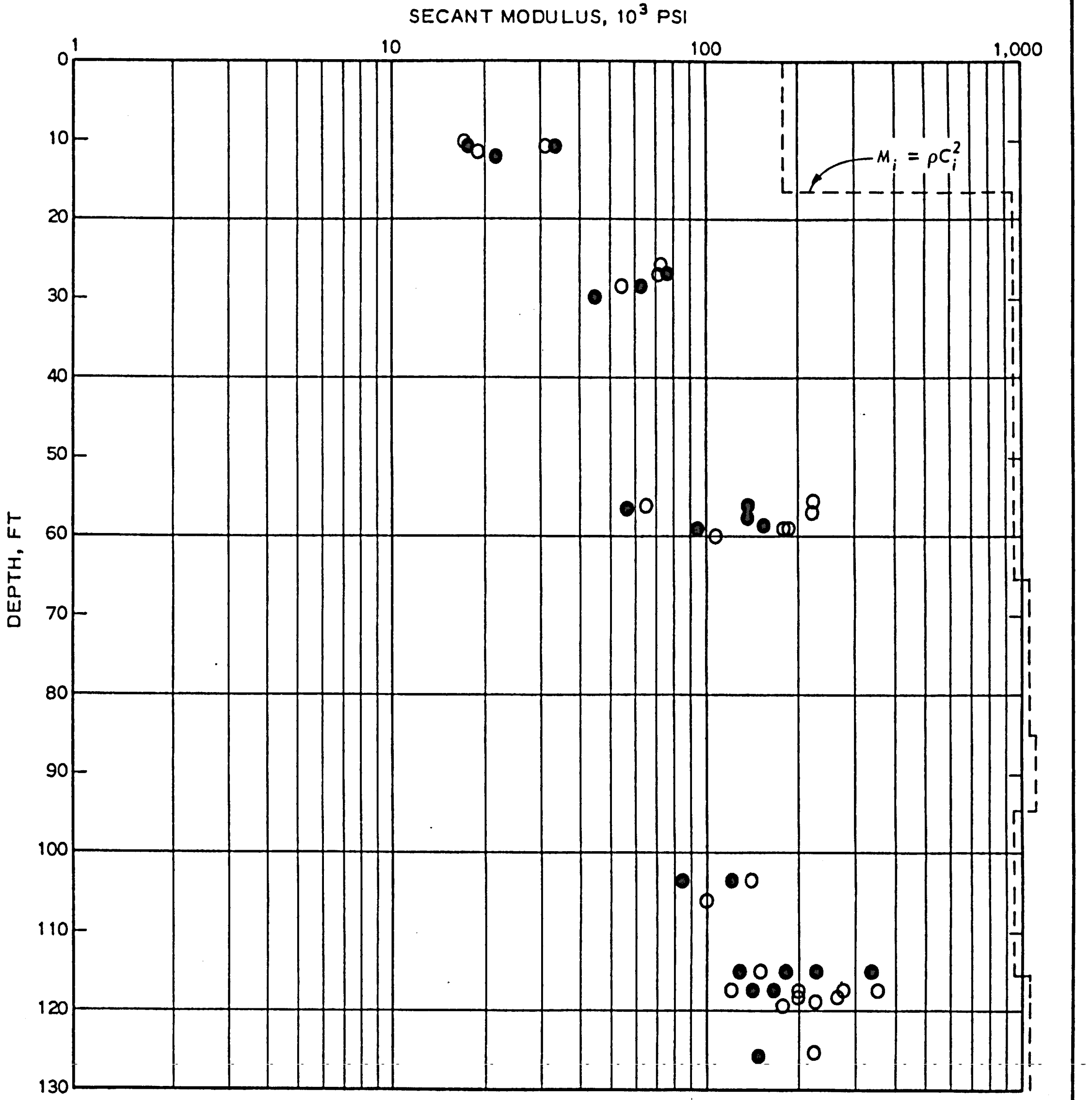
b. 100 PSI



c. 250 PSI

SECANT CONSTRAINED MODULUS TO VARIOUS STRESS LEVELS VS DEPTH

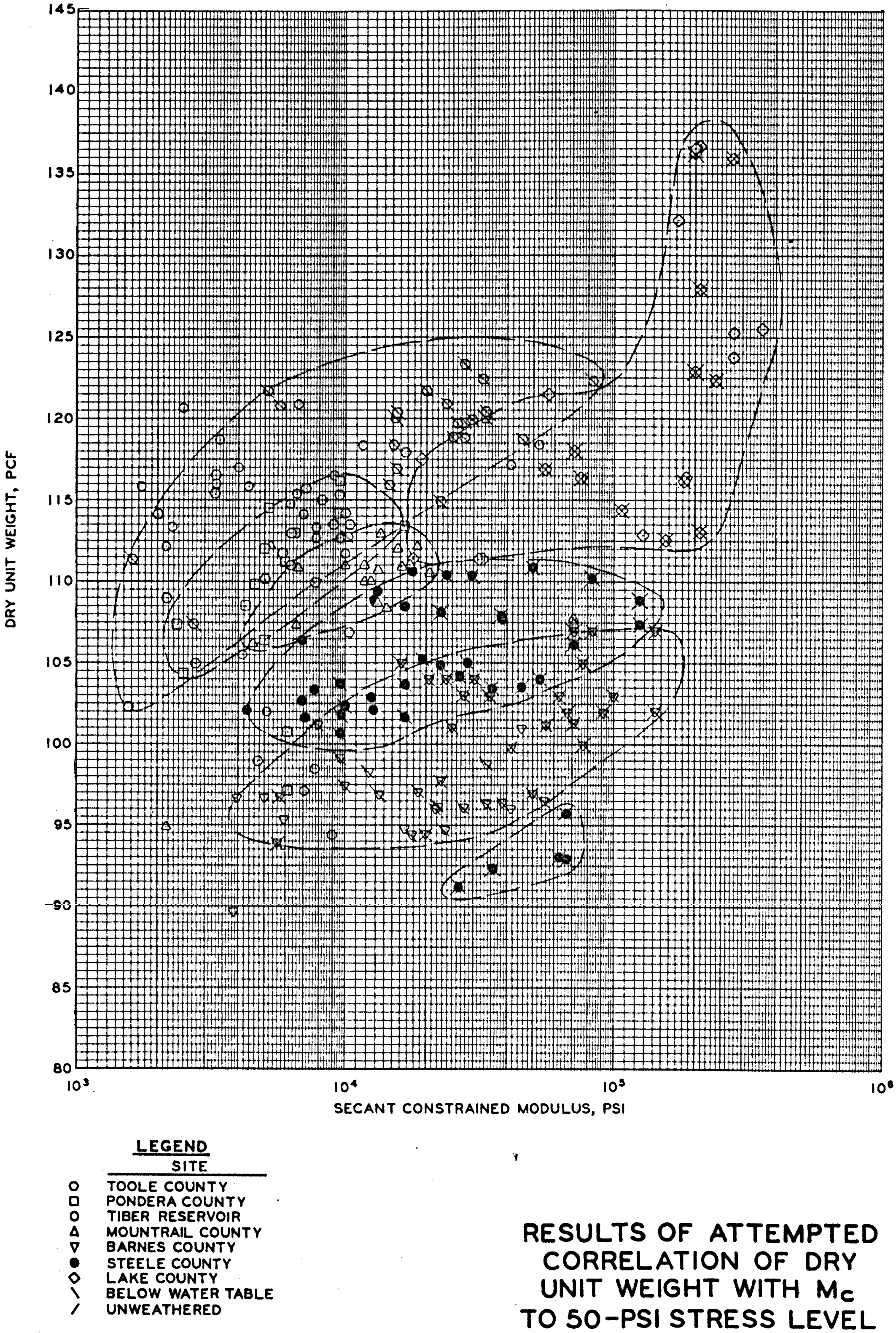
STEELE COUNTY, NORTH DAKOTA, SITE



LEGEND

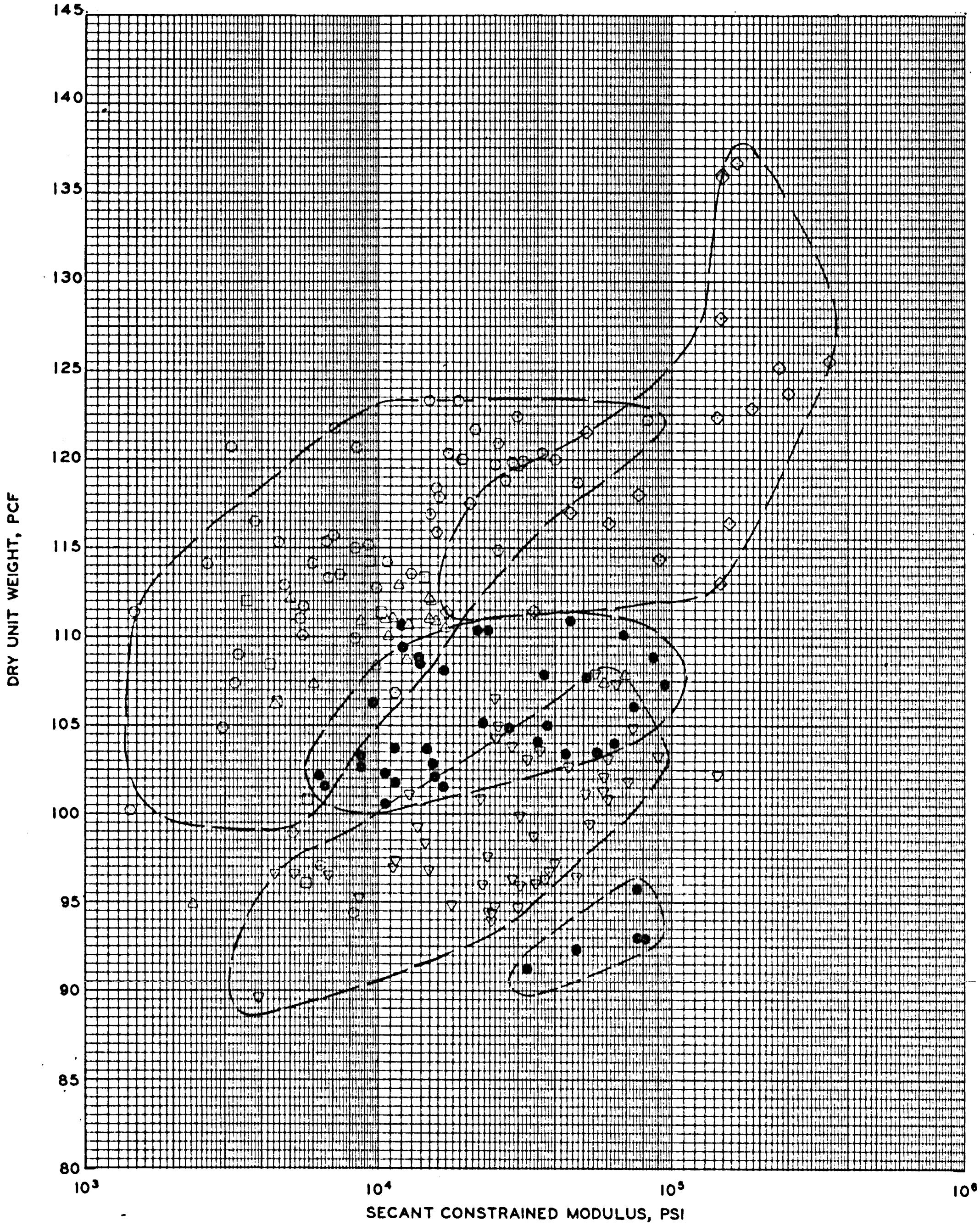
SYMBOL	MODULUS
○	M_{50}
●	M_{100}

SECANT CONSTRAINED MODULUS
TO 50- AND 100-PSI STRESS LEVELS
VS DEPTH
LAKE COUNTY, ILLINOIS, SITE



RESULTS OF ATTEMPTED CORRELATION OF DRY UNIT WEIGHT WITH M_c TO 50-PSI STRESS LEVEL

PLATE 20

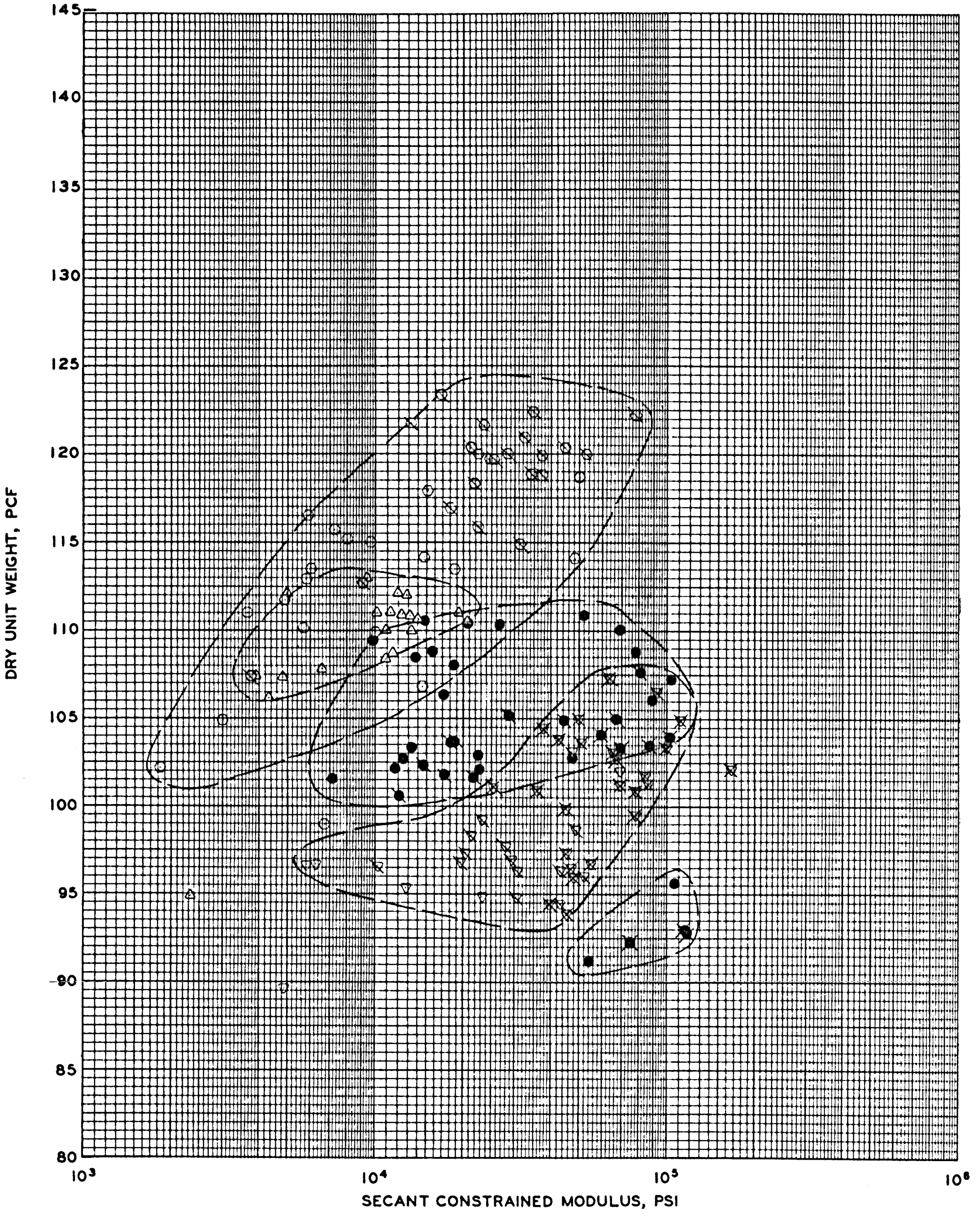


LEGEND

SITE

○	TOOLE COUNTY
□	PONDERA COUNTY
○	TIBER RESERVOIR
△	MOUNTRAIL COUNTY
▽	BARNES COUNTY
●	STEELE COUNTY
◇	LAKE COUNTY

RESULTS OF ATTEMPTED CORRELATION OF DRY UNIT WEIGHT WITH M_c TO 100-PSI STRESS LEVEL

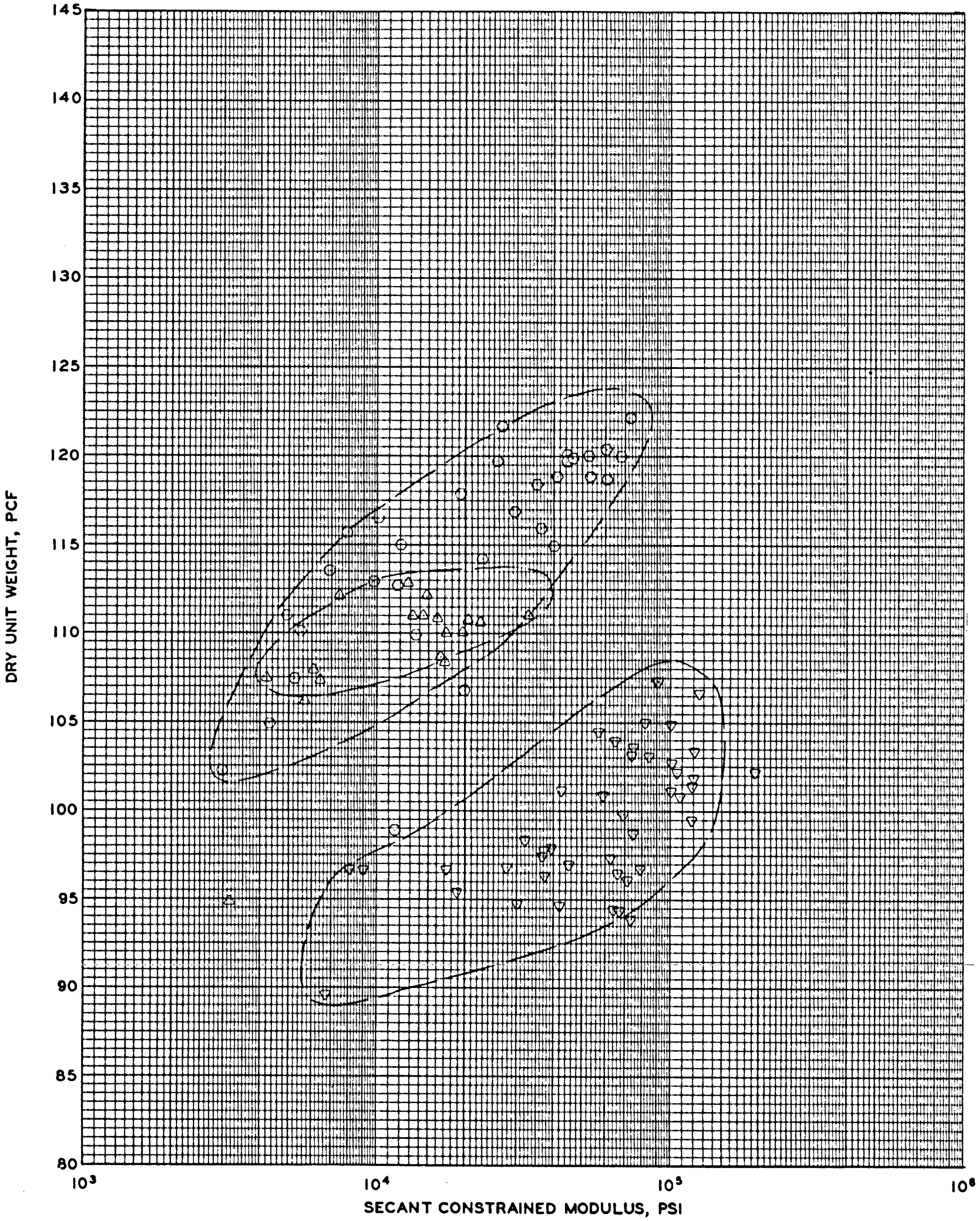


LEGEND

SITE

- ○ TOOLE COUNTY
- □ PONDERA COUNTY
- ○ TIBER RESERVOIR
- △ MOUNTRAIL COUNTY
- ▽ BARNES COUNTY
- ● STEELE COUNTY
- ◇ LAKE COUNTY
- \ BELOW WATER TABLE
- / UNWEATHERED

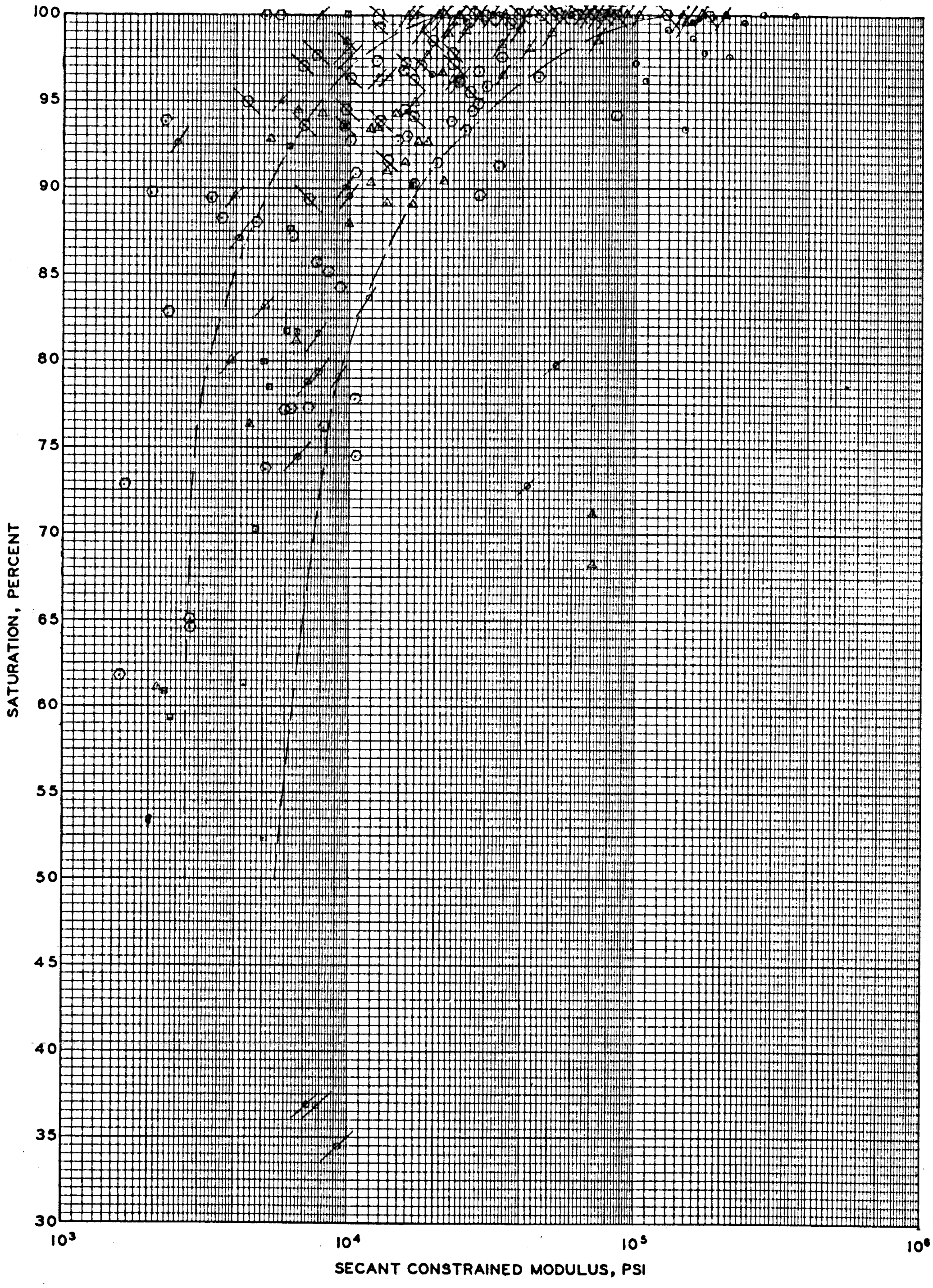
RESULTS OF ATTEMPTED CORRELATION OF DRY UNIT WEIGHT WITH M_C TO 250-PSI STRESS LEVEL



LEGEND

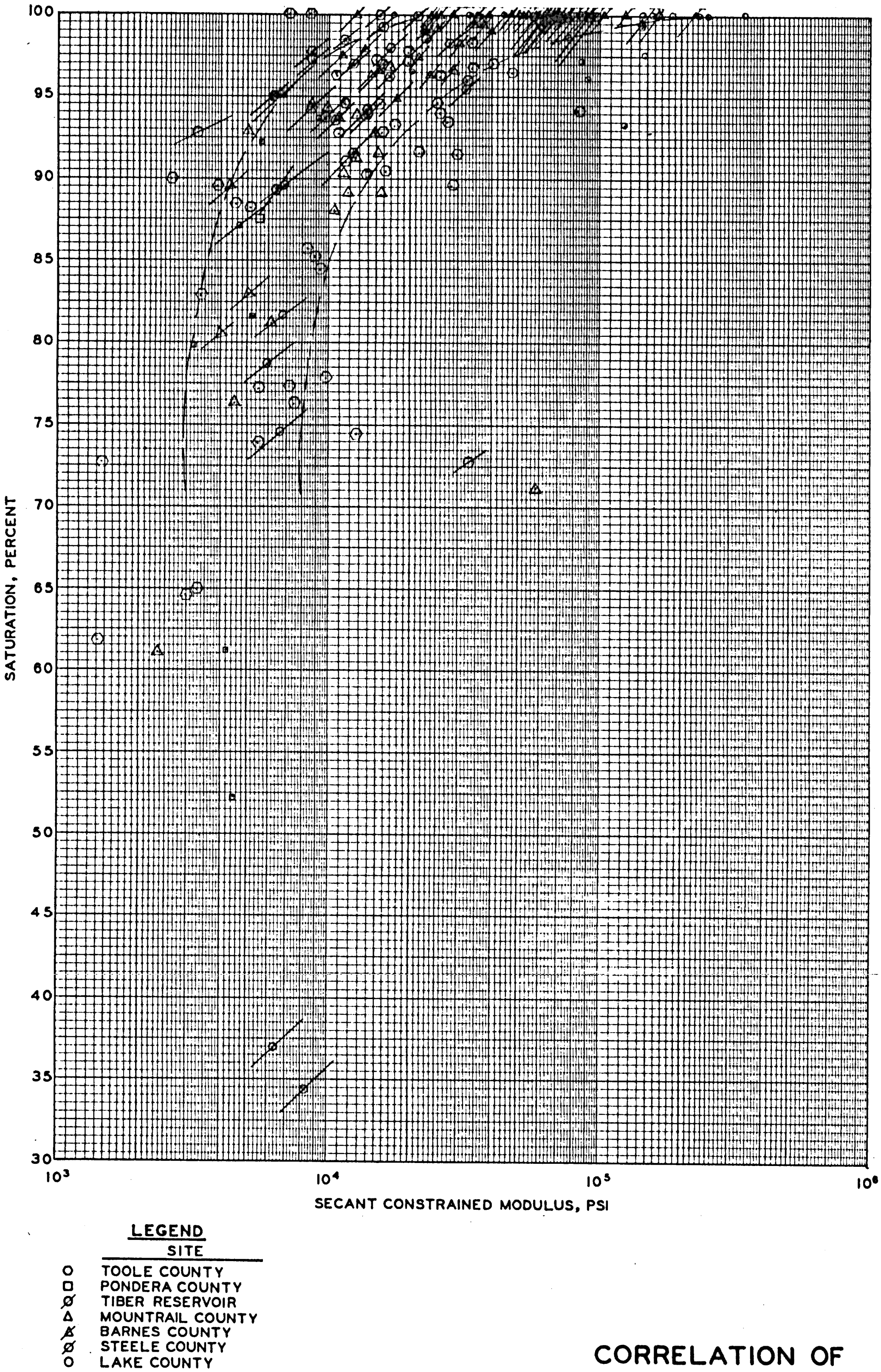
	SITE
○	TOOLE COUNTY
□	PONDERA COUNTY
○	TIBER RESERVOIR
△	MOUNTRAIL COUNTY
▽	BARNES COUNTY
●	STEELE COUNTY
◇	LAKE COUNTY

RESULTS OF ATTEMPTED CORRELATION OF DRY UNIT WEIGHT WITH M_c TO 500-PSI STRESS LEVEL

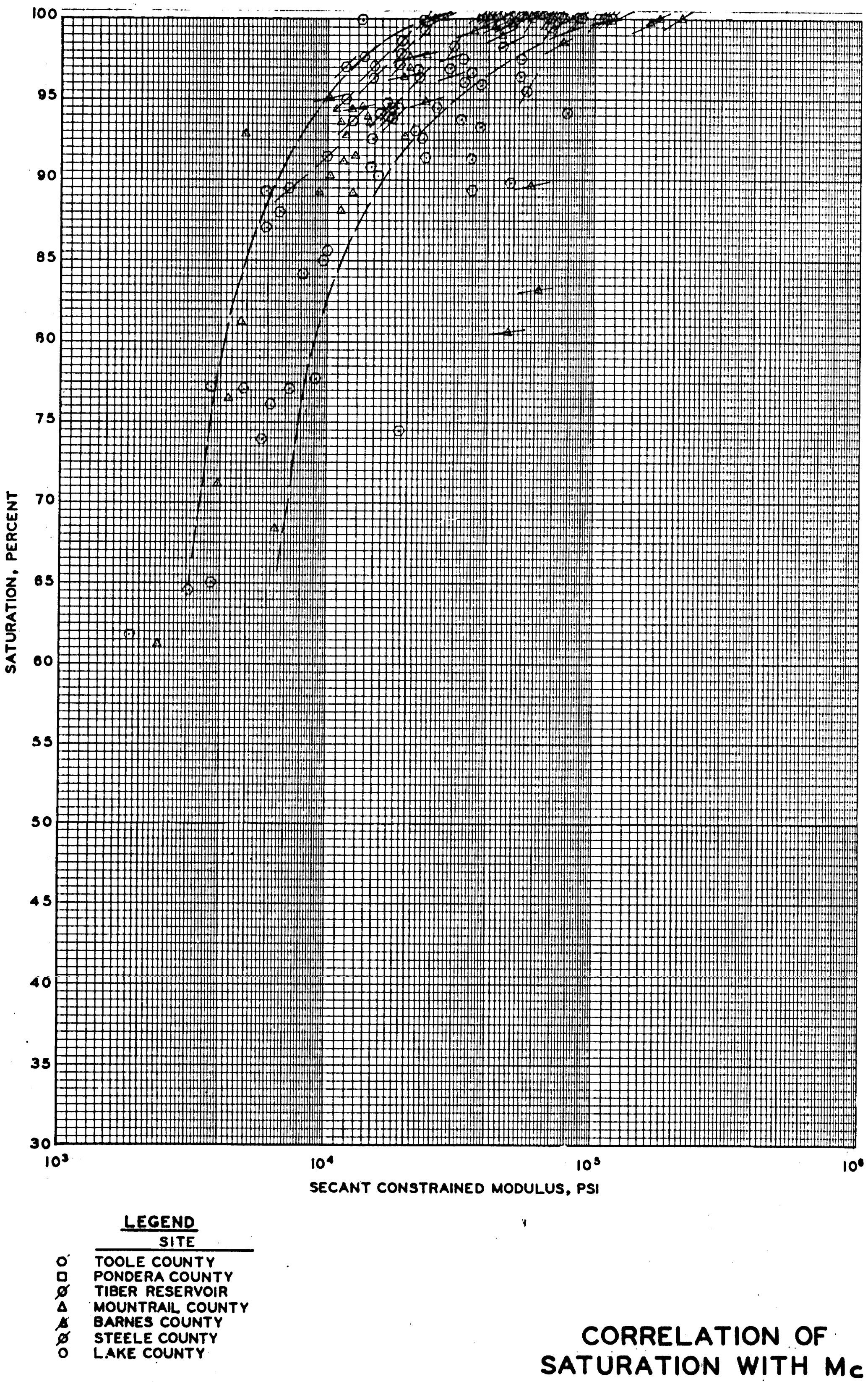


CORRELATION OF SATURATION WITH M_c TO 50-PSI STRESS LEVEL

PLATE 24

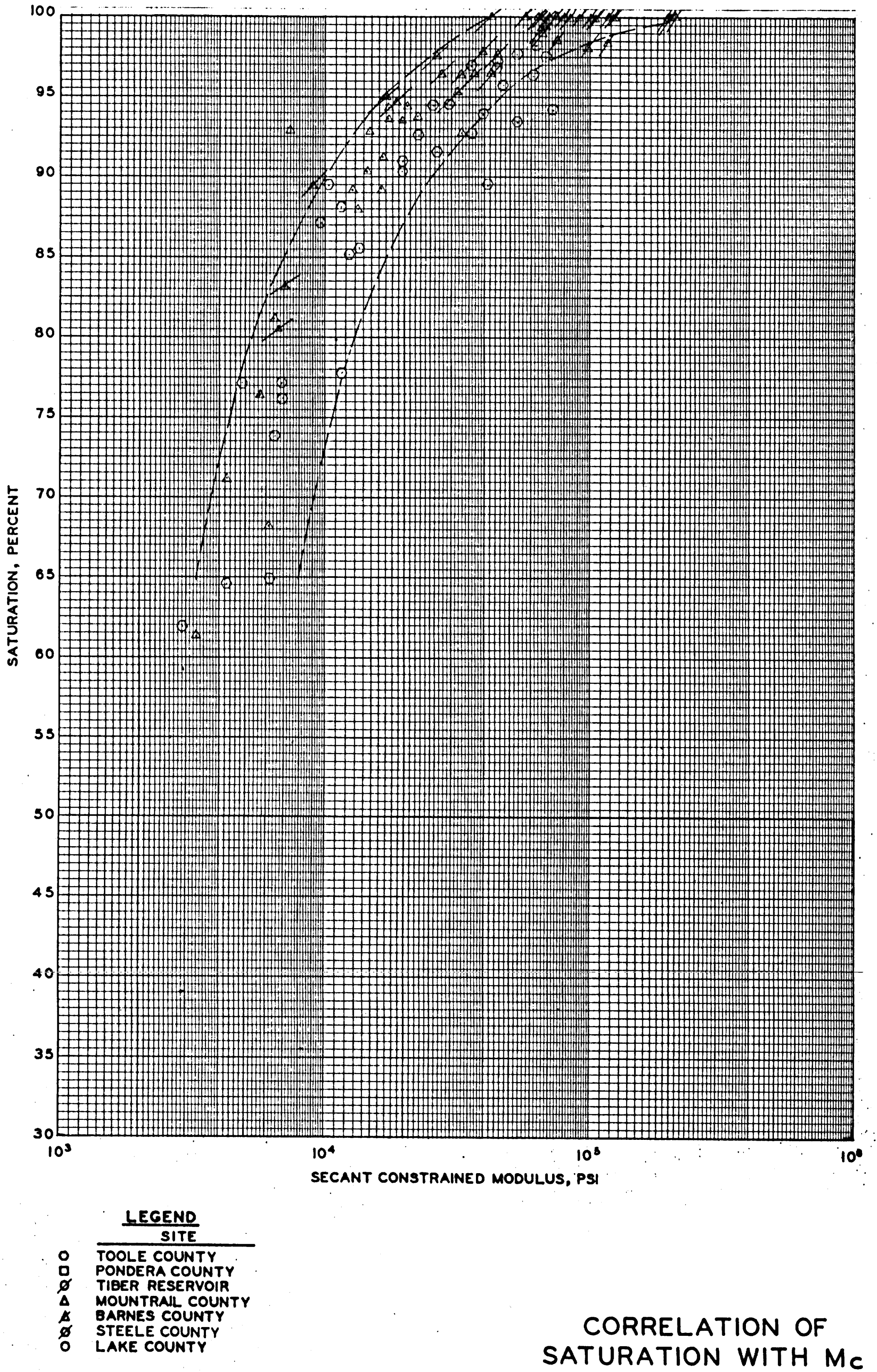


CORRELATION OF SATURATION WITH M_c TO 100-PSI STRESS LEVEL

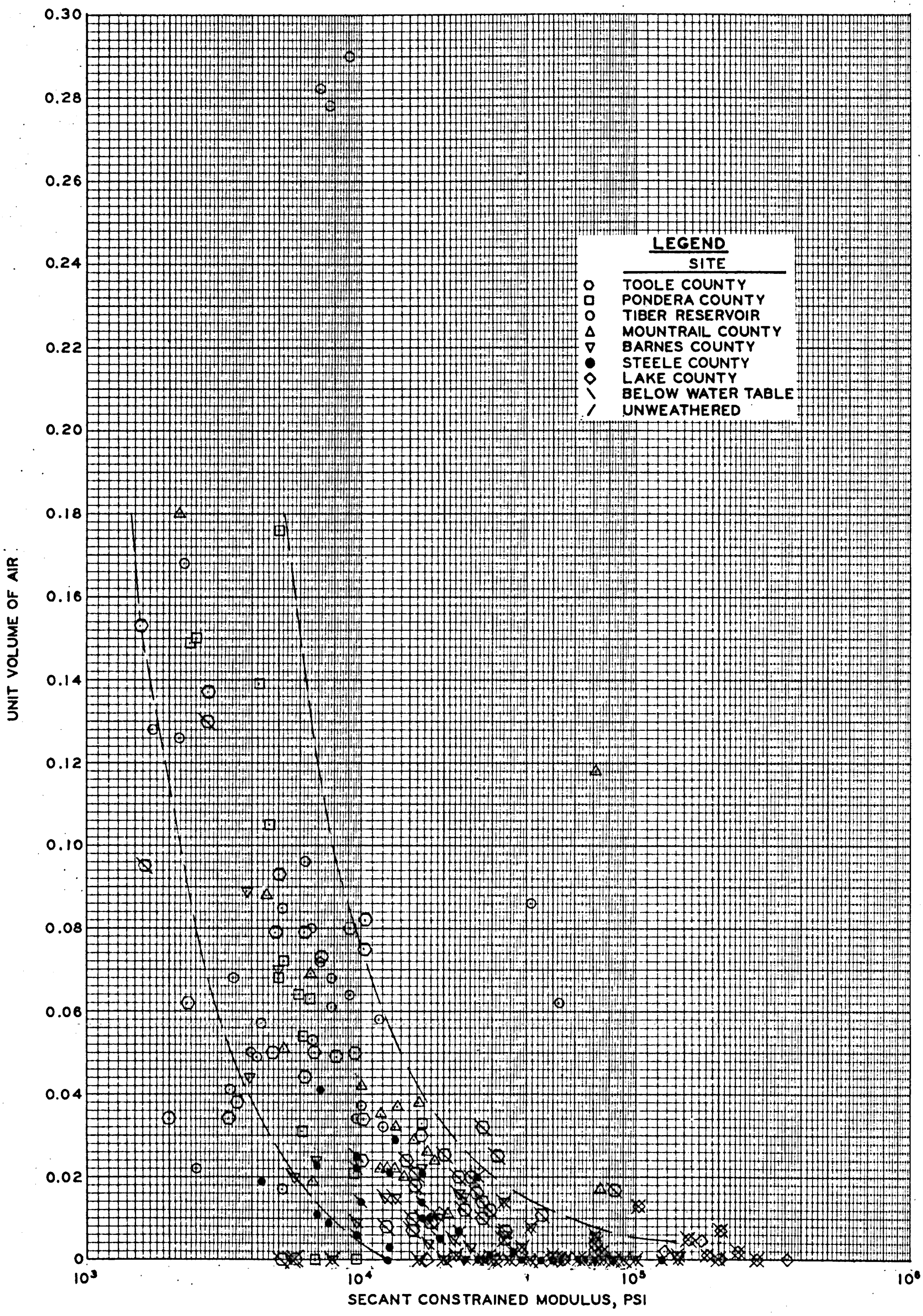


CORRELATION OF
SATURATION WITH Mc
TO 250-PSI STRESS LEVEL

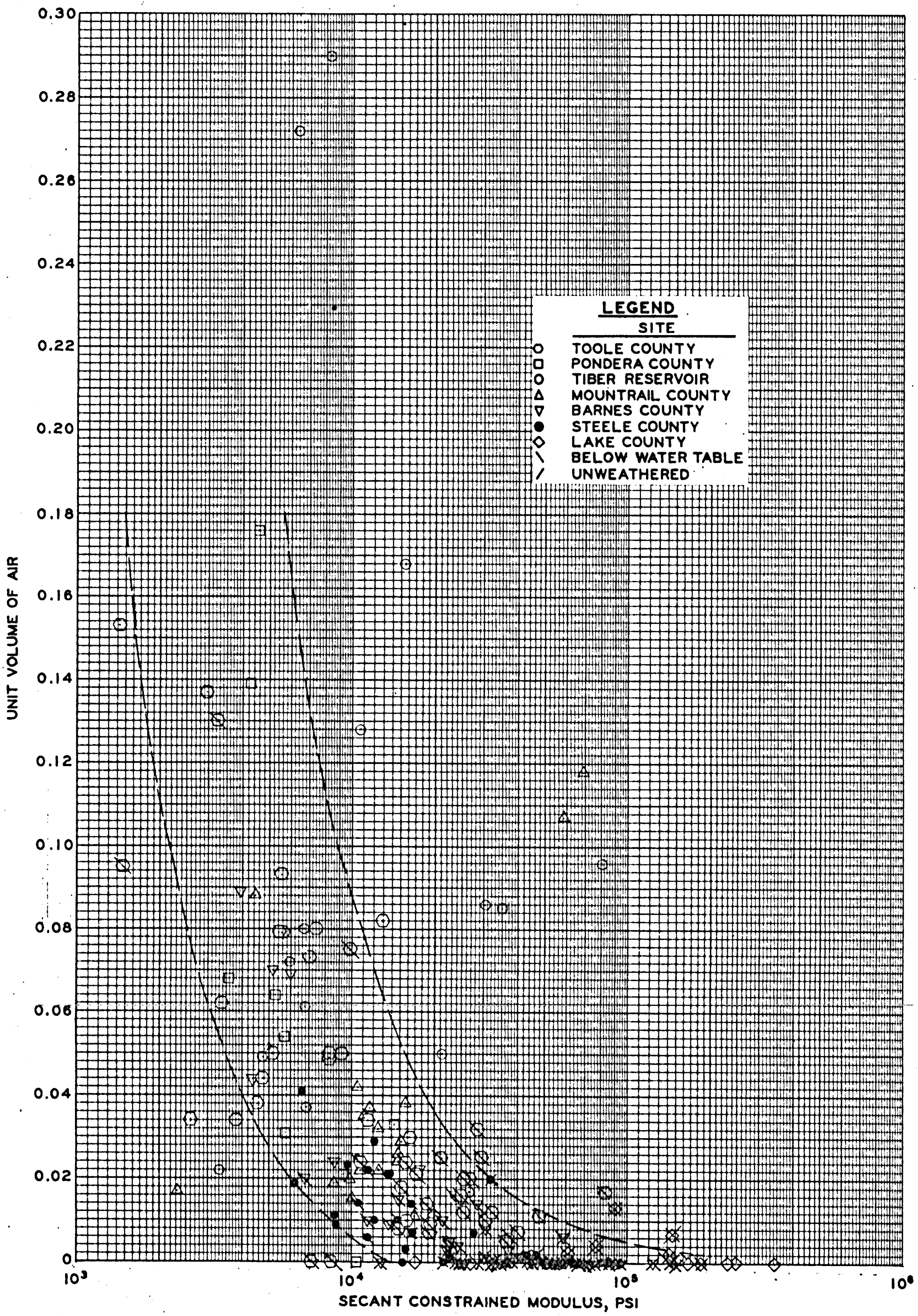
PLATE 26



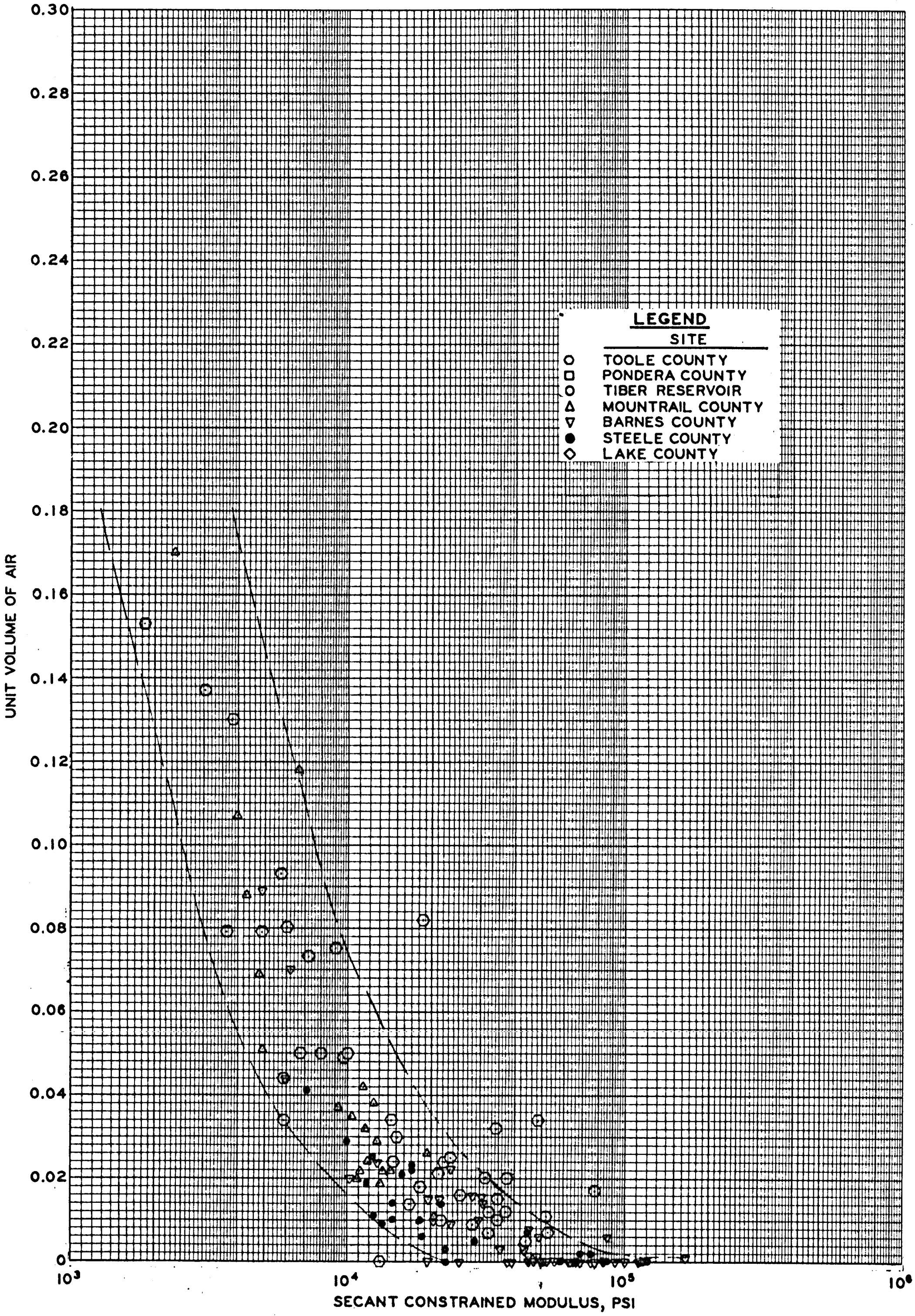
CORRELATION OF
SATURATION WITH M_c
TO 500-PSI STRESS LEVEL



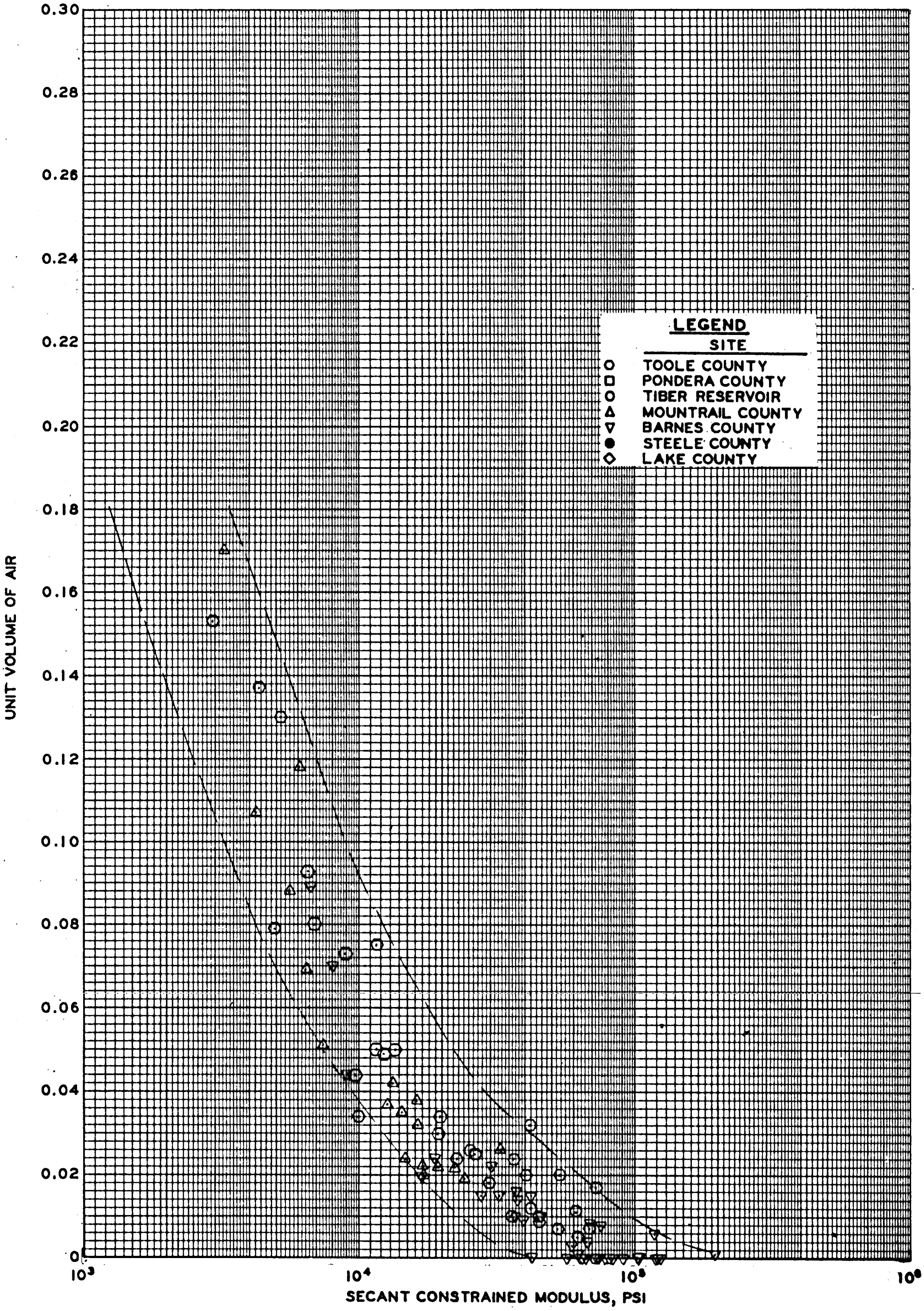
CORRELATION OF UNIT VOLUME OF AIR WITH M_c TO 50-PSI STRESS LEVEL



CORRELATION OF UNIT VOLUME OF AIR WITH M_c TO 100-PSI STRESS LEVEL

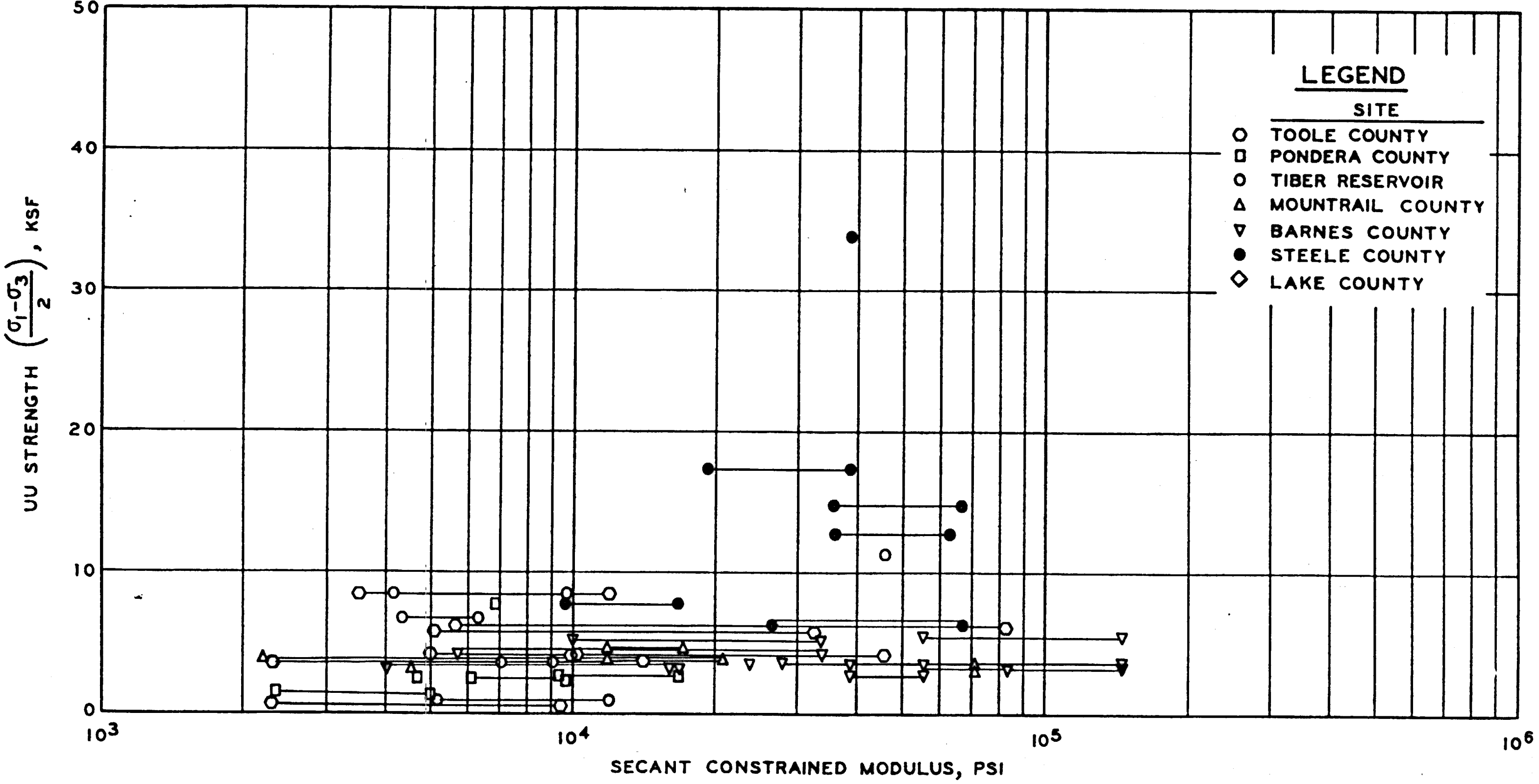


CORRELATION OF UNIT VOLUME OF AIR WITH M_c TO 250-PSI STRESS LEVEL

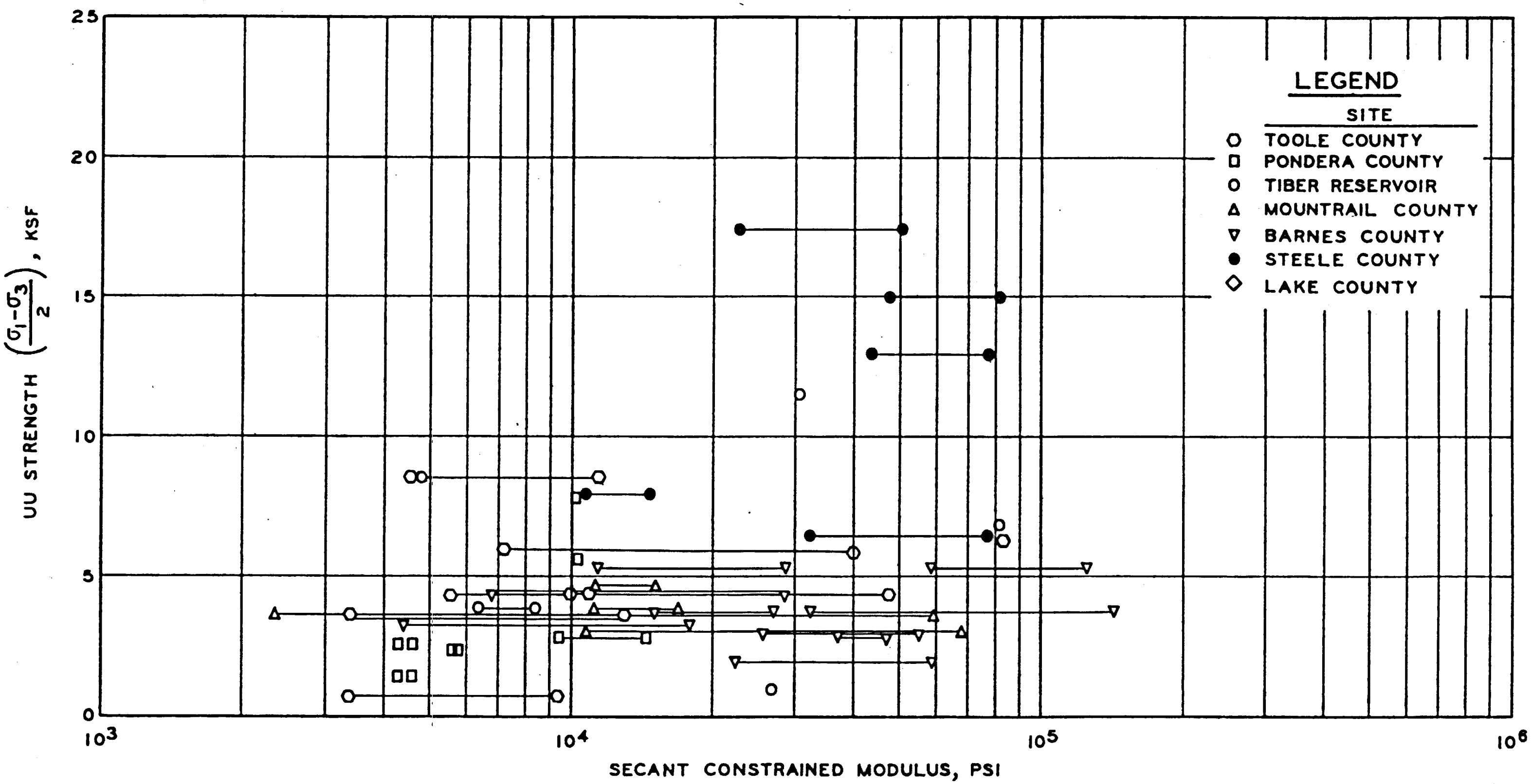


CORRELATION OF UNIT VOLUME OF AIR WITH M_c TO 500-PSI STRESS LEVEL

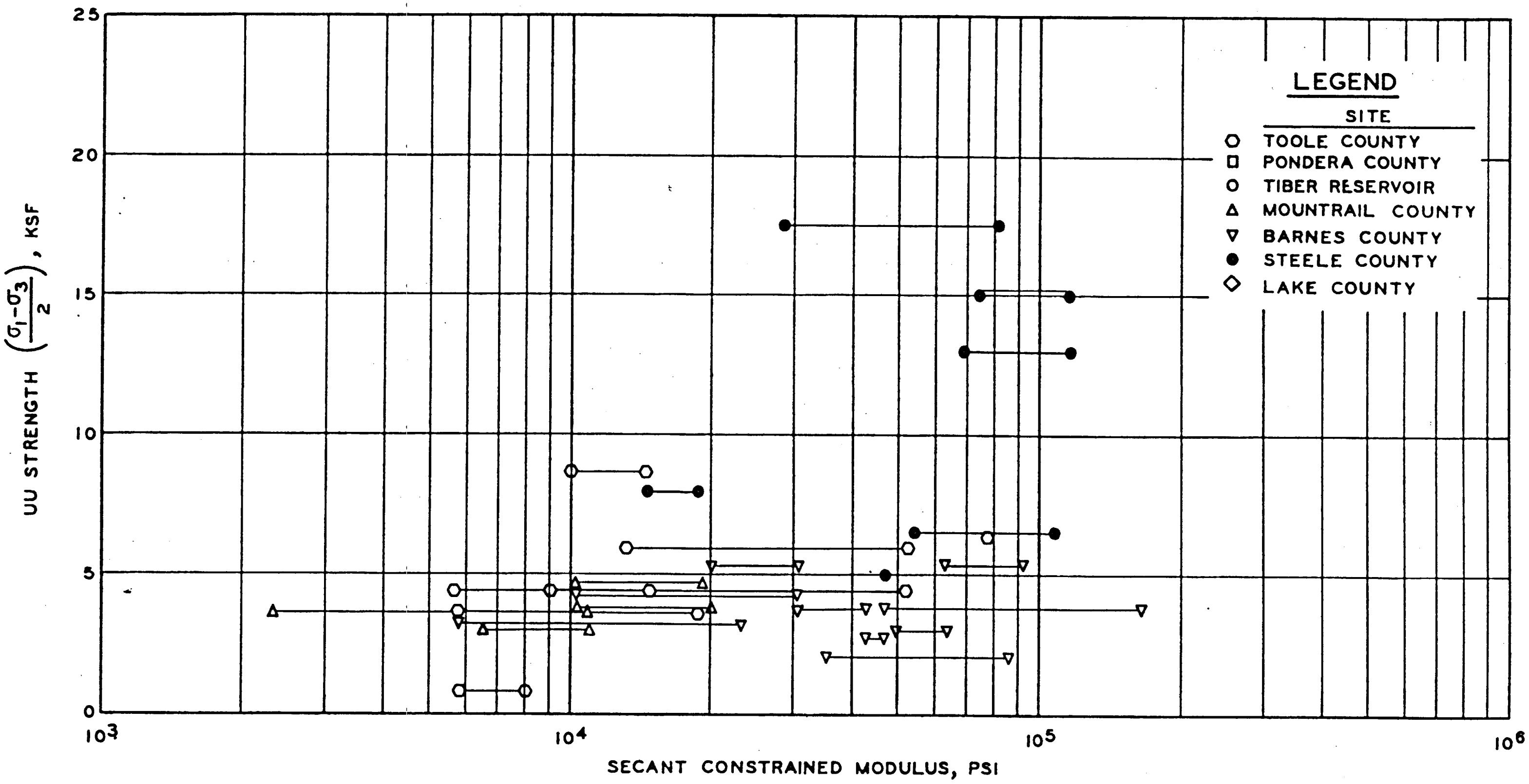
PLATE 32



RESULTS OF ATTEMPTED
CORRELATION OF
UU STRENGTH WITH M_c
TO 50-PSI STRESS LEVEL



RESULTS OF ATTEMPTED
CORRELATION OF
UU STRENGTH WITH M_c
TO 100-PSI STRESS LEVEL



RESULTS OF ATTEMPTED
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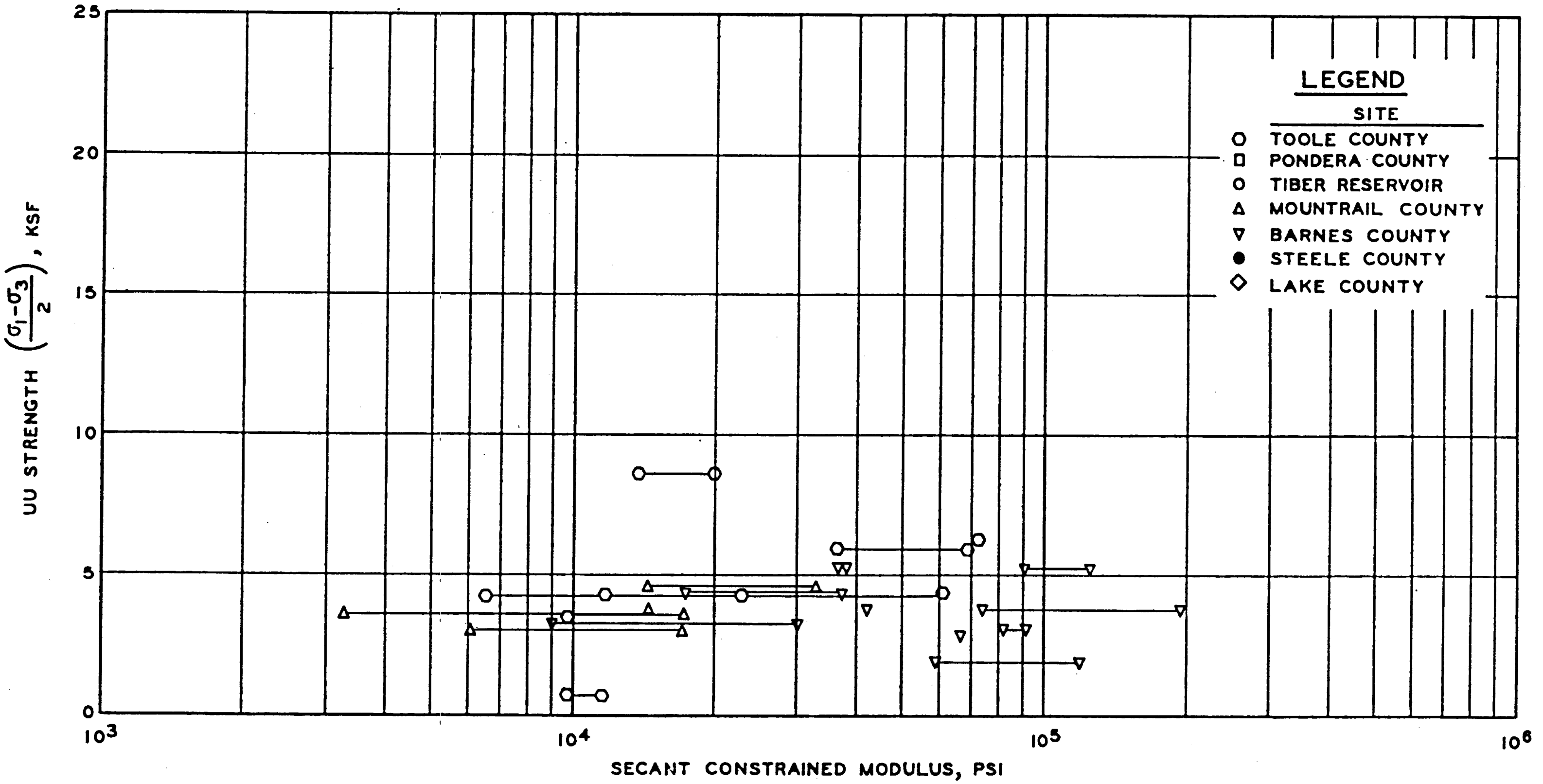
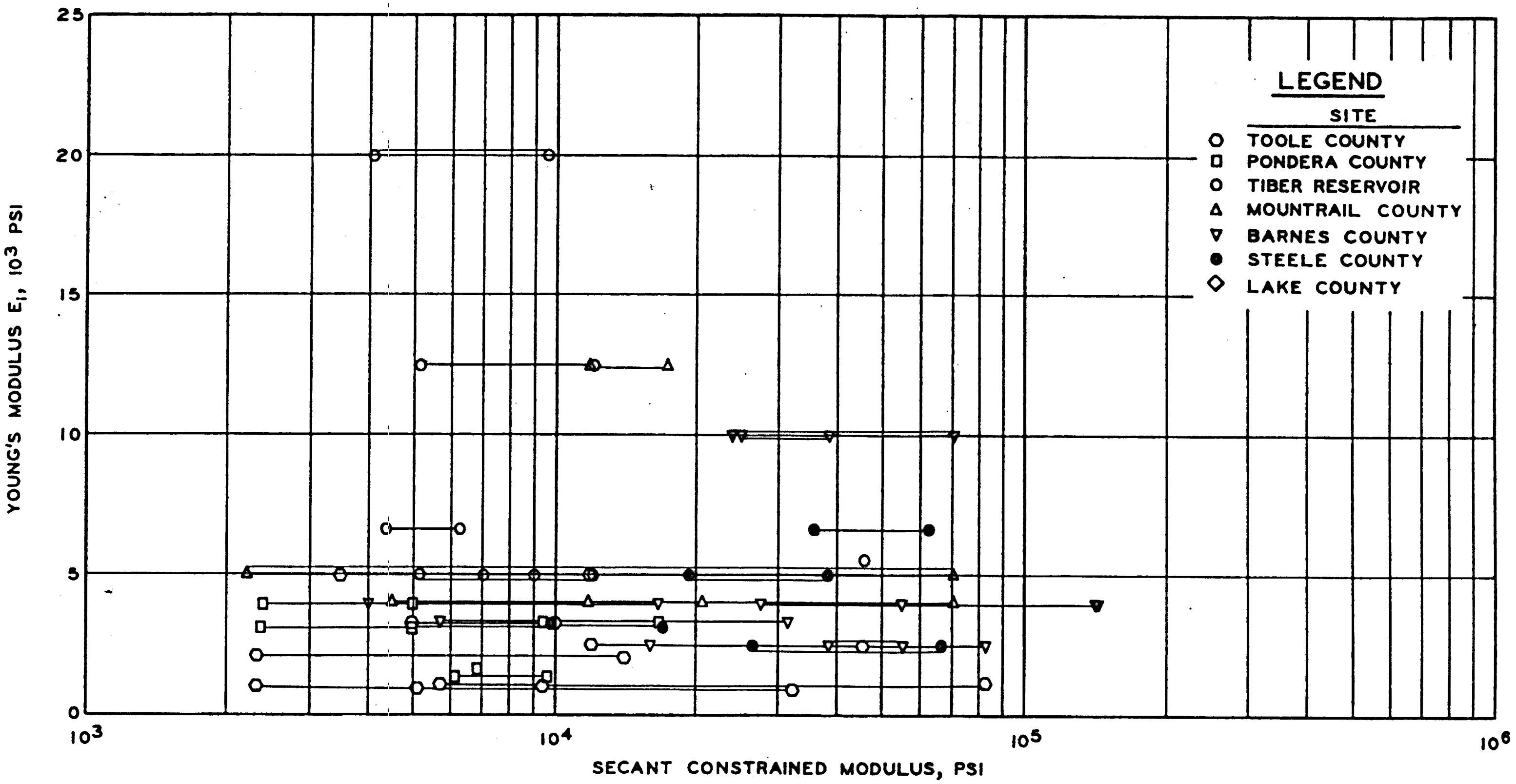
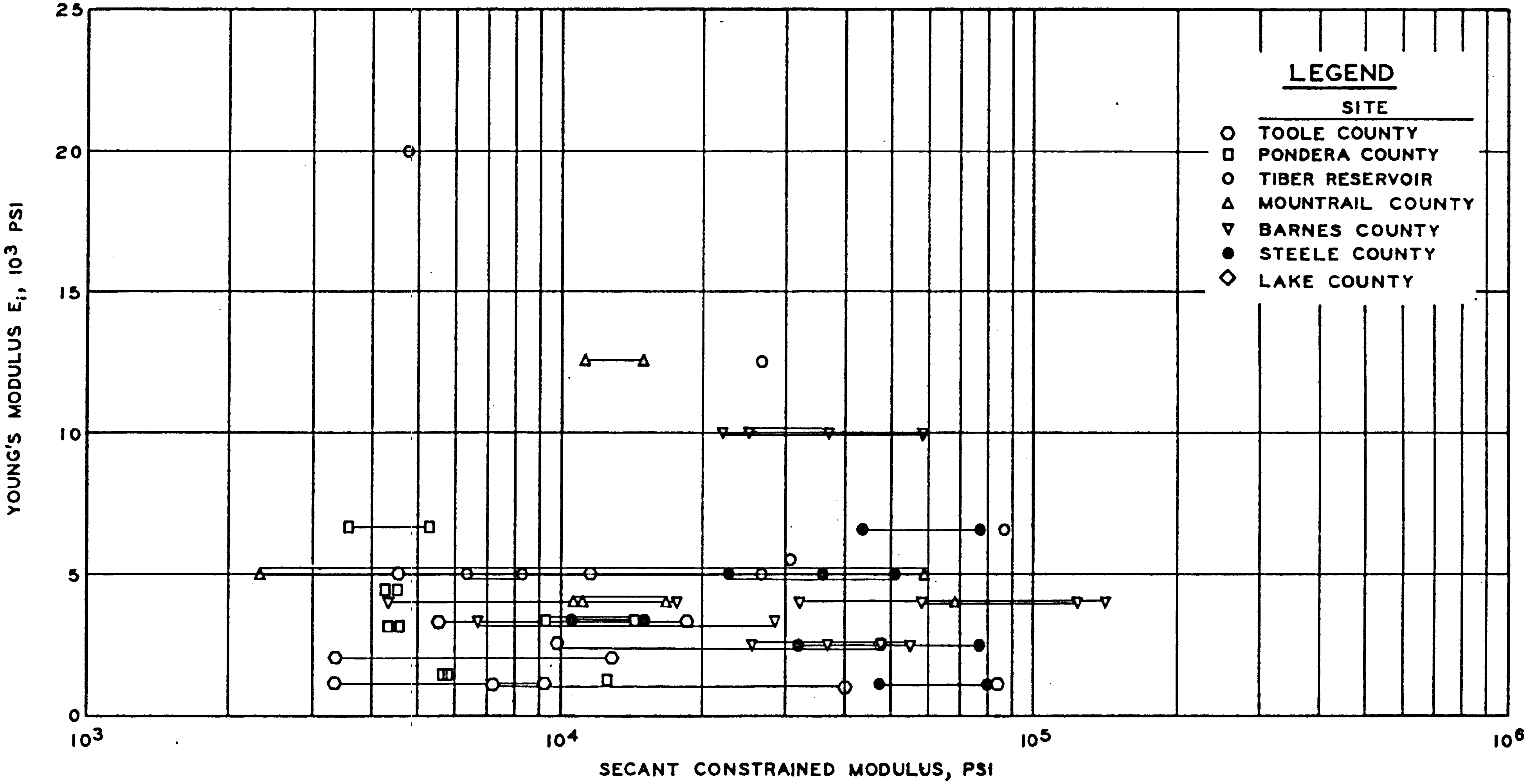
TO 250-PSI STRESS LEVEL



RESULTS OF ATTEMPTED
CORRELATION OF
UU STRENGTH WITH M_c
TO 500-PSI STRESS LEVEL

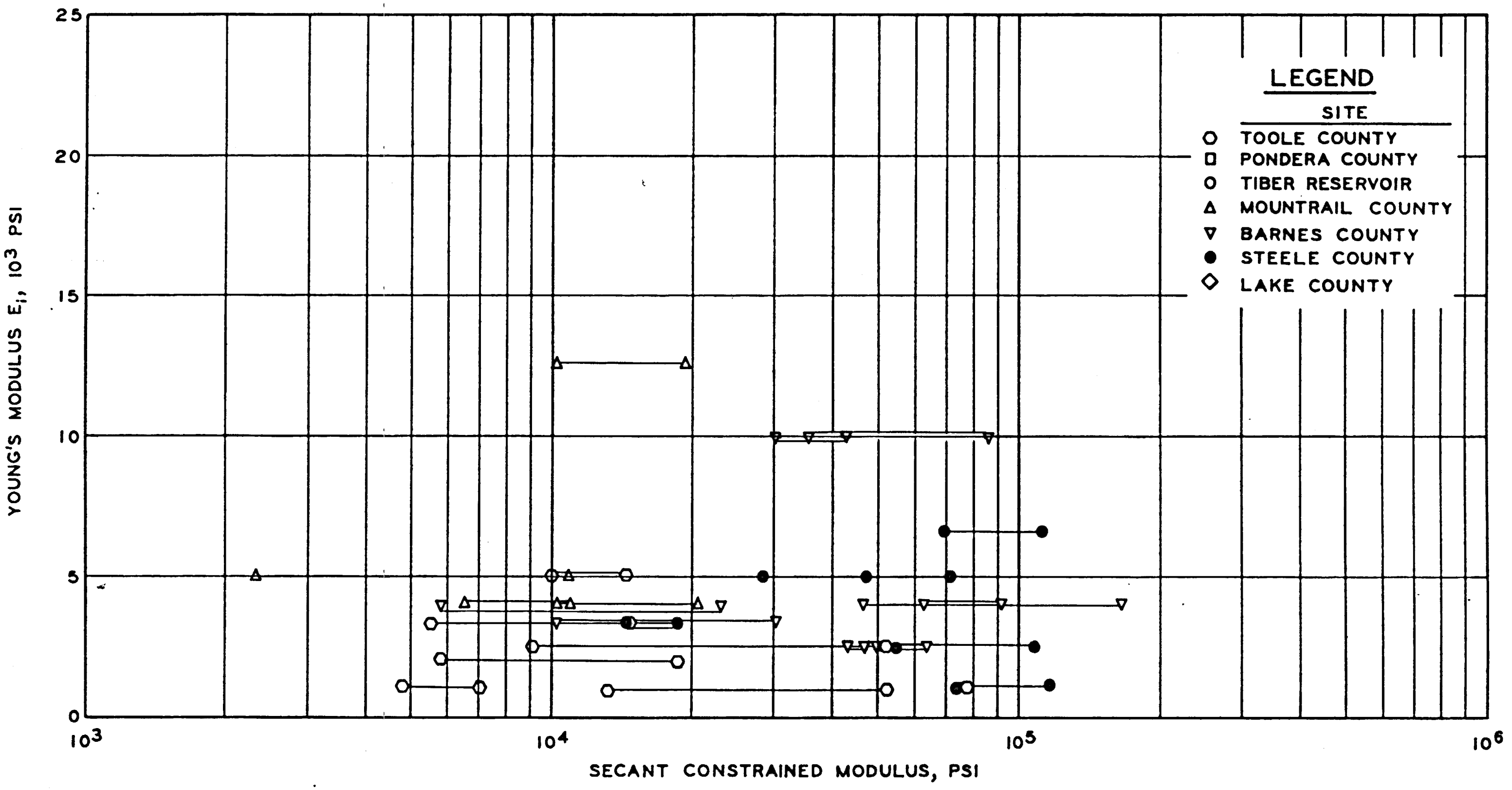


RESULTS OF ATTEMPTED
CORRELATION OF
YOUNG'S MODULUS WITH M_c
TO 50-PSI STRESS LEVEL

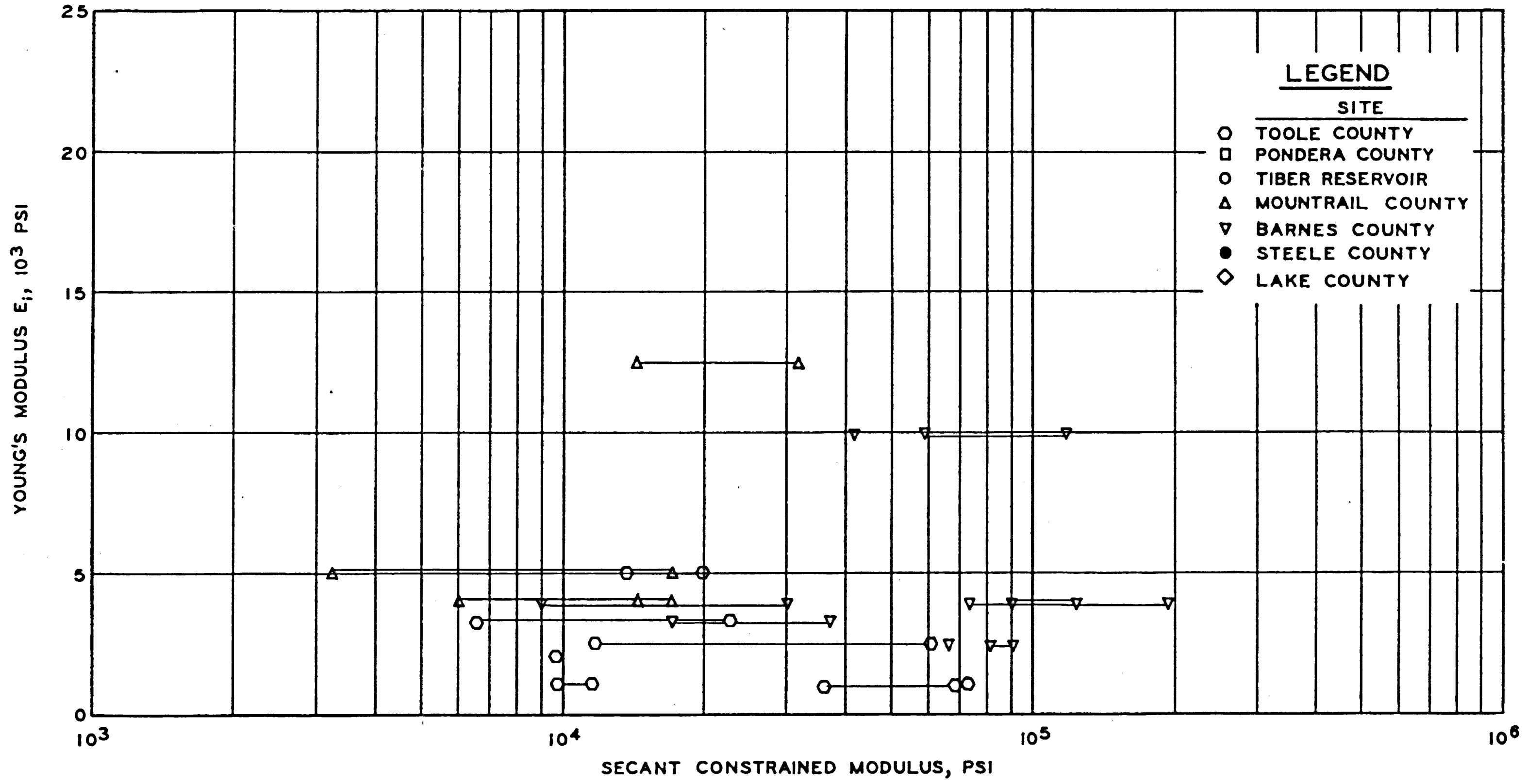


RESULTS OF ATTEMPTED CORRELATION OF YOUNG'S MODULUS WITH M_c TO 100-PSI STRESS LEVEL

PLATE 38

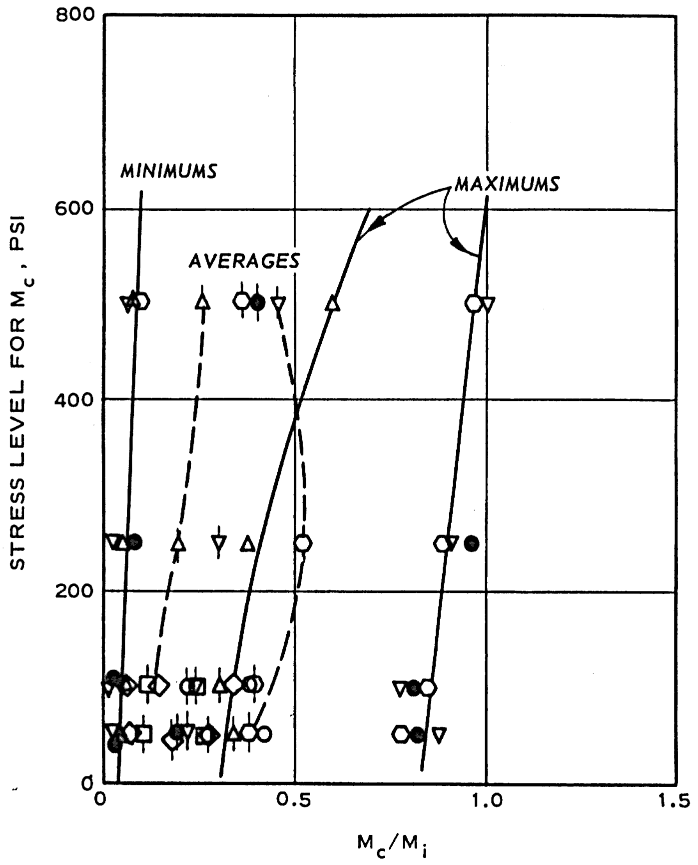


RESULTS OF ATTEMPTED CORRELATION OF YOUNG'S MODULUS WITH M_c TO 250-PSI STRESS LEVEL



RESULTS OF ATTEMPTED CORRELATION OF YOUNG'S MODULUS WITH M_c TO 500-PSI STRESS LEVEL

PLATE 39



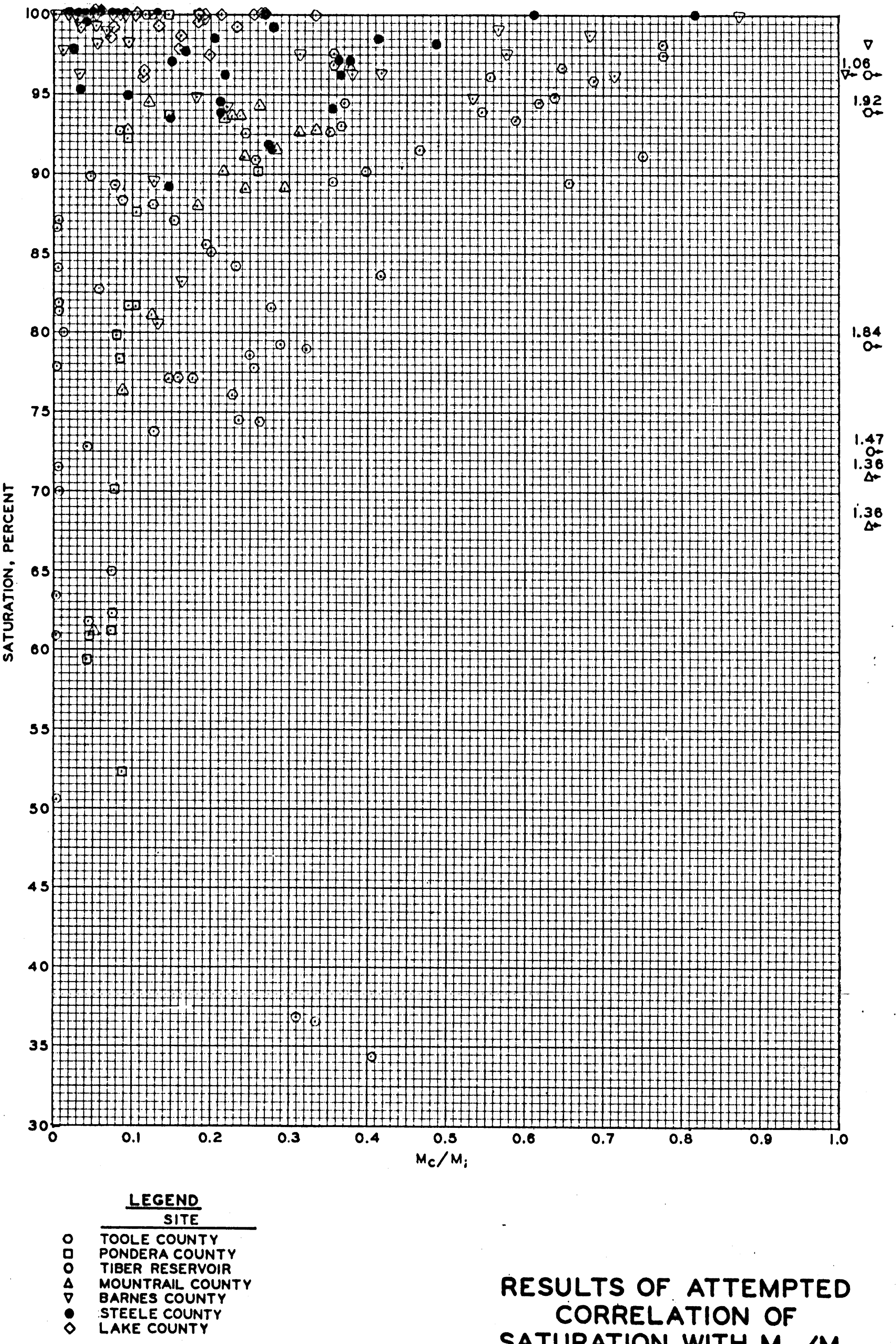
LEGEND

SITE

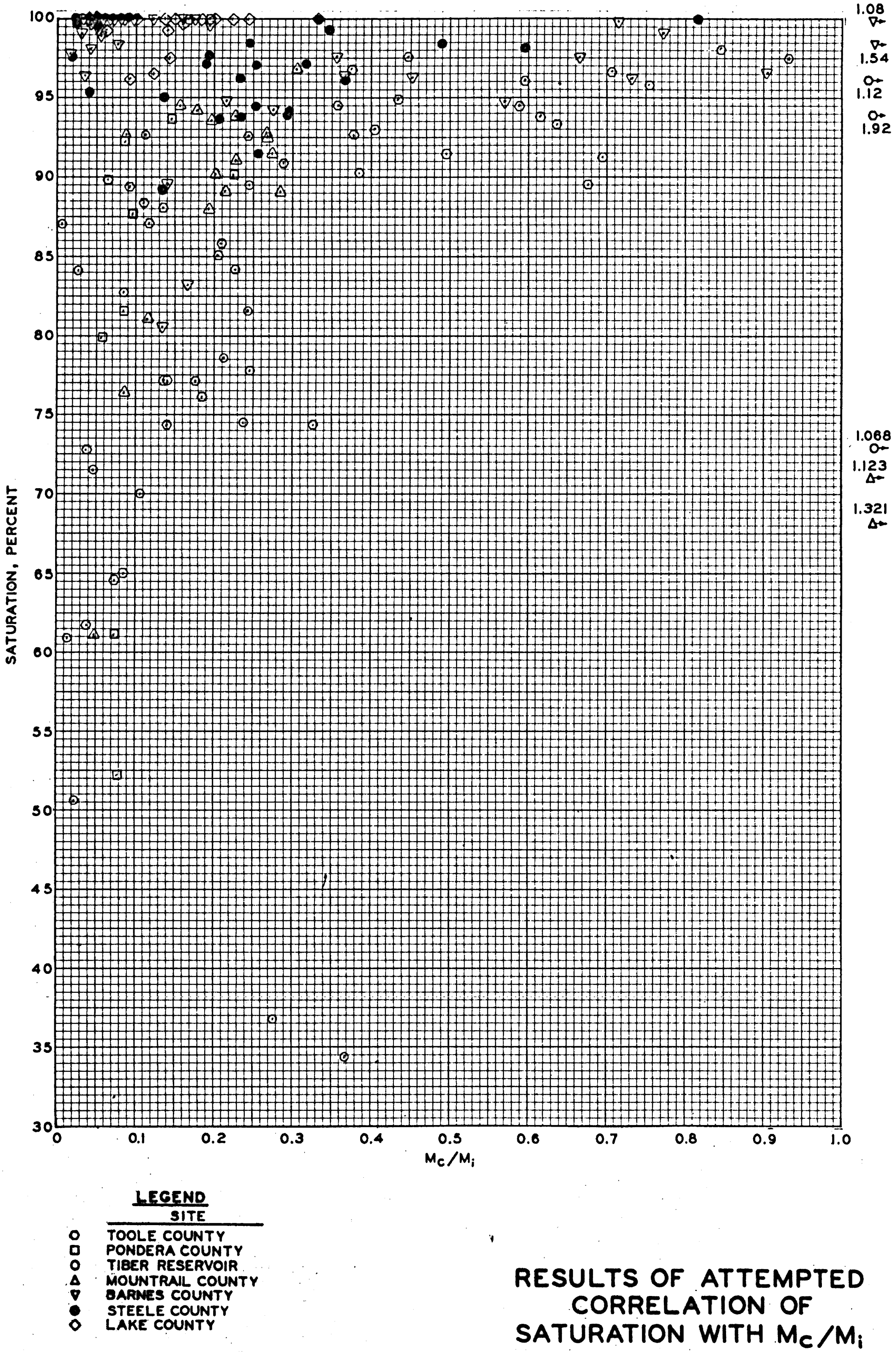
⬡ TOOLE COUNTY
□ PONDERA COUNTY
○ TIBER RESERVOIR
△ MOUNTRAIL COUNTY
▽ BARNES COUNTY
● STEELE COUNTY
◇ LAKE COUNTY
¦ INDICATES AVERAGES

EFFECTS OF VARIOUS STRESS LEVELS FOR M_c ON M_c/M_i

PLATE 40

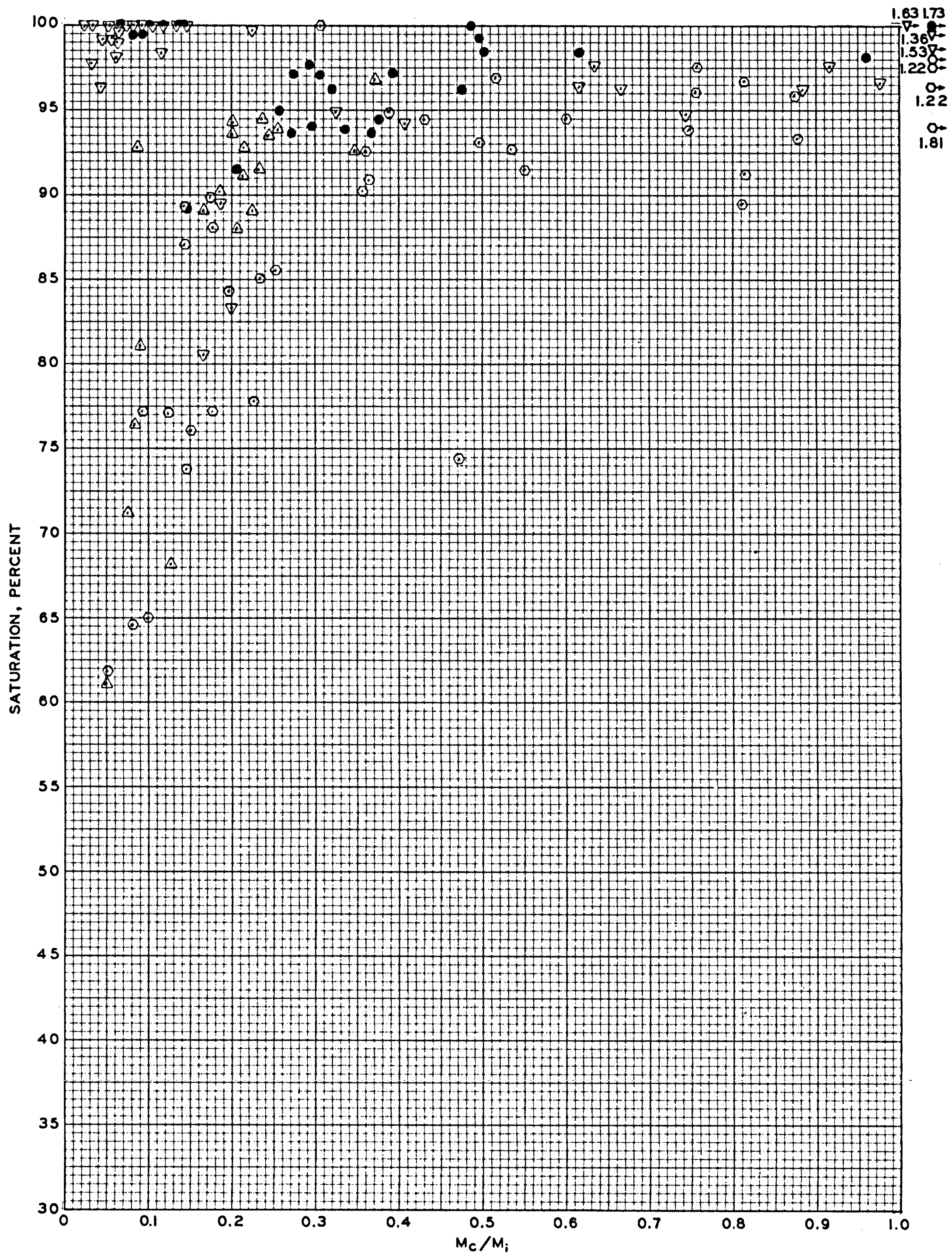


RESULTS OF ATTEMPTED CORRELATION OF SATURATION WITH M_c/M_i TO 50-PSI STRESS LEVEL

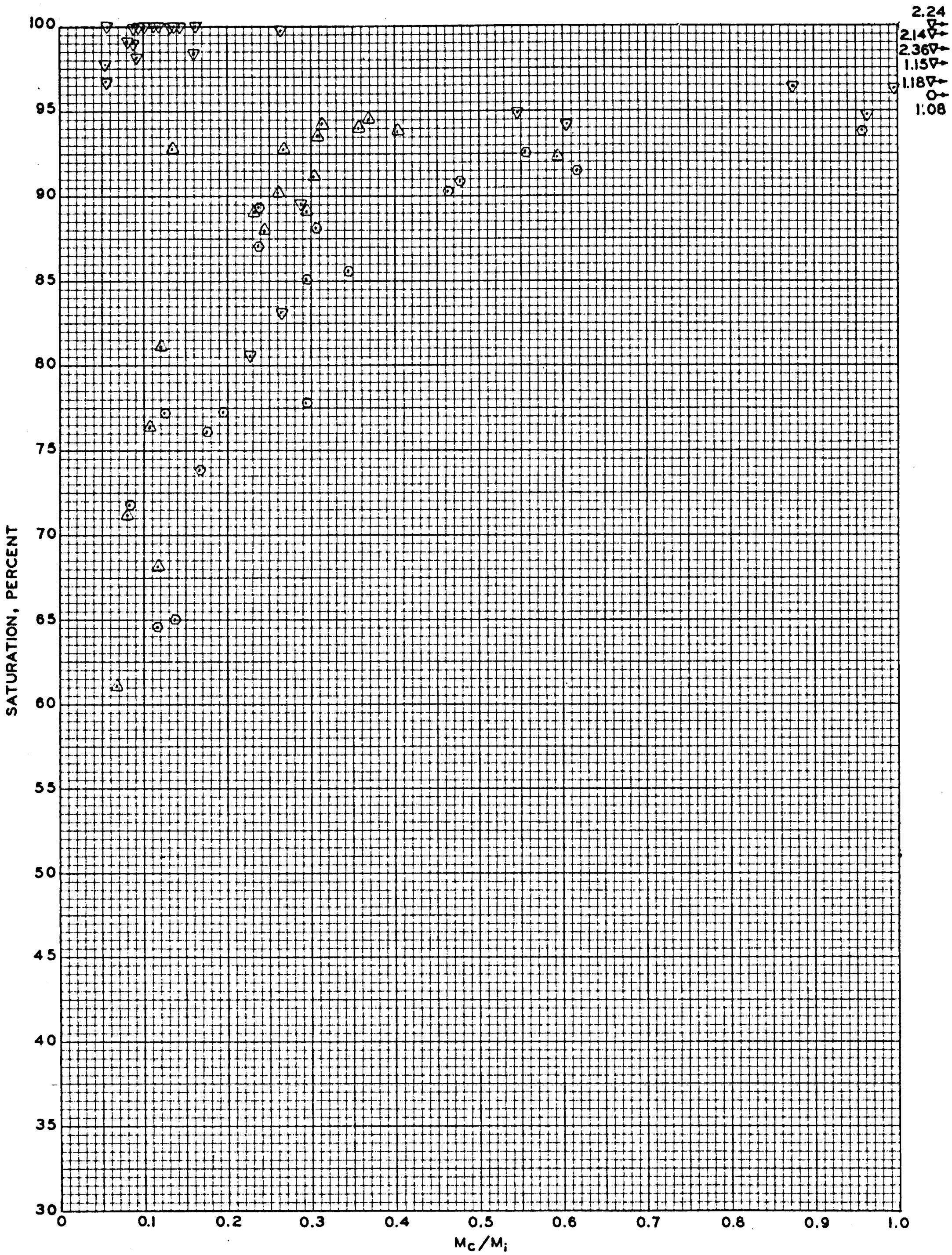


RESULTS OF ATTEMPTED CORRELATION OF SATURATION WITH M_c/M_i TO 100-PSI STRESS LEVEL

PLATE 42



RESULTS OF ATTEMPTED CORRELATION OF SATURATION WITH M_c/M_i TO 250-PSI STRESS LEVEL



RESULTS OF ATTEMPTED CORRELATION OF SATURATION WITH M_c/M_i TO 500-PSI STRESS LEVEL

APPENDIX A

EXAMPLE PREDICTION OF UX STRESS-STRAIN DATA FOR TILL

The objectives of this appendix are to illustrate the prediction of the loading portion of a UX stress-strain curve for a till of a particular degree of saturation and unit volume of air and to compare the predicted curve with actual UX stress-strain curves from a till with a similar degree of saturation and unit volume of air.

The correlations attempted with saturation (plates 24-27 in main text) and unit volume of air (plates 28-31 in main text) produced the only reasonable correlations of constrained modulus M_c with conventional property data. Hence, these correlations were used to predict the loading portion of the UX stress-strain curve for a till with a particular degree of saturation and unit volume of air as a test of their reliability.

UX Stress-Strain Curves from Correlations with M_c

Plates A1 and A2 present the loading portions of UX stress-strain curves predicted from the saturation and unit volume of air data, respectively, by using an average point within the bounds of data for the particular degree of saturation or unit volume of air of interest. Only four points on a curve could be predicted since correlations with M_c were attempted only for the 50-, 100-, 250-, and 500-psi stress levels. The strain ε for a particular stress was obtained by dividing that stress by the average M_c (i.e., $\varepsilon_{50} = 50/M_{50} \times 100\%$; $\varepsilon_{100} = 100/M_{100} \times 100\%$, etc.) from the appropriate correlation of saturation or unit volume of air with M_c.

Comparison of Predicted Curves with Test Data

Three sites were selected for comparing predicted stress-strain curves with UX test stress-strain curves. These particular sites were selected because the UX test data were readily available and the tills at these sites were generally representative of those at the seven sites considered in this study. The curves presented in plates A1 and A2 were constructed because the ranges of saturation and unit volume of air were generally representative of the ranges of like data for sites considered in this Appendix.

Plates A3-A7 present UX test loading stress-strain curves for different zones in the Pondera and Tiber, Montana, sites and the Lake County, Illinois, site. The stress-strain curves in plates A3-A7 are from UX tests on tills whose approximate ranges of saturation and unit volume of air are shown in table A1. Also shown in plates A3-A7 are the loading portions of the stress-strain curves predicted from the correlations of saturation and unit volume of air with M_c.

The loading portions of most of the stress-strain curves in plate A3 to the 50-psi stress level are nicely represented by the 80-90 percent saturation prediction and/or the 4-6 percent unit volume of air prediction.

As shown in plate A4, the 80-90 percent saturation prediction and/or the 4-8 percent unit volume of air prediction bound the loading portion of the stress-strain curves for the 6- to 15-ft depth of till at the Tiber Reservoir, Montana, site. For the 15- to 27-ft depth at this site, as shown in plate A5, the 2-8 percent unit volume of air prediction bounds all but two of the loading stress-strain curves to a stress level of about 50 psi.

As shown in plate A6, a good prediction of the loading portion of the stress-strain curve for the 96-100 percent saturated till was made by the 97.5 percent saturation prediction and/or the 1 percent unit volume of air prediction.

In plate A7, the predictions of the loading portions of the stress-strain curves for the 16- to 65-ft depth based on 0.5 percent air (99 percent saturation) are much too low to a stress level of about 50 psi. However, the zero percent air prediction is more representative of the test data.

From the comparisons shown in plates A3-A7, it is apparent that a rough approximation of the loading portion of the UX stress-strain curve for these tills can be made by use of the correlations developed. These predictions were based only on an approximate average curve through the correlations of M_c with saturation and unit volume of air. It is suggested that if these correlations are used in practice, additional qualitative consideration of saturation, unit volume of air, dry unit weight, seismic velocity, weathering, and the location of the static water level should be used as a basis for giving more weight to the upper or lower bounds of the correlations of saturation and unit volume of air with M_c .

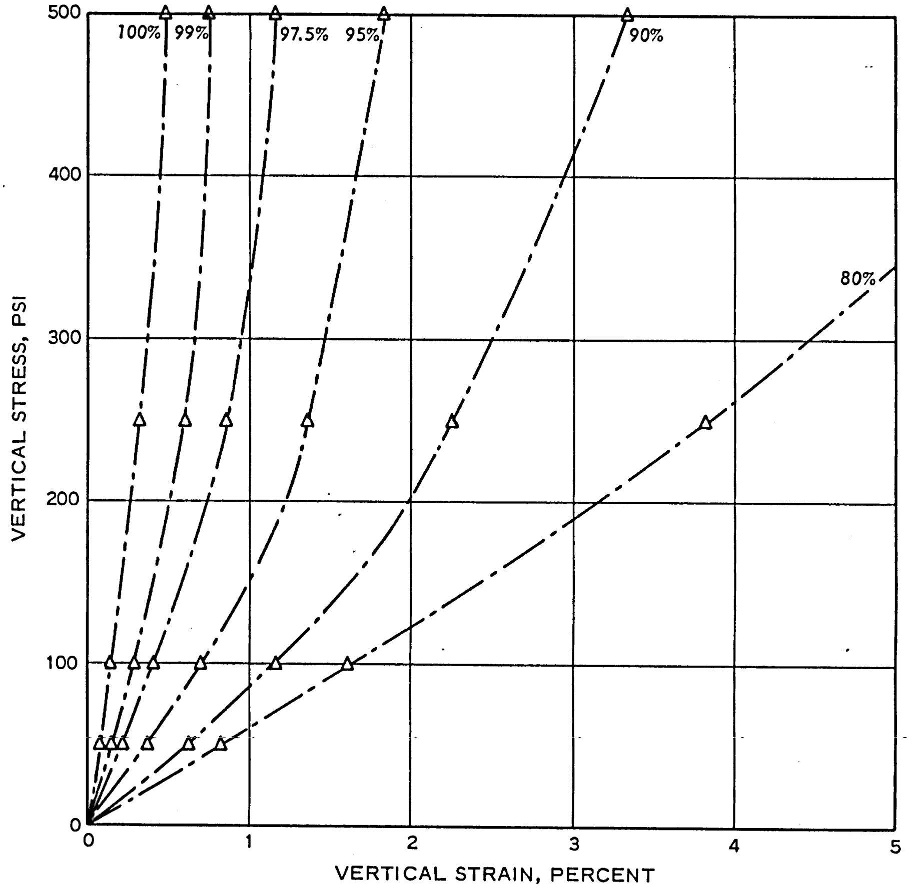
Table A1

Approximate Ranges of Saturation and Unit Volume of Air Calculated from UX Test Specimens

Site	Depth ft	Saturation Percent	Percent Air	Plate Number
Pondera County, Montana	0-8	50-80	6-18	A3
	8-15.5	80-100	0-7	A3
Tiber Reservoir, Montana	6-15	80-90	2-8	A4
	15-27	80-90	2-9	A5
Lake County, Illinois	0-16	96-100	1	A6
	16-65	96-100	0-0.5	A7

MODULI USED TO CONSTRUCT STRESS-STRAIN CURVES

SATURATION, PERCENT	MODULI, PSI 50-PSI STRESS LEVEL	100-PSI STRESS LEVEL	250-PSI STRESS LEVEL	500-PSI STRESS LEVEL
100	60,000	70,000	70,000	100,000
99	32,000	33,000	39,000	64,000
97.5	19,000	22,000	28,000	42,000
95	13,000	13,000	18,000	27,000
90	8,000	8,500	11,000	15,000
80	6,000	6,000	6,500	8,200

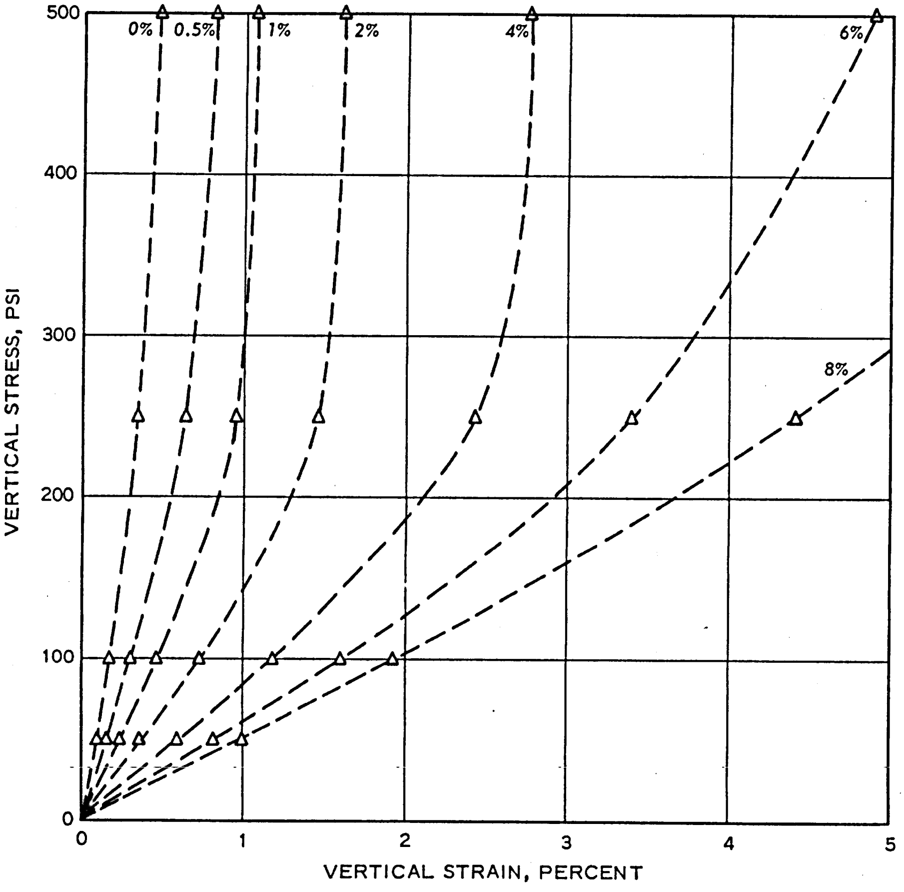


LOADING STRESS-STRAIN CURVES FOR VARIOUS PERCENTAGES OF SATURATION PREDICTED FROM CORRELATION OF SATURATION WITH M_c

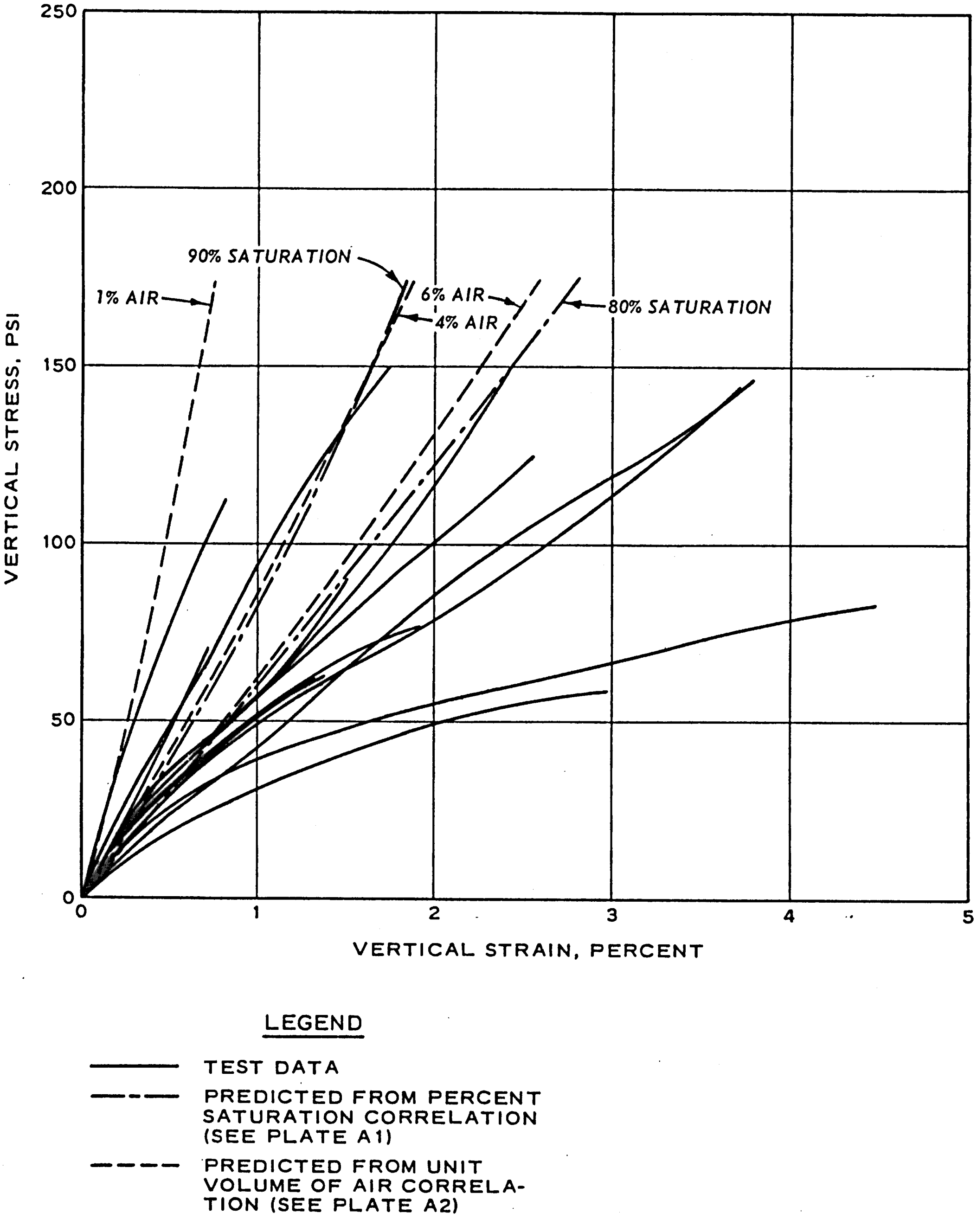
PLATE A1

MODULI USED TO CONSTRUCT STRESS-STRAIN CURVES

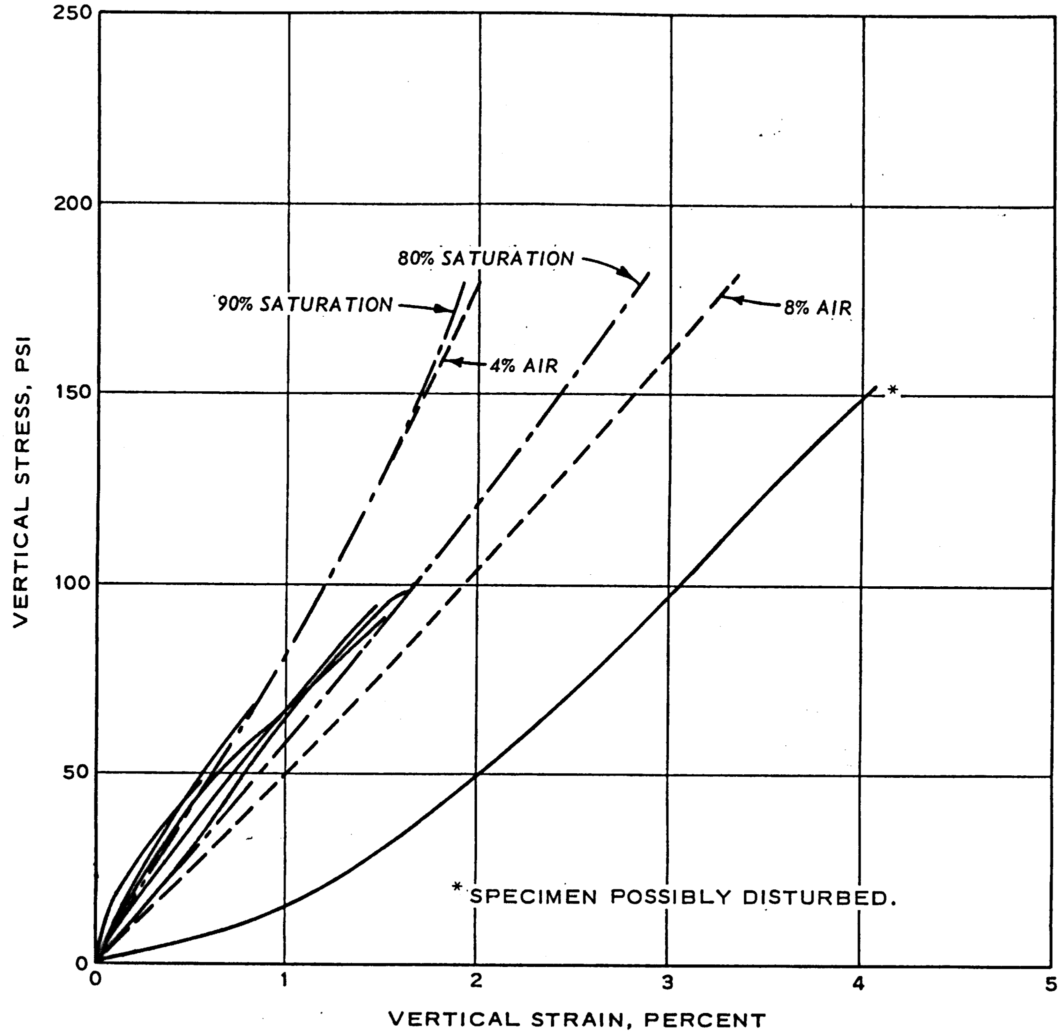
PERCENT AIR	MODULI, PSI 50-PSI STRESS LEVEL	 100-PSI STRESS LEVEL	 250-PSI STRESS LEVEL	 500-PSI STRESS LEVEL
0	50,000	60,000	75,000	100,000
0.5	34,000	32,000	37,000	60,000
1	21,000	21,000	26,000	46,000
2	14,000	14,000	17,000	31,000
4	8,300	8,700	10,000	18,000
6	6,200	6,500	7,200	10,200
8	5,000	5,300	5,500	8,000



LOADING STRESS-STRAIN CURVES
FOR VARIOUS UNIT VOLUMES OF AIR
PREDICTED FROM CORRELATION OF
UNIT VOLUME OF AIR WITH M_c



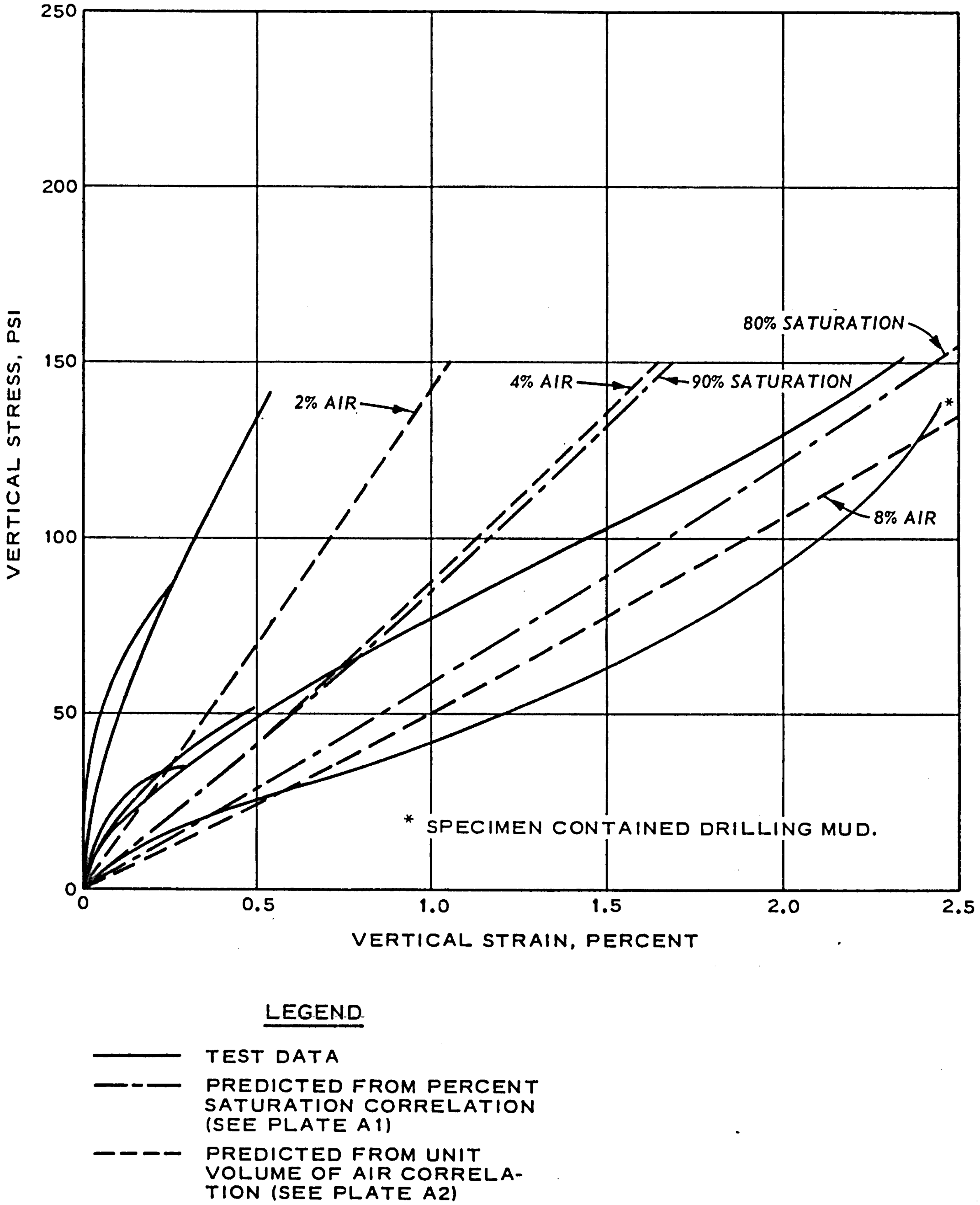
UX TEST STRESS-STRAIN CURVES
FROM 0-TO 15.5-FT DEPTH
AT PONDERA, MONTANA, SITE
AND PREDICTED CURVES



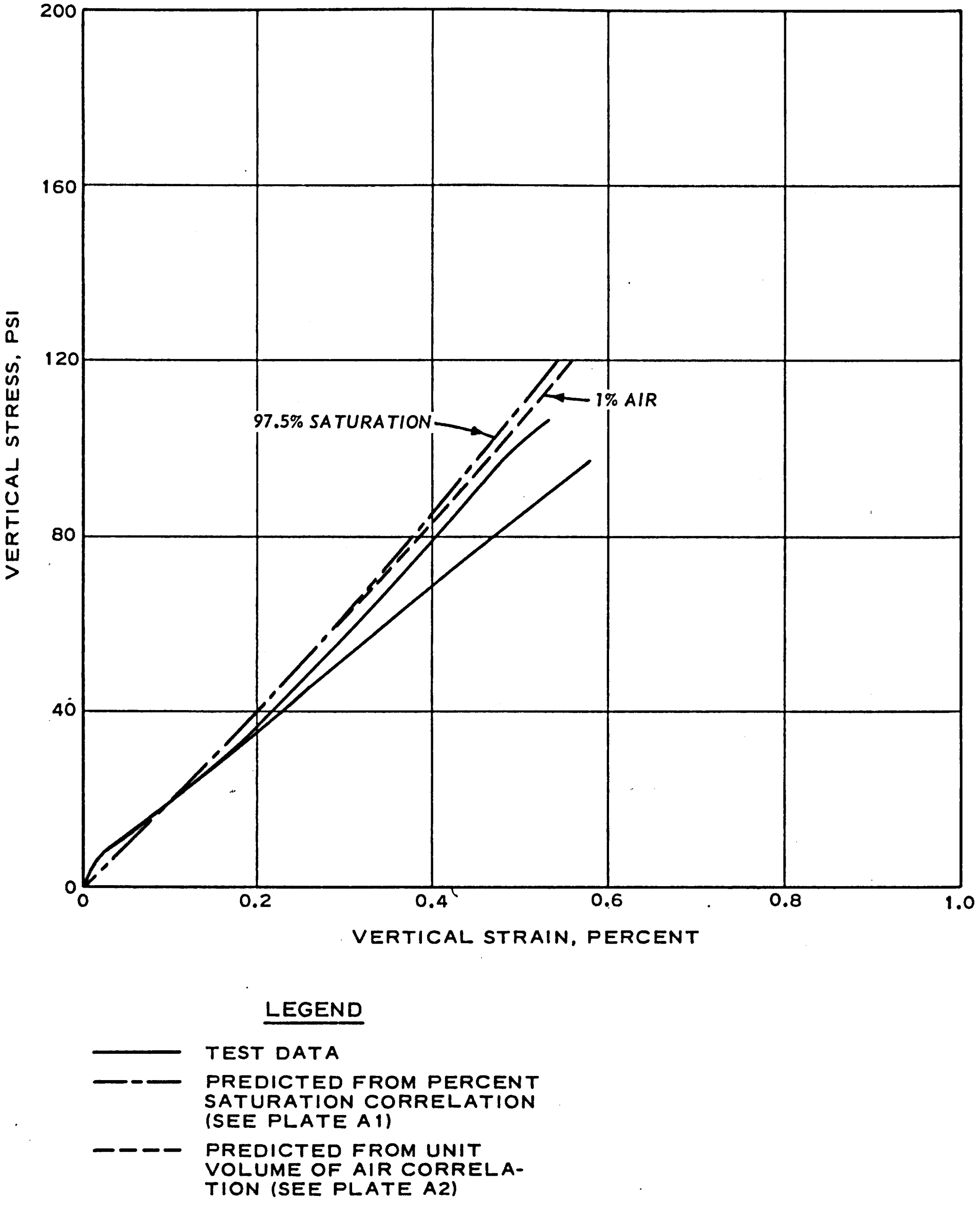
LEGEND

- TEST DATA
- PREDICTED FROM PERCENT SATURATION CORRELATION (SEE PLATE A1)
- PREDICTED FROM UNIT VOLUME OF AIR CORRELATION (SEE PLATE A2)

UX TEST STRESS-STRAIN CURVES
FROM 6-TO 15-FT DEPTH
AT TIBER RESERVOIR, MONTANA, SITE
AND PREDICTED CURVES

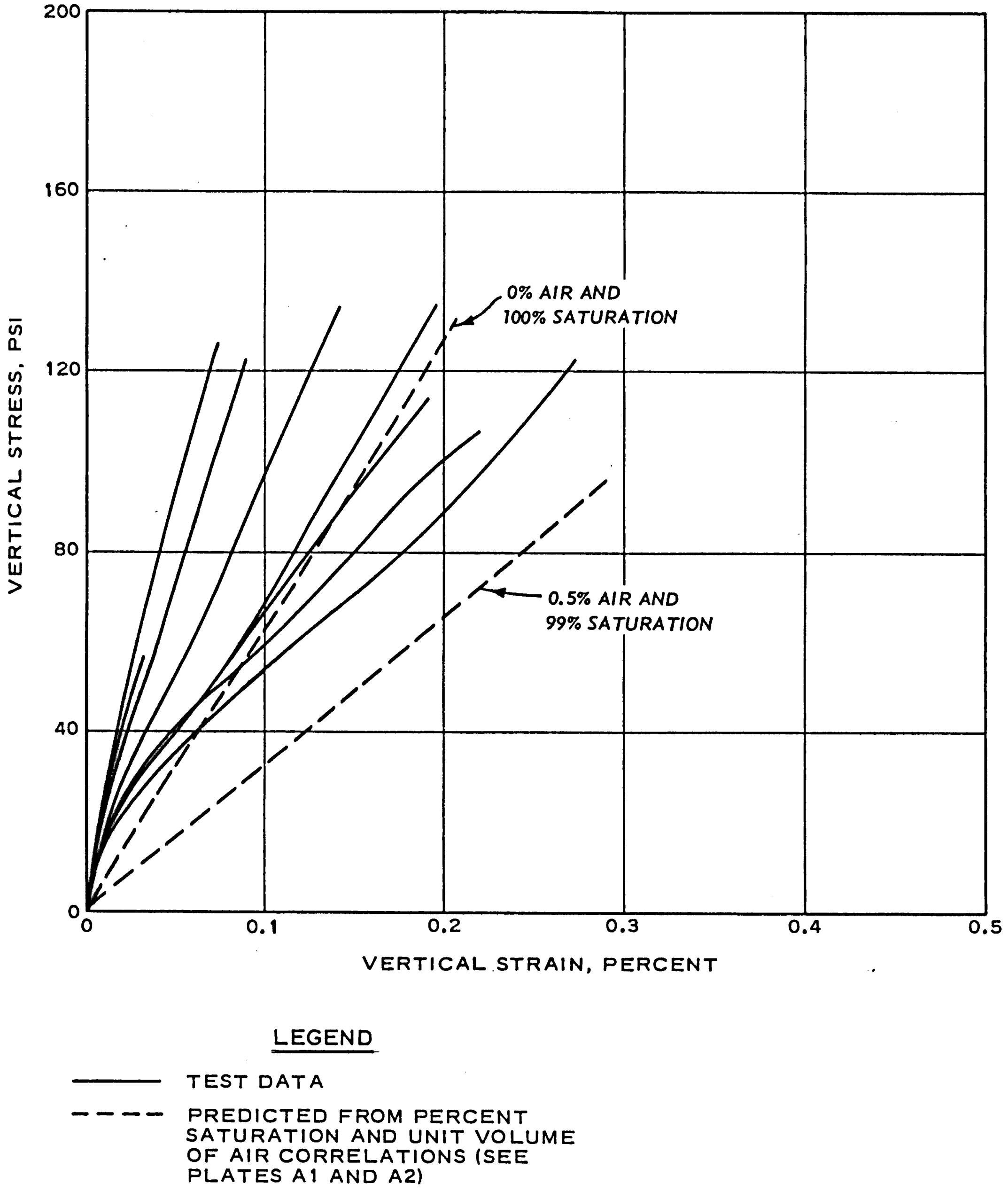


UX TEST STRESS-STRAIN CURVES
FROM 15-TO 27-FT DEPTH
AT TIBER RESERVOIR, MONTANA, SITE
AND PREDICTED CURVES



UX TEST STRESS-STRAIN CURVES
FROM 0-TO 16-FT DEPTH
AT LAKE COUNTY, ILLINOIS, SITE
AND PREDICTED CURVES

PLATE A6



UX TEST STRESS-STRAIN CURVES
FROM 16-TO 65-FT DEPTH
AT LAKE COUNTY, ILLINOIS, SITE
AND PREDICTED CURVES

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*
U.S. Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
EFFECT OF VARIATION IN CONVENTIONAL SOIL PROPERTIES ON DYNAMIC CONSTRAINED MODULUS FOR SEVERAL GLACIAL TILLS

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Final report

5. AUTHOR(S) *(First name, middle initial, last name)*
Hugh M. Taylor, Jr.

6. REPORT DATE
June 1973

7a. TOTAL NO. OF PAGES
108

7b. NO. OF REFS
12

8a. CONTRACT OR GRANT NO.

b. PROJECT NO.

c. Nuclear Construction and Engineering
Task 08

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
Miscellaneous Paper S-73-49

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT
Approved for public release; distribution unlimited

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY
Office, Chief of Engineers, U. S. Army
Washington, D. C.

13. ABSTRACT

This report presents the results of an effort to analyze and correlate data from tills to determine if the dynamic constitutive relations needed for ground shock code input are predictable from simple index and seismic tests. Data from glacial tills at seven sites in the northern United States were used successfully to correlate secant constrained moduli with percent saturation and percent air in a unit volume of soil. These correlations indicated trends distinctive enough to use either of the correlations to approximately predict, for a till, the loading portion of the UX stress-strain curve to a stress of about 500 psi. Predictions using these correlations should be made with due consideration of the validity and amount of saturation and percent air data. In addition, some qualitative consideration should be given to the unit weight and seismic velocity data, the depth of weathering, and the location of the groundwater table. For the tills investigated in this study, dry density, UU strength, and Young's modulus taken from the static UU stress-strain curve cannot generally be used to predict the secant constrained moduli to the stress levels of interest.

DD FORM 1 NOV 65 **1473** REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Constitutive relations						
Glacial till						
Ground shock						
Soil dynamics						
Soil properties						

Unclassified
Security Classification