Determination of In Situ Lateral Stresses in a Dense Glacial Till

ALAN J. LUTENEGGER

A comparison of different techniques for determining in situ lateral stresses in a dense glacial till is presented. The site is located north of Des Moines, Iowa, in the late Wisconsinan drift plain. The till is generally composed of a cohesive matrix (P.I. = 12; L.I. = 0) and extends to a depth of 19 m. In situ tests conducted at the site included flat dilatometer (DMT), full-displacement pressuremeter (FDPMT), hydraulic fracture (HFT), and prebored pressuremeter (PMT) tests. Push-in earth pressure cells were installed at various depths and were allowed to come to equilibrium to provide an upper-bound value of the in situ lateral stress conditions. Those data are also compared with DMT dissipation tests, which give an equilibrium value of σ_H. A comparison of the effective horizontal stresses obtained with the in situ tests is presented and is based on field pore pressure measurements obtained from electric and pneumatic piezometers. Estimates of the at-rest coefficient of earth pressure, K_o, were made and are based on laboratory tests, using empirical relationships between K_o and OCR. OCRs were obtained from incremental loading laboratory oedometer tests. The work energy method was also used to predict in situ effective horizontal stresses, using results of oedometer tests on horizontally trimmed samples. Results indicate that full displacement tests, such as the DMT, HFT, and FDPMT, tend to overestimate the in situ stresses while the non-displacement PMT provided results very close to the spade cell and laboratory data. A discussion of the test results is presented concerning the accuracy of each of the tests in predicting in situ stresses in dense cohesive soils.

The prediction of at-rest horizontal stresses in natural soils often represents one of the more difficult tasks in geotechnical engineering and yet has a wide application in practice. Currently, there are a number of well-known field methods to estimate in situ lateral stresses in cohesive soils and a number of techniques that use results of laboratory tests on undisturbed samples. Generally, the prediction of K_o in softer and normally consolidated clays does not present a particularly difficult task, because theoretical and empirical methods for estimating K_o provide reasonably accurate values for most design situations. Conversely, stiff or highly overconsolidated cohesive deposits present somewhat of a formidable problem: there are limited data in the literature from field investigations and what constitutes a reasonable estimate of K_o is not clearly defined.

In the midcontinental United States, abundant cohesive glacial till deposits are present and provide the base for both deep and shallow foundations. Deep excavations in many areas are also conducted in those materials, and, therefore, the in situ state of horizontal stresses is of some practical significance for design. The tills are matrix dominated in most areas (i.e., composed of sand, silt, and clay and generally behave as cohesive soils). The tills are often very dense and stiff because of the mechanics of glacial deposition, and there is a tendency to think that the soils are highly overconsolidated. This can lead to the belief that the in situ lateral stresses are high, although this has never been directly substantiated.

Department of Civil Engineering, University of Massachusetts, Amherst, Mass. 01003.

To study the magnitude of lateral stresses that exists in those deposits, a site consisting of Late Wisconsinan glacial deposits near Ames, Iowa, was selected for laboratory and field investigation. In situ lateral stresses were estimated on the basis of field measurements by using several in situ test methods and were predicted on the basis of the results of laboratory tests on undisturbed samples. The purpose of this paper is to present the results of tests conducted and to provide a comparison of the results.

SITE GEOLOGY AND SOIL CONDITIONS

The site investigated is located near Ames, Iowa, in a physiographic region known as the Late Wisconsinan Drift Plain. The surficial geologic sediments are glacial deposits, representing the advance and retreat of the Late Wisconsinan glacier into the area about 12,000 years ago. The glacial sediments in this area generally fall into two broad genetic classifications: (a) subglacial till (representing materials transported and deposited beneath or near the base of the ice mass) and (b) supraglacial diamicton (representing materials transported and deposited on or in the ice mass). Those two materials have widely different geotechnical characteristics that result from the transport and depositional modes.

The subglacial till (often referred to as "basal" till) is generally dense to very dense and is very uniform in composition. By contrast, the supraglacial diamictons (often referred to as "ablation" till) are much more heterogeneous and can range from poorly sorted to well sorted and are often highly stratified depending on the degree to which water has dominated the transport or deposition. Those materials tend to be less dense and often are loose when compared with the subjacent subglacial till. Detailed studies of differences in geotechnical characteristics of those deposits in the study area have been previously described (*1*).

Subsurface conditions at the investigated test site are generally representative of a wide geographical area in the state and, on the basis of other regional site investigations, are typical of the glacial deposits. Beneath the soil solum, the sediments are oxidized and mottled down to a depth of about 4 m. Immediately below this the soil color changes from brown to gray, indicative of unoxidized conditions. The water level in numerous boreholes at the time of field investigations was measured at about 1.5 m; however, the soil colors indicate that past water levels have been as low as the boundary between the oxidized and unoxidized materials (i.e., at a depth of about 4 m). Pneumatic and vibrating wire piezometers installed at the site indicate that in situ pore water pressures are hydrostatic in the till. The unoxidized zone represents a condition of permanent saturation and negligible oxygen activity, which accounts for the gray colors. Investigations were performed to a depth of 18.3 m and ended near the base of the unoxidized till, which is at about 22 m.

Geotechnical characteristics of the site are illustrated in Figure 1. While the grain-size distribution and plasticity data shown indicate that the site is very uniform, in actuality the upper 2 m was quite stratified on the basis of visual classification of a CME continuous core. Water content and plasticity data all show that the natural water content is very close to or less than the plastic limit, which gives a liquidity index near zero. Thus, the soils may be highly overconsolidated.

Grain-size distributions obtained by hydrometer analysis indicate that the tills are matrix dominated (i.e., clay-silt-sand) and cohesive. Matrix carbonates constitute almost 20 percent of the composition and are dominated by dolomite. Previous studies of the clay mineralogy of this till indicate that the dominant mineral is montmorillonite (*2*).

SITE INVESTIGATION

Drilling and sampling at the site were performed by using hollow stem augers and 76-mm-diameter Shelby tubes at 1.5 m intervals. A standard penetration test profile was conducted in an adjacent borehole through the center of the hollow stems. Shelby tube samples were used to conduct oedometer tests and laboratory shear strength tests. Oedometer specimens were trimmed in both vertical and horizontal directions. Tests were performed on 63-mm-diameter samples in fixed-ring lever-arm consolidometers by using a load duration of 24 h and a load increment ratio of 1. Determination of the oedometric yield stress (preconsolidation stress) was made by the Casagrande construction. A summary of geotechnical properties is presented in Figure 2.

Results of oedometer tests interpreted in the conventional sense show that the soils are generally normally consolidated below a depth of about 8.4 m. SPT blow counts and undrained shear strength determined from unconfined compression and CIUC triaxial tests show stiff to very stiff materials.

In situ tests were conducted at various depths throughout the profile to provide an estimate of in situ lateral stresses. Those included Marchetti dilatometer (DMT), prebored (Menard) pressuremeter (PMT), full-displacement pressure-

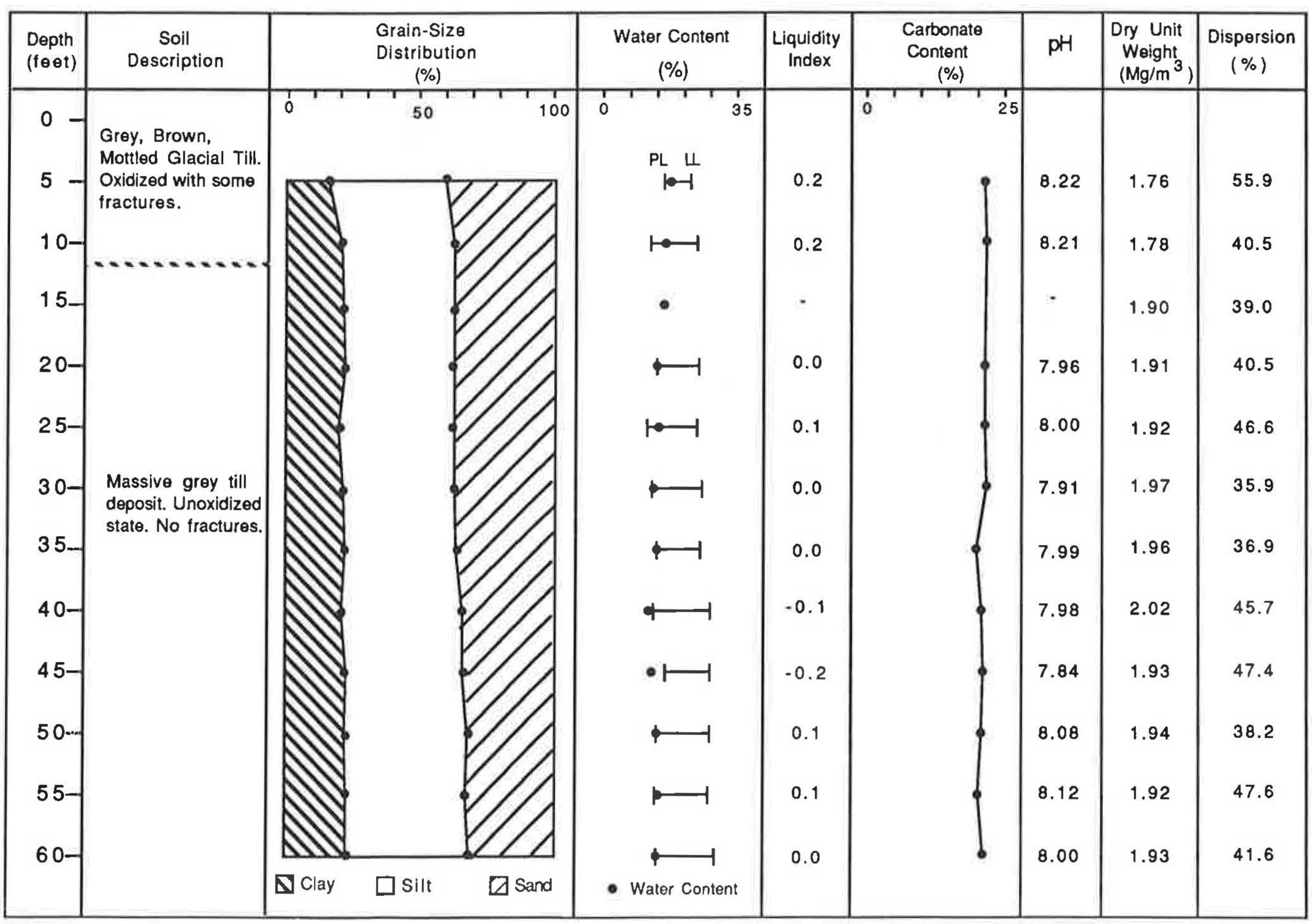

FIGURE 1 Subsurface site characteristics.

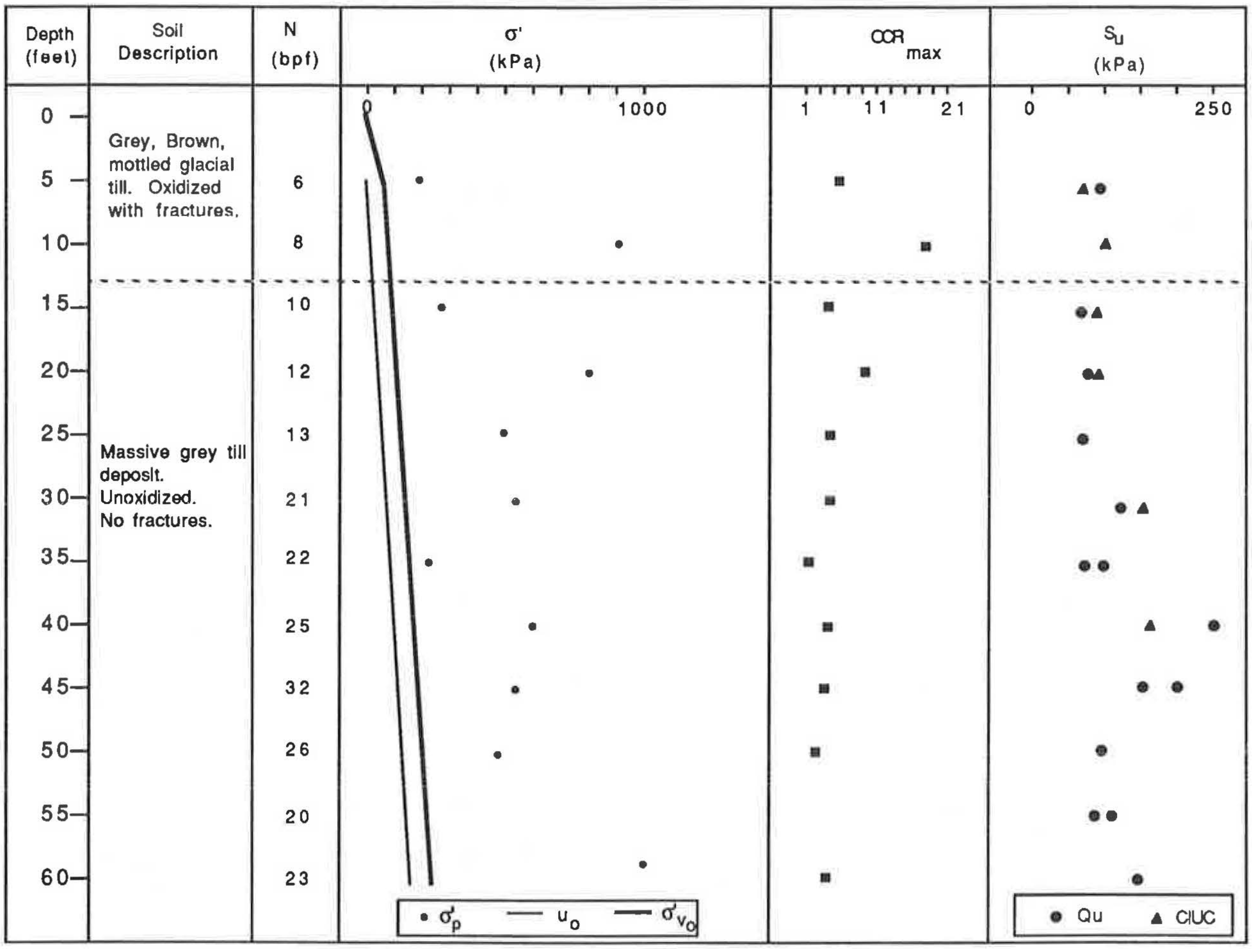

FIGURE 2 Site geotechnical characteristics.

meter (FDPMT), and hydraulic fracture (HFT) tests. DMT, FDPMT, and HFT represent a "full-displacement" method of installation (i.e., soil is forced away to install the measurement device). PMT represents a nondisplacement method of insertion and is actually installed after soil unloading. Clearly, the method of installation will affect the measured soil response. A brief description of the test procedures used for each test follows.

Dilatometer Tests

DMT tests were conducted by using a modification of the procedure suggested by ASTM subcommittee D18.02 (*3*). In addition to obtaining the lift-off (P_0) and 1 mm (P_1) expansion pressures, the recontact pressure obtained by controlled deflation (P_2) was also recorded. In soft saturated and normally consolidated clays, this last pressure reading has been shown to closely match the penetration pore pressures created by advancing the DMT blade (*4,5*). Beginning at the ground surface, tests were performed at 0.3-m intervals throughout the entire 18-m profile.

Tests were also performed by using the DMT as a total stress spade cell. After installation, repeated measurements of the lift-off (P_0) pressure were made without obtaining the P_1 reading. In this way the change in total stress on the face of the blade as a function of time after installation was obtained. Measurements were made at each test depth until a stable value of P_0 was obtained.

Prebored Pressuremeter Tests

Because the till is stiff and contains occasional gravel particles, self-boring pressuremeter tests would not be feasible. Instead, tests were performed by using prebored probe. Tests were conducted in 76-mm-diameter Shelby tube cavities, using an NX-size PMT probe. A monocell probe (sans guard cells) with a nominal height/diameter ratio of 6 was used. The probe is designed with twin sets of instrumented strain arms located at 120 degree increments around the diameter of the probe such that the strain response in three directions would be obtained. Nitrogen is used as the expansion medium. Therefore, the problems with deairing a liquid-filled probe are eliminated.

Tests were performed by using a metallic-sheathed rubber membrane. Testing was performed through the hollow stem augers immediately after opening the borehole cavity. Sufficient data points were obtained to define the in situ stress condition accurately by using graphical interpretation. Total testing time for each test was approximately 40 min.

Full Displacement Pressuremeter Tests

The FDPMT is a total stress expansion test that measures the soil response to insertion and expansion of an assumed cylindrical cavity. FDPMTs were conducted by using a Pencel pressuremeter, which was pushed into the ground at a rate of 200 mm/sec by using the quasi-static thrust of the drilling rig.

The probe has a diameter of 28 mm and is designed with a nominal cavity length to diameter ratio of 7. A 60 degree apex cone is attached to the front of the probe at about 6 diameters from the center of the probe. Because fluid is used in the cavity, the probe acts like a pressure cell during installation and the cavity total stress immediately after installation may be obtained.

Tests were performed by using two techniques: (a) immediately after installation the probe was expanded to give the cavity pressure/radial strain response and (b) after installation the total stress acting on the probe was allowed to come to equilibrium prior to conducting the cavity expansion. In both cases, a simple electrical screw pump was used to expand the probe.

Hydraulic Fracture Tests

HFTs were performed by using a push-in Casagrande-type piezometer. The probe consists of a bronze filter element 92 mm in length with an external diameter of 32 mm, giving a length-to-diameter ratio of 2.9. The tip of the probe was located 5 diameters in front of the leading edge of the filter and was constructed with a 60-degree apex.

Test procedures for hydraulic fracture have been described by Bjerrum and Andersen (*6*) and essentially involve pushing the piezometer to the test depth, forcing water through the piezometer, and then monitoring the change in water pressure with the increased volume of pushed fluid. Fluid volume was injected at a constant rate by using an electrical screw pump, and water pressure was measured by using a simple pressure gauge control console. Tests were conducted in three stages, referred to as first fracture, close up, and reopen.

First fracture refers to the first hydraulic fracture generated after the probe was pushed to the test depth. The point where this occurred was indicated by a sudden drop or a leveling off in pressure during pumping. After this occurred, the fracture was allowed to close by stopping the screw pump and then recording the drop in pressure with time. When the fracture closed, there was a sharp break in the rate of water flow into the soil. Following this, water was again forced into the fracture by using the same first-fracture procedure to reopen the fracture.

Spade Cells

To provide a basis for comparison of the in situ and laboratory test results, four push-in spade cells were installed at the site and were allowed to come to equilibrium. Earth pressure cells, manufactured by Soilinst, Inc., with dimensions of 200 mm × 100 mm and a thickness of 5 mm, were statically pushed at the bottom of drilled holes at depths of 3.0, 4.5, 7.6, and 13.7 m. Spade cells have been in place for over 5 months and are being monitored at the present time (December 1989). The use of similar spade cells for estimating in situ lateral stresses in cohesive soils has been described by a number of researchers (*7–9*).

INTERPRETING IN SITU LATERAL STRESSES FROM IN SITU TESTS

Dilatometer Tests

Marchetti had presented an empirical correlation between the DMT parameter K_D and K_o with K_D defined as

$$K_D = \frac{P_0 - u_0}{\sigma_{v0} - u_0} \tag{1}$$

in which P_0 is DMT "lift-off" pressure, u_0 is in situ pore water pressure, and σ_{v0} is in situ vertical total stress. The value of K_o in this correlation was primarily based on interpretation of laboratory oedometer tests by using the Brooker and Ireland (*10*) correlations between OCR and PI and K_o. Therefore, the accuracy of the prediction of K_o is directly related to the accuracy of the prediction of OCR.

The results of DMT tests are presented in Figure 3, in which the DMT pressure readings, P_0, P_1, and P_2 are presented along with the parameter K_D and interpreted K_o values at each 0.3 m depth. There is a rapid increase in P_0 down to a depth of about 3 m, after which the increase with depth is more gradual. K_o values interpreted from the DMT are all above a value of 1 and show a gradual decrease with increasing depth.

In clays it has been shown (*4*) that the value of P_2 represents a close approximation of the pore water pressures acting on the face of the blade as a result of penetration. Therefore, the difference $P_0 - P_2$ should closely approximate the effective horizontal stress acting on the face of the blade shortly after penetration. Those values are presented in Figure 4 in comparison with the predicted values of σ'_{H0} from the DMT K_o values. The values of $P_0 - P_2$ are about 2–3 times higher than the predicted σ'_{H0}, which may suggest that significant initial overstressing occurs in those materials as a result of the blade penetration, assuming, that is, that the DMT values are reasonably close to the correct values. This behavior is opposite of what occurs in softer clays where the initial horizontal effective stresses are very low and in fact are much lower than at-rest stresses [e.g., as measured with the piezolateral stress cell (*11*)]. This behavior is also consistent with results of spade cells (*8*), which show significant overstressing effects in stiff clays. In soft clays, spade cells generally return to K_o horizontal stress conditions.

The DMT was also used as a "spade cell" in the upper 13.7 m by conducting only the first pressure expansion or "lift-off" inflation until a constant stress reading was obtained. An example of a typical response is presented in Figure 5. Generally, equilibrium was reached in a short period, usually less than 4 hr. Those measurements represent the total horizontal stress acting on the face of the blade following dissipation of pore water pressure and relaxation of total stress generated during penetration. Those are not at-rest horizontal stresses but are in situ horizontal stresses created as a result of the

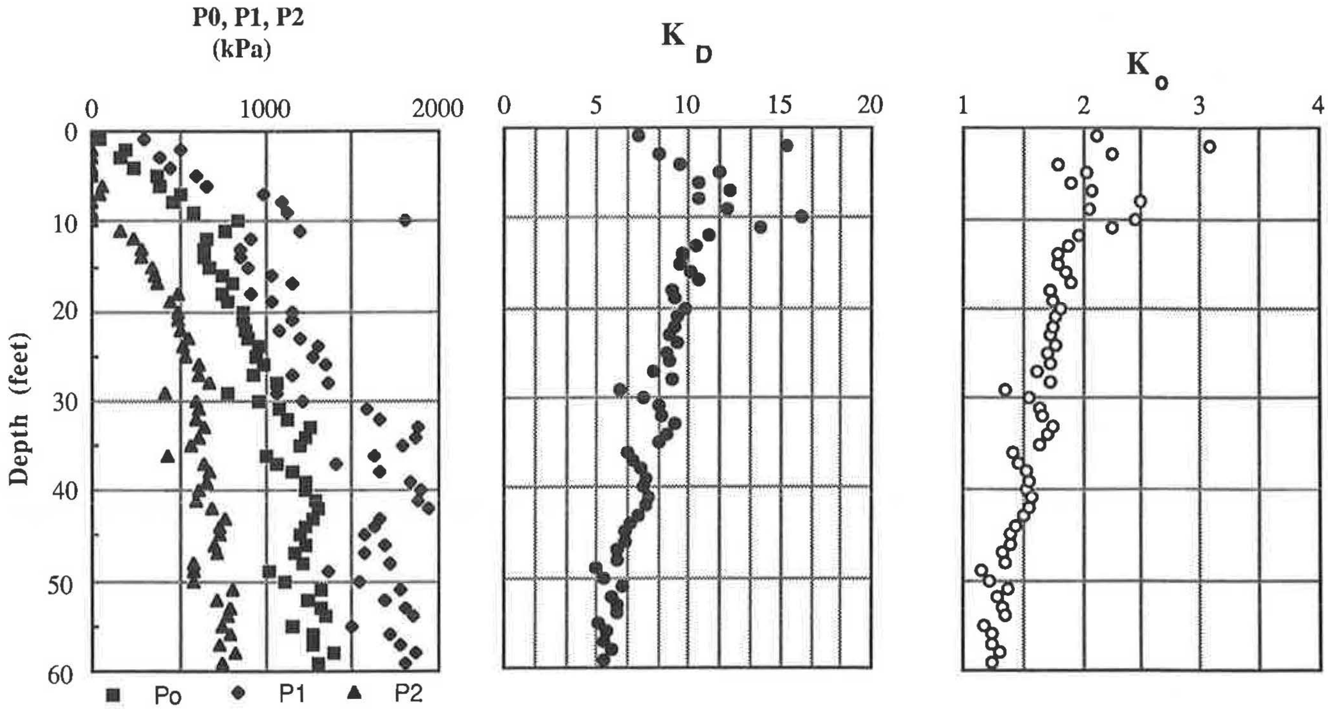

FIGURE 3 DMT results and prediction of K_o.

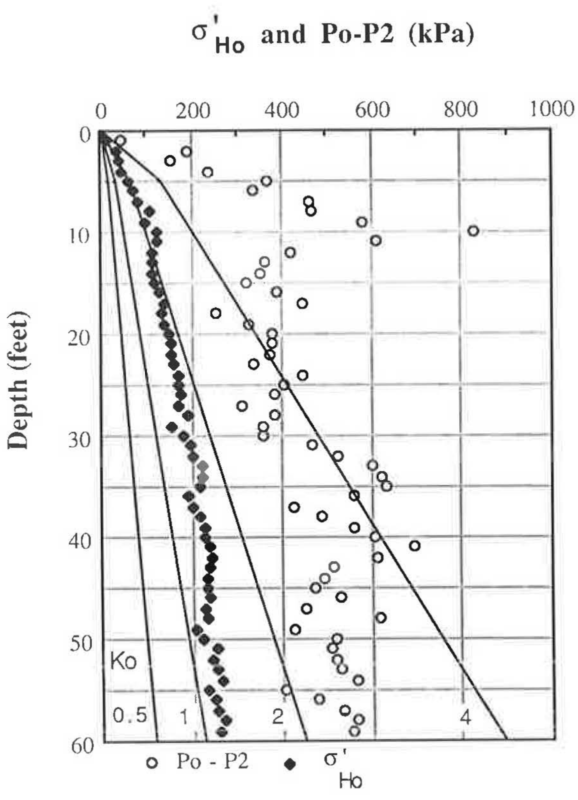

FIGURE 4 Comparison of DMT-predicted σ_{H0} and P_0 $- P_2$.

blade penetration. They may be thought of as representing an absolute upper-bound value of horizontal stress (i.e., the actual at-rest stresses must lie below those values). Thus, they provide a boundary below which all other estimates of in situ lateral stresses must lie. The profile of those values, corrected for in situ pore water pressure, are presented in Figure 6 along with lines of effective horizontal stress for various K_o values.

The trend in Figure 6 indicates increasing effective stress with depth, which would be expected in a material with a

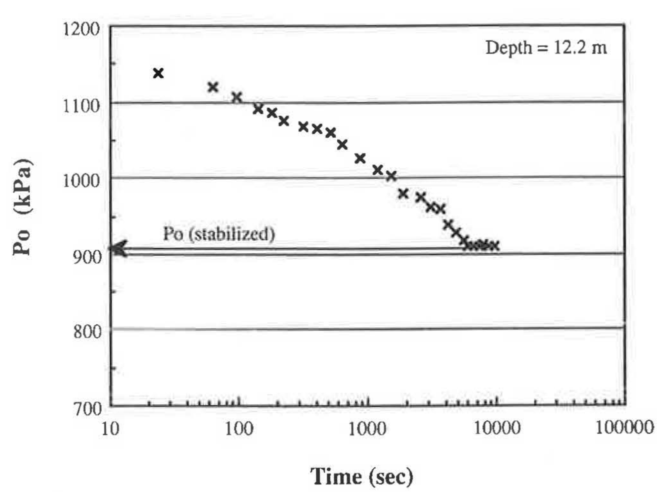

FIGURE 5 Typical results of DMT P_0 dissipation test.

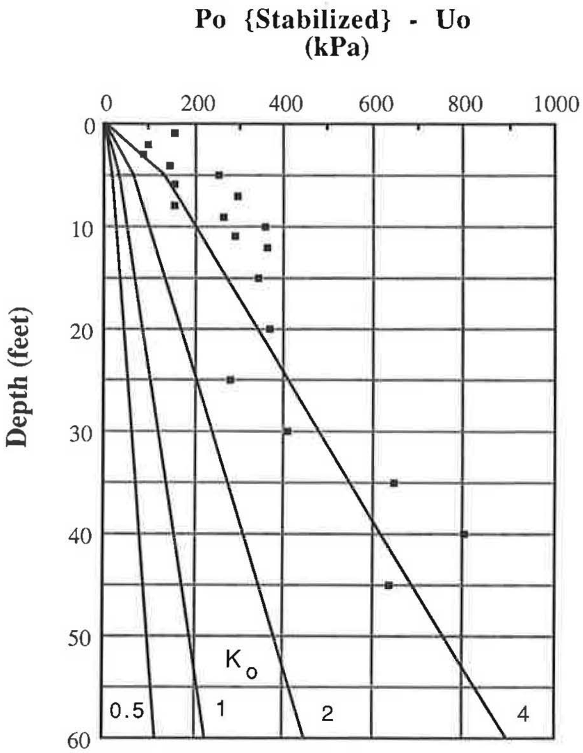

FIGURE 6 DMT P_0 dissipation results.

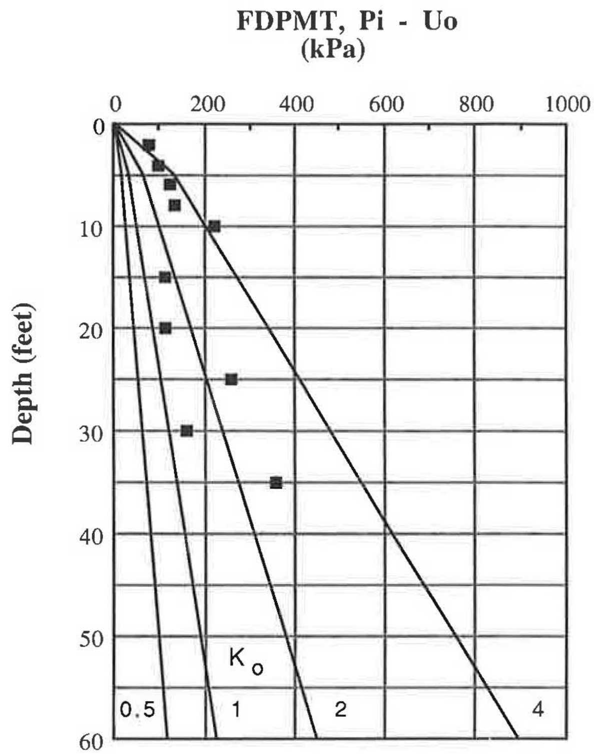

FIGURE 7 Results of full-displacement pressuremeter stabilization tests.

constant K. The values, however, indicate stress conditions generally well above a K_o value of 4 in the upper 6 m, which may seem unrealistic.

Full-Displacement Pressuremeter Tests

The insertion of the cylindrical probe of the FDPMT is much like the installation of a fluid-filled stress cell. In this study, the probe was installed by quasi-static penetration in the same way that the DMT was installed. After insertion, the stress was allowed to come to equilibrium in the same way that the DMT P_0 dissipation tests were conducted (i.e., sufficient time was allowed for the stress to reach a constant value).

The results of those stabilization tests are presented in Figure 7. Those results are generally lower than those measured with the DMT P_0 dissipation tests.

Hydraulic Fracture Tests

HFTs were interpreted by using the reopen curve following initial fracture and close up. In this way it is postulated that any tensile strength in the soil is eliminated from the stress measurement. A typical fracture curve is presented in Figure 8. The abrupt drop in pressure on first fracture represents a brittle response and was typical for most of the tests conducted in this stiff till. This is unlike fracture tests conducted in softer clays or silts by using the same probe (*12*) in which the first fracture and reopen stresses are nearly the same.

The majority of the literature concerning HFT in clays has suggested that it is not possible to measure horizontal stresses higher than vertical stresses, despite the fact that K_o values greater than 1 have been reported in a number of cases (*13,14*). The estimate of horizontal stresses in soils, using hydraulic fracture, is predicated on the fact that a vertical fracture must develop. In the past (*6,13,15*), HFT, using push-in piezometers, used a probe with a short filter located on or just above the conical tip. Lefebvre et al. (*16*) have shown that an increase in the length of the filter element increases the likelihood that a vertical fracture will develop. In the present study, the probe had a long ($L/D \approx 3$) filter located 5 diameters behind the tip. This increases the likelihood of developing vertical fractures in the soil and thus the measurement of horizontal stresses. This is also consistent with cylindrical cavity expansion theory (*17*).

The results of HFTs conducted at the site are presented in Figure 9. Two of the tests did not show brittle behavior and gave low stresses. The probe may have been in sand lenses at those two depths. The magnitude of stresses indicated in Figure 9 are close to DMT P_0 dissipation stresses previously illustrated in Figure 6 but higher than the FDPMT results in Figure 7.

Spade Cells

Tedd and Charles (*8*) suggested that a correction should be applied to the stresses measured with spade cells to account for the over stress created by insertion. The tentative correction is based on undrained shear strength, in this case obtained from unconfined compression and CIUC triaxial tests. The results of spade cell readings, both uncorrected and corrected, are presented in Figure 10. The spade installed at a depth of

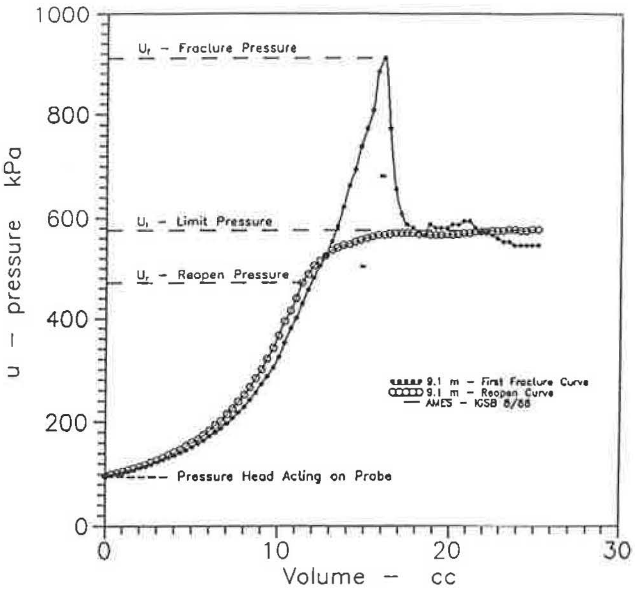

FIGURE 8 Typical hydraulic fracture test results.

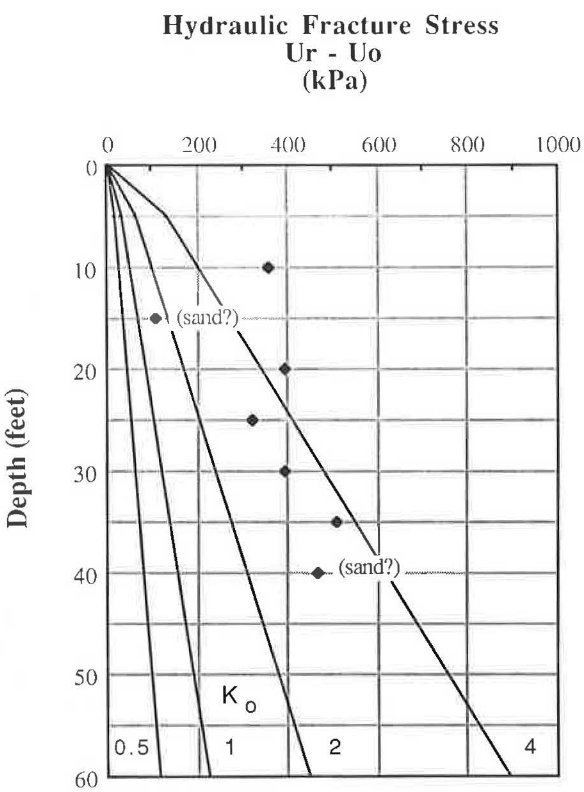

FIGURE 9 Summary of hydraulic fracture tests.

7.6 m may have been damaged during installation because the measured stress is very low.

The uncorrected values illustrated in Figure 10 are considerably less than stresses obtained from DMT P_0 dissipation tests. This suggests that in this material there is a dependency of the stabilized σ_H on geometry of the flat plate. This is the basis behind the K_o-stepped blade. Because the spade cell

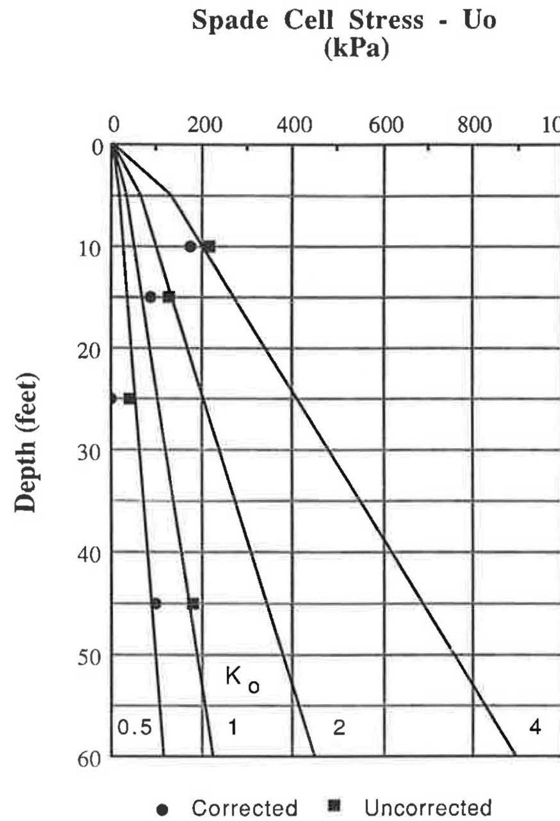

FIGURE 10 Spade cell results.

may represent a condition of less disruption in the stress field in a very stiff clay when compared with the DMT, the uncorrected values illustrated in Figure 10 may now be considered to represent upper-bound values of in situ stresses.

Prebored Pressuremeter Tests

Results of individual PMTs were analyzed graphically to provide a measure of in situ stresses. The probe alignment was fixed during testing such that the strain arms were located at the same orientation for each test depth. The results from each set of strain arms were analyzed individually to give an independent measure of horizontal stress. The results indicated very little difference and no trend with depth. Therefore, it appeared that the stresses were equal in all directions. The value of horizontal stress for each depth was taken as the average of the three directional values.

The results of interpreted horizontal effective stresses are presented in Figure 11. In the upper 5 m, values of K_o on the order of 3–5 are indicated. However, below a depth of 6 m, it appears that K_o approaches a much lower value of about 0.6. The interpreted horizontal stresses from the PMTs were taken as the tangent stress to the linear portion of the pressure expansion curve. Therefore, those values represent the maximum possible value of stress that could be interpreted from the curve. Even so, the results of Figure 11 indicate that in the lower till K_o values are all less than 1. The results of Figure 11 compare very well with corrected spade cell stresses.

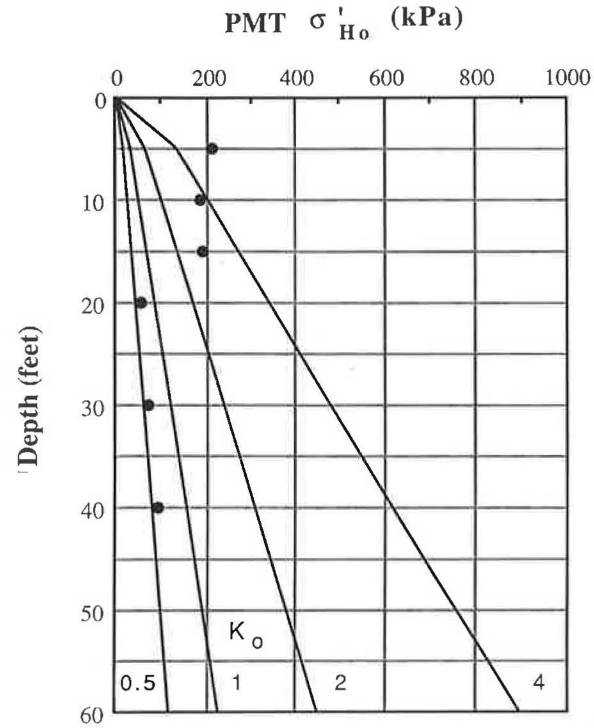

FIGURE 11 Results of pressuremeter tests.

ESTIMATING IN SITU LATERAL STRESSES FROM LABORATORY TESTS

The prediction of in situ lateral stresses based on laboratory tests in cohesive soils has generally relied on empirical relationships between stress history and K_o (most notable are those presented by Brooker and Ireland (*10*)]. Those generally make use of the oedometer OCR and plasticity. More recently, Mayne and Kulhawy (*18*) have presented suggestions for estimating lateral stresses based on stress history and effective friction angle. A distinctly different approach to estimating lateral stresses more directly was presented by Becker et al. (*19*), where the work energy method was used to estimate the in situ stress state. In this method an oedometer test on a horizontally oriented sample is needed to estimate the horizontal stress.

An accurate measure of the preconsolidation stress is needed to make use of the laboratory oedometer tests and OCR. For the tills tested in the current study, some difficulty was experienced in accurately predicting σ'_c because of the gentle curvature in the *e* log *p* curves. For this reason, and to provide an upper-bound laboratory estimate of K_o, the maximum possible value of σ'_c was taken from the oedometer curves. Therefore, OCR_{max} was used to predict K_o for the first two methods.

Brooker and Ireland

Perhaps one of the most oft-quoted methods for estimating the at-rest coefficient of lateral stress is that presented by Brooker and Ireland (*10*). A series of laboratory tests were conducted in their study, using an instrumented oedometer, by consolidating artificially remolded soil mixtures and then unloading to give a desired OCR. Thus, the results do not simulate other than young soils without a developed structure under simple mechanical unloading. The resulting curves relate K_o to OCR and P.I., although in no case is K_o greater than 3. K_o values estimated for the site investigated by using the Brooker and Ireland's data and results of oedometer tests are presented in Table 1. Those data show a decrease in K_o below a depth of 3 m as OCR decreases with K_o values all less than 1. Obviously, the prediction of K_o is solely a function of how well the oedometer yield stress may be evaluated.

Mayne and Kulhawy

Mayne and Kulhawy (*18*) conducted a comprehensive review of the literature and presented several relationships between OCR and K_o on the basis of laboratory test results. An approximate upper limit of $K_o = 3$ is again noted in cohesive

TABLE 1 PREDICTED K_o VALUES FROM LABORATORY TESTS

Depth (m)	Brooker & Ireland (10)	Mayne & Kulhawy (18)	Becker, et al. (19)
1.5	1.1	1.1	1.1
3.0	2.0	2.2	2.0
4.6	1.0	0.9	0.9
6.1	1.2	1.5	0.7
7.6	0.9	0.9	0.6
9.1	0.9	0.9	0.3
10.7	0.8	0.8	0.3
12.2	0.8	0.8	0.3
13.7	0.8	0.8	0.4
15.2	0.7	0.6	0.3
18.3	0.9	0.9	0.3

$$K_a = \frac{1 - \sin\phi'}{1 + \sin\phi'} = 0.2 \qquad K_p = \frac{1 + \sin\phi'}{1 - \sin\phi'} = 4.9$$

soils. Mayne and Kulhawy suggest that K_o during loading-unloading may be related to the effective friction angle of the soil, ϕ', and OCR by

$$K_o = (1 - \sin \phi)' \ OCR^{\sin \phi'} \tag{2}$$

A series of consolidated-drained direct shear tests conducted on the unoxidized till from the test site gave $\phi' = 41$ degrees. Resulting values of K_o predicted from Equation (2) are given in Table 1. Interestingly, those values are very close to the K_o values predicted from the Brooker and Ireland method. It is reasonable to expect that the soils at this site have undergone simple unloading as a result of removal of the ice overburden during deglaciation. No evidence of groundwater fluctuations are present in the unoxidized zone.

Work Energy Method

The two previous techniques described yield values of K_o and, therefore, give indirect estimates of at-rest lateral stress. The work energy method presented by Becker et al. (*19*) gives a more direct estimate of σ'_{H0} making use of laboratory oedometer data.

This method is essentially a graphical technique to enhance data presentation from oedometer tests to provide estimates of yield stress. Data are presented in terms of work-per-unit-volume and are plotted on arithmetic scales. By trimming a sample to apply loading in the horizontal direction, an estimate of the in situ horizontal effective stress is obtained. See the paper by Becker et al. (*19*) for more complete details.

Results of interpretations of horizontal loading oedometer tests by using this procedure are given in Table 1. K_o values calculated by using this method range from 2.0 at a depth of 3 m to 0.3 below a depth of 9.1 m. Except for the tests at 1.5 and 3.0 m, this method appears to give estimates of K_o that are lower than other estimates and, thus, may be unrealistic. Active and passive earth pressure coefficients calculated by using a simple Rankine analysis and direct shear test results are also shown in Table 1.

COMPARISON OF RESULTS

The comparison of different methods to predict at-rest horizontal ground stresses or alternatively K_o presents a dilemma: what is considered correct and what is expected? None of the methods presented have any particular preference over the others in stiff cohesive materials; that is, all of the in situ tests were performed with about the same degree of difficulty. On the basis of simple classification and property tests (i.e., liquidity index and unit weight), the soil might be expected to behave as highly overconsolidated. On the basis of geologic history (i.e., prior loading by a continental ice sheet), the soil might be expected to behave as highly overconsolidated. By themselves, those conditions may lead to a belief that the in situ state of horizontal stress is high.

Results of laboratory oedometer tests tend to indicate that although the soils are very dense they are only lightly to moderately overconsolidated below a depth of about 9 m. On the basis of various laboratory predictions, K_o would have a value of between 0.6 and 0.9 in this zone. Those values are reasonably close to the prebored PMT and the spade cell located at 13.7 m, which suggests a K_o value close to 0.5. The full-displacement tests (DMT, FDPMT, and HFT) give much higher stress values and suggest K_o values between 2 and 4, still below the theoretical predicted passive failure ratio of 4.9. Those high values should generally be expected and suggest that significant overstressing occurs in this stiff till as a result of the full-displacement mode of installation.

The overstressing should be related to the geometry and volume displacement of the probe, which may indicate that the stepped blade or tapered blade may be applicable in those stiff materials. However, to provide a more appropriate interpretation, it may be better to allow the tests to reach a stabilized value prior to extrapolating for the in situ value of effective stress.

Investigations of in situ stresses in glacial clay tills and other stiff clays by using in situ and laboratory tests have suggested that the K_o values presented from the laboratory tests in this study are reasonable. Powell et al. (*9*) presented results of oedometer, spade cell, suction tests, and Menard pressuremeter tests at Cowden in the United Kingdom. The tills have nearly the same P.I., liquidity index, texture, and unit weight as the Ames test site described here. K_o values in the upper 4 m ranged from 6 to 1.2. Below this depth, $K_o = 1$. At another site in the United Kingdom, Al-Shaikh-Ali et al. (*20*) presented K_o values ranging from 1.0 to 0.7 for a "lodgement till" with similar classification properties. The values were based on in situ packer (nondisplacement) hydraulic fracture tests, laboratory fracture tests, and oedometer tests. The material investigated was a low-plasticity low-water content-saturated till, which had a liquidity index near zero. Carder and Symons (*21*) also reported very good agreement between push-in spade cells, self-boring pressuremeter, and dilatometer tests in stiff London clay.

Because of the grain-size distribution and glacial deposition, the till investigated in the present study has a high unit weight. The cohesive nature of the material apparently has led to the development of substantial tensile strength in the soil, as was evidenced by a sudden drop in pressure during hydraulic fracture tests. This tensile strength contributes to the general conception that the till should behave as overconsolidated and exhibit high in situ stresses throughout the full depth, although this does not appear to be the case.

CONCLUSIONS

Results of a laboratory and field investigation to predict in situ horizontal effective stresses at rest in a dense, stiff glacial till have been presented. In the upper 3 m of the deposit, K_o values as high as 4 may be realistic. However, in what appear to be moderately overconsolidated soils, K_o values on the order of 0.7 to 0.9 appear more realistic below a depth of about 7 m.

The full-displacement in situ tests used only serve to provide an upper bound on the actual at-rest horizontal stresses, while the prebored strain-arm pressuremeter gave results more in line with conventional laboratory interpretation and push-in spade cells. In this soil, the empirical correlation offered by the dilatometer gave reasonably good estimates of K_o. However, this should be expected, considering the source of the correlation. In a strain-hardening soil that requires significant strain to reach peak strength such as investigated in this study, field techniques such as the stepped blade or tapered blade, used in a full dissipation mode, may provide meaningful results.

ACKNOWLEDGMENTS

The work presented in this paper was sponsored by the Iowa Geological Survey Bureau, Department of Natural Resources. Their financial support is greatfully acknowledged. Hydraulic fracture tests were conducted by J. Blanchard. Other field assistance was provided by R. Bruner, IGSB.

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Publication of this paper sponsored by Committee on Soil and Rock Properties.