Measurement of Lateral Stress in Cohesive Soils by Full-Displacement In Situ Test Methods

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Estimation of lateral stress in cohesive soils from in situ tests by using full displacement probes is considered. The stress and pore pressure changes around a penetrating probe are briefly discussed before comparisons between data obtained from four different test methods are made. The application of cavity expansion models to the evaluation of lateral stress cone data in clays is evaluated with favorable results. A normalized pore pressure parameter is also introduced as an indicator of K_o conditions.

Increased understanding of soil behavior has emphasized the importance of the contribution of in situ stress state. Numerical and analytical methods almost routinely incorporate stress-dependent behavior in some form. Recent developments in the interpretation of in situ test data suggest that horizontal stress is one of the major factors controlling soil response.

Specific data related to in situ lateral stress conditions at a site may be obtained from either laboratory or field tests. A review of existing methods is given by Schmertmann (*1*), Jamiolkowski et al. (*2*), and Tavenas and Leroueil (*3*).

The evaluation of K_o can be classified into four main groups according to type of measurement made:

1. Direct methods such as the self-boring pressuremeter and self-boring load cell: Direct methods suffer from the significant effects of even small degrees of disturbance, the consequences of which become more important as the soil stiffness increases.
2. Semidirect or back-extrapolation methods: Developments in this area include the stepped blade and wedge blade, both of which require additional calibration or correlations at specific sites prior to general use.
3. Indirect methods used where a lateral stress value is measured during or after the installation of a full-displacement probe: In some cases, the dissipation of stress and pore pressure induced during insertion can be monitored with time so that an equilibrium value for the inserted probe can be obtained. Each of the full-displacement methods causes significant but repeatable disturbance to the soil.
4. Empirical methods as an important source of information for evaluating the stress history of soil deposits: Existing correlations are generally derived from laboratory or calibration chamber data and modified to incorporate field parameters.

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The measurement of horizontal stress, using the self-boring pressuremeter, is generally considered to be the best available technique for evaluating in situ stress state and is often taken as the reference value for any comparative study. The results of disturbance during installation of the probe and quantifying its effect on the measured data are, however, problematical. Full-displacement probes were developed to produce conditions of repeatable degrees of disturbance. The problem is then one of relating the measured lateral stress to the prepenetration value as opposed to one that evaluates whether or not the soil has been disturbed during probe installation. The idea of predicting small strain behavior from large strain parameters has been validated, at least in sands, by results of calibration chamber tests (*4*).

In the ideal case for undrained penetration, the initial lateral stress σ_* measured by a full-displacement probe results from two components:

$$\sigma_* = \sigma_{ho} + \Delta\sigma \quad (1)$$

where σ_{ho} is in situ total horizontal stress and $\Delta\sigma$ is the total stress increment caused by insertion.

In any particular soil, the magnitude of the total stress increment is made up of both stress and pore pressure components and can be expected to be related to the relative displacement caused during penetration of a probe. The idealized change in the lateral stress coefficient (defined in terms of an effective stress ratio) for various in situ testing probes is shown schematically in Figure 1. Although this simplified representation is instructive, it is, however, complicated by the fact that for each test method the stress/strain paths are very different and that for even under undrained conditions no single curve exists. The relative positions of the tests are also very subjective and dependent on individual probe characteristics.

A series of in situ tests has been performed to compare and evaluate lateral stresses measured by full-displacement probes as part of a research program being carried out at the University of British Columbia (UBC). The results of tests performed at two research sites are presented here to illustrate the effects of equipment and soil characteristics on measured lateral stresses in cohesive soils. In addition, several empirical correlations that provide a rational basis for correlation between large strain and small strain behavior are presented for evaluating K_o.

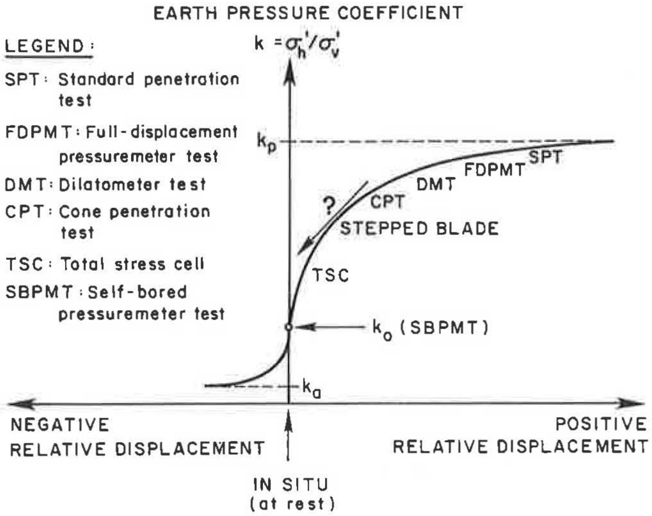

FIGURE 1 Idealized change of lateral stress coefficient, *K*, caused by full displacement probes.

DESCRIPTION OF TEST SITES

The data presented here were obtained from two sites in the Lower Mainland of British Columbia, where fine-grained soils predominate. The soils are very similar in terms of geotechnical parameters (Table 1) but have undergone differing mechanisms of overconsolidation.

Strong Pit is the site of an abandoned gravel pit. The well-graded surface sand and gravel in the area is fluvioglacial in origin and overlies marine and glaciomarine clayey silt. The stony clayey silt is of varying thickness with numerous discontinuous lenses of dense fine sand. The present-day profile consists of 1 m of gravel underlain by up to 9 m of stony clayey silt. Approximately 15 m of gravel overburden have been removed at the location of the test site.

The equilibrium pore pressure in the clay varies between 0 and 10 kPa. Those conditions result from a perched water table at the base of the surface gravel layer and underdrainage at the base of the clay. The overconsolidation of soil can be explained solely on the basis of unloading owing to overburden removal (*5*).

The second site is known as Lower 232 St. and is located in Langley, British Columbia. The Quaternary sequence consists of marine silt to clay deposited during the glacial regression, which is occasionally interbedded with minor sand layers. The slightly organic silts and clays are underlain by dense glaciomarine sands and gravels. The fine-grained soils have been subjected to leaching subsequent to deposition. The soils are overconsolidated at the surface primarily because of dessication and minor unloading and become normally consolidated at depth.

TABLE 1 AVERAGE GEOTECHNICAL PARAMETERS FOR TEST SITES

Index/Parameter	Strong Pit	Lower 232 St.
Water content (%)	19	45
<60 μm (%)	85	100
<2 μm (%)	45	48
LL	27	40
PI	13	21
Unit weight (kN/m³)	21	16
S_t (FVT)	2-5	5-25
OCR	2-10	1-6
$(S_u/\sigma'_v)_{nc}$	0.35*	0.26

* Calculated using $S_u(FVT)/\sigma'_{vm}$ where σ'_{vm} is the maximum past pressure obtained from incremental oedometer tests.

EVALUATION OF LATERAL STRESS CONDITIONS AT TEST SITES

For comparative purposes, the measurements of lateral stress with depth at each site, using the total stress cells, were taken as reference values. The total stress cells are 6 mm thick and are installed in a full displacement mode. Consequently, the lateral stress measured may be altered by this process, and some correction is required. Tedd and Charles (*6*) evaluated field data from several sites and suggested that the over-read of lateral stress approximates to one half the undrained shear strength at the depth of measurement for firm-to-stiff soils. On the basis of field data, they established an undrained shear strength limit of about 30 kPa below which no correction was recommended.

The adjustment of measured stress to account for disturbance caused during the insertion of the spade cell is approximate and does not necessarily guarantee the correct result. Nevertheless, on the basis of 10 years' experience, Tedd et al. (*7*) suggest that the method approximates to the average over-read conditions in firm-to-stiff soils.

FIELD TESTING PROGRAM

The following equipment is available at UBC for measurement of horizontal stresses with full-displacement probes:

- Push-in spade-shaped total stress cells (TSC),
- Flat dilatometer (DMT),
- Lateral stress piezocone (LSC), and
- Seismic cone pressuremeter (SCPM).

Push-In Total Stress Cells

In situ lateral stresses have been measured at both sites with push-in spade cells (*8,9*). The TSC that were used measure both the total pressure in the cell and the piezometric pressure and were supplied by Solinst Canada Ltd. Minor modifications were made to the pressure cells by using the UBC Geotechnical Research Vehicle to facilitate insertion. In addition, platinum RTD temperature sensors were installed in several of the cells to allow temperature correction of field data. All the total stress cells were calibrated, before installation, in the laboratory for the effects of temperature and external applied pressure. Identical calibrations were performed again after the stress cells were recovered from the ground.

All temperature corrections applied to the blade pressures were made with respect to the equilibrium temperature in the ground, as measured by the sensors placed on several of the stress cells. At other depths, where blades were not instrumented for temperature, the ground temperature was estimated by interpolation from the other temperature measurements. The complete calibration results, description of installation, and interpretation of data obtained at Strong Pit are detailed by Sully and Campanella (*5*).

The total stress cell is a spade-shaped oil-filled chamber approximately 100 mm wide, 200 mm long, and 6 mm thick. The oil-filled chamber is formed by two welded plates and pressurized to maintain plate separation. The chamber is connected to a pneumatic transducer. The pore pressure filter is connected hydraulically to a second pneumatic transducer, which is also located in the cell housing. Total stress and pore pressure measurements were taken by using a portable pneumatic readout box incorporating a Druck electronic transducer with a 0- to 2000-kPa range. Accuracy of the transducer is ±0.05 percent FS (i.e., ±1 kPa). The corrected lateral stress measurements obtained by using the spade cells were taken as the reference values for comparison with data from other in situ methods.

For comparison with other measurements, the penetration lateral stress and pore pressure measured with the spade cells were taken as the values recorded immediately after the cell had been pushed to the required depth.

Flat Dilatometer

The flat DMT was first introduced by Marchetti (*10,11*) and since has become increasingly popular as an in situ testing tool. Interpretation of the test data is based on empirical correlations, using the measured parameters (thrust, P_0, P_1, P_2). Details of test procedures and interpretation methods are given by Marchetti (*11*) and Lutenegger (*12*). The penetration lateral stress is taken to be equal to the DMT lift-off pressure (P_0), and the P_2 reading is taken as the penetration pore pressure.

Lateral Stress Piezocone

The LSC developed at UBC consists of a standard UBC 15 cm^2 piezocone unit followed by a lateral stress module. The lateral stress module is located 0.69 m behind the cone tip and consists of a friction sleeve instrumented to measure hoop stresses in an under-reamed section of the sleeve. Pore pressure measurements are also performed at the LS sleeve location. Lateral stress measurements are made both during cone penetration and during the dissipation phase when penetration is halted. The total lateral stress and the pore pressure measured during penetration are considered here. Further details of the LSC and its calibration are given by Campanella et al. in another paper in this Record.

Seismic Cone Pressuremeter

The concept of the UBC SCPM has been described by Campanella and Robertson (*13*). Details of the test procedures and interpretation methods are given by Hers (*14*) and Howie (*15*). During penetration, the SCPM allows simultaneous measurement of cone resistance, sleeve friction, pore pressure at two locations, slope, and temperature. During pauses in the penetration, the shear wave velocity can be evaluated by using the downhole technique and a pressuremeter expansion curve obtained. The PM lift-off pressure is used for comparison with stresses measured by the other in situ probes. Pore pressure measurement near the PM section is not possible with the UBC SCPM.

STRESS AND PORE PRESSURE AROUND FULL DISPLACEMENT PROBES

Disturbance as a result of the installation of full-displacement probes causes significant changes in the in situ stress state of the soil. Those changes occur for both flat plate and cylindrical probes, although the relative magnitude for each type depends on many factors.

Stress Measurements

Results obtained by Azzouz and Morrison (*16*) for lightly overconsolidated Boston Blue Clay indicate that the total stress on a probe immediately after halting penetration is dominated by the pore pressure generated during full displacement installation. Thereafter, the effective stress reduces during an initial relaxation period before finally climbing to approach a K_o condition as the excess pore pressure dissipates. For tests performed by the same authors in Lower Empire Clay, the final effective stress after complete dissipation of the generated excess pore pressure was considerably larger than the initial condition prior to insertion of the probe. Boston Blue Clay (OCR = 1.2) is a sensitive clay (S_t = 7), whereas Lower Empire Clay (OCR ~ 1.5) is insensitive. This confirms the importance of soil characteristics on the stress induced during probe insertion because the same probe was used for the data presented.

Stress measurements around flat total stress cells in soft-to-stiff clays give similar results to those presented by Azzouz and Morrison (*16*) for a cylindrical piezo-lateral stress cell.

Pore Pressure Measurements

Most of the pore pressure comparisons have been performed with data from piezocone (CPTU) testing. It has been demonstrated that in a particular deposit the measured pore pressure is dependent on the location and geometry of the pore pressure sensor (*17*). Evaluation of pore pressure during cone penetration suggests that the measured pore pressure is maximum on the cone face. A large gradient of pore pressure (and stress) exists at the cone shoulder. Behind the tip, the dynamic pore pressure during penetration may be either positive or negative, depending on the soil characteristics. At some distance behind the tip and along the shaft, the pore pressure attains a reasonably constant value. Those changes can be related qualitatively to changes in normal and shear stresses as the soil moves around the cone (*18*). Numerical analyses, using simplified soil models, confirm the results obtained from field tests (*19,20*).

In conclusion, stress and pore pressure changes around a penetrating probe are very complex. Furthermore, the distribution and dissipation of excess pressures will also be a function of probe geometry and soil characteristics during pauses in penetration.

COMPARISON OF PENETRATION PRESSURES

This paper only evaluates the initial stresses and pore pressures measured during penetration at those sites. No consideration is given to the dissipation phase and associated stress and pore pressure changes.

The stresses recorded by the four methods described previously (TSC, DMT, SCPM, LS-CPTU) for the Lower 232 St. site are presented on Figure 2, where the relative magnitude of lateral stress (LS) obtained is

$$LS_{DMT} > LS_{LS\text{-}CPTU} > LS_{SCPM} \approx LS_{TSC} \quad (2)$$

The dominance of the generated excess pore pressure in the essentially normally consolidated clay is illustrated by comparison with Figure 3. Only pore pressures for the DMT, TSC, and LS-CPTU are shown. The SCPM does not measure pore pressure at the location of the pressuremeter module. In the near-surface overconsolidated soils, the pore-pressure response is relatively small and the initial effective stress level may rapidly decrease to an expected K_o condition. This may result in part because of partial saturation above or close to the water table. The difference between the total stresses and pore pressures gives very low initial K values in the normally consolidated horizon. This is generally true of all the full-displacement probes installed.

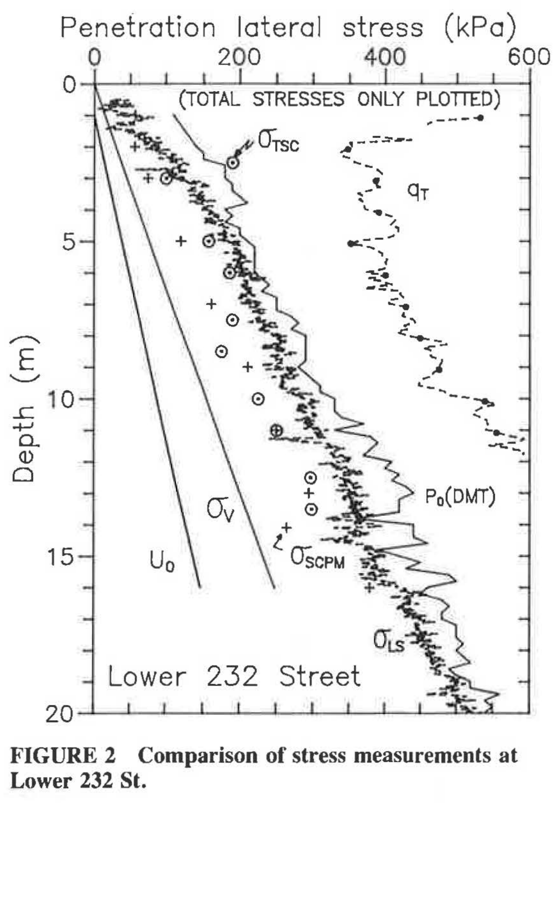

FIGURE 2 Comparison of stress measurements at Lower 232 St.

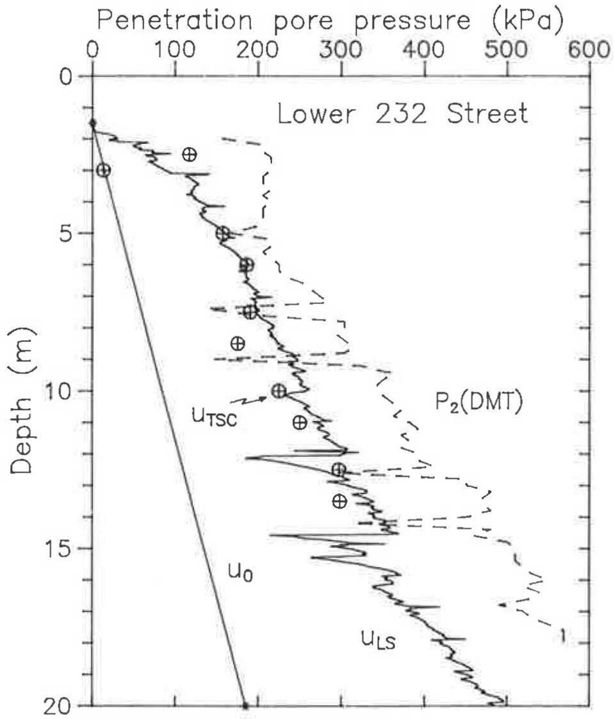

FIGURE 3 Comparison of pore pressure measurements at Lower 232 St.

The data presented in Figures 4 and 5 for the overconsolidated silty clay at Strong Pit give total stress measurements approximately 50 percent higher than the generated pore pressure, even though the hierarchy given in Equation 2 is maintained (no SCPM data exist for this site at present). On the basis of a comparison of the stress and pore pressure response at those two sites of differing overconsolidation states, it would appear that the ratio between total stresses and pore pressures

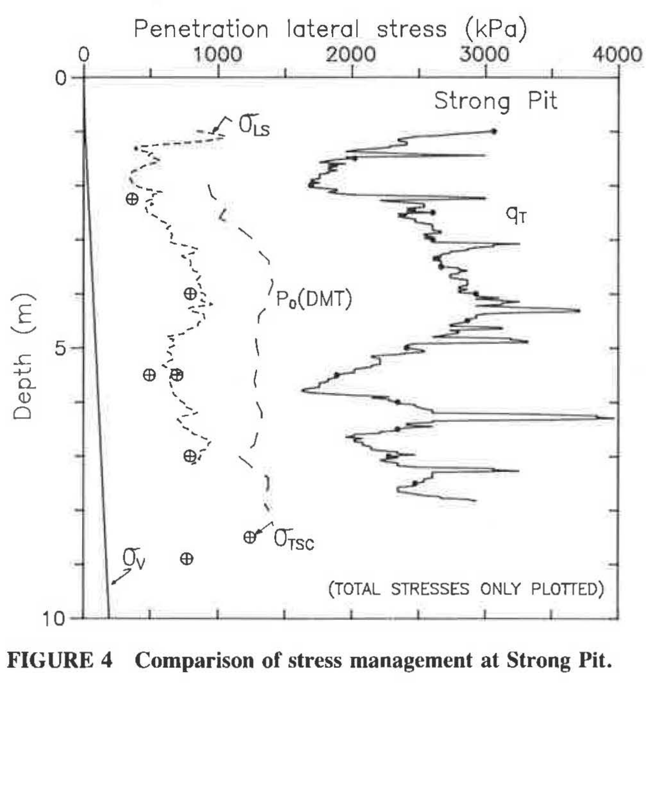

FIGURE 4 Comparison of stress management at Strong Pit.

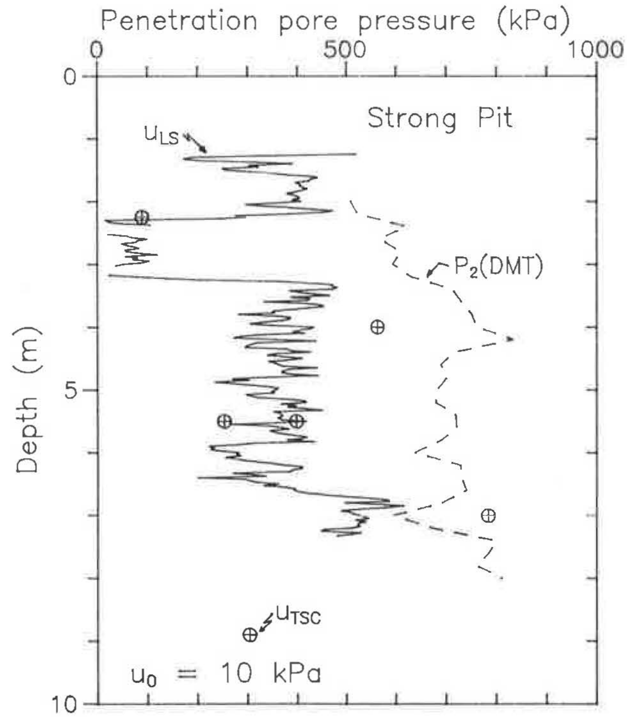

FIGURE 5 Comparison of pore pressure measurements at Strong Pit.

measured by full-displacement probes may be indicative of the stress history of the deposit.

Also presented on Figures 2 and 4 are the cone resistance profiles. Although q_t is more a limit rather than lift-off pressure, its dependence on horizontal effective stress has been demonstrated (in granular soils) and, as such, can be considered as a good indicator of horizontal stress changes.

The initial decrease and subsequent increase in q_t at Lower 232 St. suggests the presence of an overconsolidated surficial crust (with higher K_o), which becomes normally consolidated at about 5 m depth (Figure 2). Below 5 m, q_t increases linearly with depth. With the possible exception of the TSC data, none of the direct lateral stress measurements show the same pronounced near-surface changes as does q_t. The data from the LS-CPTU give rise to increased lateral effective stresses near the surface, because the pore pressures are proportionally lower than the total stress. This may be a consequence of partial saturation of the soils above the water table. The ratio of the two becomes reasonably constant at about 5 m. Finally, the disturbance caused by the SCPM and DMT appears to mask the near-surface feature, even though at depth the SCPM and TSC pressures are in remarkable agreement.

This latter effect, with respect to the cone pressuremeter, may result from the unloading caused by the slightly undersized pressuremeter section (*15*) or it may indicate that similar pore pressure trends to those measured with the LS-CPTU are in existence during SCPM penetration.

It should be possible to estimate a pore pressure value corresponding to the location of the pressuremeter module considering the pore pressure distribution around a penetrating cone and the absence of large gradients along the shaft away from the tip. However, the pore pressure measured at the lateral stress module (0.69 m behind tip) is larger than the total stresses at the PM location (1.31 m behind tip). Thus, it would appear that the true pore pressure that would be measured at the PM location, if a sensor were present, would also be reduced owing to the unloading effect. This emphasizes the importance of pore-pressure measurement in the vicinity of the pressuremeter section if rational interpretation of measured total stresses is to be attempted. The fact that the PM section is slightly undersized does not preclude at least an empirical interpretation of the measured stresses, that is, provided that the corresponding pore pressures are also known.

The cone bearing is reasonably uniform at Strong Pit with depth suggesting a similar trend in horizontal stress (Figure 4). The trends in both initial stress and pore pressure measured by the four methods also give data similar to that from the CPTU.

EVALUATED K_o CONDITIONS FROM FULL-DISPLACEMENT PROBES

The variation of the lateral stress coefficient is defined by

$$K = \sigma'_h/\sigma'_v \tag{3}$$

where

$K = K_{DMT}$, using the Marchetti (*11*) DMT correction,
$K = K_{TSC}$, using corrected TSC pressures (*6*), and
$K = K_{LS}$, using LS-CPTU data interpreted by using a cylindrical cavity expansion solution.

The variation has been evaluated from full-displacement probe measurements.

The variation of those coefficients is presented in Figure 6 for Lower 232 St. Also presented is the variation of K_{lab},

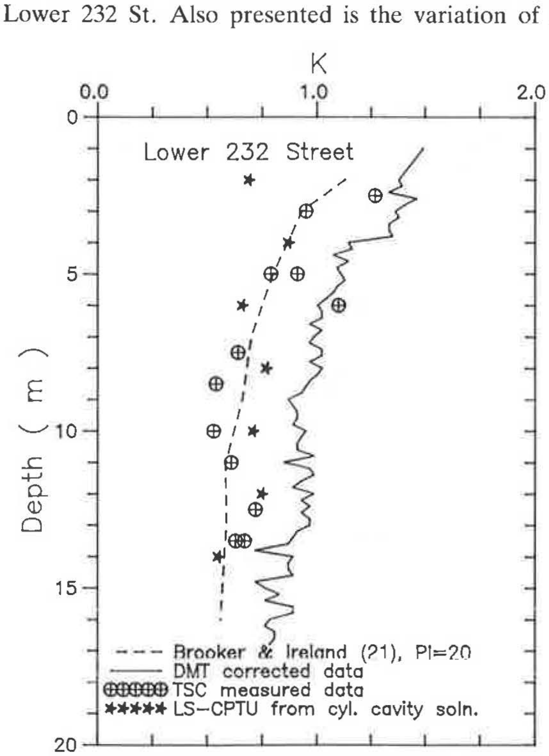

FIGURE 6 Evaluated K condition from full displacement probes: Lower 232 St.

obtained by using the correlation of Brooker and Ireland (*21*), which is based on an empirical relationship between PI and $(K_o)_{nc}$ from laboratory tests and adjusted for the effects of OCR (*22*). The TSC data presented have not been corrected for over-read owing to the low undrained shear strength of the soil. A good degree of similarity exists between the K_{TSC}, K_{lab}, and K_{LS} values. Assuming the K_{TSC} value provides the best estimate of the in situ lateral stress coefficient, the K_{DMT} value overestimates the true K_o at this site.

The LS-CPTU data have been interpreted by assuming that the stress measured by the LS cone corresponds to the cylindrical cavity limit pressure. The total horizontal stress σ_{ho} in an elastic perfectly plastic soil for the infinite expansion of a cavity is given by Gibson and Anderson (*23*):

$$\sigma_{ho} = P_L - \left[S_u * (1 + \ln I_r)\right] \quad (4)$$

where

- P_L = assumed to be equivalent to σ_{LS} measured by LS module,
- S_u = the undrained shear strength obtained by using the field vane,
- I_r = the rigidity index of the soil ($I_r = G/S_u$), and
- G = shear modulus obtained in this case from pressuremeter data.

Initially, attempts were made to use I_r defined in terms of G_{max} (from seismic cone penetration test), but this gave rise to excessive stress increments in Equation 4. I_r obtained from the Houlsby and Withers (*24*) unloading analysis gave data better suited to this type of analysis (*14*) and was subsequently used to obtain the K_o data in Figure 6.

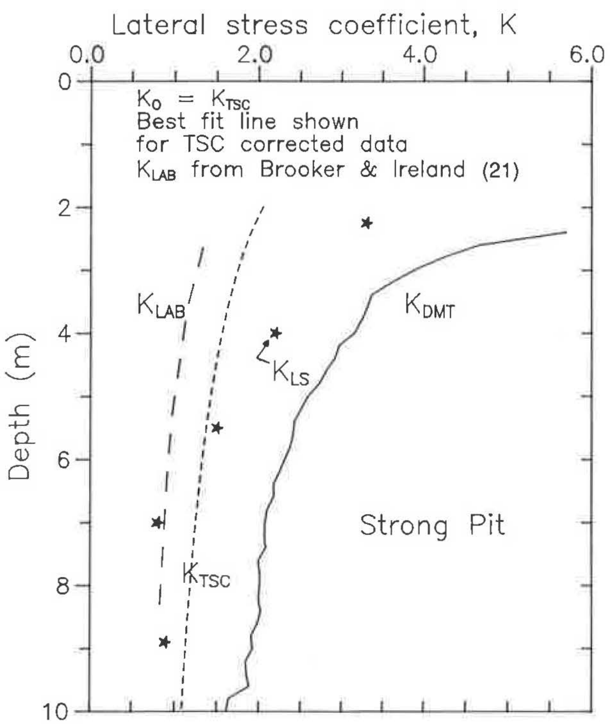

FIGURE 7 Evaluated *K* condition from full displacement probes: Strong Pit.

Data obtained at Strong Pit is presented in Figure 7. The DMT profile again overestimates the K_o value if K_{TSC} is taken as the reference value.

To date, no SCPM data have been obtained at this site, so it was not possible to evaluate the rigidity index $(G/S_u)_{HW}$ from the Houlsby and Withers method. However, evaluation of the Lower 232 St. data suggests that

$$\frac{(G_{max}/S_u)\text{SCPM}}{(G/S_u)_{HW}} \approx 9\text{–}10 \quad (5)$$

where $(G_{max}/S_u)_{SCPM}$ is the rigidity index calculated by using G_{max} from seismic cone penetration test data.

To interpret the LS-CPTU data as before, this relationship has been employed to evaluate I_r for use in Equation 4. The results are also indicated on Figure 7. The agreement between K_{LS} and K_{TSC} is remarkably good. Those data would suggest that interpretation of stresses measured by full displacement probes may be possible by using (cylindrical) cavity expansion theory. Theoretical studies performed by Teh (*20*) lead to the same conclusion and indicate that the solution improves for locations away from the shoulder area of the cone.

Calculated K_{LAB} values are also presented in Figure 7 and would appear to provide a lower bound to the range of measured lateral stress coefficients.

EMPIRICAL CORRELATIONS TO OBTAIN K_o

Various empirical correlations exist for evaluating K_o coefficients in cohesive soils. Probably the most widely used are those suggested by Brooker and Ireland (*21*) and Mayne and Kulhawy (*22*). Those methods estimate the overconsolidated K_o value from a relationship between PI, $(K_o)_{nc}$, and OCR, usually based on laboratory-derived correlations (K_{lab} in Figures 6 and 7). Reasonable estimates of $(K_o)_{nc}$ can be obtained by using index properties of the soil. Stress history is the main factor to be evaluated. Recently, various methods have been proposed for evaluating stress history from CPTU (*25,18*). Undrained shear strength data can also provide good estimates of OCR (*26,27*). Once the stress history (OCR) and $(K_o)_{nc}$ have been ascertained,the empirical relationship described can be employed to evaluate $(K_o)_{oc}$.

The method proposed by Sully et al. (*18*) relates the OCR of the soil to a pore pressure difference parameter (PPD) defined as

$$\text{PPD} = \frac{u_1 - u_2}{u_o} \quad (6)$$

where

- u_1 = the penetration pore pressure measured on the face of the cone,
- u_2 = the pore pressure measured behind the cone tip, and
- u_o = the equilibrium in situ pore pressure.

measured pore pressures are a function of both soil (PI, G, S_u, K_o, OCR, S_t) and cone characteristics.

The pore pressure gradient around the cone tip is related to $u_1 - u_2$ and, thus, also to q_t; that is,

$$u_1 = f_1(q_t) \quad (7)$$

$$u_2 = f_2(q_t) \tag{8}$$

Because the cone resistance is a function of the in situ horizontal effective stress, as was discussed earlier, it follows that

$$u_1 - u_2 = f_4\,(q_t) = f_5\,(\sigma'_h) \tag{9}$$

Therefore, the normalized pore pressure parameter (PPSV) can be defined as

$$\text{PPSV} = \frac{u_1 - u_2}{\sigma'_{vo}} = f_6\,(K_o) \tag{10}$$

The PPSV-K_o data for Strong Pit is presented in Figure 8. The PPSV parameter appears to map directly onto the best fit variation of K_o.

The same data for Lower 232 St. are presented in Figure 9. For this site the correlation is not 1–1 (PPSV = 2 K_o), but similar depth trends are shown. Data from other clays are being evaluated to determine other factors that affect the PPSV-K_o correlation (Figure 10).

CONCLUSIONS

The evaluation of stresses and pore pressures induced during full displacement penetration has shown that measurements at any particular site are dependent on soil and probe characteristics. For flat plate penetrometers, the excess pressures appear to correlate well with the degree of displacement. However, location of the stress or pore-pressure sensor and

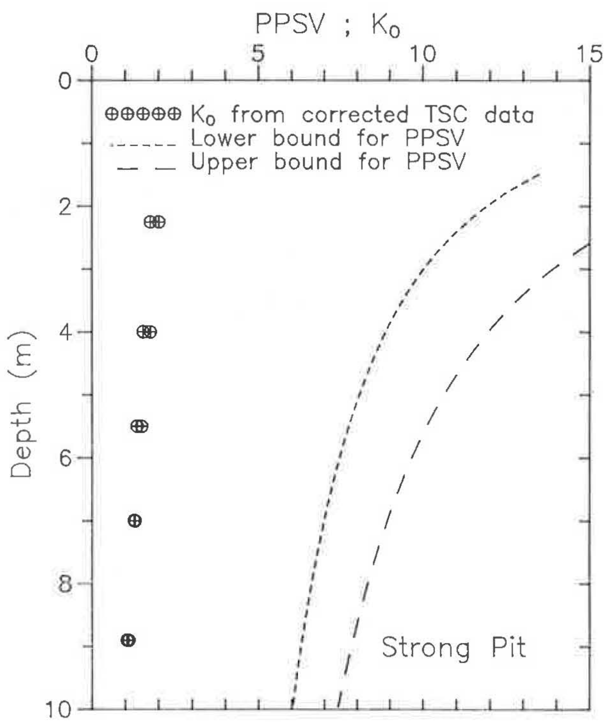

FIGURE 8 Correlation between PPSV and K_o for Strong Pit.

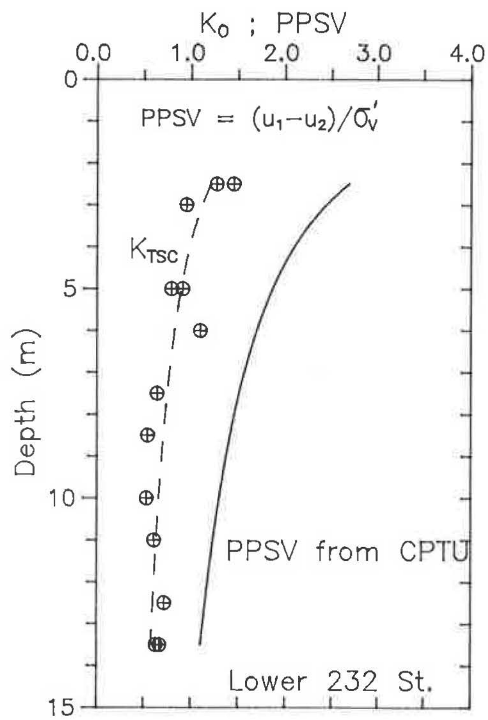

FIGURE 9 Correlation between PPSV and K_o for Lower 232 St.

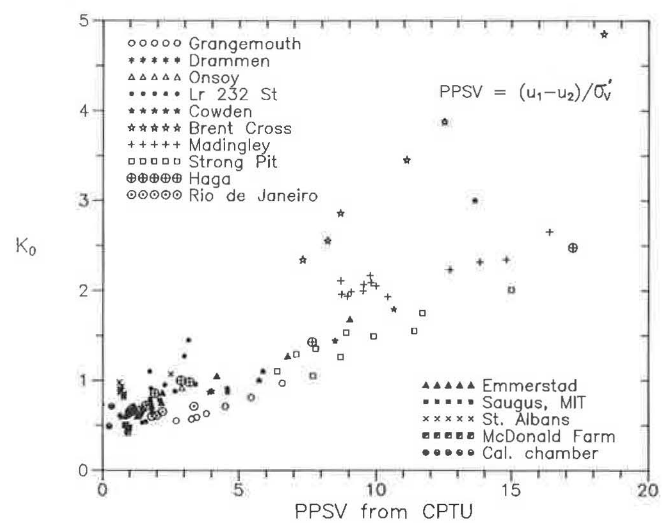

FIGURE 10 PPSV-K_D correlation for clays.

its geometry appear to have an important influence. This is confirmed by results obtained with the stepped blade. For successive increases in blade thickness the zone of unloading around the step shoulder extends farther back because of the progressively higher stress levels involved. This causes discrepancies between the measured step stresses and consequently problems in the extrapolation of σ_{ho} arise. The problem may possibly be resolved by maintaining a constant ratio between blade thickness and distance of the sensor behind the shoulder.

Where cylindrical probes are used, it appears that, provided the lateral stress and pore pressure sensors are at least 12D behind the cone shoulder (*13*), stress and pore pressure measurements are comparable provided no local unloading/reloading occurs owing to changes in section geometry near the sensors. The application of cylindrical cavity expansion theory to interpret stresses measured at remote locations on the shaft may provide rational estimates of the in situ pre- and postpenetration stress conditions. Further studies are being conducted to verify this finding.

On a more general note, as was discussed by previous researchers, the definition of K_o is problematical especially for near-surface data, where small errors in either σ'_h or σ'_v can cause large changes in K_o. Similar problems were encountered when defining pore pressure parameters from CPTU (*5*). In that case, a pore pressure difference parameter was found to be more convenient. To correlate the results of numerical analyses for differing stress ratios, Houlsby and Teh (*28*) define a horizontal stress factor in clay, Δ, based on a normalized stress difference:

$$\Delta = \frac{(\sigma_v - \sigma_h)}{2\,S_u} \tag{11}$$

The adoption of a similar expression for in situ data may provide more consistent parameter correlations for soils with near-surface overconsolidated crusts.

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