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R & D OF A LATERAL STRESS PIEZOCONE

BY

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ABSTRACT

The possibility of evaluating in situ horizontal stress during cone penetration has been suggested by recent laboratory calibration chamber research (3,8,9,10,11,13). This has been confirmed by field trials with lateral stress sensing cones. This paper describes a lateral stress piezocone developed at UBC. Detail is given of the laboratory calibration procedures and corrections for cross talk and temperature effects. Field data from two Lower Mainland sites are presented in order to evaluate the amplification of lateral stress that occurs in sands during penetration of full-displacement probes. The results suggest that lateral stresses measured in granular soils with the LS cone are dependent on, inter alia, the existing horizontal stress, in situ state of the sand and its grain characteristics.

INTRODUCTION

Recent research into the behaviour of granular soils during cone penetration has highlighted the importance of the existing in situ horizontal effective stress (σ'_h) on the parameters being measured. Laboratory measurements made using calibration chambers (CC) have demonstrated the effects of in situ stress state on both cone resistance and sleeve friction (1).

Similar effects noted for other penetration parameters are consistent with these findings.

The development of cones capable of measuring lateral stress originated from the idea that the sleeve friction measured during penetration in sand would be related to the pre-penetration lateral stress. Robertson (13) evaluated the CC data for sand presented by Baldi et al (1) and showed that the ratio of pre- and post-penetration horizontal stress, as deduced from sleeve friction measurements, varied from 1 to 7 and was related to the maximum dilation angle of the soil. The data were obtained for the friction sleeve located directly behind the tip. The CC tests were performed under conditions of constant lateral stress (BC1).

Huntsman (8) reviewed similar Italian CC data and related σ'_h and sleeve friction, f_s, by means of the relative density, D_r, of the sand. Two sets of data were presented corresponding to the boundary conditions of constant lateral stress (BC1) and zero lateral strain (BC3). The scatter in the results is appreciable; however, the data trends do illustrate the effect of boundary condition on the σ'_h-f_s correlation (Fig. 1). It also indicates that at low relative densities the measured sleeve friction is less sensitive to the applied boundary condition. The true correlation representing "in ground" conditions probably lies somewhere between the two data sets shown in Fig. 1 and can be estimated by applying the appropriate chamber corrections.

Based on the above findings, several types of cone penetrometer have been produced capable of measuring the lateral stress acting on an underreamed section of a friction sleeve, namely:

- lateral stress sensing cone penetrometer (8)
- horizontal stress cone (10).

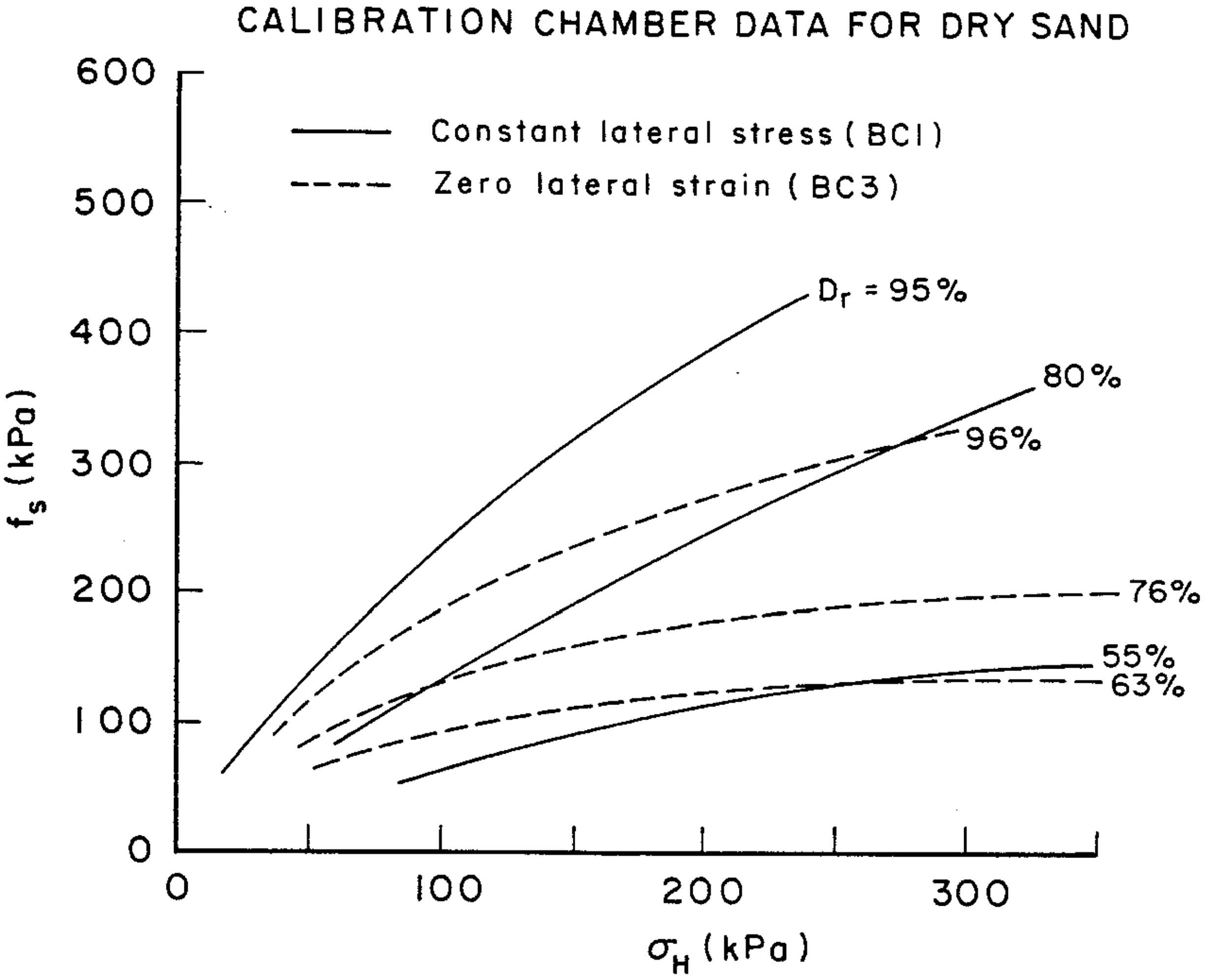

Fig. 1 Influence of relative density on f_s-σ_h' relationship from CC test data (after Huntsman, 1985)

A similar type of instrument designed specifically for evaluation of pile capacity in cohesive soils - the piezo lateral stress cell - has been built and tested at MIT (2).

This paper describes a lateral stress (LS) piezocone designed and built at the University of British Columbia (UBC) for use as part of a research project into the evaluation of in situ lateral stress from full displacement probes.

DETAILS OF LATERAL STRESS PIEZOCONE

The lateral stress (LS) piezocone designed and built at UBC comprises two separate measurement systems; a standard UBC piezocone unit followed by a lateral stress module. The 8 channel cone has a tip area of 15 cm^2, a friction sleeve area of 225 cm^2 and allows the simultaneous measurement of the following parameters:

- cone resistance, q_c (bar)
- pore pressure on the face, u_1, or behind the tip, u_2 (m of water)
- sleeve friction, f_s (bar)
- pore pressure behind the friction sleeve, u_3 (m of water)
- temperature (°C)

The above channels operate over a 7.5 V range. The calibration factors for each channel are given in Table 1. The lateral stress module, which essentially consists of an instrumented friction sleeve, is located 0.69 m behind the tip and permits the following values to be recorded:

- sleeve friction, LS-FS (bar)
- pore pressure, u_{LS} (m of water)
- lateral stress, σ_{LS} (kPa)
- temperature (°C)

TABLE 1. Calibration data for LS piezocone

Channel No.	Parameter	Units	Calibration Factor
1	Cone resistance	bar	0.13 bar/mV
2	Sleeve friction	bar	0.013 bar/mV
3	Lower pore pressure	m of water	0.23 kPa/mV
4	Upper pore pressure	m of water	0.23 kPa/mV
5	Temperature	degree C	*
6	LS-FS	bar	0.013 bar/mV
7	LS-PP	m of water	0.23 kPa/mV
8	σ_{LS}	kPa	1.44 kPa/mV

* Temperature in degrees Celsius is obtained from $(V_T x4)-11$ where V_T is the voltage measured from a resistance temperature device (RTD).

Even though two temperature sensors are located in the LS-CPTU, only the temperature at the lateral stress module position is recorded when the cone is being used in this format.

The transducer ranges are again 7.5 V for all the channels except the lateral stress channel which operates on 1 V full scale. The choice of location for the lateral stress module requires some comment.

Design Considerations

Previous studies into soil behaviour have demonstrated that large gradients of both stress and pore pressure exist around a penetrating cone and that these gradients are related primarily to the geometry of the equipment. In effect, the singularity at the base of the cone tip causes a large normal stress reduction to occur as the soil passes the shoulder. The extent of the reduction has been experimentally evaluated with respect to pore pressures (5) but little information exists with respect to lateral stress reduction and the relative importance of stress redistribution and creep. For sands, indirect evidence based on the variation of average sleeve friction, f_s, with distance (4) suggests that at approximately 12D (D = diameter of cone) behind the tip, the lateral stress should be essentially constant for any particular D_r.

Location of the lateral stress sensor close to the tip would require measurement in an area of highly variable stress. Furthermore, at this location dimensional tolerances may have unacceptable effects on the measured values, i.e., a slightly undersized friction sleeve will promote a larger stress reduction whereas an oversized sleeve will reduce the unloading effect. Strain rate changes near the tip and rotation of principal stresses may also be important. This aside, both Huntsman (8) and Jefferies, Jönsson and Been (10) present data where the lateral stress measured during cone penetration by a sensor located 1 D behind the tip corresponds remarkably well to results of self bored pressuremeter tests. This is surprising considering the disturbance caused by insertion of the cone and may well result from the loose nature of the soils tested. When penetration is stopped, however, the tests performed by Huntsman in the Beaufort Sea (8) show a slight increase in measured total lateral stress with time. This increase may result from redistribution and/or dissipation of excess pore pressures generated during penetration. However, no pore pressure measurements are available to confirm this.

The location of the sensor close to the tip is advantageous where reference tests are performed in calibration chambers. Calibration of an upper stress sleeve is not possible due to the limited penetration distance resulting from chamber size. CC data suggest that the measured lateral stress is always lower when measured close to the tip. Field data from the Beaufort Sea indicate that the difference between the stresses measured behind the tip (1 D) and up the shaft (8 D) decreases with depth, becoming equal at approximately 20 m (8). However, the relative magnitudes of σ_{LS} would depend on the location and spacing of the lateral stress sensors.

No CC facility exists at UBC and consequently it was planned to calibrate the lateral stress cone initially in the laboratory and then in the field at sites where the K_o condition was approximately known. As such, the geometry of the cone in terms of sensor location was not a restriction.

Finally, with a view to developing some kind of theoretical interpretation, it is reasonable to expect that data obtained away from the tip may more closely represent conditions of cylindrical cavity expansion. Stress changes near the tip may cause significant deviation from the cavity expansion condition.

Details of LS Module

For the UBC lateral stress piezocone the sensor is located 0.69 m (15.6 D) behind the cone shoulder (Fig. 2). The lateral stress sleeve is 88 mm long and 44 mm in diameter (surface area of 121.6 cm^2), with a wall thickness of 3 mm. At the centre of the sleeve, a 20 mm long section has a reduced wall thickness of 1 mm. An arrangement of strain gauges is oriented at this location to measure the hoop stress in the section induced by the lateral stress acting on the sleeve. Several different gauge arrangements

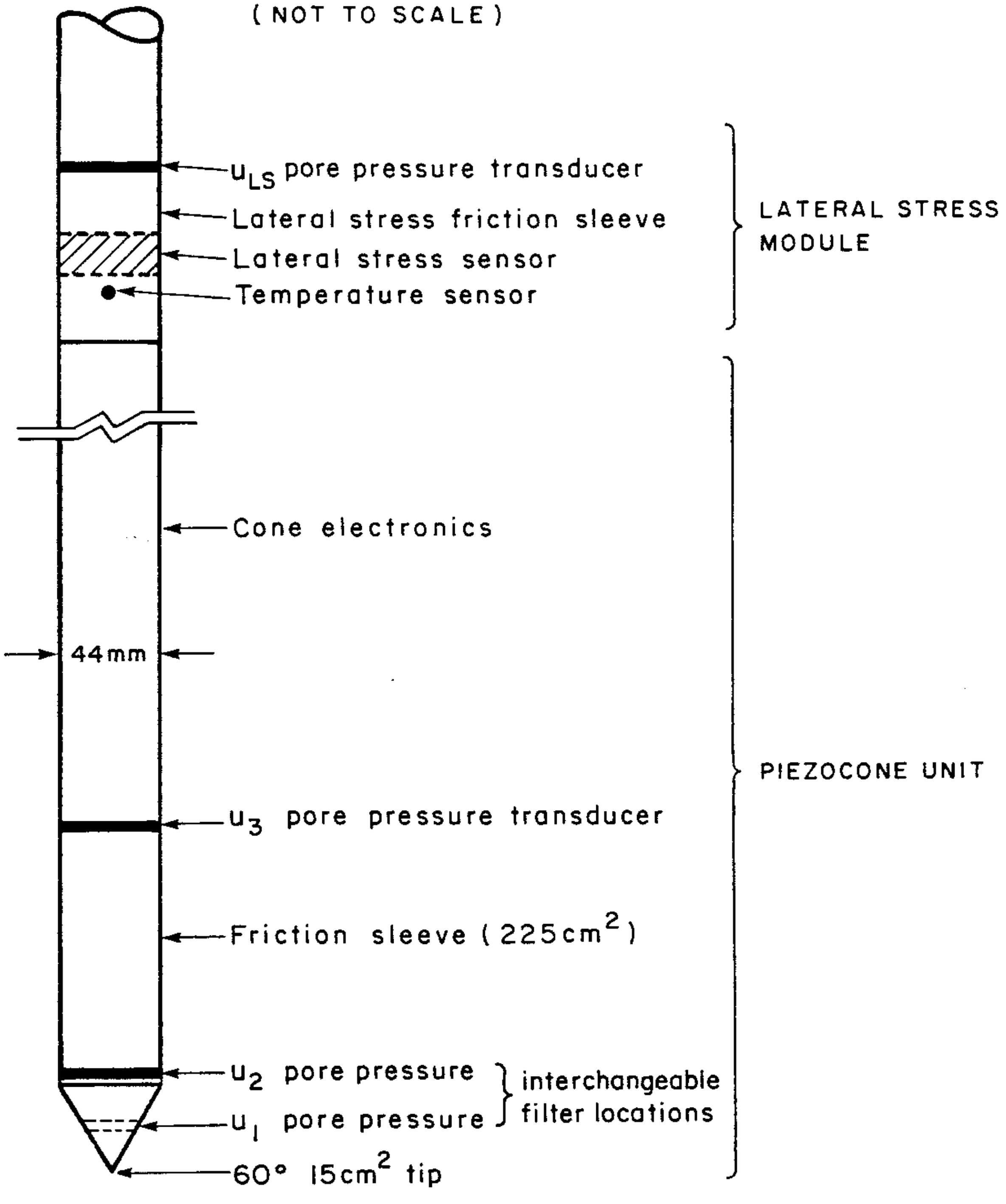

Fig. 2 LS cone details

were tested to optimize the lateral stress response and minimize both temperature and friction cross talk effects.

A full bridge configuration is mounted on the sleeve. Each arm of the bridge consists of two 1000 ohm strain gauges. The active arms are located on the thin walled section of the sleeve whereas the inactive arms are on the thicker section. The current design remains temperature sensitive to some degree and consequently a platinum RTD sensor has been installed in the sleeve to allow for temperature compensation corrections to both the lateral stress and sleeve friction measurements.

The differential signals from the lateral stress gauges are amplified in the cone to give a full scale output of 1 volt for an external hydrostatic pressure of approximately 1500 kPa. The analog signals are converted at the surface to a 12 bit representation of their voltage giving a sensitivity of 4.9 mV or 7.4 kPa of lateral stress. The IBM PC based data acquisition system (UBC DAS) consists of an analog to digital (A/D) converter, depth controller board, counter timer board and a battery backed-up power supply (6). A schematic layout of the UBC DAS is shown in Fig. 3.

The data acquisition program interfaces the various components of the system to provide a means of collecting and storing the data. Data storage is either on floppy or hard disk. The program operates in two modes: cone penetration and dissipation. The change to dissipation mode is automatic when penetration is halted.

LABORATORY CALIBRATION OF LSC

Laboratory calibration of the load cells and pore pressure transducers for the piezocone unit were performed according to standard procedures adopted at UBC. Only the laboratory calibration of the lateral stress module is considered here.

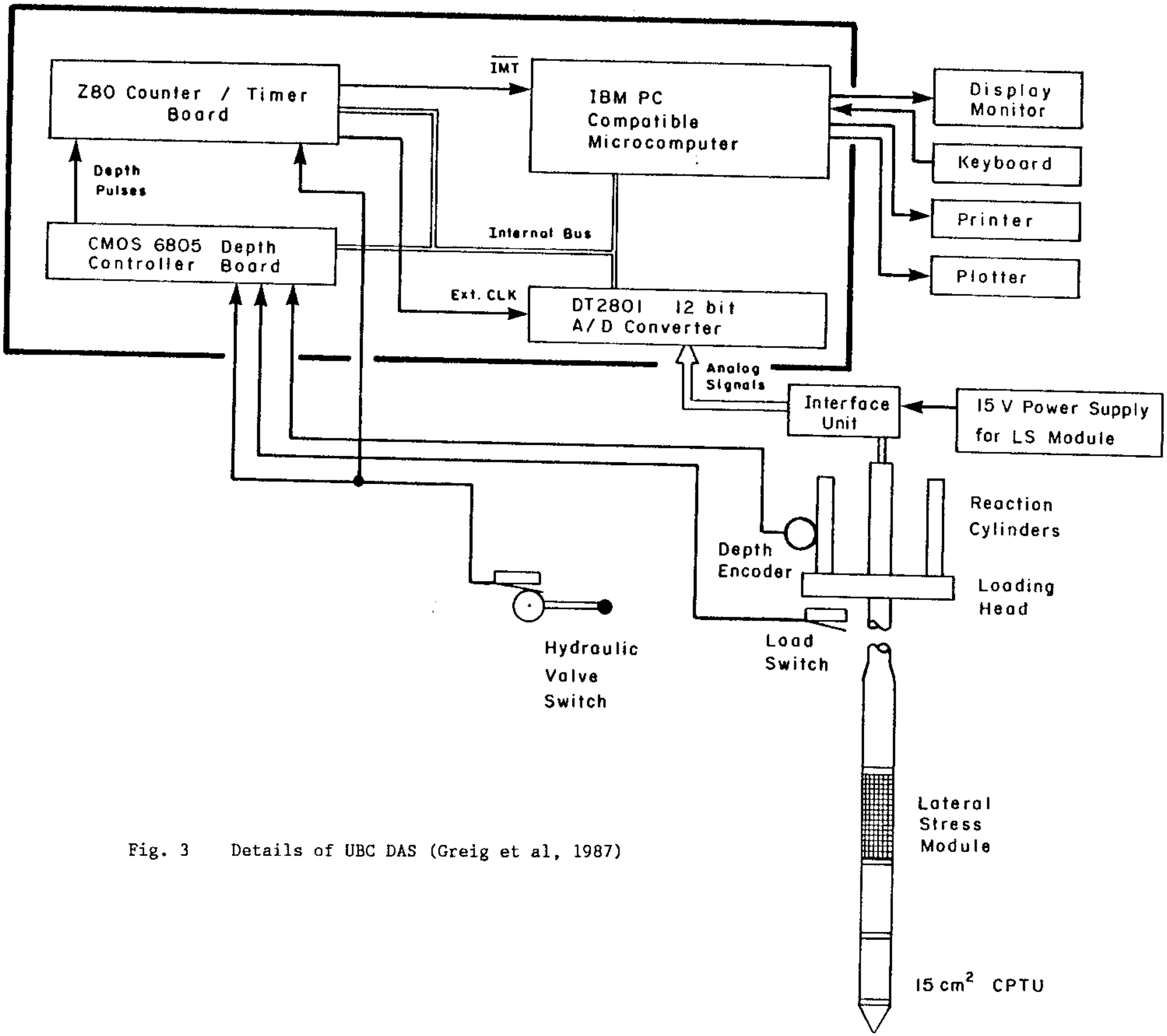

Fig. 3 Details of UBC DAS (Greig et al, 1987)

Due to the nature of the design of the module it was necessary to calibrate the module for the following conditions:

- hydrostatically applied confining pressure
- lateral stress cross talk on friction sleeve due to axial loads
- temperature sensitivity
- time-dependent stability of all channels.

During each of the calibrations performed, all eight cone channels were monitored to ensure the absence of channel interference.

Hydrostatic Calibration of LS Module

To calibrate the bridge output for applied hydrostatic pressure a special sleeve was fitted over the LS module and connected to a dead weight pressure tester. Pressure increments of 20 psi (∿138 kPa) were used up to a maximum of 250 psi (1724 kPa) maintaining a constant temperature throughout. Hydrostatic loading and unloading sequences were performed for conditions of zero axial load. The results are shown in Fig. 4 which give a calibration factor of 0.000695 V/kPa or 1440 kPa/V, with little or no hysteresis effects and no baseline drift over full scale cycling. The factor was independent of temperature for the range of application (6-20°C).

Friction-Lateral Stress Cross Talk

Axial loading of the friction sleeve causes an output voltage on the lateral stress channel due to the Poisson effect. For the strain gauge arrangement employed, increasing sleeve friction on the LS sleeve causes a negative offset on the lateral stress channel.

The cone was set up in a frame so that the axially applied load was transferred by slip rings to the LS friction sleeve. Data from both the

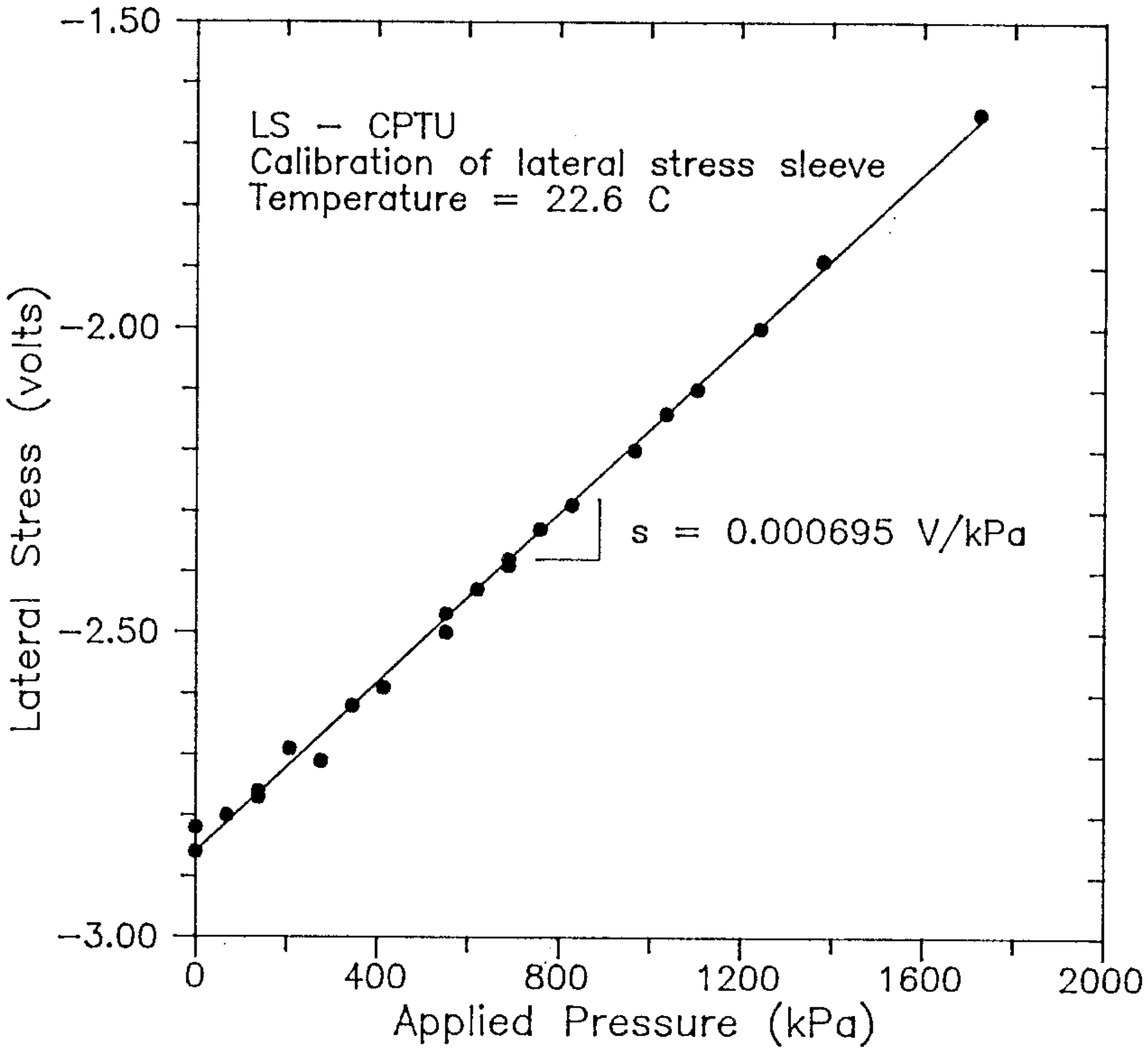

Fig. 4 Pressure calibration of LS module

lateral stress and sleeve friction channels were recorded by means of an HP7090A measurement plotting system. The load-unload was performed under zero confining pressure over a period of approximately 1 minute with readings taken every 0.1 sec. Linear regression of the data gave gradients of -0.2136 and -0.2150 for loading and unloading (Fig. 5). A correction factor of 0.807 is applied to the slope in Fig. 5 which takes into account the difference between the axial load distribution imposed for the laboratory calibration and actual field conditions.

An average value was used to correct the lateral stress data according to the equation:

$$(V_{LS})_C = (V_{LS})_M + [0.2143 * V_{fs}] \tag{1}$$

where

$(V_{LS})_C$ = corrected relative lateral stress voltage

$(V_{LS})_M$ = measured relative lateral stress voltage

V_{fs} = relative sleeve friction voltage.

Calibration for Temperature Effects

To evaluate the temperature sensitivity of the LS module, the whole cone was immersed in a bath of ice water and was left to warm to room temperature over a 24 hour period during which time readings on all channels were taken every minute. The results for the LS channel are shown in Fig. 6. The temperature coefficient, B_T, for the LS channel was calculated to be +3.6 mV/°C on cooling. (Similarly, temperature coefficients were also evaluated for other channels.)

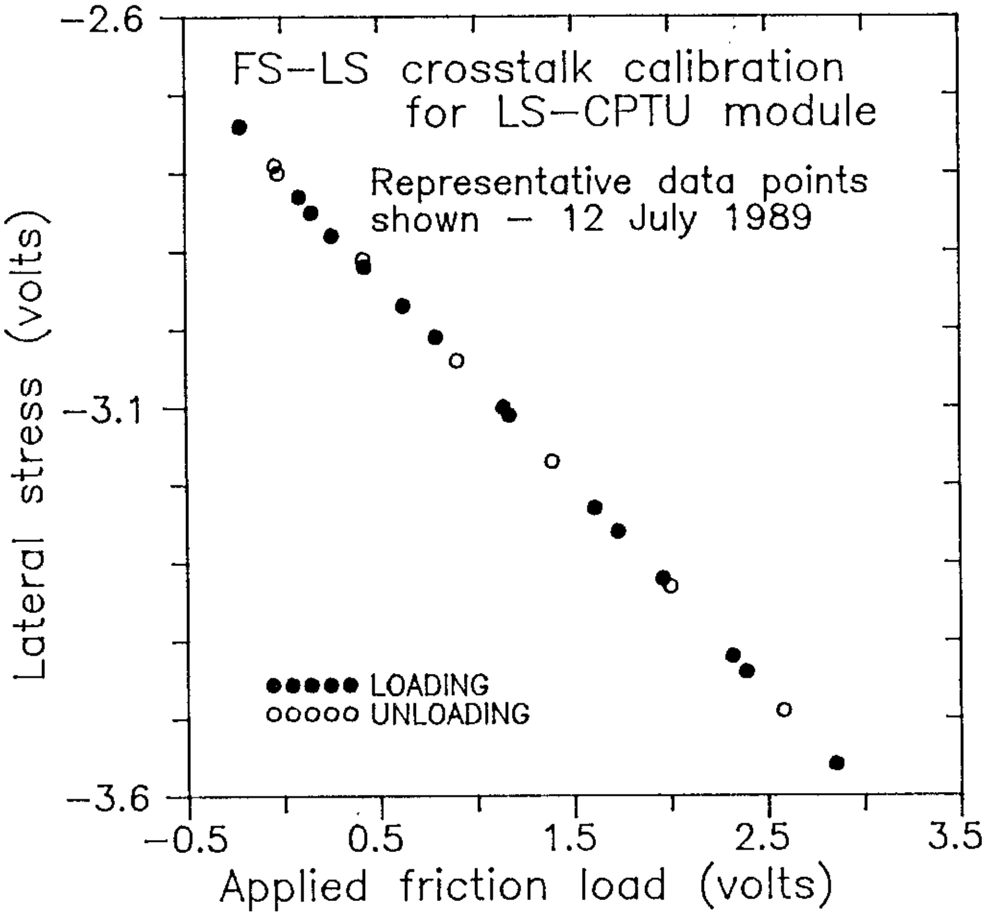

Fig. 5 Evaluation of cross talk on LS channel due to axial friction load

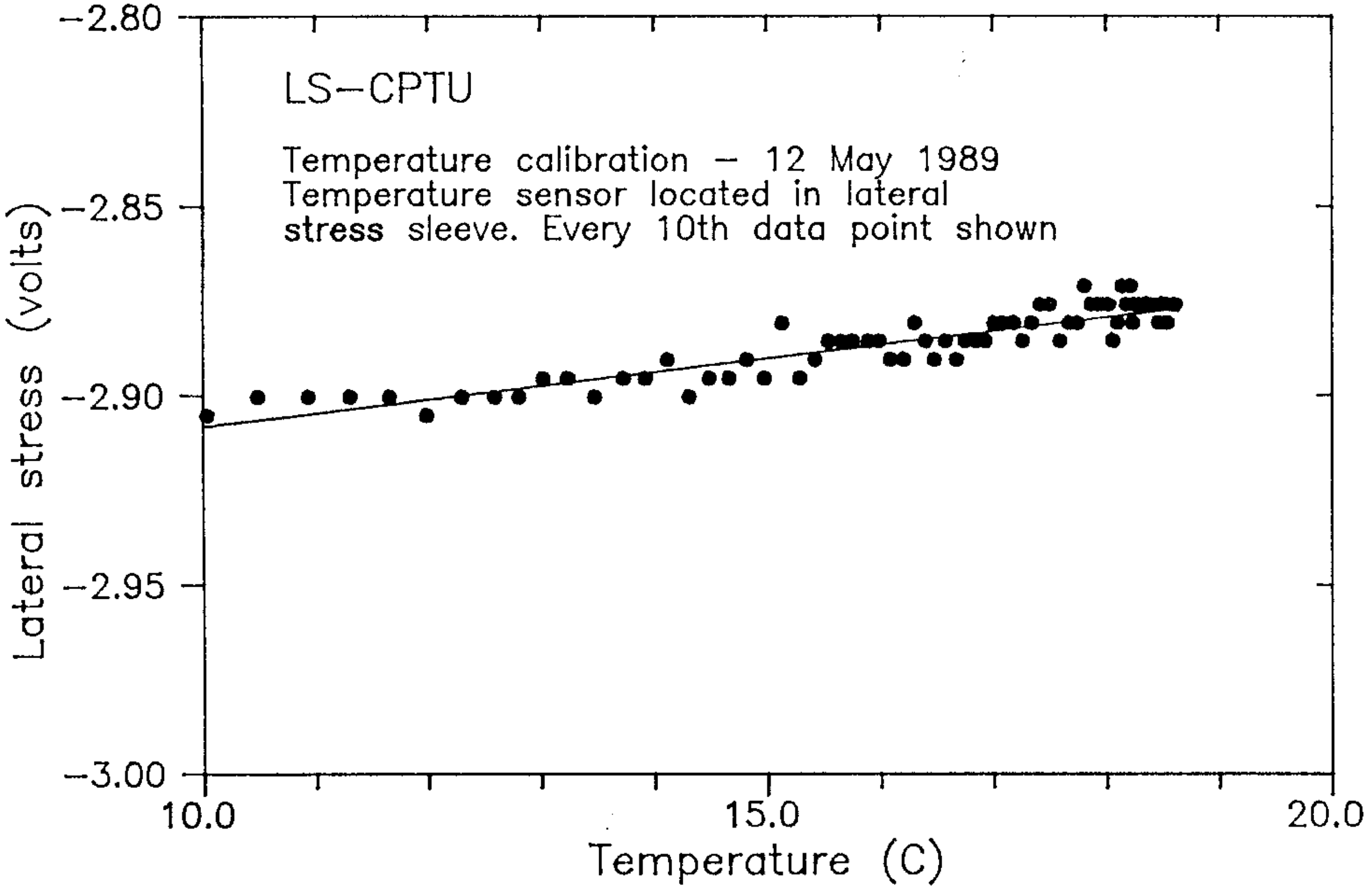

Fig. 6 Temperature sensitivity of LS baseline

Evaluation of Baseline Drift

During the latter part of the temperature calibration, when the system was in equilibrium with the ambient temperature, continued monitoring allowed baseline drift on each channel to be evaluated. For all eight channels, the time dependent drift was found to be negligible.

The calibration factors obtained as outlined above have been incorporated into the data acquisition program so that the output is given in corrected engineering units.

FIELD CALIBRATION OF LS PIEZOCONE

As mentioned previously, it was decided to perform a field calibration of the LS cone equipment at UBC test sites where information on lateral stress conditions was available. For the purpose of this paper, only tests in granular soils are considered. Data obtained in cohesive soils are presented in a companion paper to this symposium (17).

The lateral stress measured during cone penetration is generally larger than the pre-penetration in situ horizontal stress. This results from the full-displacement mode of insertion whereby soil is displaced both laterally and vertically to permit penetration of the cone. Consequently, an overall stress increase around the penetrating cone usually occurs and it is this value that is measured by the instrumented sleeve. The magnitude of the measured stress increase depends on the location of the sensor, geometry of the probe and soil characteristics. For a particular probe the stress increase can thus be related to one or more soil parameters.

Previous studies have suggested that the stress increment due to full displacement penetration in granular soils is a function of one or more of the following:

- relative density of the soil, D_r (8)
- peak friction angle, ϕ, or maximum angle of dilation, μ (13)
- voids ratio, e (10)
- state parameter, ψ (8,10)

The state parameter/voids ratio approach has been used primarily for evaluating CC data where sample characteristics can be controlled and measured with acceptable accuracy (10). The application of the state parameter approach to in situ data appears promising but requires further confirmation. As suggested by Sladen (15), the approach may necessitate additional specialized in situ tests to confirm the void ratios evaluated on the basis of CPT data, i.e, nuclear density/electrical resistivity voids ratio determinations. It also requires, a priori, knowledge of the in situ lateral stress.

A considerable data base exists for estimating both relative density and peak friction angle from CPT data. The use of either one of these parameters would also concur with the philosophy of field calibration. Alternatively, correlation with the ratio q_c/σ'_v would appear logical as the dependence on a CC derived relationship is removed.

Description of Test Sites

Data from two UBC test sites in the Lower Mainland of British Columbia are presented where consistent information on K_o conditions exists, namely: Laing Bridge South (LBS) and McDonald Farm (MDF). The two sites are located on Sea Island at Vancouver International Airport, are about 1 km apart and have very similar characteristics. The sediments are post glacial Holocene deltaic deposits which are essentially normally consolidated. The surficial soils (<4 m) are underlain by granular marine and tidal flat deposits (medium sands) to a depth of around 20 m. The granular layer is finer grained, more uniform and deeper at LBS than at MDF. Underlying the sands are at least 40 m of soft to firm marine silts and clayey silts.

The variation of K_o for the LBS site is shown in Fig. 7 and has been evaluated by three empirical correlations (16). The K_o value varies between 0.45 and 0.5. Preliminary results obtained using the UBC self-boring pressuremeter confirm the K_o values shown in Fig. 7.

Data presented by Hughes and Robertson (7) from self-bored pressuremeter tests suggest that the LBS trend of K_o is a good lower bound for the McDonald Farm site, where an average coefficient of 0.6 is taken as representative for the normally consolidated sands.

RESULTS OF IN SITU TESTS

A summary of the measured cone resistance and lateral stress profiles for McDonald Farm (MDF) and Laing Bridge South (LBS) are shown in Figs. 8 and 9.

The trends in q_c at the two sites are notably different considering the proximity of the sites. At McDonald Farm the q_c values are reasonably constant over specific depth intervals within the sand. The gradual increase in q_c with depth at Laing Bridge is a good indicator of the uniformity of the sand at this location. At both sites the effects of interbedded silt on the cone resistance can be seen throughout the profile. Pore pressures throughout the profile are close to hydrostatic for both the behind friction sleeve (u_3) and lateral stress (u_{LS}) pore pressure sensor locations. Behind the tip (u_2), a small excess pore pressure is measured. At around 14 m, the anomalously high q_c results from the presence of an organically cemented sand layer, a remnant of an active beach deposit. At the base of the sand layer

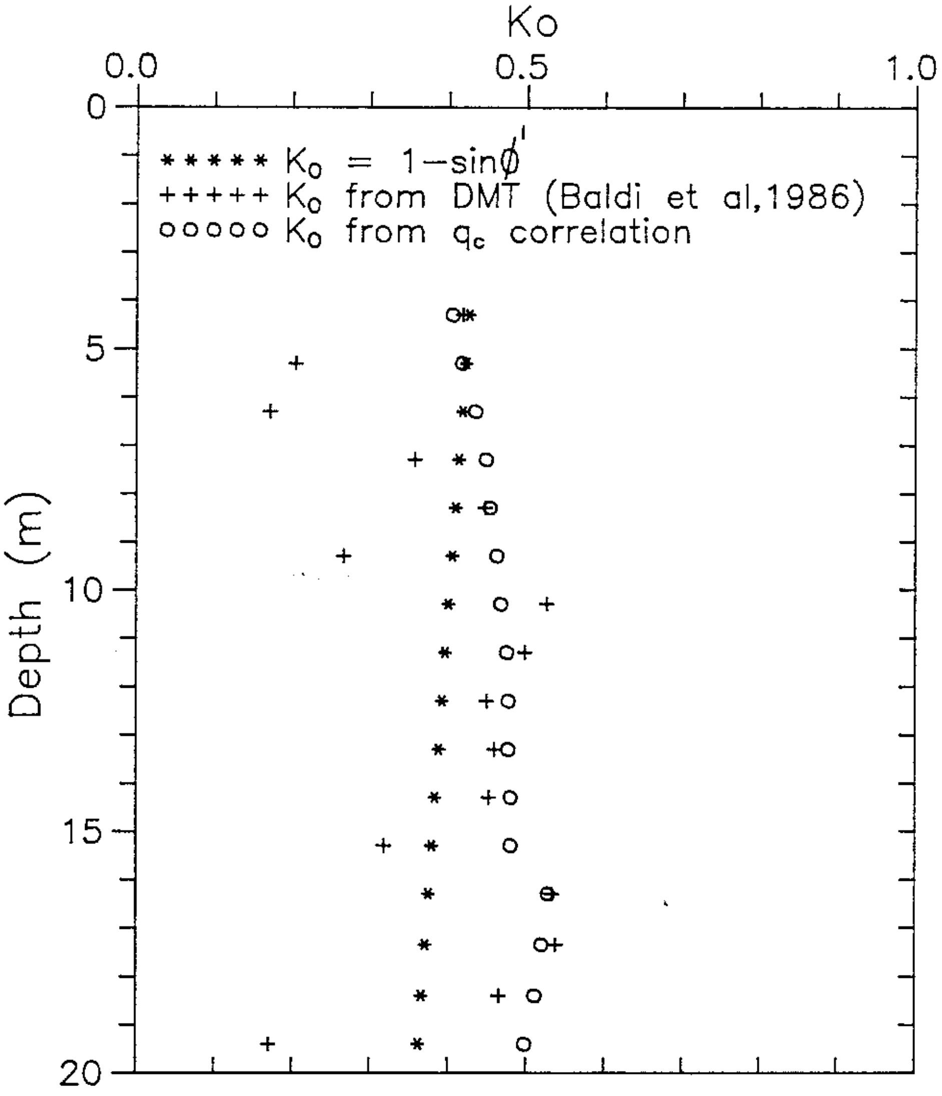

Fig. 7 Evaluated K_o conditions for Laing Bridge South

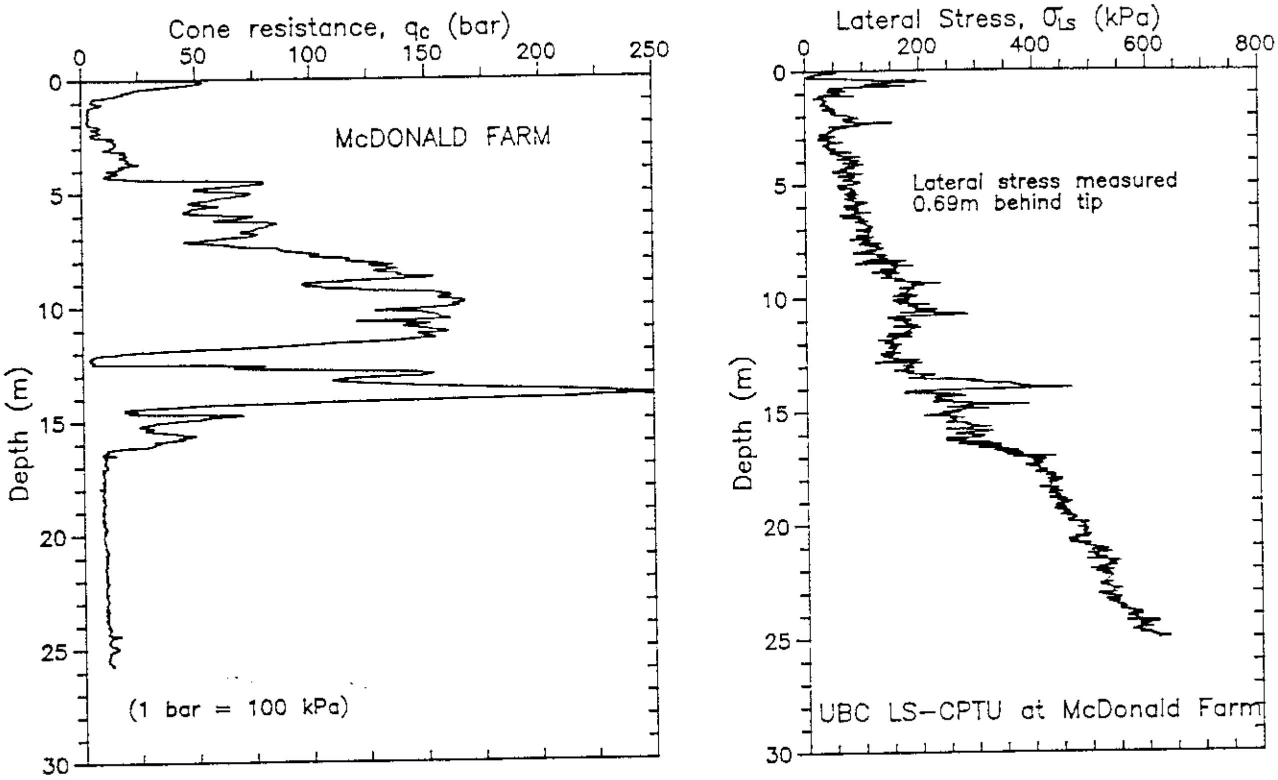

Fig. 8 LS-CPTU results at McDonald Farm

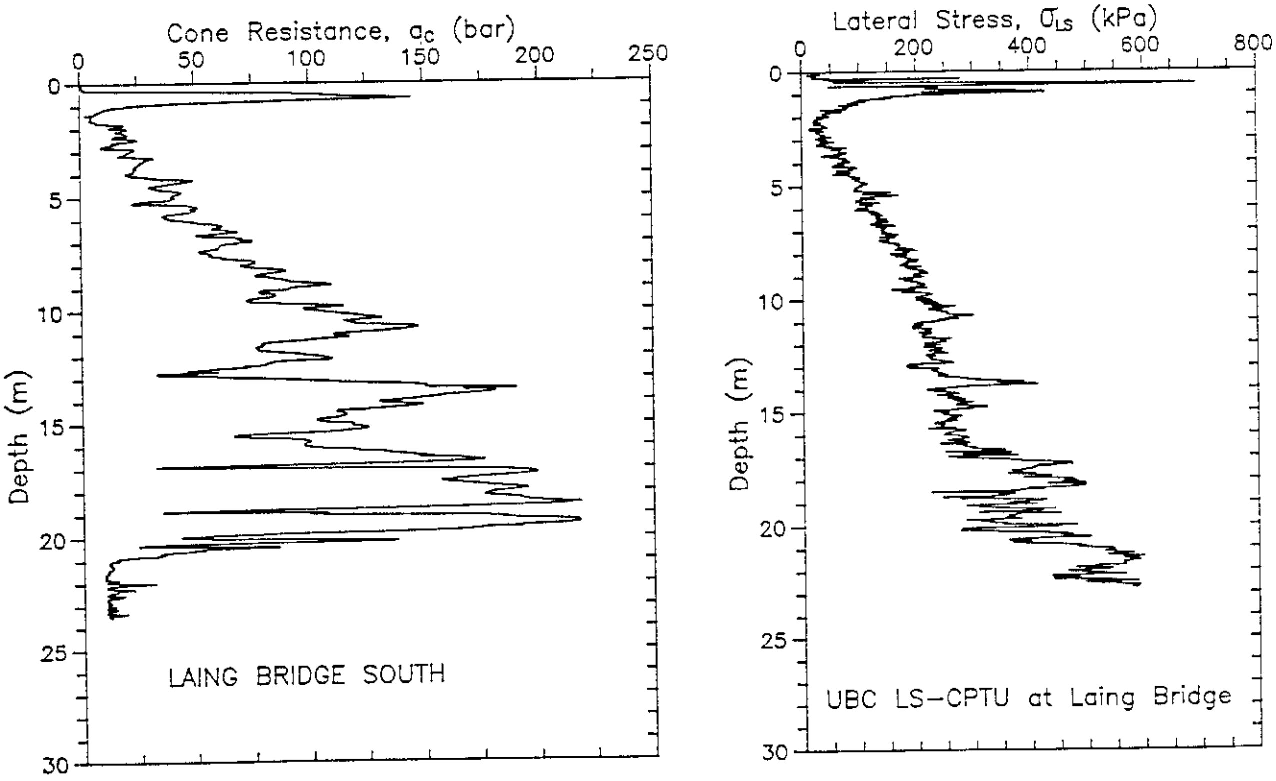

Fig. 9 LS-CPTU results at Laing Bridge South

the q_c values drop rapidly to around 10 bar and large excess pore pressures are recorded indicating the presence of the soft normally consolidated clay silt.

The lateral stress profiles measured by the LS cone at the two sites are also shown on Figs. 8 and 9. Contrary to the relative magnitudes of cone resistance, the measured total lateral stress, σ_{LS}, in the sand layer at Laing Bridge is consistently larger than that at McDonald Farm. The σ_{LS} profiles are otherwise very similar. At both sites, the variation in measured σ_{LS} is increased in the transition layer between the sand and clay silt.

A comparison of average friction stress measured at the two sleeve locations is shown in Fig. 10 for Laing Bridge South. Good agreement between the two measurements is evident which concurs with the distribution suggested earlier by Campanella and Robertson (4). This also suggests that the lateral stress measurements at the 15.6 D position might be similar to those at the 1 D location previously investigated. This conclusion however would depend on the stress gradient behind the tip and the exact location of the lateral stress sensing section in relation to the stress distribution.

The penetration pore pressures measured at the three sensor locations, i.e. behind tip, behind friction sleeve and at lateral stress sleeve, are presented in Fig. 11 for the McDonald Farm LS-CPTU. The similarity of the pore pressures measured behind the friction sleeve (u_3) and at the lateral stress section (u_{LS}) indicate the absence of large gradients once away from the tip-shoulder singularity. It is also apparent when comparing Figs. 8 and 11 that the measured lateral stress in fine grained materials is dominated by the pore pressure response.

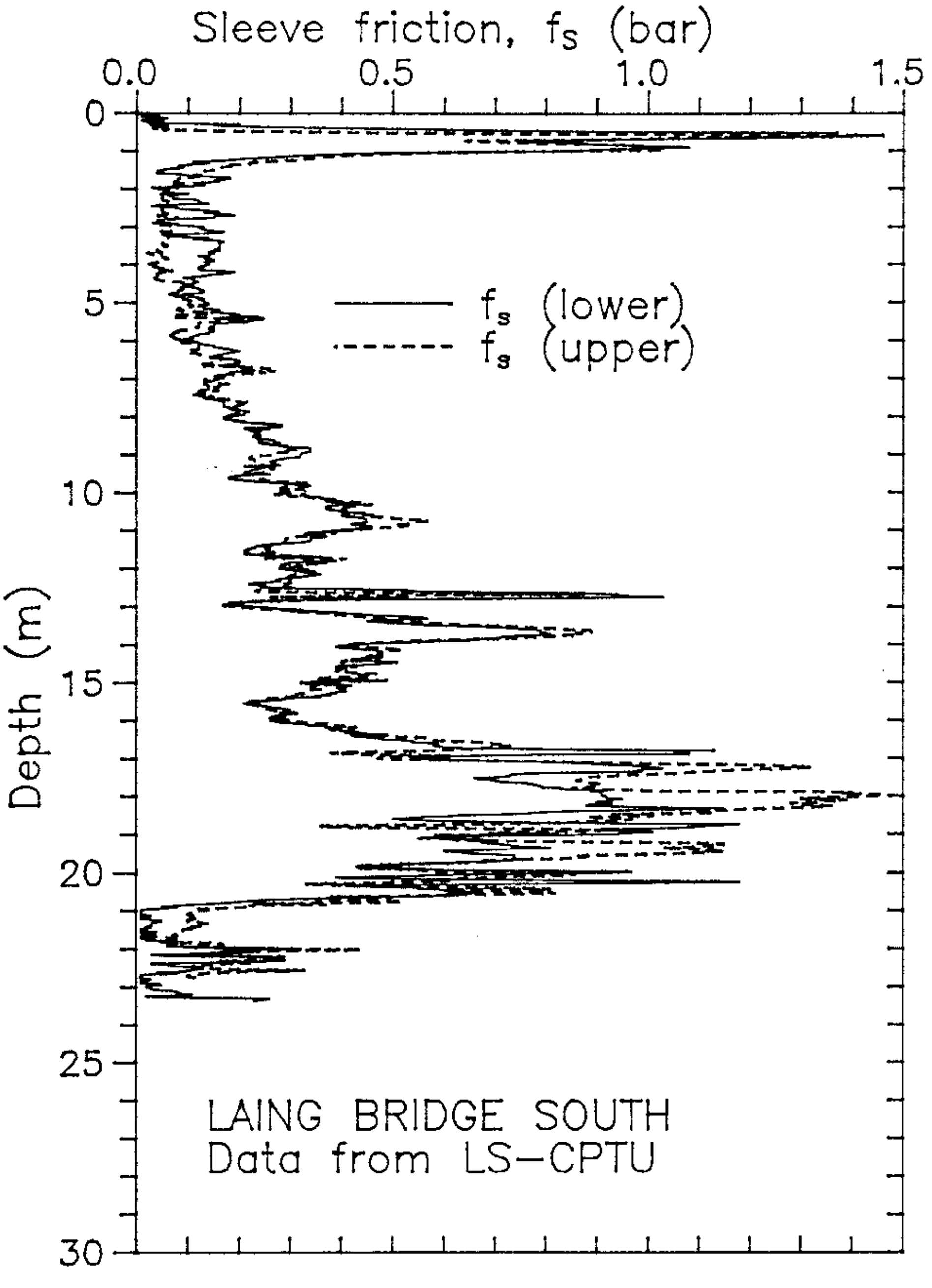

Fig. 10 Comparison of average sleeve friction measured at two locations on LS cone

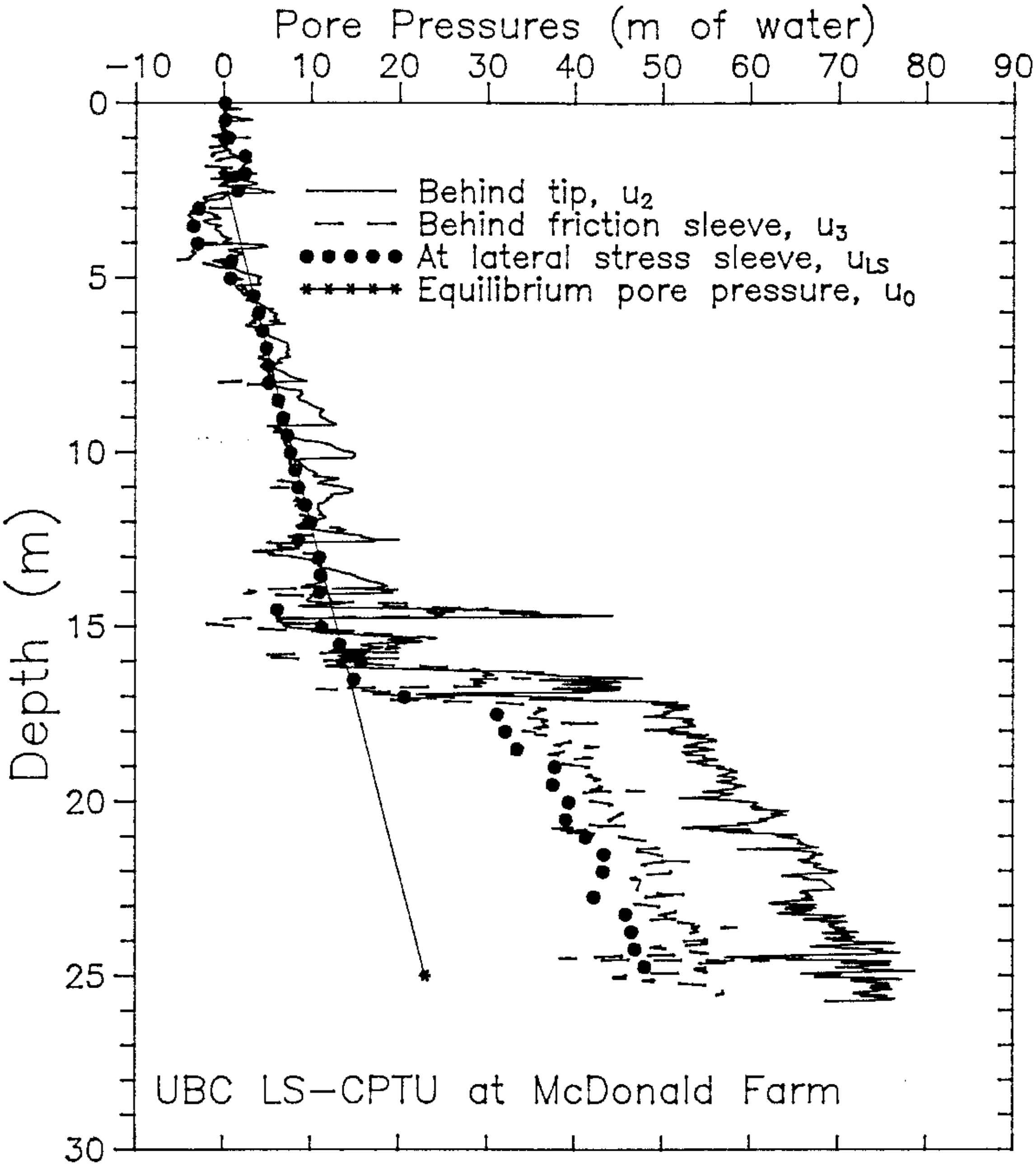

Fig. 11 Pore pressures measured during LS-CPTU

Lateral Stress Coefficient from LS-CPTU

The lateral stress coefficient obtained from LS-CPTU profiling, K_{LS}, is defined as:

$$K_{LS} = \frac{\sigma_{LS} - u_{LS}}{\sigma'_v} \qquad (2)$$

where

σ_{LS} = measured total lateral stress

u_{LS} = penetration pore pressure measured at lateral stress section

σ'_v = calculated effective overburden pressure.

Statistical filtering of calculated K_{LS} values at 2.5 cm intervals was performed over a 25 cm window. All data outside 1 standard deviation of the median was removed and replaced by the mean value (19). The filtered profiles of K_{LS} for both sites are shown on Fig. 12, where it can be seen that in general $K_{LS} > K_o$. To evaluate the amplification of lateral stress caused by cone penetration, the effective lateral stress in Fig. 12 has been normalized with respect to the in situ σ'_h and replotted in Fig. 13 against q_c/σ'_v. The amplification factor for the lateral stress cone, A_{LS}, is defined as:

$$A_{LS} = \frac{\sigma'_{LS}}{\sigma'_h} = \frac{\sigma_{LS} - u_{LS}}{\sigma_h - u_o} \qquad (3)$$

where

σ'_h is the pre-penetration effective horizontal stress

u_o is the equilibrium in situ pore pressure.

By definition:

$$K_o = \frac{K_{LS}}{A_{LS}} \qquad (4)$$

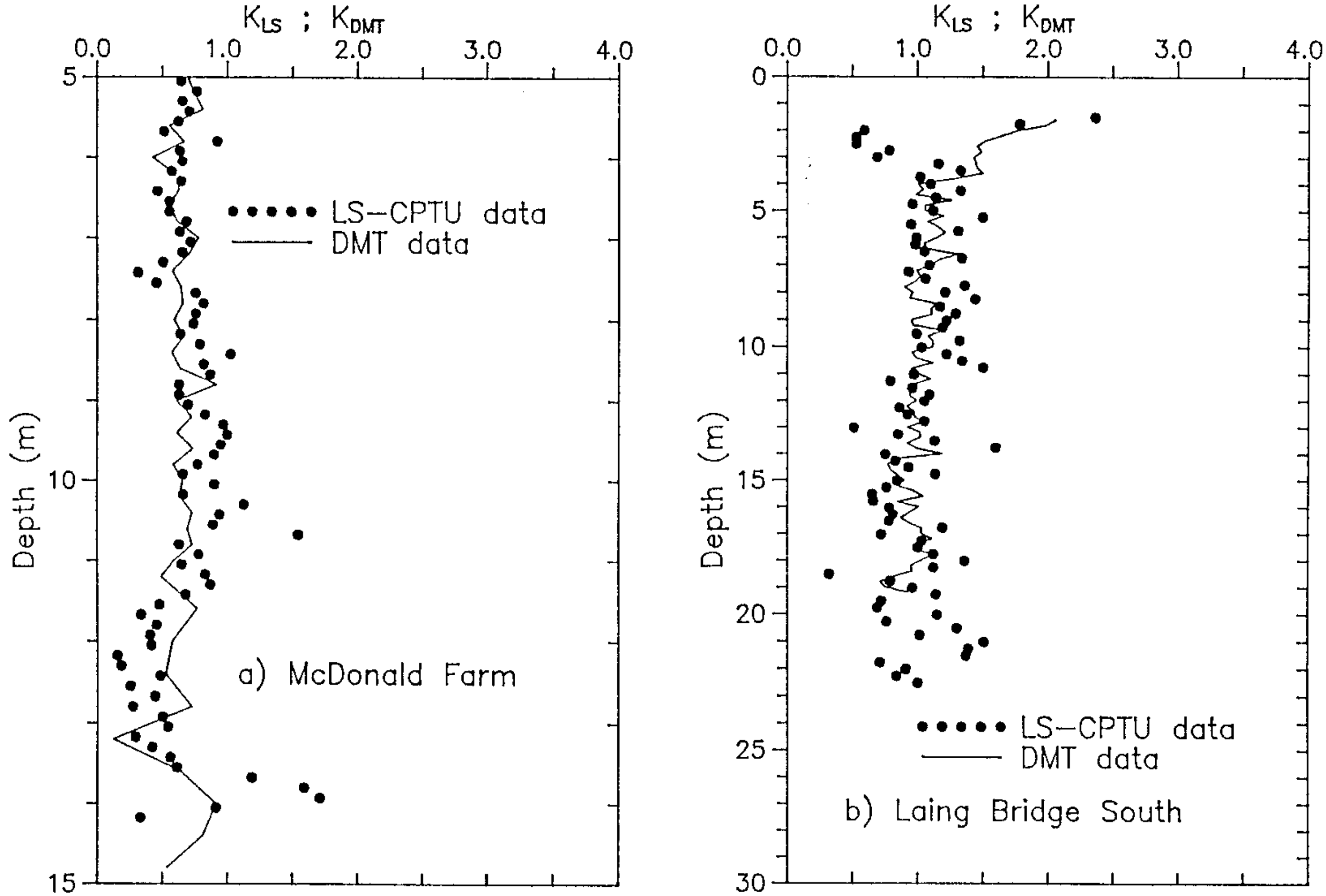

Fig. 12 K_{LS} factors for test sites

The basis of obtaining σ'_h was discussed earlier. Use of q_c/σ'_v as an index parameter appears logical since it is related to the principal soil behaviour characteristics which are thought to control the stress amplification effect (8,10,13). Furthermore, q_c is a parameter which is measured during the LS-CPTU and correlates directly with the σ_{LS} values measured, i.e. at the same location.

Two effects are apparent from the trends shown in Fig. 13:

- the amplification factor, A_{LS}, is very sensitive to small changes in q_c/σ'_v ratio.
- the shape of the $A_{LS}-q_c/\sigma'_v$ relationship appears to be similar for the two sites studied; however, the curves are offset laterally due to some secondary effect.

The position of a tentative curve for data obtained in silt/silty sand is also shown. This further suggests that grain size characteristics (D_{50}, silt content, grain angularity) of the sand may be important factors when evaluating lateral stress amplification factors in the manner used here.

DISCUSSION

The results obtained in this study agree with other data trends obtained from calibration chamber tests and interpreted to evaluate lateral stress from full-displacement tests (3,9,11,13). In clays, the LS cone response is dominated by pore pressure effects.

It is interesting to note that lateral stress coefficients obtained from the DMTs performed at MDF and LBS, interpreted using Schmertmann's method (14) to give an estimate of in situ K_o, give the same relative magnitudes as those obtained from direct measurements during LS-CPTU profiling (Fig. 12). In general terms:

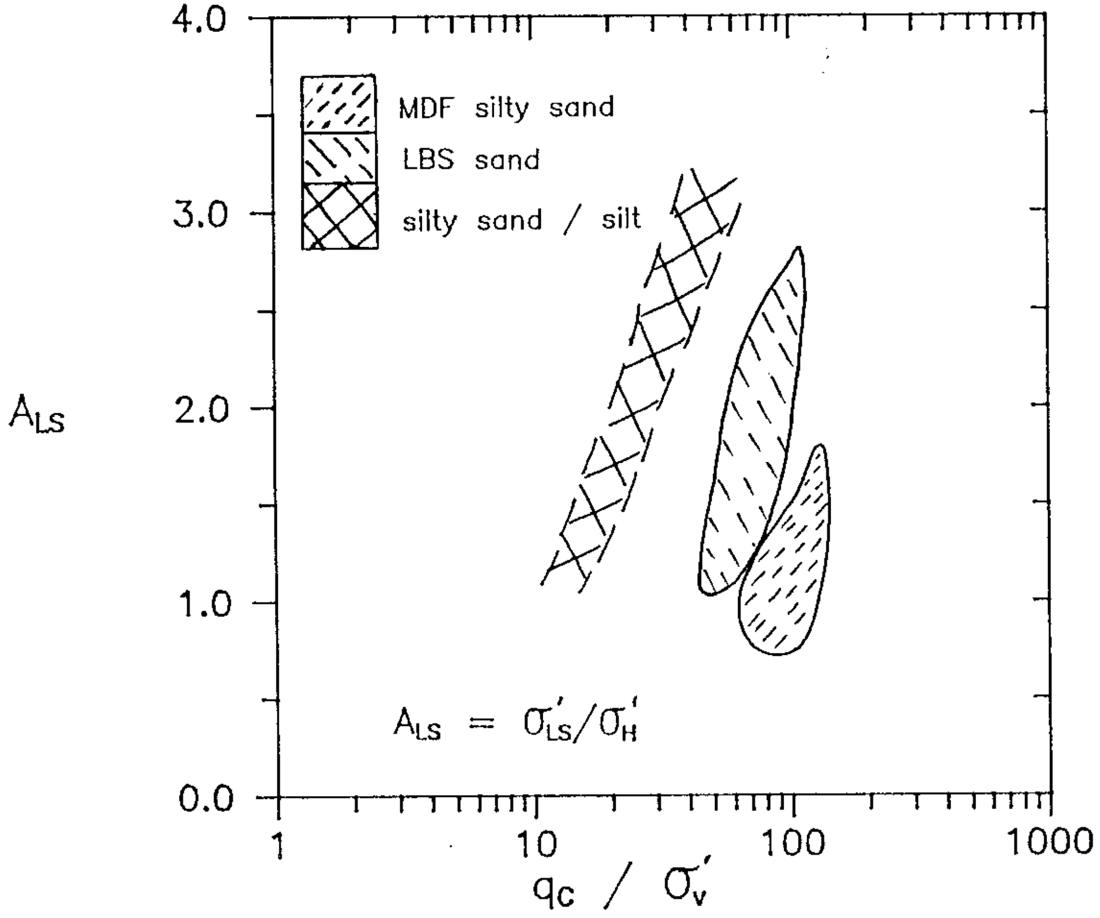

Fig. 13 Lateral stress amplification factor for soils tested

$$K_{LS} \approx K_{DMT} = 1\text{-}1.2\ (K_o) \text{ for McDonald Farm} \qquad (5)$$

$$K_{LS} \approx K_{DMT} = 1.5\text{-}2.5\ (K_o) \text{ for Laing Bridge South} \qquad (6)$$

where

K_{DMT} is the K_o value obtained from the interpreted DMT profile (14).

The DMT soil type index, I_D, also suggests that the LBS sand is finer than the MDF sand as indicated in Fig. 13.

Measurement of both friction and normal stress at the upper sleeve location permits an evaluation of the average mobilized soil to steel friction angle during penetration. Friction angles varying between 18° and 25° were obtained for the sand layer at McDonald Farm. Lower values were measured for Laing Bridge South. Tomlinson (18) suggests from his experience with steel piles in sand that a soil-steel friction angle of 20° is appropriate. The data is also in agreement with results suggested by a literature review of measured soil-steel friction coefficients together with measurements in ring shear tests performed at UBC (12). This would suggest that the relative values of the parameters being measured during LS-CPTU profiling are realistic.

SUMMARY AND CONCLUSIONS

Data have been presented from laboratory and field measurement using a lateral stress piezocone. Laboratory calibrations have shown that the measured lateral stress is sensitive to both axial loads on the friction sleeve and temperature. These effects can, however, be calibrated out by making corrections to the measured data. The corrections applied are stable and repeatable.

Field measurements made suggest that the lateral stress measured by the LS cone is greater than the in situ horizontal stress. In sand, the increase over and above the in situ condition has been shown to be partly a function of the normalized cone resistance, q_c/σ'_v. It would also appear that grain size, grain size distribution and angularity may be important.

During stops in the penetration of the cone, the measured lateral stress undergoes some degree of dissipation. The reduction in lateral stress appears to be controlled by the characteristics of the soil at the tip and at the sleeve location. Further work is being carried out to evaluate these effects. Additional studies are presently being performed to evaluate the application of LS cone data to the interpretation of in situ horizontal stress. Refined signal processing will allow the present ± 7 kPa resolution on the LS channel to be considerably improved. Variations in the mechanical design of the LS module are also underway.

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