

LATERAL STRESS MEASUREMENTS IN A GLACIOMARINE SILTY CLAY

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by

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ABSTRACT. The paper presents the procedure used for installation of spade-like total stress cells (TSC) in an overconsolidated silty clay and subsequent interpretation of the data obtained. Prior to installation, all the spade cells were calibrated in the laboratory for both pressure and temperature effects. After extraction from the ground, the stress cells were recalibrated and changes in the calibration characteristics were noted. These changes presumably result from the effects of installation. The stress cells were read over a period of three months. The measured stresses, pore pressures and temperatures are evaluated to provide a profile of the lateral stress coefficient for the site.

INTRODUCTION

Increased understanding of soil behaviour has emphasized the importance of the contribution of the in situ stress state. Numerical and analytical methods almost routinely incorporate stress dependent behaviour in some form. Recent developments in the interpretation of in situ test data suggest that horizontal stress, along with stress-strain history, is the major factor 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 (1985).

Methods for evaluating the lateral stress condition in situ can be separated into three main groups (Marchetti 1985, Robertson 1986):

- (i) direct methods
- (ii) semi-direct or back-extrapolation methods
- (iii) indirect methods.

In addition, empirical correlations may also be used to provide estimates of in situ lateral stress.

Direct methods of determination of lateral stress such as the self boring pressuremeter, suffer from the significant effects of even small degrees of disturbance. To produce repeatable degrees of disturbance, full displacement probes were developed and attempts made to evaluate in situ stress. The possibility of using large strain parameters to predict small strain behaviour has been confirmed by the results of calibration chamber tests (Baldi et al. 1988). Developments in this area include the stepped blade, and wedge blade

which fall into the semi-direct group; and the dilatometer, lateral stress cone and cone pressuremeter which are included under indirect methods. Each of the full displacement methods causes significant but repeatable disturbance to the soil. Figure 1 illustrates the trend between relative displacement and measured stress ratio, K , defined as:

$$K = \frac{\sigma'_h \text{ (measured)}}{\sigma'_v} \quad (1)$$

where:

K = earth pressure coefficient in terms of effective stress

σ'_h = horizontal effective normal stress

σ'_v = vertical effective normal stress

and K_0 represents the lateral stress ratio or earth pressure coefficient at zero lateral strain for in situ conditions and K_a and K_p are active and passive earth pressure coefficients.

From Fig. 1 it would appear that an instrument capable of both positive and negative displacement may be able to completely define the stress-strain curve. Numerous problems, however, exist with this type of measurement.

As part of a research program oriented towards the evaluation of lateral stress in the ground, a series of in situ tests have been performed to compare lateral stresses measured by full displacement probes. The paper focuses on the use of spade-like total stress cells (TSC) in an over-consolidated silty clay.

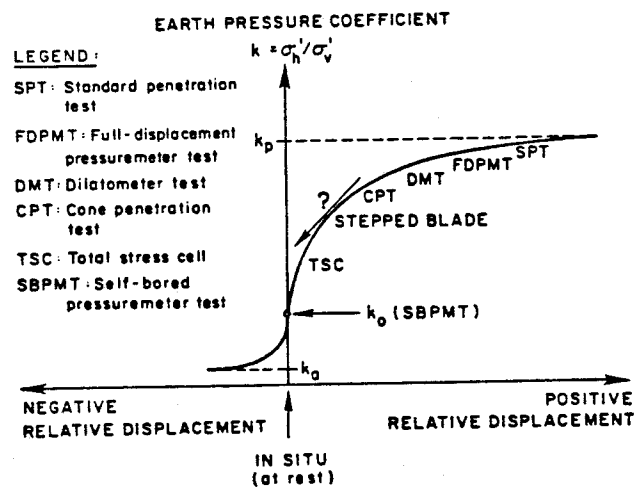


Fig. 1 Idealized change of lateral stress coefficient, K, caused by full displacement probes.

SITE CHARACTERISTICS

The data considered in this paper were obtained from the site of an abandoned gravel quarry called Strong Pit in the Lower Mainland area of British Columbia. The pit was abandoned approximately 12 years ago, although minor usage still occurs periodically.

The site is located at the edge of the hummocky kame-and-kettle terrain near the town of Aldergrove. The surface gravel in the area is fluvioglacial in origin having been transported seaward by meltwater streams during the three major glaciations which occurred in the area (Clague and Luternauer 1982). The poorly sorted sand and pebble-cobble gravels, which irregularly overlie marine or glaciomarine clayey silt, have been assigned to the Sumas Drift, and attain thicknesses of 30 m in the area. At the location of Strong Pit the gravel is about 15 m thick but has been excavated to a depth of approximately 14 m at the location of the in situ tests.

The underlying stony silty clay could be part of the Sumas Drift but is more likely to be a deposit of the Fort Langley Formation (Pleistocene), the fines being deposited from meltwaters and seawater with the stones and some finer material being transported by floating ice and deposited as it melted. Sediments are dominantly massive to weakly stratified containing dropstones. Stones can be up to cobble size. Lenses of sand and gravel up to several metres thick may be present. Discontinuous stringers of fine sand are numerous. Shells are usually common but none have been found at this location.

As mentioned previously, gravel has been removed from the area where testing has been performed. Since the deposits have not been overridden by ice, reasonable

estimates of the stress history of the silty clay are possible.

The present profile consists of 1 m to 1.5 m of gravel underlain by up to 9 m of stony silty clay. Below this level, the clay is interbedded with dense fine sands and gravel.

Groundwater conditions at the site are somewhat unusual in that the measured pore pressure throughout the upper silty clay varies between 0-10 kPa. These pressures arise due to the clay layer being underdrained; a perched water table is present in the gravel at the top surface of the clay and maintains saturation of the clay. Piezometer measurements in the underlying granular layer indicate that the pore pressure distribution becomes hydrostatic at the base of the clay which coincides with the location of the water table.

The results presented here refer to the stiff stony silty clay horizon. Hydrometer analyses indicate an average clay content of 45%, a silt size fraction of 40%, and sand and rock fragments the remaining portion. Sampling shows the clay to be intact with no indications of fissures or fractures. The index characteristics of the clay are summarized in Table 1.

TABLE 1 Geotechnical parameters of Strong Pit silty clay

Index	Range	Average
Water Content (%)	15-21	19
Size < 60 μm (%)	82-90	85
Size < 2 μm (%)	39-46	45
LL (Liquid Limit) (%)	26-32	27
PI (Plasticity Index) (%)	11-15	13
Unit Weight (kN/m ³)	20-22	21
S _t (Sensitivity) (FV)	2-5	3
OCR	2-10	-
(S _u /σ' _v) _{nc} *	0.31-0.38	0.35

*Obtained from (S_u)_{FV}/σ'_{vm}
σ'_{vm} = maximum past pressure from consolidation test

The overconsolidation ratios (OCR) were obtained from incremental oedometer tests (Espezel et al. 1988) and undrained strengths, (S_u)_{FV}, from Nilcon field vane tests. The vane tests were correlated with cone data to evaluate the undrained shear strength at greater depths where vane penetration was no longer possible.

STRESS CELL CALIBRATION

The stress cells used for this investigation are of the push-in pressure cell and piezometer type supplied by Solinst Canada Ltd. For details of the

design the reader is referred to the manufacturer's literature (Soil Instruments Ltd., Bell Lane, Uckfield, East Sussex, U.K., TN221QL, 1987). Minor modifications were made to the pressure cells to facilitate insertion using the UBC Geotechnical Research Vehicle. In addition, several of the cells had platinum temperature sensors (RTD's) installed. The cables from the sensor were taken to the ground surface inside the return pressure line for the cell pressure transducer. Total stress and pore pressure measurements were taken with pneumatic transducers and an RST Instruments digital readout box incorporating a Druck electronic transducer with a range of 0-2000 kPa. Resolution of the transducer reading is $\pm 0.05\%$ FS, i.e. ± 1 kPa.

Prior to installation, all the total stress cells (TSC) were calibrated in the laboratory for the effects of temperature and external applied pressure. Each cell was placed into a water-filled pressure chamber with a temperature sensor attached at the midpoint of the blade. An external pressure source was used to vary the pressure inside the chamber. Temperature variations were achieved by immersing the chamber in a temperature bath. The temperature calibration was checked for cooling and warming conditions in the range 0-20°C. Typically, a series of cell and porewater pressures were taken at the nominal confining pressures of 0, 50, 100, 150 and 200 kPa for loading and unloading conditions.

The results from the calibration of TSC1542 are shown in Fig. 2. It is evident that:

- the TSC's have an internal pressure at zero applied stress which has to be subtracted from the actual reading to give the stress increase resulting from the increase in external pressure
- an offset in the baseline internal cell pressure occurs as the temperature of the blade changes (Felio & Bauer 1986)
- the offset with temperature is essentially independent of the applied stress.

The latter point facilitates easy correction for temperature effects. The calibration constants for the cells used at this location are given in Table 2 for a confining pressure equal to zero (Fig. 3). Similar values are obtained at other confining pressures, as indicated by Fig. 2. Temperature coefficients of up to 1.35 kPa/°C were measured although average values are around 0.5 kPa/°C. However, since temperature changes of 10°C or more may occur between laboratory calibration and in situ stabilized conditions, the temperature corrections become appreciable, especially where low stresses are being measured.

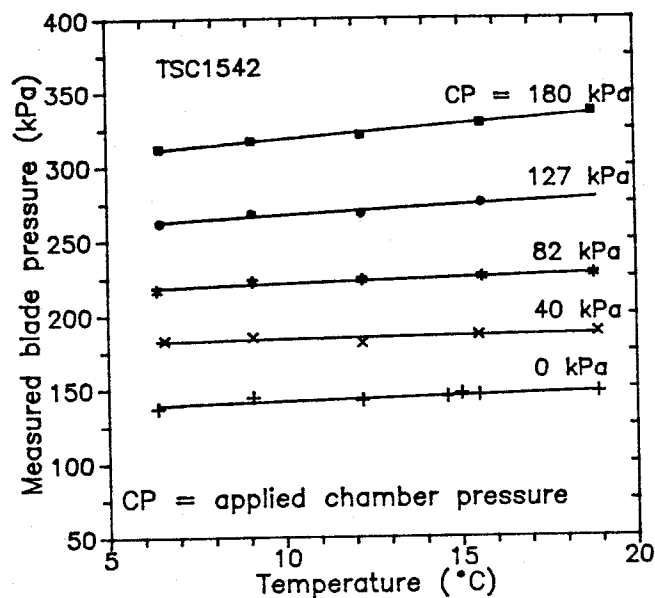


Fig. 2 Calibration data for TSC1542.

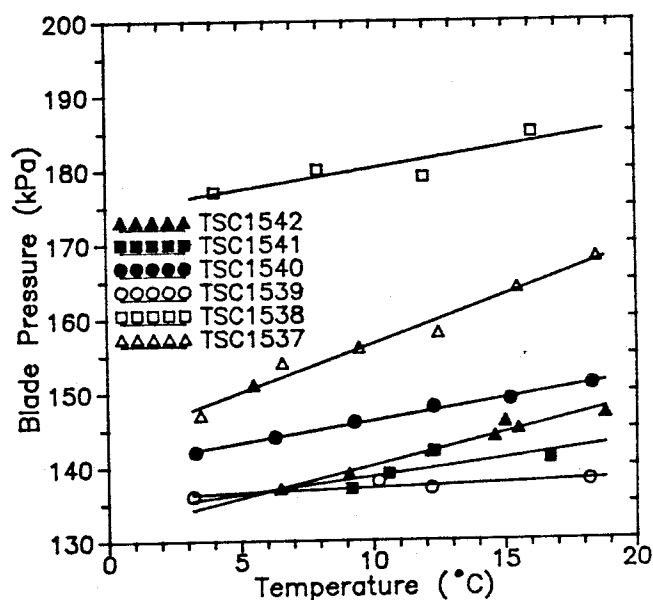


Fig. 3 Temperature dependence of baseline pressure for all spade cells.

The cells that were removed from the site were again calibrated; these values are shown in parentheses in Table 2. As can be seen, the baseline and temperature calibration factors have changed somewhat due to the effects of installation. The values from the recalibration were used to interpret the field measurements for blades 1537, 1538 and 1541. Blades 1539 and 1540 were broken during installation and thus did not produce data, while the remaining two cells (1350 and 1542) are still in the ground. For these two blades, the pre-

TABLE 2 Calibration data for spade cells

Spade Cell No.	Reference Temperature T_R (°C)	Baseline Pressure σ_b (kPa)	Factor, B_T kPa/°C on cooling
TSC1350	22	130	+ 0.45
TSC1537	9.5 (9.5)	156 (147)	+ 1.35 (+0.67)
TSC1538	8.0 (9.5)	179 (164)	+ 0.58 (+0.47)
TSC1539	10.2	138	+ 0.14
TSC1540	9.3	146	+ 0.14
TSC1541	10.5 (9.5)	135 (136)	+ 0.48 (+0.25)
TSC1542	9.1	139	+ 0.91

Thus, the measured in situ pressures can be corrected according to:

$$\sigma_{TSC} = \sigma_m - \sigma_b - [(T_R - T_I) B_T] \quad (2)$$

- σ_{TSC} = Temperature corrected net blade pressure (kPa)
- σ_m = Measured total blade pressure (kPa)
- σ_b = Baseline pressure at reference temperature (kPa)
- T_R = Reference temperature (°C)
- T_I = Temperature in situ (°C)
- B_T = Blade pressure calibration factor for temperature (kPa/°C)

installation calibration data were used to reduce the field data. Baseline values were also determined for the pore pressure transducer, but these were not subject to temperature effects. All temperature corrections applied to the blade pressures were made with respect to 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 other temperature measurements.

INSTALLATION OF TSC's

The total stress cells (TSC's) were installed using the UBC Geotechnical Research Vehicle. At each location, prior to installation, a dilatometer (DMT) profile was performed to a level 0.5-1.0 m above the intended depth of the TSC. (The flat dilatometer is similar in shape to a TSC.) After withdrawing the DMT, the TSC was slowly pushed to the intended depth at which time the first reading was taken. The maximum pushing force required to install the TSC's was 5.5 tonnes. All the blades were installed with the same orientation since DMT profiles of differing orientation suggest that no appreciable

directional stress changes occur across the site. The stress cells were read over a period of three months to ensure dissipation of excess pore pressures and allow creep/relaxation to occur, if at all.

A typical variation of the measured and corrected pressures is shown in Fig. 4. The effect of the equilibrium pore pressure approximating zero is indicated by the calculated total and effective horizontal stresses becoming equal as the excess porewater pressure generated during installation dissipates.

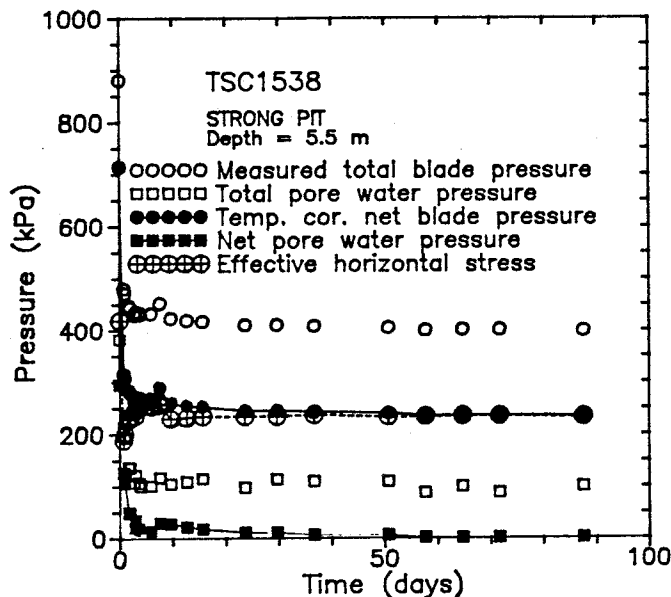


Fig. 4 Measured and corrected pressures for TSC1538.

To obtain an estimate of the lateral stress in situ, the measured blade pressures have to be corrected. The over-read is due to the full displacement method of installation and has been shown to be a function of the undrained shear strength of the soil (Tedd & Charles 1983). The empirical correction method suggested by Tedd and Charles (1983) is:

$$(\sigma_{TSC})_{CORR} = \sigma_{TSC} - 0.5 (S_u) \quad (3)$$

where:

$(\sigma_{TSC})_{CORR}$ = corrected TSC lateral stress which is assumed to be equivalent to the in situ horizontal total stress

σ_{TSC} = total lateral stress measured by TSC (temperature adjusted)

S_u = undrained shear strength of the soil at depth of TSC

A profile of total vertical and horizontal stresses for the Strong Pit location is shown in Fig. 5. Both uncorrected and corrected lateral stress values are shown as well as the vertical preconsolidation stress obtained from laboratory consolidation tests. The equilibrium pore pressure varies between zero and 10 kPa. The resulting K_0 profile from corrected and uncorrected measured horizontal stresses is shown in Fig. 6. The variations in OCR and S_u/σ'_v are also superimposed on the figure. The primary dependence of both K_0 and S_u/σ'_v on OCR is evident from the data. The results in Fig. 6 show that the corrected value from TSC gives a maximum K_0 of nearly two at 2 m depth where OCR is about ten, reducing to a K_0 value of around 1.1 at a depth of 9 m where OCR is about 2.7.

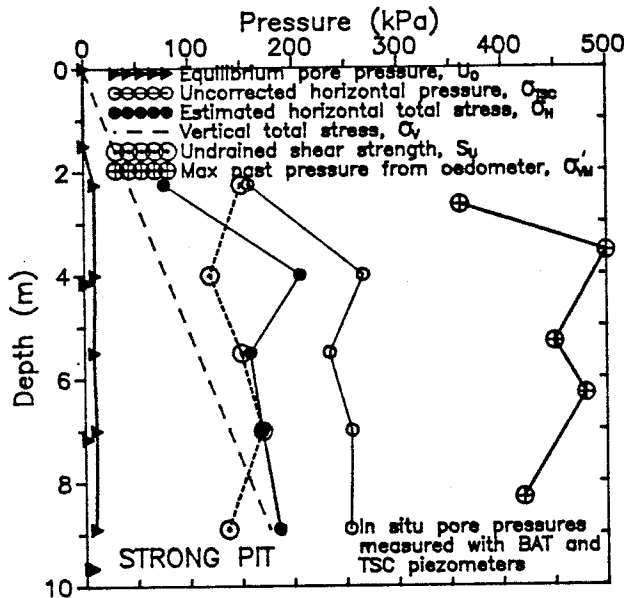


Fig. 5 Evaluated stress profile for Strong Pit based on field and laboratory measurements.

DISCUSSION

It is generally accepted that K_0 varies with OCR in an uncemented clay. The following empirical relationship has been shown to exist using published results (Mayne & Kulhawy 1982):

$$(K_0)_{oc} = (K_0)_{nc} (OCR)^\alpha \tag{4}$$

where:

- $(K_0)_{nc}$ = normally consolidated K_0 value
- $(K_0)_{oc}$ = overconsolidated K_0 value
- α = exponent.

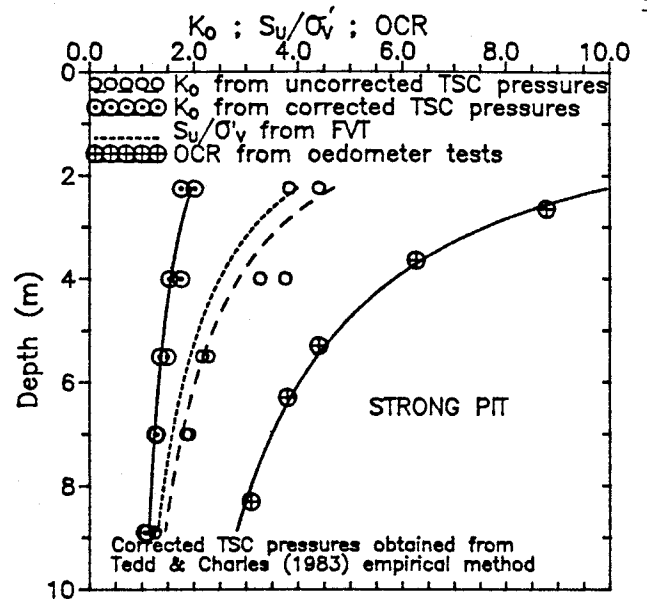


Fig. 6 Profile of stress history related parameters for Strong Pit silty clay.

For the Strong Pit data shown in Fig. 6, the addition of the constants in Eq. (4) gives

$$(K_0)_{oc} = 0.55 (OCR)^{0.61} \tag{5}$$

The normally consolidated value of K_0 is based on data for a similar Lower Mainland silty clay (Campanella & Vaid 1972). The value of the exponent α was found to vary between 0.50 and 0.67 using the possible range of K_0 values for both conditions of equilibrium water pressure, i.e. $u_0 = 0$ and $u_0 = 10$ kPa.

The stress history at the site has been evaluated from the results of both laboratory (oedometer) and field (vane, piezocone) tests (Sully & Campanella 1989) and is considered to be reliable. All the stress history test data are verified by the calculated height of overburden removed during gravel extraction. Hence, it appears that the overconsolidated state of the stony silty clay can be explained solely on the basis of unloading due to removal of overburden. This suggests that the form of Eq. (4) is primarily dependent on errors in the evaluation of $(K_0)_{oc}$. More specifically, the adjustment of the spade cell pressures in stiff clays to account for over-read is high and may induce unacceptably large errors due to the very empirical nature of the correction applied. The ratio of measured total pressure to corrected pressure varies from 1.5 to 2.0 for the soils at this location.

Apart from the magnitude of the correction required in order to obtain the in situ lateral stress, it would appear to be a somewhat unsatisfactory method to apply since it employs the use of the undrained shear strength (Tedd & Charles 1983). The stiffness of the soil and actual in situ horizontal effective stress may be more important - and more appropriate - parameters to consider when evaluating spade cell corrections. To evaluate these effects, a series of measurements are presently under way in soft to firm cohesive deposits in the Lower Mainland area of British Columbia.

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