Push-in total stress cells for horizontal pressure measurement in clay

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ABSTRACT: The paper discusses the use of push-in total stress cells for the evaluation of in situ lateral stresses in the ground. Details of the stress cells and modifications made are given. Temperature and pressure calibrations are reported and the importance of these corrections are discussed. The installation and data recorded from several push-in total stress cells at clay sites in the Lower Mainland of British Columbia are presented and the results are compared with other independent measurements of in situ horizontal stress. Laboratory measurements are also compared with the field data.

1 DETAILS OF TOTAL STRESS CELL

The spade-shaped push-in total pressure cells (TSC) used for this study were purchased from Solinst Canada Ltd. The spade cell is a plate 6.4 mm thick with a pressure sensitive area of dimensions 100 mm by 200 mm. The rectangular oil-filled chamber is formed of two thin steel sheets welded at the edges. The pressure sensitive area is welded to a support plate. The cavity so formed is pressurized to maintain plate separation. The welded plates are strengthened by a solid metal strip which is welded on to the cell perimeter. The oil pressure in the chamber is connected via a short length of steel tube to a pneumatic transducer located on a connector boss behind the support plate (Fig. 1). A ceramic porous disc is also located on the support plate and connected hydraulically to a second pneumatic transducer which is tandem-mounted behind the first. Both transducers are protected within a steel sleeve adaptor which connects the spade cell to the installation rod.

A pre-set baseline (zero reading) and calibration is supplied for each cell by the manufacturer. The zero reading corresponds to the oil pressure in the chamber formed by the two steel plates. The manufacturer recommends an initial storage life to check that no baseline changes occur.

Twin nylon tubes, sheathed in polythene, are attached to the compression fittings located on each of the pneumatic transducers. Quick release couplings are attached to one of the nylon tubes at the other end of the twin tubing. The quick release couplings are used to connect the down pressure-line to the pressure readout box. The twin tubing lines are usually cut at lengths determined by the depth at which the spade cell is to be installed in the ground.

The cell and pore pressure measurements are taken using a portable pneumatic readout box. The readout unit contains a compressed nitrogen pressure bottle which is used to obtain field measurements. With the quick release coupling connected to the readout box, the pressure valve on the box is opened and a gradually increasing pressure is applied to the spade cell pressure transducer. When the applied pressure just exceeds the pressure in the cell, the diaphragm in the transducer deflects and vents the applied pressure to the return line (the second nylon tube). The readout box then measures the gas pressure required to just maintain a continuous flow through the diaphragm chamber. The same technique is used for reading both the oil chamber pressure (which corresponds to the total lateral stress acting on the spade cell) and the pore water pressure transducers. The pressures are measured at the surface by a Druck electronic transducer with a 0 to 2000 kPa (kN/m2) range. Resolution of the transducer is +/- 0.05% full scale, i.e. +/- 1 kPa.

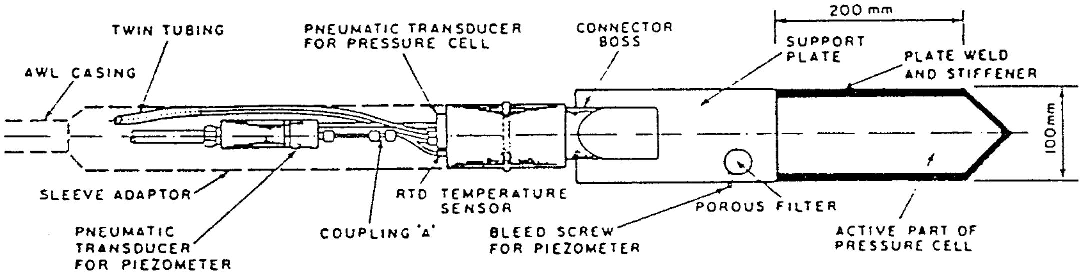


Fig. 1 Typical detail of modified push-in total stress cell

Prior to installation in the field, minor modifications were made to the cells and calibration checks were performed.

Because the pressure cells are oil-filled and sealed, the differing temperature characteristics of the cell components will cause the baseline to be sensitive to variations in temperature. This is recognized by the manufacturer but no data have been presented to evaluate the effects. Furthermore, for none of the cases reported in the literature, are the pressure cell data corrected for temperature effects. To provide data on the in-ground ambient temperature and its variation during the period when the cells are installed, platinum RTD temperature sensors were installed in several of the cells. The RTD sensors were installed adjacent to the compression fittings on the connector boss (Fig. 1). The electrical cables from the sensor were taken up to the ground surface through the return pressure line attached to the pressure cell transducer. The presence of the two thin wires did not restrict the venting action required for diaphragm movement during readout.

2 PRESSURE CELL CALIBRATION

Temperature and hydrostatic pressure calibrations were simultaneously performed in the laboratory prior to field installation of the pressure cells. For this purpose, a pressure chamber was constructed. Each cell was placed in the chamber with an RTD sensor attached (only for calibration purposes) to the midpoint of the pressure sensitive cell area. The chamber was then water-filled and sealed. An external pressure source was used to vary the chamber confining pressure. Temperature variations were achieved by immersing the complete chamber in a temperature bath.

The stabilized temperature for each set of pressure calibrations was measured by the RTD sensor attached to the face of the blade. A temperature range of 0° to 20° C was used for both cooling and warming temperature cycles. To ensure that stable temperature variations were achieved, a set of pressure and temperature readings took between 12 and 24 hours to complete. Typically, a series of cell and porewater pressures were taken at nominal chamber pressures of 0, 50, 100, 150 and 200 kPa for both loading and unloading cycles for both warming and cooling temperature cycles.

The results of the pressure and temperature calibration for one of the total stress cells (blade cells) are presented in Fig. 2. From the results of the calibration it is evident that:

- the total stress cells have an internal pressure at zero applied confining stress which must be subtracted from the actual reading to give the stress increase resulting from the increase in external pressure,
- an offset in the internal cell pressure occurs (baseline drift) as the temperature of the blade changes. This concurs with results presented by Felio and Bauer (1986) for other types of pressure cell,
- the baseline drift resulting from the temperature change is essentially independent of the external applied pressure and can be related linearly to the temperature change. This facilitates easy correction of field measurements since the temperature adjustment does not vary with the in-ground stress acting on the blade.

The temperature drift for all the blades initially used is shown in Fig. 3 for the condition of zero applied chamber pressure. The temperature coefficient, B_T, for the cells is listed in Table I.

Temperature coefficients of up to 1.35 kPa/°C were measured although average values are around 0.5 kPa/°C. Since temperature changes of 10°C or more may occur between the laboratory and field environments, the temperature corrections become appreciable, especially where low stresses are being measured.

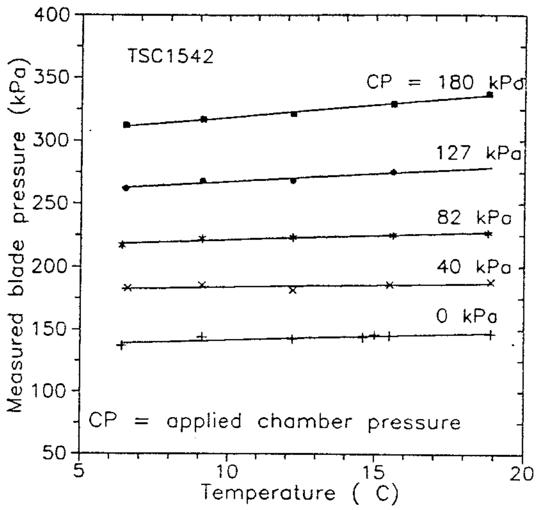


Fig. 2 TSC temperature and pressure calibration

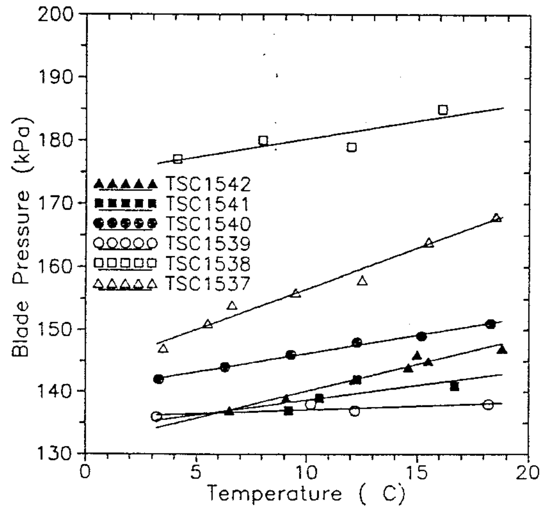


Fig. 3 Temperature dependence for all TSC blades

Calibration measurements were performed on the pressure cells before field installation and again after the cells had been recovered from the ground; the latter calibration was used for data interpretation.

Table 1 Calibration data for spade cells

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

The baseline pressure (at zero chamber or confining pressure) for the individual total stress cells given in Table I is governed by the arbitrary choice of the reference temperature. For this study, all temperature corrections to the in situ blade pressures were made with respect to the equilibrium ground temperature, as measured by the RTD sensor installed on the cell. At any one site, a sufficient number of cells were instrumented so that a representative temperature profile could be obtained. At depths where blades without temperature sensors were installed, the ground temperature was estimated by interpolation from the other temperature measurements. Thus, the measured blade pressures from *in situ* measurements can be corrected according to:

$$\sigma_{TSC} = \sigma_m - \sigma_b - [(T_R - T_I)B_T] \qquad (1)$$

where:

σ_{TSC} = temperature corrected net total blade pressure (kPa),

σ_m = measured total blade pressure (kPa),

σ_b = baseline total pressure at reference temperature (kPa),

T_R = reference temperature (°C),

T_I = in-ground temperature (°C),

B_T = cell pressure temperature calibration factor (kPa/°C).

Similar baseline readings were also determined for the pneumatic pore pressure transducers; these transducers were not found to be temperature sensitive.

3 TSC INSTALLATION PROCEDURE

Total stress cells of the push-in type are normally installed in the base of an existing borehole (Tedd and Charles 1981,1983); this reduces the risk of damaging the cell. Due to the high costs involved in the boring operation and the availability of an alternative technique, minor modifications were made to the spade cells to facilitate installation using the University of British Columbia (UBC) Geotechnical Research Vehicle. This involved the machining of a steel sleeve adaptor to connect the spade cell to the installation rods. The adaptor also serves as a protective housing for the pneumatic transducers. One end of the adaptor is screwed on to the cell connector boss (Fig. 1) while the other accepts the AWL casing (44.7 mm OD, 4.6 mm wall thickness) that was used to push the spade cell into the ground. High buckling strength rods were required to avoid rod damage due to the large loads neccesary to push the cell assembly - most of the resistance resulting from the larger diameter sleeve adaptor. Unlike the borehole situation, where the TSC is only advanced 0.5 m to 1.0 m below the base, the use of the UBC vehicle (normally used for penetrating CPT equipment) required the cells to be pushed from ground level to their final depth. To avoid buckling and breakage of the rods, it was decided to use AWL casing for installation. The 35 mm ID of the rod permits easy passage of the two lines of twin tubing from the cell to the surface.

The TSC blade itself is most susceptible to breakage, under axial loading, at the weld where the two plates connect to the support plate. To reduce the axial loads on the pressure cell during installation, a dummy plate was pre-pushed to a final depth approximately 1.0 m above the planned depth for the TSC. In this way, the TSC was only pushed in virgin soil for a depth of about 1.0 m. In order to obtain more information on soil variations at the instrumented location, the dummy push was performed using the standard dilatometer (DMT) and data taken every 0.2 m (thrust, p_0, p_1, p_2).

After installation of the total pressure cell, the lateral stress and pore pressure were monitored with time until a stable equilibrium value was reached.

4 OVERVIEW OF TSC EXPERIENCE

The concept of the push-in spade-like total pressure cell to measure *in situ* horizontal stress was first utilized bt Massarsch (1975) in a soft clay. The Gloetzl cell used was 4 mm thick and was pushed into the ground protected within a steel casing. The casing frame was withdrawn about 0.3 m above the intended depth and the cell alone advanced and left in the ground until a stable stress equilibrium was reached. The maximum membrane deflection of the Gloetzl cell is about 5 µm (negligible in soft soils). Use of this full-displacement method gave consistent K_0 values for the normally consolidated deposit tested. Satisfactory results with push-in total stress cells have also been reported by Massarsch et al. (1975), Tavenas et al. (1975), Massarsch and Broms (1976) and Massarsch (1979). Reported multiple measurements at one depth were within 1 kPa (Tavenas et al. 1975).

During installation of the TSC, the soil is displaced and excess pore pressures are generated which then subsequently decay with time. Once these excess pore pressures have dissipated, the lateral stress acting on the blade should still be higher than the pre-installation value. However, if the viscoelastic characteristics of the soil permit, the lateral stress increment induced by TSC installation may also dissipate so that no additional stress (over and above the original K_0 stress) remains. Under differing conditions, the stress increment will remain and the measured lateral stress acting on the TSC will require some correction in order to obtain an estimate of the pre-installation horizontal stress.

$$\sigma_{TSC} = \sigma'_{ho} + \Delta\sigma_h(t) + u_o \qquad (2)$$

$$\Delta\sigma_h(t) = u(t) + \Delta\sigma'_h(t) \qquad (3)$$

$$u(t) = u_o + \Delta u(t) \qquad (4)$$

$$\Delta u(t) \dashrightarrow 0 \text{ and } u(t) \dashrightarrow u_o \qquad (5)$$

where:

σ'_{ho} is the *in situ* pre-penetration horizontal stress,
$u(t)$ is the time dependent pore pressure measured by the TSC,
$\Delta\sigma'_h(t)$ is the time dependent stress increment induced during installation of the TSC,
u_o is the equilibrium *in situ* pore water pressure,
$\Delta u(t)$ is the excess pore pressure induced during TSC installation.

In soft clays, it is generally accepted that no correction to the final equilibrium measured blade pressure is required since stress relaxation is assumed to occur, i.e.

$$\Delta\sigma'_h(t) \dashrightarrow 0 \quad \text{for } t > 1 \text{ to } 2 \text{ months} \qquad (6)$$

In fact, $\Delta\sigma'_h(t)$ may seldom be zero, but may be small enough so as to not to cause significant deviations from the expected K_o value.

Results obtained with push-in pressure cells in stiff overconsolidated soils by Tedd and Charles (1981, 1983), however, indicate that the TSC overreads by an amount approximately equal to one half the undrained shear strength, S_u (as determined from unconsolidated undrained triaxial compression tests). The reference lateral stress used to evaluate the amount of overread was taken as that obtained from self-boring pressuremeter tests. While Tedd and Charles (1983) argue that it should be possible to relate the magnitude of the overread to the soil modulus, they suggest that, due to the impracticality of deciding upon a relevant modulus value, it is more realistic to empirically correlate the overread to S_u. Data presented by Powell et al. (1983) for a stiff glacial till confirm the magnitud of the correction suggested by Tedd and Charles (1981). For soft soils with S_u < 30 kPa, no correction is recommended, but for S_u > 30 kPa, the suggested *in situ* total horizontal stress is given by:

$$\sigma_{ho} = \sigma_{TSC} - 0.5(S_u) \qquad (7)$$

A review of all published data where stress history (OCR) and K_o (from TSC) are available, leads to the following correlation (Fig. 4):

$$(K_o)_{TSC} = 0.581(OCR)^{0.432} \qquad (8)$$

Equation (8) suggests an average drained friction angle of 25° for the reported data.

The data in Fig. 4 are from both Gloetzl and Solinst type pressure cells, corrected according to the recommendation of Tedd and Charles (1981), developed initially for the Solinst cells. The data would suggest that the corrected lateral stress from TSC data represents fairly well the actual *in situ* lateral conditions, as referenced by the self-boring pressuremeter.

5 INTERPRETATION OF TSC DATA

The TSC instruments described above were installed at two UBC clay research sites, namely Lr. 232 St. and Strong Pit. Both clays are overconsolidated; at Strong Pit the overconsolidation arises from unloading resulting from quarrying activities, while at Lr. 232 St. the stress history is more uncertain, being a combination of unloading due to construction activities and drying/wetting cyles due to ground water level fluctuations.

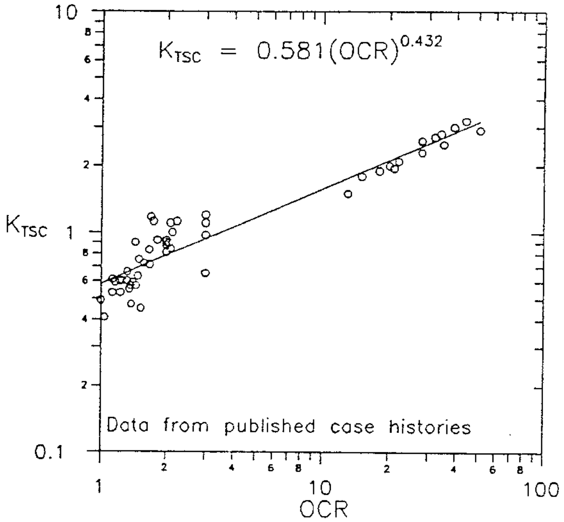


Fig. 4 K_{TSC}-OCR relationship from published data

Typical field data obtained at Strong Pit are presented in Fig. 5 where it is apparent that for this particular deposit, monitoring periods in excess of 60 days are necessary before the stress measurements stabilize. At Lr. 232 St. similar periods of time were also found to be necessary.

At Strong Pit, the equilibrium pore pressure throughout the clay profile is approximately zero. The results in Fig. 5 indicate this condition since the total and effective horizontal stresses become equal as the excess pore water pressure dissipates to the in situ equilibrium value. The corrected net blade pressure is also presented on Fig 5 - this is the measured blade pressure corrected for overread according to the Tedd & Charles (1983) method.

At the Strong Pit site, the undrained shear strengths of the clay silt are in the range 100 kPa to 175 kPa. Hence at the surface, the correction for overread may be as much as one half of the initial measured blade pressure value. At Lr. 232 St. the undrained strengths are much lower (20 kPa to 40 kPa), but so too are the measured field stresses (100 kPa to 300 kPa).

Hence two major problems are considered to exist in relation to the use of the push-in TSC for engineering measurements:

(i) the long delay required for the pressure cell to come to equilibrium in the ground after insertion, and

(ii) the large correction required to the measured horizontal pressures and particularly the uncertainty or error involved in the adjustment.

5.1 Dissipation Modelling of Stress Change

A typical result from the TSC's installed at Strong Pit is shown in Fig. 5. Theffective horizontal stress is obtained by subtracting the pore water pressure measured on the blade (u_{TSC}) from the temperature corrected net blade pressure (σ_{TSC}). After the long dissipationperiod, the pore pressure at this site is zero and u_{TSC} is equal to u_o.

The dissipation of the total stress data has been evaluated using a power function relationship of the form:

$$\sigma_{TSC}(t) = \alpha_i t^{-\beta} \qquad (9)$$

where $\sigma_{TSC}(t)$ is the time dependent stress measured with the TSC, α_i is the value of σ_{TSC} at t=1, t is the time after installation and β is the exponent which controls the rate of stress relaxation.

Data from both Strong Pit and Lr. 232 St. were evaluated using Eq. (9) and corresponding α_i and β values were obtained. The variation in both α_i and β is presented in Fig. 6 as a function of depth - the relationship is remarkably linear. It is also interesting to note that:

- α_i is greater for the stiff clay at Strong Pit than for the soft to firm clay at Lr. 232 St. This is intuitively correct since larger pressures will develop due to full-displacement penetration in stiffer soils;

- β for Strong Pit is more largely negative than for Lr. 232 St. which implies a more rapid post-installation reduction in σ_{TSC} for stiff clay than and may also indicate a larger degree of disturbance.

The rate of change of the measured total stress incorporates both the pore pressure dissiption and the soil relaxation. In soft soil, the effect of stress relaxation may be such that the final corrected lateral stress may be very close or equal to the in situ value. This is not likely to be the case for stiff soils since some amplification of the equilibrium horizontal stress will certainly remain.

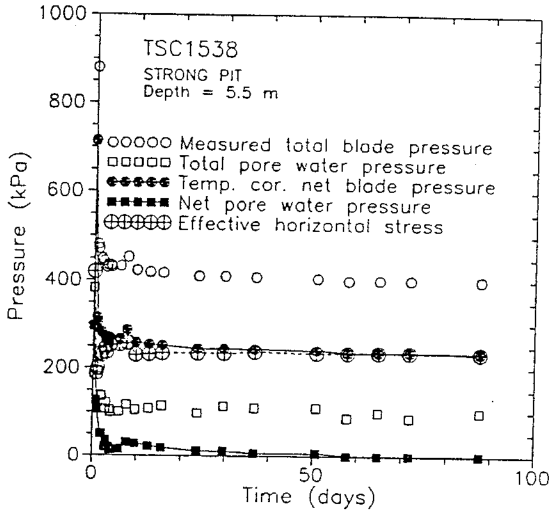


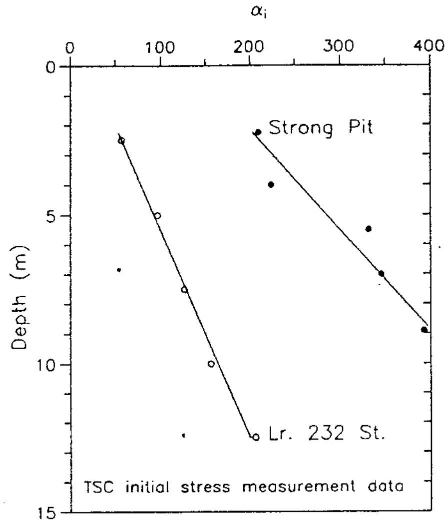
Fig. 5 TSC1538 data from Strong Pit

5.2 Validation of Overread Correction

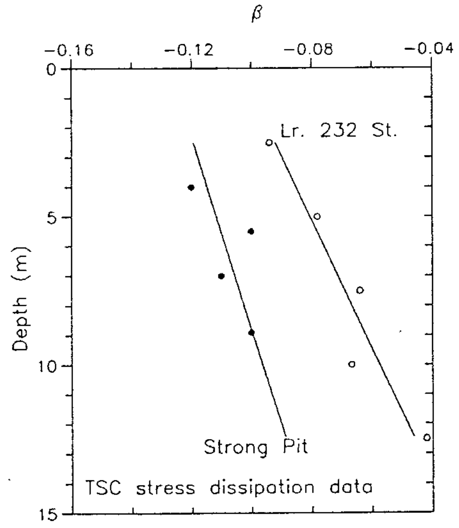
Since the stress history at this site is reasonably well documented and is confirmed by laboratory test results, it was decided to try and back figure the overread correction based on laboratory derived K_o - OCR relationships, obtained from Lateral Stress Oedometer tests performed on undisturbed samples recovered at the site. In situ vane shear tests were also performed and the data used to verify the stress history profile (Sully and Campanella 1989). Using the OCR profile, an estimate of the in situ K_o was made using a normally consolidated value of 0.54 and exponent of 0.38 (average from 8 tests). This K_o value was used to calculate the in situ horizontal effective stress. The magnitude of the overread associated with the push-in total stress cell was then calculated as the difference between the net corrected measured total blade pressure and the calculated in situ horizontal total stress obtained from the K_o-OCR relationship. The overread of the lateral stress was found to be approximately 75 kPa which corresponds on average to one half of the undrained shear strength of the soil as determined from the in situ vane test. This is in agreement with the Tedd & Charles correction method dicussed earlier.

6 CONCLUDING COMMENTS

The use of push-in total stress cells for measuring in situ horizontal stresses was implemented with varying degrees of success at a total of four sites in the Lower Mainland of British Columbia. At Strong Pit where the glaciomarine clay contains ocassional cobble and boulders, three of the nine blades installed were damaged. The blades usually break at the end of the stress sensitive section as this is the weakest point. Blade breakage is an important consideration as the TSC equipment is expensive. In the soft to firm clay at Lr. 232 St. no problems were encountered and all blades were installed, worked well over a period of nearly a year and were recovered



a) Alpha variation for clay sites



b) Beta variation for clay sites

Fig. 6 Variation of ai and b for Equation (9) from TSC data at clay sites in the Lower Mainland of BC

. An unsuccesful attempt was made to install one blade cell in a loose to medium dense sand layer at McDonald Farm. As expected, the blade bent and snapped early in the attempted installation.

The measured stresses from the blades were consistent and repeatable. However, due to the location and setup of the pore pressure measuring system it was difficult to ensure complete saturation. This was reflected in many of the pore pressure measurements which varied considerably throughout any one profile. Similarly, the final dissipated pore pressures do not generally agree with expected values based on knowledge of the equilibrium pore pressure at the sites.

The spade cells were calibrated in the laboratory prior to installation and again after recovery from the ground. Small variations in the baseline readings occurred between the two calibrations. The latter calibration was used for data interpretation. In the case of the Strong Pit cells, after recovery it was found that the temperature calibration factors had changed. The calibration changes for three of the cells are shown in Table 2. The change is thought to arise as a result of wear on the blade during installation in the stiff stony clay. At Lr. 232 St. no changes were noted on recovery of the cells.

Table 2 Calibration changes for spade cells before and after installation at Strong Pit

Spade Cell No.	Base Pressure σ_b (kPa)	Temp. Factor, B_T (kPa/°C)
Before Installation:		
TSC1537	156	1.35
TSC1538	179	0.58
TSC1541	135	0.48
After Installation:		
TSC1537	147	0.67
TSC1538	164	0.47
TSC1541	136	0.25

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