Field Response of Push-In Earth Pressure Cells for Instrumentation and Site Characterization of Soils

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ABSTRACT: The use of Push-In Earth Pressure Cells in Geotechnical Engineering is described. Applications for both instrumentation and site characterization are discussed. Several examples of the field response of Push-In Earth Pressure Cells in soils are shown to illustrate their behaviour. These instruments can provide a reasonably simple, economical and reliable tool for a wide range of applications in geo-construction and site characterization and should be considered by engineers more frequently. A discussion of the interrelationships between the Initial Lateral Stress Ratio and the Reconsolidation Lateral Stress Ratio suggests that in fine-grained soils these values should be related to the stress history of the soil through the overconsolidation ratio.

1. INTRODUCTION

Push-In Earth Pressure Cells represent a fairly unique tool in Geotechnical Engineering. They may be used to monitor changes in lateral earth pressures resulting from some type of geo-construction and provide a means of evaluating the response of the ground to that construction. They may be used to measure the decrease in lateral earth pressure, as from adjacent excavation or tunnelling or they may be used to measure the increase in lateral earth pressure as from driving piles or surface compaction or loading. They are simple to install and operate and are relatively inexpensive as compared to other typical instrumentation, but most importantly, they provide unique insight into a difficult ground parameter to measure, i.e., lateral earth pressure.

Even with these distinct attributes it appears that Push-In Earth Pressure Cells are not used with great frequency by Geotechnical Engineers; perhaps simply because the lack of information and some confusion as to their applicability and reliability. The use of Push-In Earth Pressure Cells in a range of soils and for a variety of applications are described in this paper. Applications for both instrumentation and site characterization are described. By far, the greatest amount of experience has been obtained using Push-In Earth Pressure Cells in saturated fine-grained soils, ranging from near normally consolidated to highly overconsolidated. Their use in coarse-grained soils has been more limited but there does not appear to be any obvious impediment to their use in such soils, especially fine to medium sands.

The use of electronic transducers in stress cells and readouts in some newer style push-in earth pressure cells provides for more precise measurements over early gas operated transducers. The sensitivity may also be increased by the design to allow for accurate stress readings at very low values, such as in under-consolidated sediments.

Push-in earth pressure cells, sometimes referred to as push-in spade cells, are often considered only as a tool for instrumentation, i.e., to monitor changes in lateral earth pressure, rather than as an in situ test for site characterization. The author however considers Push-In Earth Pressure Cells as both and when used as an in situ test they can be extremely useful in helping to evaluate the current state of lateral stress in soils, whether under at-rest conditions or as a result of some construction or change in stress.

2. BACKGROUND

2.1 Historical Development

It is not fully known where the concept of Push-In Earth Pressure Cells may have been initially suggested however, it appears that the first reported use was more-or-less simultaneously by Massarch (1975), Massarch et al. (1975) and Tavenas et al. (1975) for use in soft sensitive clays as a means of evaluating at-rest lateral stress. However, it is possible that the technique may have derived from the work presented almost 10 years earlier by Kenney (1967). Kenney used both total earth pressure cells and pore-water pressure transducers to measure the in situ stresses in Norwegian quick clays. The pressure cells were flush mounted at several locations onto an open ended steel pile fabricated in a square section. Tests obtained at three sites in Norway showed that this approach could be used, even though it appeared that the total stress cells were more reliable than the pore pressure cells. In effect the pile was allowed to "slide" into the soft clay, producing some disturbance but minimal disruption to the soil. The field response showed that equilibrium total lateral stresses were obtained after about 5 to 10 days in these soils. Interestingly, Kenney (1967) used vibrating wire pressure transducers in both his earth pressure cells and pore water pressure cells.

The concept of a Push-In Earth Pressure Cell is to introduce a thin pressure cell into the ground with minimal disruption and then monitor the change in stress with time until an equilibrium value is obtained. This suggests that the spade should be as thin as possible, but still be able to be installed without bending or other damage. A practical lower bound thickness of the blade, probably in the range of 4 to 5 mm (0.16 to 0.20 in.) (e.g., Massarch 1975) was used in early field work in very soft and soft soils, but a thicker blade, on the order of 6 to 8 mm (0.25 to 0.32 in.) may have more application over a wider range of soil stiffness.

Since their introduction in the mid 1970s, Push-In Earth Pressure Cells have been used in a number of other soft clays and in clays with varying degrees of overconsolidation and stiffness. The use of spade cells in stiff and very stiff clays and glacial tills has been reported by a number of investigators (e.g., Tedd and Charles 1981; 1983; Tedd et al. 1984; Lutenegger 1990; Ryley and Carder 1995).

2.2 Equipment

The equipment necessary for using Push-In Earth Pressure Cells in the field consists of: 1) a thin flat rectangular plate or blade that is filled with fluid, usually hydraulic oil, connected to a pressure transducer mounted at the top of the plate; 2) an adapter attached to the back end of the blade to attach drill rods or pipe for installation; a readout device at the ground surface; and 4) either a pneumatic line or electrical cable between the readout and the pressure transducer. The leading edge of the blade is usually either pointed or is simply rectangular with an angled wedge. The entire system, i.e., blade and transducer, is deaired and sealed so that the system response to applied stress will be very rapid and more direct. In most cases, a small amount of back pressure or internal pressure is built into the system to insure good response. This means that in atmospheric pressure, the transducer will have some initial positive pressure or zero offset. It's important to know this offset prior to testing so that all subsequent readings can be corrected. Having an initial internal pressure also allows the user to determine if the cell develops a leak, which would be indicated by a reduction in the initial pressure.

As noted above, in addition to the spade and transducer, the only other equipment needed to conduct the test is a readout or control console to operate or read the transducer. In some cases, twin tube pneumatic transducers are used and the control console is a simple gas control panel which as able to apply pressure in order to read the transducer. In most cases, a small bottle of nitrogen gas is used to supply the console. Vibrating wire transducers have also been used and are now more common; in which case a vibrating wire readout is needed. Electrical resistance pressure transducers have also been used to a limited degree and require a simple bridge readout device or a constant power voltage supply and precision voltmeter.

The simplest and most common configuration of Push-In Earth Pressure Cells provides for a measurement of only total stress. The measurement is made by using either an electronic (usually vibrating wire) or pneumatic transducer located above the sensing face of the blade. In some cases, a second transducer is included to allow a companion measurement of pore-water pressure using a porous element located on the face of the cell, usually above the sensing face.

There is a required balance between the dimensions of the blade so that the blade is sufficiently thin the reduce disturbance of the soil during insertion but be thick enough to provide sufficient rigidity against bending when installed. Historically, most Push-In Earth Pressure Cells have been on the order of 100 mm (3.9 in.) in width and about 200 mm in length and are fabricated from plain steel or high strength stainless steel. These dimensions allow the Pressure Cell to be conveniently installed in routine size open boreholes or through standard drill casing or hollow-stem augers. The width and thickness should be small enough to be manageable and to fit into normal size boreholes, yet large enough to provide a reliable soil response over a sufficiently large area. The length should not be too long since a flat-plate tends to drift from vertical when pushed into the ground. It appears that a width of 100 mm (3.9 in.) and a length on the order of 200 to 300 mm (7.9 to 11.8 in.) provides the necessary stiffness and area for use in most soils. Figure 1 shows a schematic of the Push-In Earth Pressure Cells used by the author. Figure 2 shows a photograph of a typical cell. Note that in this case, a small porous element (white circle) is included to allow pore water pressures to be measured. Table 1 summarizes different geometries used.

Since the use of Push-In Earth Pressure Cells is not currently controlled by any regulating agency such as ASTM, there is no standard that defines the geometry of the spade cell or the exact test procedures. The procedures are relatively straight forward, as will discussed, however, as noted, the geometry of the spade can vary, depending on the manufacturer and the user. Recently, some manufacturers have marketed Push-In Earth Pressure Cells that are much narrower than those noted in Table 1, with blade width on the order of about 55 mm. In the author's opinion, such narrow widths may create issues with accuracy in the measurement. A thin wide blade is preferred over a thin narrow blade to reduce possible arching effects and potential errors associated with stress concentrations that may occur using a narrow blade. A wide blade also provides for contact with a larger volume of soil and provides better averaging of stress conditions at a specific location. However, to date, no comparative test results have been published between the traditional configurations and the newer style cells. Table 1 shows that there is a noticeable difference in the thickness of spades used historically, with thickness ranging from 2 mm to 12 mm (0.08 to 0.50 in.). This is in contrast to the thickness of a Flat Dilatometer blade, which is on the order of 15 mm (0.60 in.).

Because of the differences in plate geometry, it is likely that not all spades will give the same response in all soils. It appears that the most important factor in the soil response may be the aspect ratio or width/thickness ratio of the blade. That is, as the width becomes very large in relation to the thickness, the blade begins to look like a wide plate or sheet. As the width approaches the thickness, i.e., W/T = 1, this is the geometry of a circular probe. At the present time, there has been no detailed and systematic research evaluating the importance of spade cell geometry (W/T) on the response.

Table 1 Summary of Push-in Earth Pressure Cell Geometry

Reference	**Width (mm)**	**Length (mm)**	**Thickness (mm)**
Massarch (1975)	100	200	4
Massarch et al. (1975)	100	200	4
Tavenas et al. (1975)	300	450	12
Massarch & Broms (1976)	N/A	N/A	3
Ladd et al. (1979)	114.5	565	9
Penman & Charles (1981)	100	200	2
Tedd & Charles (1981)	100	200	5
Fukuoka & Imamura (1983)	120	220	5
Ohya et al. (1983)	90	210	7
Chan & Morgenstern (1988)	200	200	6
Sully & Campanella (1998)	100	200	6.4

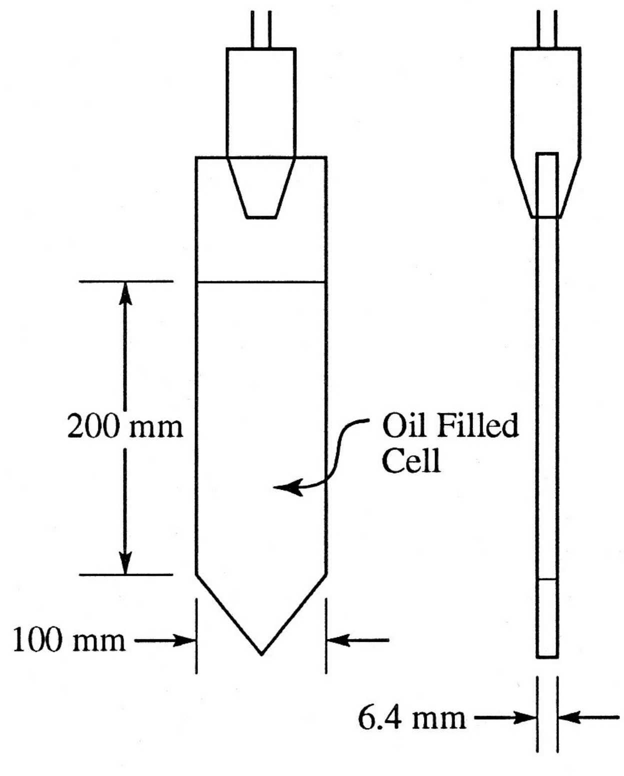

Figure 1 Schematic of Push-In Earth Pressure Cell

Push-in earth pressure cells are total stress cells, i.e., when pushed vertically into the ground they provide a response of the total horizontal stress. In cases where spades have been equipped with a porous element and a pore water pressure transducer, the reported responses have not always been that good and in most cases, the test is restricted to only giving total stress response. This means that an accurate estimate of the in situ pore water pressure must be obtained at each test location, preferably with piezometers, so that the final equilibrium effective stress may be determined.

Much of the early field work in the 1980s using Push-In Earth Pressure Cells was conducted by the Geotechnical Section of the Building Research Establishment in the U.K. Much of this work has been summarized by Tedd et al. (1989).

Figure 2 Typical Push-In Earth Pressure Cell Geometry

2.3 Procedures

Unlike the DMT or PCPT, which are pushed into the ground in a continuous manner without drilling a borehole, Push-In Earth Pressure Cells are typically only installed at the bottom of a drilled hole. The reason for this is mostly practical as experience has shown that if the spade is pushed more than 1 to 1.5 m (3 to 5 ft.) ahead of hole, there is a high probability of damage, mostly from bending, to the blade. This means that in order to use the blade as a profiling tool, the testing will need to be planned out over several days or weeks, with the spade removed and borehole advanced only after the test has been completed by achieving an equilibrium stress. The final response varies with soil stiffness and is fastest in very stiff clays, on the order of several hours to one day, and slowest for very soft clays, on the order of several weeks. The author has damaged several blades attempting to push in excess of 3 m ahead of a drilled borehole and on one occasion lost a blade in the borehole when the rod connector snapped.

In normal operation, the spade is pushed hydraulically into the ground at the base of the borehole with a drill rig and is never driven. On only one occasion has the author driven a spade from the bottom of a borehole, in fine silty sand, using light taps from the SPT hammer. Immediately after insertion, the test clock begins so that time zero for the test is taken as the time when pushing stops and the load is removed. The pressure in the transducer is recorded at relatively close intervals at the beginning of the test and at progressively increasing intervals as the test proceeds, much like an oedometer tests in the laboratory or PCPT pore pressure dissipation tests. In the case of tests performed in soft clays, where it may take several weeks to obtain the final response, pressure readings every day or every other day are typical after obtaining the initial response throughout the first day.

After removing the spade from the test zone at the completion of the test, the blade is cleaned off and a zero reading obtained so that each test will have a before and after test zero or initial reading. This will alert the operator of any potential problems with the cell. Cells are normally calibrated in a pressure chamber by the manufacture.

3. TYPICAL FIELD RESPONSE

3.1 Response in Soft (NC) Clays

In soft clays (OCR = 1), Massarch (1979) suggested that the values of K_o measured using spade cells were very close to values estimated using soil plasticity index (P.I.), ranging from 0.4 to about 0.8 over the range of P.I. from 10 to 100%.

Since the test data obtained are total soil stress over time, the results of individual tests are normally presented graphically as shown in Figure 3. The test data shown in Figure 3 were obtained by the author at a clay site consisting of Connecticut Valley Varved Clay (CVVC) in Amherst, Ma. where the soil stiffness and stress history generally decrease with depth, i.e., the stratigraphy consists of an overconsolidated clay crust overlying near normally consolidated clay extending to a depth of about 18 m. The subsurface conditions at this site have been characterized in detail and are described by Lutenegger (2000) and DeGroot and Lutenegger (2002). Results from push-in earth pressure cell response at this site are presented elsewhere in this paper.

At a test depth of 5.3 m the soil is near normally consolidated (OCR = 1.2) and as can be seen, the test curve shows a characteristic "S" shape when presented on a semi-log plot. In other cases, such as, massive soft clays, where the horizontal hydraulic conductivity may be two orders of magnitude lower, i.e., 10^{-8} cm/sec., the final response may take several weeks. In this case, since the soil is a varved clay deposit with silt lenses and a relatively high horizontal hydraulic conductivity (10^{-6} cm/sec.) the final response in the soft clay occurs relatively fast, i.e., on the order of one week.

The equilibrium or final value of total horizontal stress is defined as σ_{hf} and is used to define the Reconsolidation Lateral Stress Ratio as:

$$K_c = (\sigma_{hf} - u_o)/\sigma'_{vo} \qquad (1)$$

where:
u_o = in situ pore water pressure at the test depth
σ'_{vo} = in situ vertical effective stress at the test depth.

In this case, equilibrium lateral stress was obtained after about 6000 minutes or approximately 4.2 days. Also note that the term K_c has been used in Equation 1 and not K_o, the at-rest coefficient of earth pressure. This is because the test does not actually measure the at-rest horizontal earth pressure but measures the earth pressure <u>after insertion of a flat blade.</u> The two terms should not be considered as the same parameter. Naturally, it is desirable to use the measured value of K_c to estimate K_o , which is generally the purpose in performing the test.

An argument can be made that in geologically young clay deposits in which little aging has occurred, the soil is more forgiving for insertion of the blade so that once any excess porewater pressures generated from insertion have equilibrated back to ambient in situ conditions, the later stress acting on the face of the blade may be very close to the pre-insertion or at-rest condition, This has generally been shown to be the case and in effect there is no "overstress" in these soils. However, this is generally not the case for stiff overconsolidated soils which are not as forgiving for the insertion of the blade.

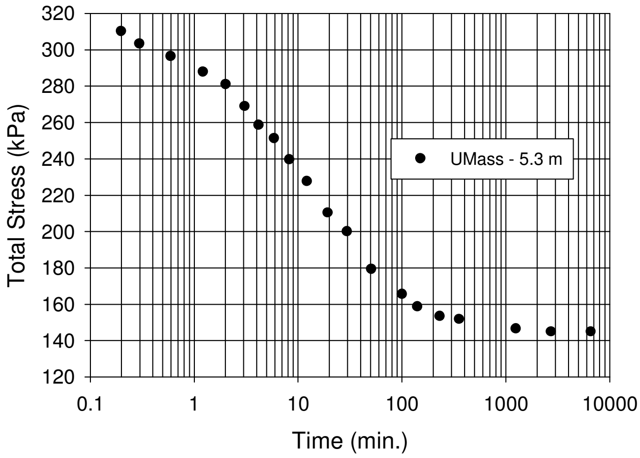

Figure 3 Typical Push-In Earth Pressure Cell Response in Soft (NC) Clay

3.2 Response in Stiff (OC) Clays

In overconsolidated clays, the response for equilibrium is much faster than for the normally consolidated zone. Figure 4 shows a typical response in an overconsolidated clay, at the same site and profile as Figure 3, but at a depth of only 1.5 m, in the stiff clay crust. The shape of the response curve is very different as compared to Figure 3 and equilibrium lateral stress was obtained after about 1000 minutes or slightly less than 1 day. As will be seen, there is an overstress which occurs in stiff clay; that is, the final equilibrium lateral stress is higher that the at-rest lateral stress in effect the soil is less forgiving of the blade insertion. As will be shown, it is suggested that this overstress is related to the stress history of the soil.

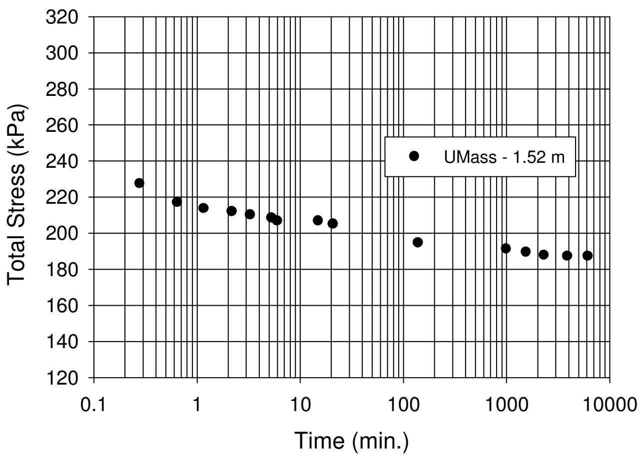

Figure 4 Typical Push-In Earth Pressure Cell Response in Stiff (OC) Clay

Values of K_c within the same geologic deposit at a site may be expected to decrease with depth if the OCR deceases with depth. That is, since there is a general expectation that the at-rest lateral stress ratio decreases as OCR decreases, we may expect the same trend in K_c. Figure 5 shows results obtained using identical Push-In Earth Pressure Cells in three adjacent test borings located approximately 5 m apart in CVVC test site at Amherst, Ma. As can be seen, calculated values of K_c, obtained using equilibrium lateral stress measurements from the Earth Pressure Cells and Equation 1, show a deceasing trend with depth as the soil transitions from the upper overconsolidated crust to the underlying more normally consolidated state.

Tedd and Charles (1983, 1989) suggested that a simple empirical correction factor could be applied to σ_{hf} to obtain σ_{ho} to account for the overstress. Based on a series of tests where spades were used under known stress conditions, it was suggested that a stress equal to one-half of the undrained shear strength should be subtracted from the measured final total stress to account for the overstress created by inserting the blade. Considerable scatter was displayed in these data and may be partly related to the selection of s_u and partly related to the reference test used for the "true reading".

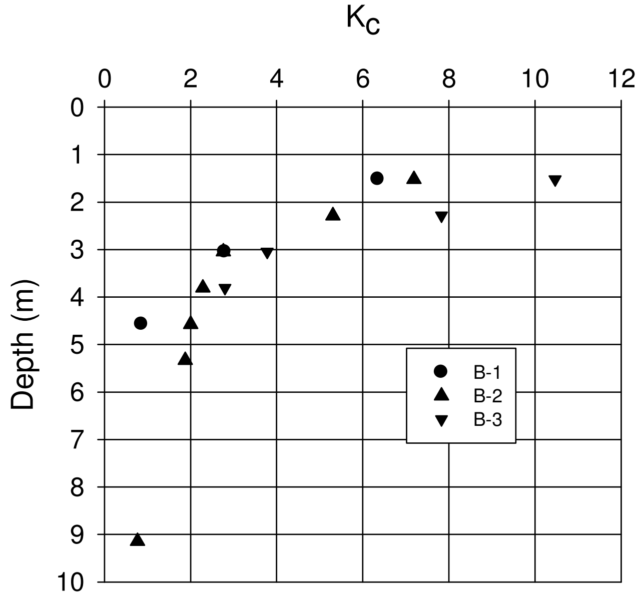

Figure 5 Variation in K_c in CVVC at Amherst, Ma

Intuitively, correcting Push-In Earth Pressure Cell equilibrium data using undrained strength makes sense, since in a very soft very young clay of low shear strength, the soil may be more forgiving and the final total stress measured by the spade returns closer to the stress prior to insertion. In an extreme case, such as a "liquid soil", with zero shear strength, the spade would essentially read the correct stress, like calibration in a fluid, e.g., air or water. One example of a very young very soft "liquid soil" is a bentonite-based slurry trench where a new soil is manufactured at very high water content and would be more forgiving to insertion of the blade even after consolidation.

On the other hand, an aged, very stiff highly overconsolidated clay with high undrained shear strength would be less forgiving to disruption by the spade and would tend to produce a large overstress from insertion. Since the shear strength is likely to be larger than shear strength of the soft clay, Additionally, there may be higher tensile strength in an overconsolidated clay that may not be overcome during blade penetration, especially for very thin blades, which may also contribute to overstress. a larger correction would be needed to account for the overstress.

Ryley and Carder (1995) showed that for clays with undrained shear strength in the range of 70 to 150 kPa that a best-fit correction for the overstress would be to adjust equilibrium lateral stress by a factor of 0.8 s_u. The use of a correction factor of 0.5 s_u would be conservative for retaining walls as it would give higher stresses than may actually be present. On the other hand, this would be unconservative for the design of driven piles, suggesting lateral stresses that are higher than actual values.

The problem with this approach is that the value of undrained shear strength for a given clay is not unique and depends on the test used, so which value should be used to correct the test data? While the approach at first seems to be reasonable it may be misleading. This being the case, it may be more appropriate to consider an overstress adjustment related to the normalized undrained shear strength, rather than simply the absolute undrained shear strength. For example, in a soft clay profile in which OCR = 1 but the undrained shear strength increases with depth, i.e., s_u/σ'_{vo} is a constant, this approach would suggest that a different correction factor be applied for tests at different depths, which does not seem logical. For a constant OCR, we should expect a constant value of K_o for the same soil.

A more direct approach to evaluating the results of spade cells tests may be to develop a functional relationship between K_c and K_o as will be discussed.

3.3 Response in Sands

There are no reliable data available in the literature on the use of Push-In Earth Pressure Cells in coarse-grained or granular soils such as sands. However, we may expect that the response to reach equilibrium lateral stress might be very fast and that there would be an overstress in excess of the at-rest lateral stress. It is also likely that the overstress will be related to the initial state of the sand, including in situ stress state and relative density. The complexity of advancing a flat plate into sands might be expected to be more similar to that observed when using the Flat Dilatometer, as compared to a CPT. Clearly this is an area that requires additional field research and it may be especially usefully to apply the results obtained from Push-In Earth Pressure Cells to the behaviour of open ended (small displacement) pipe piles of H-piles in sands.

4. PUSH-IN EARTH PRESSURE CELLS AS INSTRUMENTATION

Spade cells have been used on several projects involving cut and cover tunneling to monitor the changes in lateral stress associated with the construction (e.g., Tedd et al. 1984; 1985; Carder and Symons 1989; Symons and Carder 1992). Push-in spade cells have also been used to measure lateral stresses in slopes in Sweden (Rankka 1990). The author has also used Push-In earth Pressure Cells to assess lateral stresses behind retaining walls and to evaluate changes in lateral stress from pile driving.

5. PUSH-IN EARTH PRESSURE CELLS AS AN IN SITU TESTING TOOL FOR SITE CHARACTERIZATION

In addition to the clear application of Push-In Earth Pressure Cells as an instrumentation tool, there are other possibilities for site characterization beyond simply their application as a first order approximation for at-rest lateral stress. In general, the evaluation of post-insertion reconsolidated lateral stresses, which may be over and above the magnitude of at-rest lateral stresses, has strong potential for design of driven piles as will be discussed. Initially however, it is important to distinguish the possibilities for extracting additional information from the test results.

5.1 Lateral Stress Ratios in Clay

It is useful to consider some basic definitions of lateral stress ratios in clay soils for the purpose of considering possible interrelationships.

5.1.1 At-Rest Lateral Stress Ratio

Most engineers are familiar with the in situ lateral stress ratio under at-rest conditions which is defined as:

$$K_o = \sigma'_{Ho}/\sigma'_{vo} \qquad (2)$$

where σ'_{Ho} = effective in situ at-rest lateral stress and σ'_{vo} = effective in situ vertical stress. The value of K_o is an important parameter for a number of design problems and for clays having undergone simple unloading K_o has been shown to be related to the oedometric yield stress, σ'_p, through the overconsolidation ratio, OCR (= σ'_p/σ'_{vo}) (e.g., Brooker and Ireland 1965; Mayne and Kulhawy 1982); i.e.,

$$K_o = f(OCR) \qquad (3)$$

5.1.2 Dilatometer Lateral Stress Ratio

The Flat Dilatometer provides a determination of a lateral stress ratio through the lift-off pressure, P_o, defined by Marchetti (1979) as the Dilatometer Lateral Stress Index; K_D, in which:

$$K_D = (P_o - u_o)/\sigma'_{vo} \qquad (4)$$

where: P_o = DMT lift-off pressure; u_o = in situ pore water pressure. Note that u_o is used in the definition of K_D as a matter of convenience, since the actual pore water pressure at the time P_o is obtained is unknown and not determined routinely. The value of P_o reflects the lateral stresses prior to installation plus any changes that may occur as a result of the blade penetration:

$$P_o = \sigma'_{Ho} + u_o + \Delta\sigma'_H + \Delta u \qquad (5)$$

Marchetti (1979) and many others have shown that in clays and other fine-grained soils an empirical relationship may be established between K_D and the stress history (OCR) such that:

$$OCR = f(K_D) \qquad (6)$$

5.1.3 Initial Lateral Stress Ratio

We may also find it convenient to define the Initial Lateral Stress Ratio which may be used to reflect the effective stress ratio immediately after insertion of a probe or a driven pile:

$$K_i = (\sigma_{Ho} - u_i)/\sigma'_{vo} \qquad (7)$$

where: u_i is the total pore water pressure ($u_o + \Delta u$) immediately after insertion of the probe. Values of K_i were shown by Baligh et al. using the Piezolateral Stress Cell (Baligh et al. 1985).

In the case of the Flat Dilatometer, the value of u_i is not measured directly, but may be estimated from the recontact pressure P_2 which is obtained after the DMT lift off pressure (P_o) and 1 mm expansion pressure, (P_1). Therefore, for the Dilatometer Eq. 7 may be rewritten as:

$$K_{i(DMT)} = (P_o - P_2)/\sigma'_{vo} \qquad (8)$$

K_i may be a useful reference parameter for evaluating soil behavior such as soil type, strength, stress history and drainage characteristics. In cases where a Push-In Earth pressure Cell is not equipped with a pore water pressure transducer, the initial (post-insertion) pore water pressure is not know, and K_i may not be evaluated.

5.1.4 Reconsolidation Lateral Stress Ratio

As has already been discussed, in the past thirty years, a number of researchers have shown that it is possible to use Push-In Earth Pressure Cells to obtain a measurement of the lateral stress in the ground after the effects of installation have dissipated. Essentially this is achieved by taking long term measurements of total stress until a stable value is obtained. In this way, any excess pore water pressures, which are difficult to measure, are no longer present and only the in situ pore water pressure, u_o, remains. In this case, the Reconsolidation Lateral Stress Ratio may be defined as:

$$K_C = (\sigma_C - u_o)/\sigma'_{vo} = \sigma'_C/\sigma'_{vo} \qquad (1)$$

Naturally, the final effective lateral stress is composed of the initial at-rest effective lateral stress (prior to probe insertion) and any change in effective stress as a result of the probe insertion and reconsolidation; i.e.

$$\sigma'_{C} = (\sigma_C - u_o) = \sigma'_{Ho} + \Delta\sigma'_{H} \quad (9)$$

It should be expected that in very soft clays the value of $\Delta\sigma'_H$ will be very small; in very stiff clays $\Delta\sigma'_H$ may be very large.

Data obtained by the author and available in the literature from Push-In Earth Pressure Cells ("spade cells") at sites with OCR measured from oedometer tests are shown in Figure 6. These data show a clear trend of increasing K_c with increasing OCR as expected. Some of the scatter from the spade cell data may result from the fact that not all of the spade cells used by various investigators had the same geometry. The data in Figure 6 support the observation that K_C is generally related to OCR.

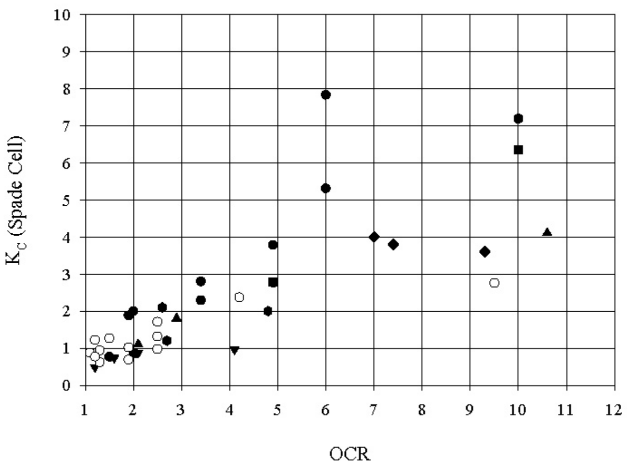

Figure 6 Variation in K_C with OCR from Push-In Earth Pressure Cells at Several Sites

Naturally, one problem with determining K_C from Push-In Earth Pressure Cell tests is the potentially long time period required to obtain a stable equilibrium reading. To investigate a more expedient approach, the relationships between K_C and K_D and between K_C and K_i were explored. The rationale behind this approach is that for clays having undergone simple unloading:

$K_C = f$ (OCR) and $K_D = f$ (OCR)

therefore it can be expected that: $K_C = f(K_D)$

Figure 7 presents a summary of available results from a number of sites from the literature and tested by the author showing the observed relationship between K_D and K_C. Again it can be seen that K_C may be related to K_D . The results show that K_D is clearly related to K_C and with the exception of one site, the scatter is not all that great, again considering that the geometry of the spades was not the same at all sites. In very soft clay, it may be expected that K_C will be very near K_o and that over time the soil will be somewhat "forgiving" for the intrusion of inserting the blade. This is not to be expected in stiffer clays however, and there will be an "overstress" resulting from the blade insertion, the $K_C > K_o$. The "overstress" is a component of effective stress and/or soil tensile strength that remains in place after the excess pore water pressure produced from blade insertion dissipates and reconsolidation is complete.

This is illustrated from a comparison of between K_C and K_o for the CVVC at the UMass site shown in Figure 8. K_o data were obtained from tests on undisturbed samples using an instrumented oedometer capable of measuring lateral stress at known OCR produced by simple unloading. The "overstress" indicated in Figure 8 clearly increases as the initial stress or K_o increases and as OCR increases.

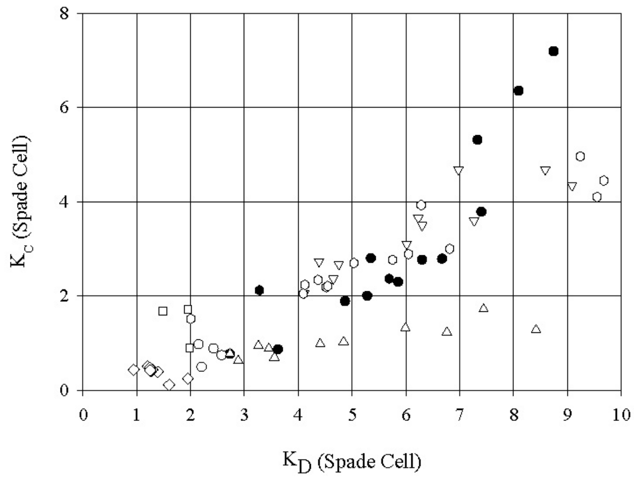

Figure 7 Relationship Between K_D and K_C from Push-In Earth Pressure Cell tests

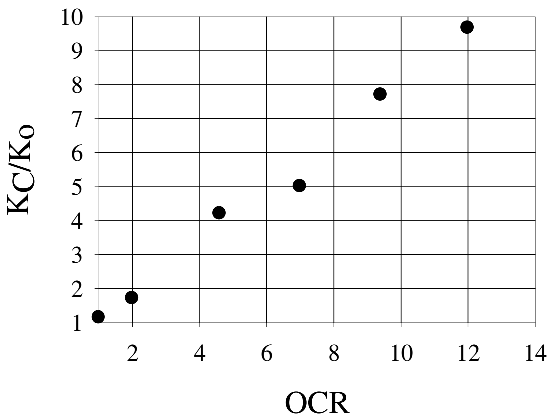

Figure 8 "Overstress" Related to Stress History

One expects that if K_o, K_D, K_C , and K_i are all related to OCR then they are all related to each other. Of course, any relationship between K_D or K_i and OCR may also be used to develop a direct relationship between $(P_o - u_o)$ or $(P_o - P_2)$ and σ'_p.

If the soil exhibits normalized behavior and the normalized undrained shear strength is related to stress history via OCR, then K_D, K_C and K_i will in turn be related to undrained shear strength. This argues that one should expect the DMT to provide a fairly reliable estimate of OCR, undrained strength and K_o through K_D, provided there has been sufficient reference calibration.

K_c is related to the stress history through OCR. The scatter in reported results is probably related to differences in blade geometry as previously discussed. Even for OCR = 1 there may be scatter in the test results. For a given clay, under simple unloading, there is a relationship between K_o and OCR as demonstrated for example by Mayne and Kulhawy (1982). Therefore, it is a relatively simple matter to establish a relationship between K_c and K_o since both appear to be related to OCR.

For tests performed at a single site using a single test arrangement, there is likely to be less scatter. The approach suggested by Tedd and Charles (1981) could still be applied if the absolute undrained shear strength can be obtained at different OCR's provided the soil exhibits normalized behavior and the normalized undrained strength - OCR relationship is known. Unfortunately, not all clay soils have been subjected to simple unloading or simple reloading, and may have complex stress histories. Additionally, not all clay soils exhibit well defined normalized behavior. This means that a simple approach to correcting test results may have considerable merit.

Benoit and Lutenegger (1992) found that results from Push-In Earth Pressure Cells compared very favorably with results obtained from Self-Boring Pressuremeter Tests, which suggest in softer clays again very little adjustment would be appropriate.

5.2 Flat Dilatometer as a Push-In Earth Pressure Cell

The Flat Dilatometer, shown in Figure 8, may also be used as a "Push-In Earth Pressure Cell" to provide a measurement of the final horizontal stress after the equilibrium of penetration pore pressures. In this case, the DMT is advanced to the test depth and only repeated, timed, A-Readings are obtained. This is identical to the DMTA dissipation procedure suggested by Marchetti et al.(1986, 1992) and referred to as a DMTA test. In this case, the blade is left in the ground until the A-Reading remains constant and an equilibrium value of P_o is obtained. This value is termed the "final" P_o value and designated as P_{of}. P_{of} is a total stress measurement obtained after penetration excess pore pressures have dissipated and may be used along with the in situ pore water u_o to define a "consolidated" lateral stress ratio, K_C, as:

$$K_C = (P_{of} - u_o)/\sigma'_{vo} \quad (10)$$

Equation 10 is essentially the same as Equation 1, previously given for Push-In Earth Pressure Cells. Figure 10 shows results of a typical Dilatometer reconsolidation test; i.e., using the DMT as a Push-In Earth Pressure Cell, in CVVC at Amherst, Ma. The results look similar to the results previously shown in Figure 3 for soft clay. The results obtained from seven soundings at this site show the variation in KC with depth in the clay at this site, Figure 11. These results clearly show the sharp decrease in KC through the stiff overconsolidated crust, down to a about 6 m and then a more gradual decrease throughout the remainder of the profile in the softer, near normally consolidated zone. In the lower 6 m, the value approaches a constant of about KC = 0.8.

Values of KC at this site may be related to the stress history of the soil through OCR using the results of laboratory oedometer tests on undisturbed samples obtained at the site. These data are shown in Figure 12. It can be seen that the reconsolidation lateral stress ratio, KC, from the DMT is a function of the stress history of the soil, an observation that has been made by others using instrumented model-scale and full-scale piles in clays. This suggests that a first order estimate of KC for use in pile design might be initially made using OCR if laboratory oedometer test results are available.

Figure 9 Flat Dilatometer Blade

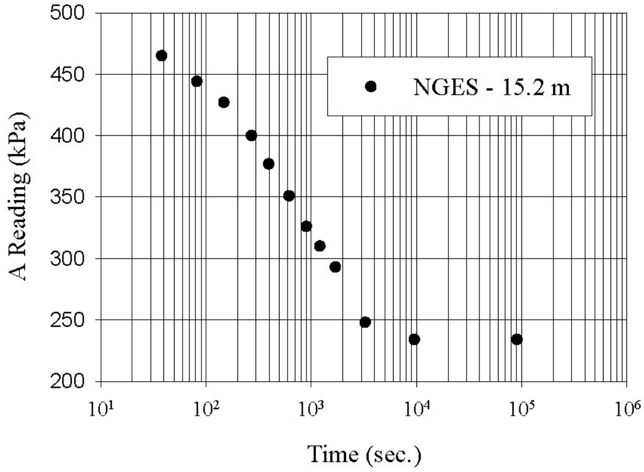

Figure 10 Typical Dilatometer Reconsolidation Tests Results

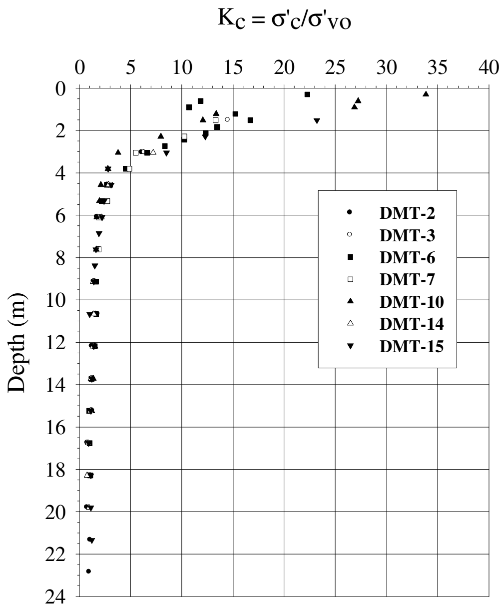

Figure 11 Variation in K_C from Flat Dilatometer with Depth in CVVC at Amherst, Ma

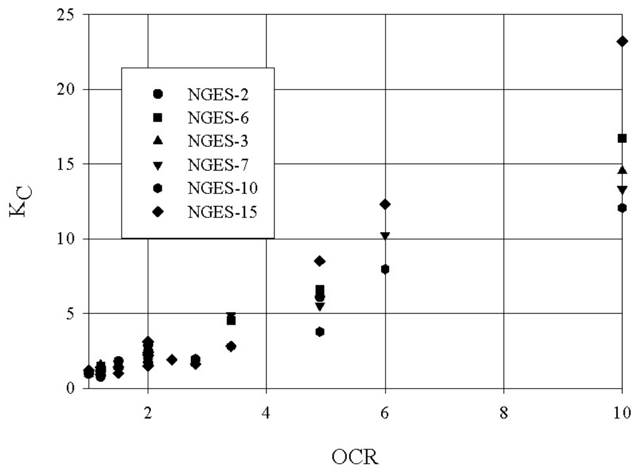

Figure 12 Variation in K_C from Flat Dilatometer with Laboratory OCR

The results presented in Figure 12 also show less scatter that the results previously shown in Figure 6 for several reasons: 1) the equipment used for all tests was the same; 2) there is only one site shown; and 3) the same laboratory procedure was used to determine stress history.

The Flat Dilatometer has the advantage over traditional Push-In Earth Pressure Cells in that it may be used as a profiling tool and advanced without a borehole or intermediate drilling to obtain a detailed profile of soil response. However, the equipment may be tied up to the site for a long period of time.

5.3 "Passive" Push-In Earth Pressure Cell

The Flat Dilatometer is an "active" in situ instrument, that is, an active operation at the ground surface is used to "activate" and operate the probe in the ground. In the case of the DMT, the operator actively applies gas pressure to the flexible membrane on the face of the blade to obtain the measurement. This is in contrast to "passive" instruments which are largely electronic and in which the operator simply records the desired measurement at the ground surface from the in ground response of the blade.

The author (Lutenegger 2012) recently described a new style Push-In Spade Cell (PISC) which is a slight departure from the previous approach and is more in line with an in situ test used to estimate soil properties throughout a subsurface profile, much like the Flat Dilatometer (DMT). The spade consists of a stainless steel blade with dimensions of 102 mm x 250 mm x 12.5 mm and has an leading apex angle of 60 degrees at the front as shown in Figure 1. This geometry was intentionally selected to be similar in design to the Flat Plate Dilatometer. The PISC is equipped with a 72 mm diameter flat pressure cell mounted flush with the face of the blade. The earth pressure cell is fluid filled and connected to a vibrating wire pressure transducer that senses changes in total stress. The transducer has a working stress range of 350 kPa and a sensitivity of 0.7 kPa. Pressure readings are obtained using a Geokon Model GK403 portable digital readout. A temperature reading is also obtained at each test depth using the internal thermister built into the vibrating wire transducer. Tests were performed by advancing the spade from the ground surface to the desired test depth at a rate of 2 cm/sec. Pressure readings were obtained immediately after stopping penetration (t = 0 sec.) and at intervals of 15, 30 and 60 sec. after stopping penetration. After obtaining the 60 sec. reading, the PISC was advanced to the next test depth by quasi-static penetration. Tests were performed at depth intervals of 0.3 m.

Unlike the DMT, the PISC only has the initial "passive" phase of testing, i.e., there is no "active" membrane expansion phase. This means that the PISC cannot be used to give a direct estimate of soil stiffness or modulus. In contrast to the Dilatometer, which has a central diaphragm that must be activated using air pressure from the ground surface, the PISC only responds to the horizontal stress and does not involve any active expansion phase.

In addition to obtaining readings during profiling, at one of the sites total stress dissipation tests were performed at selected depths to determine the change in total stress over time to obtain equilibrium total stress conditions. These tests typically lasted several days.

Like traditional Push-In Earth Pressure Cells the PISC may also be used to evaluate the change is total stress with time (time rate of total stress dissipation) by leaving the spade in place at any specific test depth and recording the total stress at given time intervals after penetration. As previously noted, this has been the primary use of other push-in spade cells in the past. Typical results of a dissipation test obtained from the UMass DOE site are shown in Figure 14. These results may be interpreted as has previously been done for Push-In Erath Pressure Cells and DMT total stress dissipation tests (e.g., Marchetti et al 1986; Lutenegger and Miller 1993; Marchetti and Totani 1989; Lutenegger 2006).

5.4 Application to Driven Piles

It is now generally well established that the design of driven piles in both clays and sands is related to the post-driving lateral stresses adjacent to the pile at the time of loading. Unfortunately, the determination of operational lateral stresses depends on a number of variables, including soil type and stress history, pile geometry, i.e., open vs. closed end, and specific installation procedure. In relation to the previous discussion related to the reconsolidation lateral stresses observed from Push-In earth Pressure Cells, it may now be possible to make a direct analogy to small-displacement and large-displacement piles.

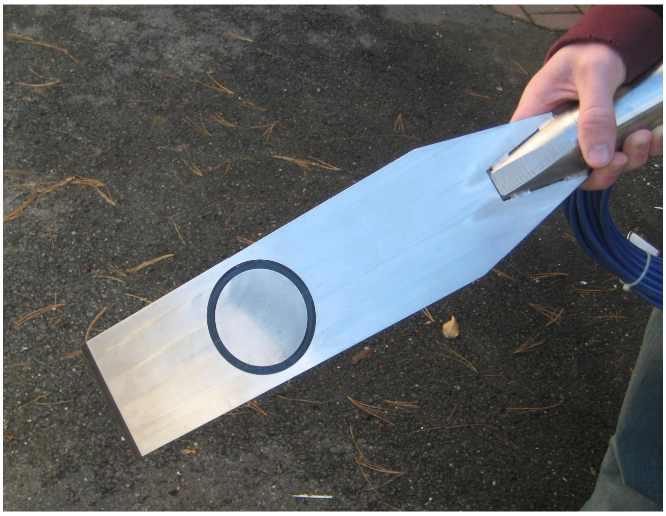

Figure 13 Push-In Spade Cell (Lutenegger 2012)

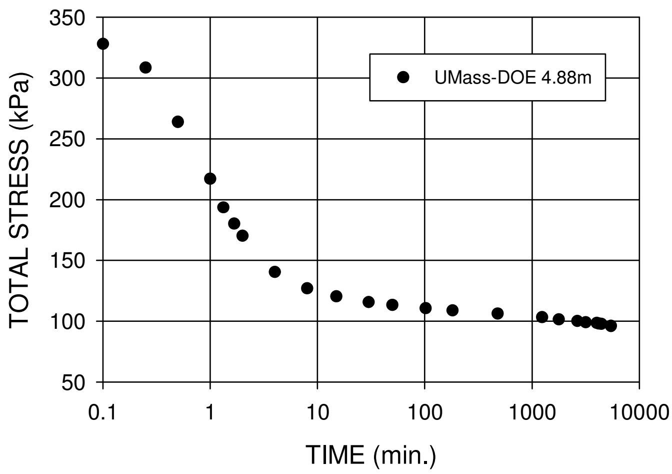

Figure 14 Typical PISC Response in Soft Clay

Results obtained from small-scale instrumented piles (e.g., Baligh et al. 1985; Azzouz and Morrison 1988; Jardine and Potts 1988; Coop and Wroth 1989; Bond et al. 1991; Bond and Jardine 1991; Totani et al. 1994; Lehane et al. 1994; Bond and Jardine 1995) as well as the Flat Dilatometer (e.g., Marchetti et al. 1986, 1992; Lutenegger and Miller 1993) as well as full-scale instrumented piles essentially all show that reconsolidation lateral stress ratios all show a similar dependency on the OCR of the soil, nearly independent of soil type. For example, Bond et al. (1993) and now others have shown that the reconsolidation lateral stress ratio from instrumented piles is related directly to the OCR of the soil and has similar magnitude to the values shown in Figures 6 and 11 of the current paper.

6. SUMMARY

Push-In Earth Pressure Cells offer the engineer a unique technique for evaluating in situ stress conditions in soils. Applications for both instrumentation, to evaluate changes in lateral stress from geo-construction or other site activities, and for evaluating soil behavior are well documented and should be considered as a viable option on projects. Test results are reliable and repeatable and offer an economical approach for engineers to obtain specific insight into soil behavior through evaluation of the lateral stress state. They are easily deployed and readily retrieved at the end of a project for use on other projects.

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