Consolidation lateral stress ratios in clay from flat Dilatometer tests

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ABSTRACT: The Flat Dilatometer may be used as a push-in earth pressure spade cell to obtain a measure of the reconsolidated lateral stress after penetration excess pore pressures have dissipated. In this procedure, a DMT A-Dissipation test is performed until a constant equilibrium value is obtained and the DMT acts as a total stress cell. Results obtained at several test sites ranging in consistency from very soft to very stiff fine-grained soils are presented. The test data show that the value of $K_C = (\sigma_c - u_o)/\sigma'_{vo}$, the reconsolidation coefficient of lateral stress, obtained after allowing installation effects to stabilize and the lateral stress to reach equilibrium, may be related to the initial state of stress and the stress history (OCR) of the soil. The results demonstrate that the value of K_C is very close to estimated values of K_o in soft and very soft clays but that there is a potential error associated with using the test results directly to infer the at-rest coefficient of lateral stress in stiff clays. The results also give some insight into the magnitude of effective lateral stresses acting on the face of driven piles in clay for use in an effective stress analysis of axial pile skin friction capacity. The results also show that K_C is related to both the initial lateral stress ratio, $K_i = (P_o - P_2)/\sigma'_{vo}$ and the Dilatometer lateral stress index, $K_D = (P_o - u_o)/\sigma'_{vo}$. This eliminates the need to wait until all of the penetration effects have dissipated to make an initial estimate of K_c.

1 INTRODUCTION

Engineers often need to estimate horizontal stresses acting in the ground either under at-rest conditions or on the face of driven piles for using an effective stress design approach. The Dilatometer may be useful in providing a measure of the effective lateral stress by conducting a reconsolidation test. In this way the DMT is used much like a push-in spade cell. Results presented in this paper illustrate this procedure and test results show that K_C is related to K_D.

2 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.

2.1 At-Rest Lateral Stress Ratio

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

$$K_o = \sigma'_{Ho}/\sigma'_{vo} \qquad (1)$$

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.,

$$K_o = f(OCR) \qquad (2)$$

2.2 Dilatometer Lateral Stress Ratio

The 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:

$$K_D = (P_o - u_o)/\sigma'_{vo} \qquad (3)$$

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 and any changes that may occur as a result of the blade penetration:

$$P_o = \sigma'_{Ho} + u_o + \Delta\sigma'_H + \Delta u \quad (4)$$

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:

$$OCR = f(K_D) \quad (5)$$

2.3 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:

$$K_i = (\sigma_{Ho} - u_i)/\sigma'_{vo} \quad (6)$$

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 Dilatometer, the value of u_i is not measured directly, 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, Eq. 6 may be rewritten as:

$$K_{i(DMT)} = (P_o - P_2)/\sigma'_{vo} \quad (7)$$

K_i may be a useful reference parameter for evaluating soil behavior such as soil type, strength, stress history and drainage characteristics.

2.4 Reconsolidation Lateral Stress Ratio

In the past twenty years, some researchers have shown that it is possible to use special probes such as push-in earth pressure cells or instrumented model piles 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:

$$K_C = (\sigma_C - u_o)/\sigma'_{vo} = \sigma'_C/\sigma'_{vo} \quad (8)$$

where: σ'_C is equal to the final effective lateral stress (corrected for u_o) acting on the probe. 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.

In the case of the Dilatometer, the value of σ_C may be estimated from a reconsolidation test and Eq. 8 may be rewritten as:

$$K_{C\,(DMT)} = (P_{of} - u_o)/\sigma'_{vo} \quad (10)$$

The value of P_{of} is obtained by observing the change in P_o with time until a stable value is obtained as described in the next section. Previous results (Marchetti et al. 1986; Lutenegger and Miller 1993) have shown that these tests are simple to perform and give reliable results in clays.

3 DETERMINING THE DILATOMETER RECONSOLIDATION STRESS

The Dilatometer may be used in much the same way that push-in earth pressure cells are used to obtain a direct measure of the reconsolidation lateral stress after the effects of installation have come to equilibrium. The test is performed by taking only A-Readings without expanding the diaphragm further to obtain the B-Reading. This procedure is similar to the procedure sometimes referred to as an "A-Dissipation" test. The diaphragm is expanded to obtain the lift-off pressure (A-Reading) but no B-Reading is taken. In this way, the soil remains in contact with the face of the blade and the flexible diaphragm throughout the test. As soon as the DMT penetration is stopped, a stopwatch is started so that the elapsed time between blade penetration and the A-Readings may be obtained.

Successive A-Readings are then taken over time in order to track the decrease in A with time until a stable value is obtained, indicating that the insertion effects, i.e., excess pore water pressure, have dissipated. Depending on the soil conditions, this may require a waiting period ranging from several hours to several days. Since the A-Reading (or P_o) is a total stress measurement, this procedure provides a record of the decay of total horizontal stress with time and is essentially the same as using a push-in total earth pressure cell as previously reported (e.g., Massarch 1975; Tavenas et al. 1975; Tedd and Charles 1981). Once a stable condition is reached and the final A-Reading is taken, the test is performed as in

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any other DMT test, i.e., a B-Reading (1 mm expansion) and C-Reading (re-contact) are obtained.

4 RESULTS

DMT reconsolidation tests have been conducted at a number of sites consisting of medium stiff and soft clays. Figure 1 gives results of a typical reconsolidation curve showing the change in total stress (Po) with time. These results were obtained in a soft clay and show the characteristic "S" shaped curve that is similar to results obtained from push-in spade cells and from pore pressure dissipation tests, such as from a Piezocone or Piezoblade. In this case however, Figure 1 represents the change in total horizontal stress with time. The stable value thus becomes the final total horizontal stress, σ_C, and since the pore water pressure has returned to in situ conditions, i.e., prior to blade insertion, the final effective horizontal stress may be obtained from $\sigma'_C = (\sigma_C - u_o)$. Figure 2 shows a set of reconsolidation curves obtained from a single DMT sounding in a deposit of Connecticut Valley Varved Clay (CVVC) at the NGES at the University of Massachusetts in Amherst.

The results obtained from seven soundings at this site show the variation in σ'_C with depth, Figure 2. These results clearly show the sharp decrease in σ'_C through the stiff overconsolidated crust, down to a

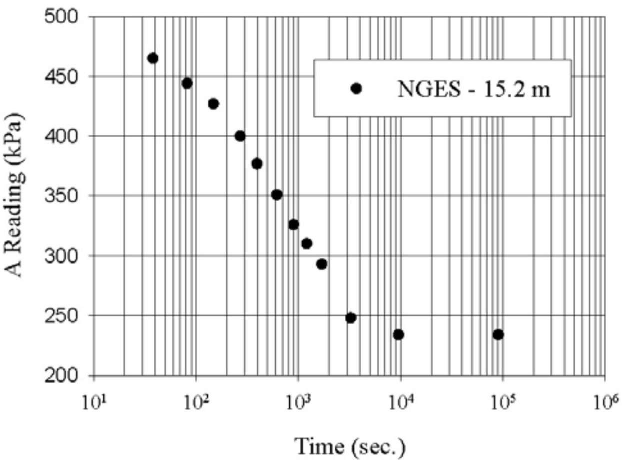

Figure 1. Typical DMT reconsolidation test results.

depth of about 6 m and then a more gradual decrease throughout the remainder of the profile in the softer, near normally consolidated zone. Figure 3 shows the variation in K_C (Eq. 10) at the site using the results from Figure 2. Again it can be seen that in the upper 6m K_C decreases rapidly. In the lower 6m, the value approaches a constant of about $K_C = 0.8$.

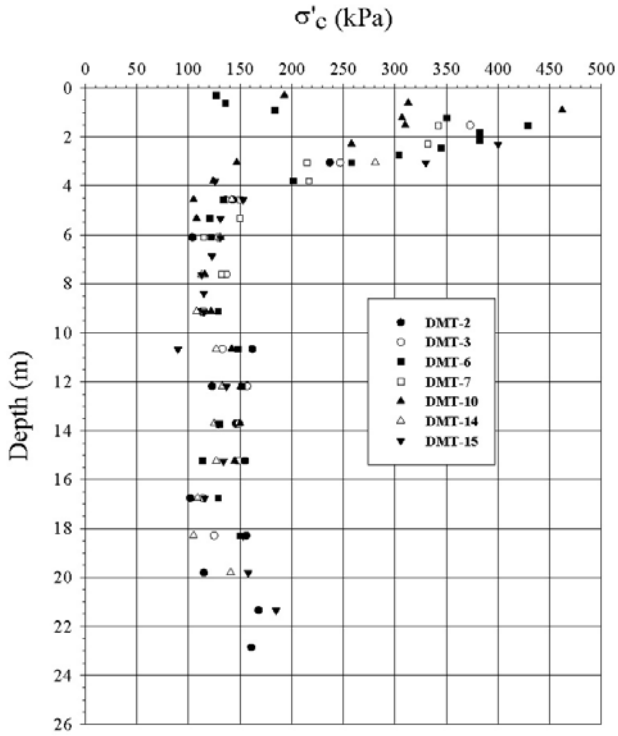

Figure 2. Variation in σ'_C with depth at UMass-Amherst.

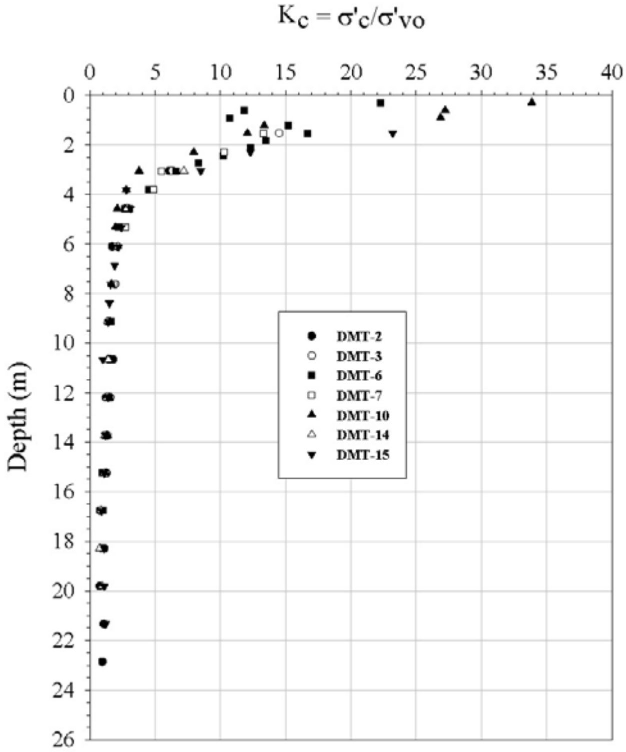

Figure 3. Variation in DMT K_C with depth at UMass-Amherst.

Values of K_C 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 4.

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It can be seen that the reconsolidation lateral stress ratio, K_C, 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 K_C for use in pile design might be initially made using OCR if laboratory oedometer test results are available.

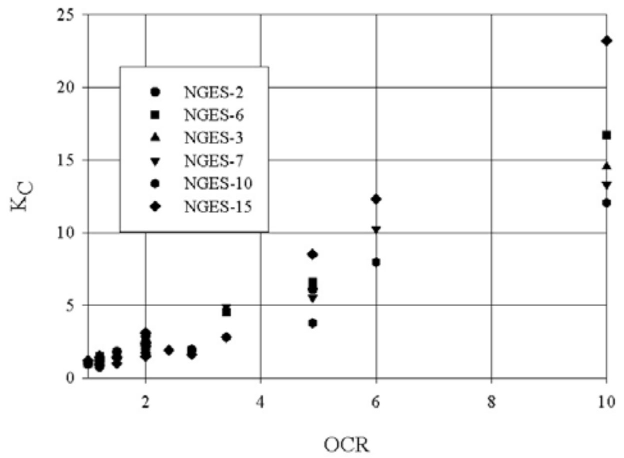

Figure 4. Relationship between DMT K_C and OCR. – UMass.

Figure 5 shows additional DMT results obtained by the author at several other sites, confirming the observations presented in Figure 4 for a wider range of clays. The scatter in the results is likely related to the fact that not all of the sites developed overconsolidation by simple unloading, which will tend to complicate a single straightforward relationship between OCR and K_C for all clays.

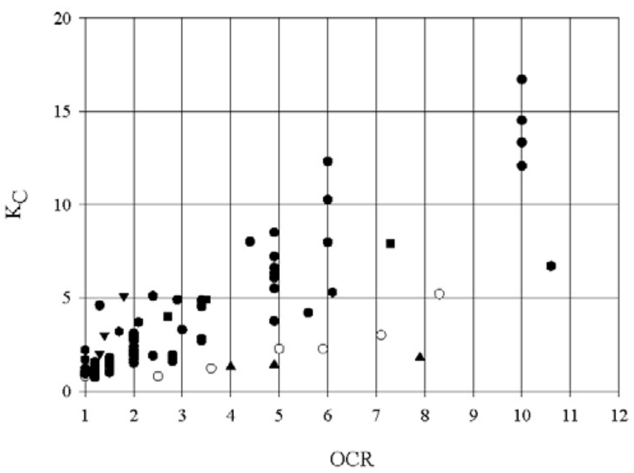

Figure 5. Variation in DMT K_C with OCR for several sites.

The data shown in Figure 5 are supported by additional test results 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. These data are shown in Figure 6 and show scatter similar to DMT results. Some of the scatter from the spade cell data may also result from the fact that not all of the spade cells used had the same geometry, whereas the data presented in Figure 5 are all from a probe of constant geometry. The data in Figure 6 support the observation that K_C is generally related to OCR.

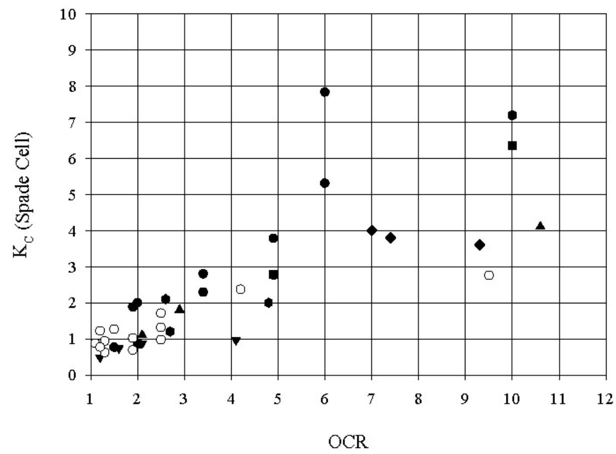

Figure 6. Variation in K_C with OCR from push-in spade cells.

5 INTERRELATIONSHIPS

Naturally, one problem with determining K_C from a full DMT or spade cell reconsolidation test is the long time period required to obtain a stable 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 DMT results showing the relationship between K_D and K_C. Additional results obtained by the author and from the literature from push-in spade cells is shown in Figure 8. Again it can be seen that K_C may be related to K_D (where K_D is obtained from spade cell data rather that the DMT). 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.

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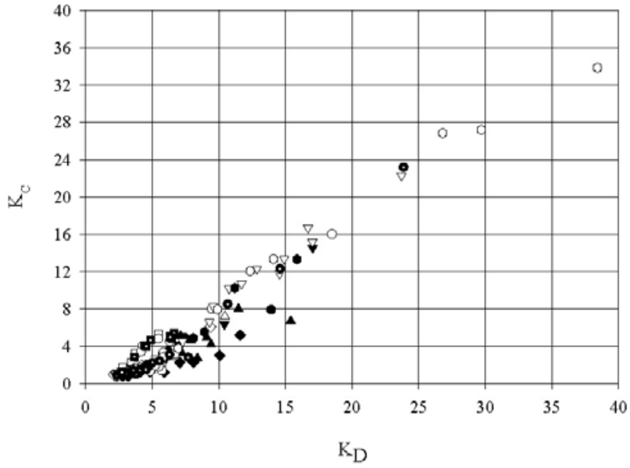

Figure 7. Observed relationship between K_D and K_C from DMT reconsolidation tests.

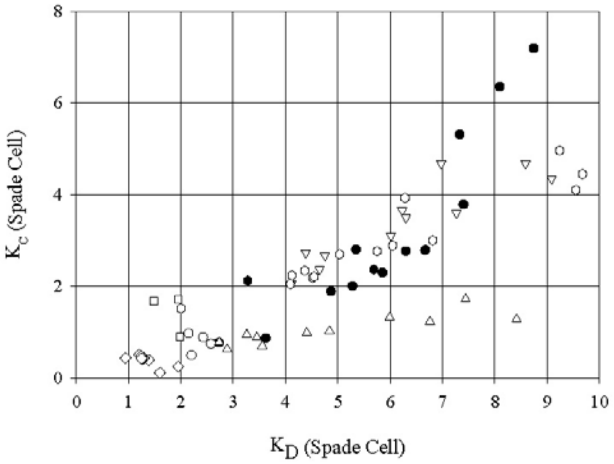

Figure 8. Relationship between K_D and K_C from push-in spade cell reconsolidation tests.

In very soft clay, it may be expected that K_C will be very near K_o and 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 9. 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 9 clearly increases as the initial stress or K_o increases and as OCR increases.

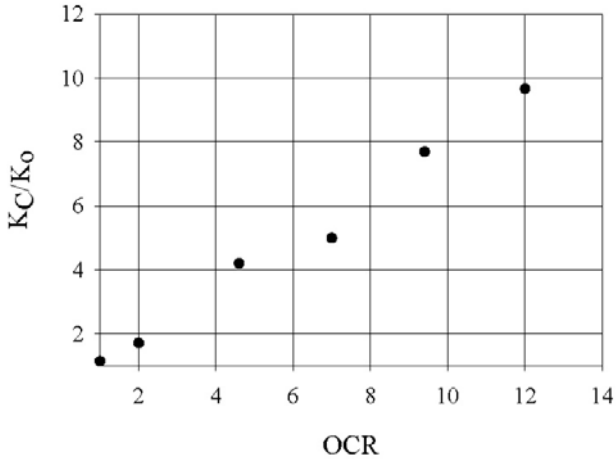

Figure 9. Variation in DMT K_C and laboratory K_o with OCR for CVVC.

Tedd and Charles (1981) suggested that in stiff clays the "overstress" acting on a push-in spade cell could be related to the undrained shear strength and that the final reconsolidation stress measured in the test might be adjusted to obtain a value closer to the true value. Intuitively, one could argue that the overstress is related to the normalized undrained shear strength or, as shown in Figure 9, the OCR.

The initial lateral stress ratio, K_i, may be related to stress history as shown in Figure 10, which shows results obtained by the author in Champlain Sea Clays. Additionally, K_i should be expected to relate to both K_C and K_D. The ratio K_D/K_i will be close to unity in very stiff clays where u_o and P_2 are very low or zero.

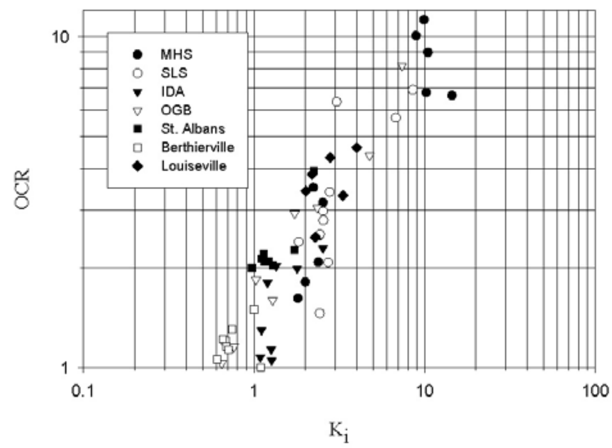

Figure 10. Variation in K_i with OCR.

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. Figure 11 shows a comparison between K_C and K_i obtained at several clay sites. 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.

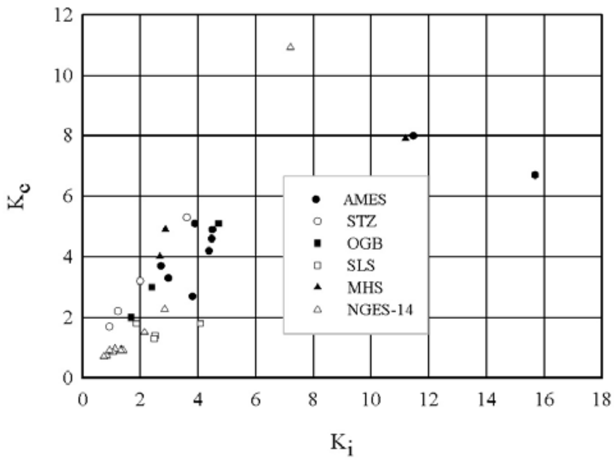

Figure 11. Comparison between K_C and K_i at several clay sites.

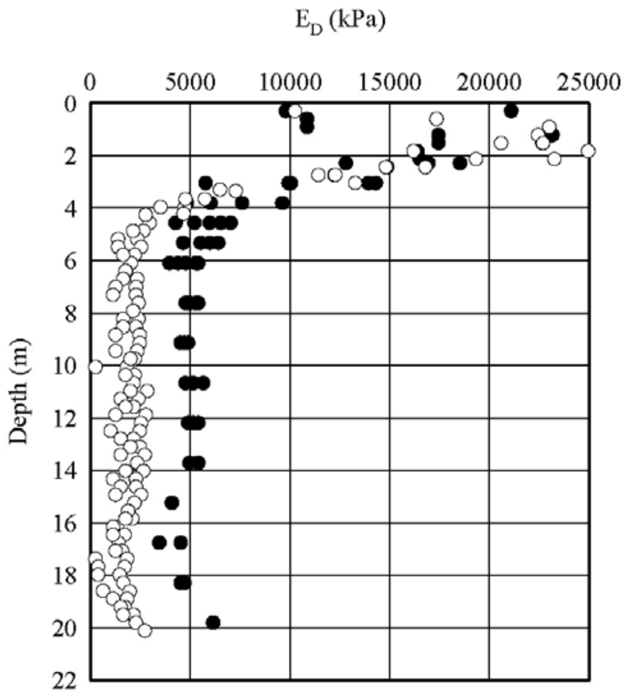

Figure 12. Comparison between DMT E_D and $E_{D(Consol)}$.

Since a regular DMT (i.e., with both A- and B-Readings) is performed after installation effects have dissipated, reconsolidation tests may also be used to obtain a measure of the consolidated DMT Modulus. In soft clays $E_{D(Consol)}$ will be higher than E_D. An example from the UMass Site is shown in Figure 12 where the open symbols represent regular tests and the closed symbols represent consolidated tests.

6 CONCLUSIONS

A measure of the reconsolidation lateral stress may be obtained in clays using the Dilatometer. The reconsolidation Lateral Stress Ratio, K_C, which may be useful for design of driven piles or for estimating at-rest lateral stresses in soft clays is seen to be related to the soil stress history. The test data presented indicate that in clays the Initial Lateral Stress Ratio, K_i, the DMT Lateral Stress Index, K_D, and the Reconsolidation Lateral Stress Ratio, K_C are all interrelated and related to OCR. The DMT Lateral Stress Index, K_D, may be used to make an initial estimate of K_C in the absence of a full reconsolidation test. However, when possible, it may be necessary to perform reconsolidation tests in order to obtain additional test data for use in design. In addition to obtaining a measure of soil behavior after reconsolidation, the time rate of dissipation may be useful as has been previously noted by others.

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