Lateral Earth Pressure Measurements in a Marine Clay

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A series of self-boring pressuremeter (SBPM), self-boring lateral stress cell (SBLC), and flat dilatometer (DMT) tests have been performed at a marine clay test site in Massena, New York. Three strain arm readings from the SBPM tests were recorded individually. The SBLC has two stress cells 180 degrees apart. By rotating the SBLC it was possible to measure the lateral stresses in different directions. The DMT tests were performed by pointing the blade in five directions, each 45 degrees apart. The tests performed are described, and the performance of the individual methods are evaluated in light of the test results.

Measuring the field lateral earth pressure σ_{ho} is one of the most intriguing challenges for geotechnical engineers. Such measurements have included the use of hydraulic fracturing, different types of pressuremeters, and lateral stress probes (*1*,*2*) as well as a variety of flat-plate penetrometers (*3–5*). Among all the available methods, the self-boring probes (e.g., the camkometer) may be the most sophisticated and elaborate ones. Representing the other end is the flat dilatometer (*3*), which is simple and efficient. Little information is available as to the relative performance of those two different approaches (i.e., simplicity versus accuracy).

The at-rest lateral earth pressure coefficient K_o is often used in lieu of σ_{ho}. Here, the term K_o will be defined as

$$K_o = \frac{\sigma'_{ho}}{\sigma'_{vo}} \tag{1}$$

where σ'_{ho} is the effective lateral earth pressure, and σ'_{vo} is the effective overburden stress.

Apparently, because of its relatively low disturbance, the self-boring pressuremeter (SBPM), such as the Camkometer, has been accepted as one of the more reliable tools for measuring the in situ lateral earth pressure. Three strain arms are located at the mid height of the camkometer probe. In theory, as the probe pressure exceeds the surrounding lateral earth pressure it starts to expand. This "lift-off" pressure during the SBPM probe expansion has been linked directly to the lateral earth pressure. However, the lift-off pressures according to the individual strain arms do not always agree with one another. This can be attributed to the anisotropic nature of the lateral earth pressure or nonuniform disturbance of the soil. Despite the studies conducted (*2*), there has been no general conclusion as to which of the two is the more prominent factor (*6*).

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The flat dilatometer (DMT) is a relatively new addition to the in situ testing devices. Many empirical methods have been proposed to relate K_o to the DMT horizontal stress index K_D [e.g., those of Marchetti (*3*) and Powell and Uglow (*7*)], which is defined as

$$K_D = \frac{P_0 - u_o}{\sigma'_{vo}} \tag{2}$$

where P_0 is DMT lift-off pressure, and u_o is hydrostatic pore water pressure before DMT insertion.

Reports of such applications have been encouraging (*7–9*). The DMT is generally considered a rugged, simple, and practical testing device. The SBPM, on the other hand, is viewed as being complicated and mainly a research tool. In an effort to evaluate the relative performance of such drastically different approaches, a series of SBPM, self-boring lateral stress cell (SBLC), and DMT tests were carried out at a test site. This paper presents the tests performed and discusses the efficacy of those methods in measuring lateral earth pressures.

FIELD EXPERIMENTS

Site Conditions

The test site is located east of the town of Massena, New York. Figure 1 presents the layout of the test site and the testing location. Highway 37 runs east to west immediately to the north of the test site. A creek located to the west of the test site had eroded the soil and created an approximately 4-m deep cut. The soil consists of approximately 12 m of a marine clay deposit underlain by glacial till. Below the 1.5-m thick highly weathered and fissured crust and a layer of overconsolidated clay (from 1.5 to 3.5 m), the marine clay is soft and lightly overconsolidated (OCR = 1.5–3). Figure 2 presents profiles of the available laboratory, field vane shear (FVT), and piezocone penetration (CPTU) test results at the site.

SBPM Tests

A total of 13 SBPM tests were performed by using a Camkometer. The use of the Camkometer has been widely reported. Readers are referred to Wroth and Hughes (*10*) for details of the Camkometer design and its operation. Depths of SBPM tests ranged from 3.5 to 6.7 m. The orientations of the three strain sensing arms were recorded before the probe insertion.

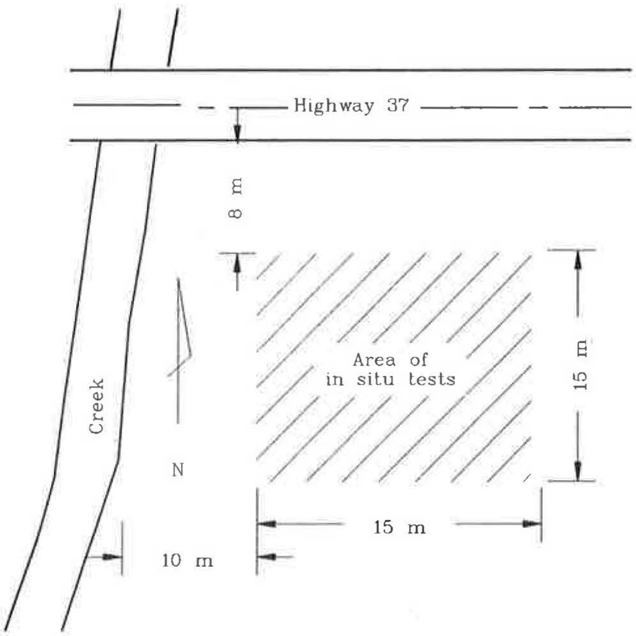

FIGURE 1 Layout of the test site.

Insertion of the SBPM was carried out at a rate of 80 mm/min. The cutter was set at 20 mm from the leading edge of the SBPM probe. Initial trials showed that cutter settings less than 20 mm could result in an apparent unloading to the surrounding soil, as was indicated by the negative pore pressure readings during and immediately after the probe insertion. The probe expansion started after the pore pressure had stabilized. Nine of the SBPM expansion tests were strain controlled. The strain rate of 1 percent/min was used in the probe expansions. The rest of the SBPM tests were stress controlled. Initial stress increment of 14 kPa was used until 1 percent strain was reached to facilitate P_0 readings. Beyond the 1 percent strain, a 28-kPa stress increment was used. A 1-min duration was used for each of the stress increments. An unload reload loop was applied at 2.5 percent radial strain for all the SBPM tests. The data were recorded at a rate of 2 per second, using a computer data logging system. Figure 3 shows the beginning part of the SBPM expansion curve recorded for the individual strain arms.

SBLC Tests

The SBLC (Figure 4) used in this study was manufactured by Cambridge Insitu. It has the same diameter as the Camko-

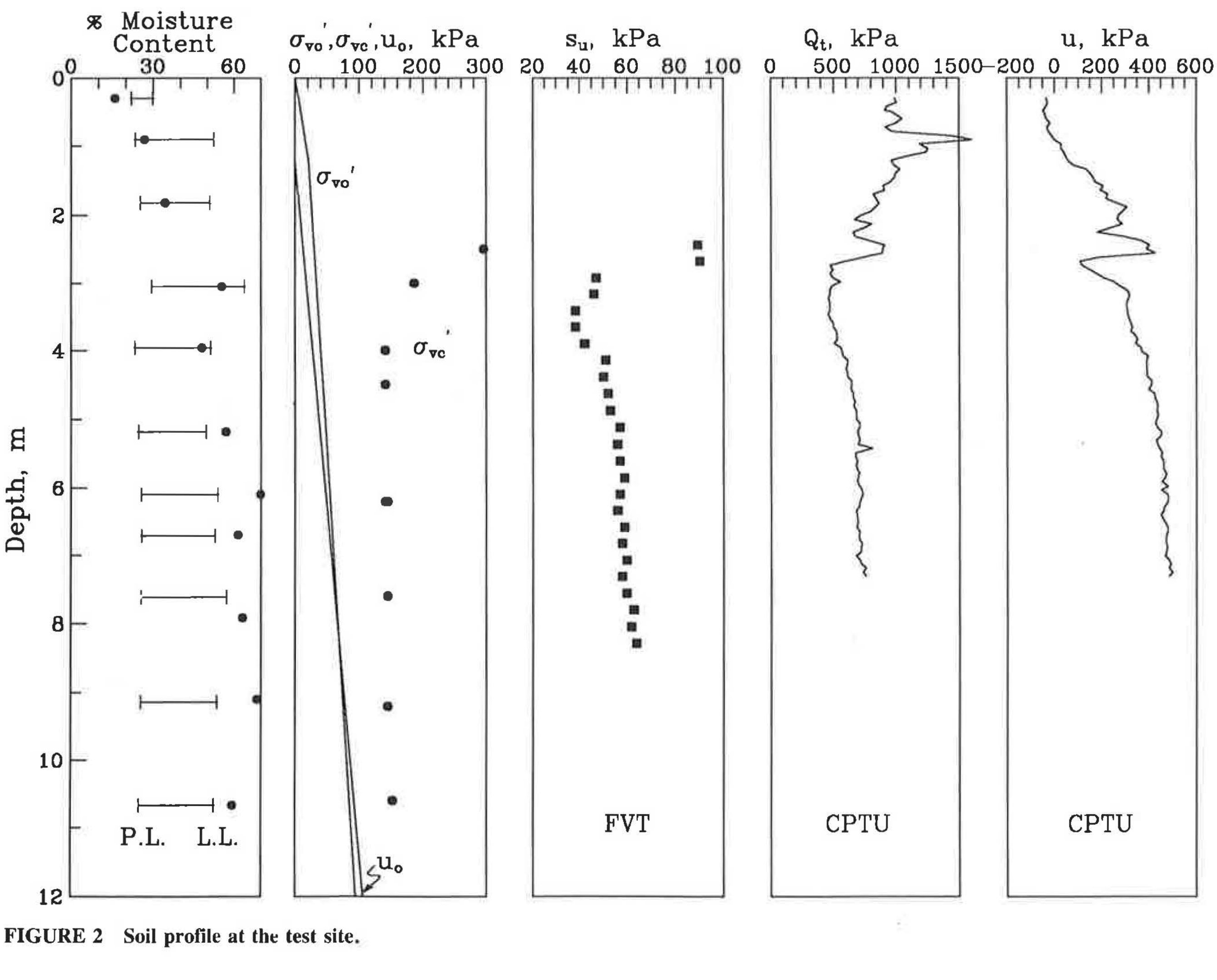

FIGURE 2 Soil profile at the test site.

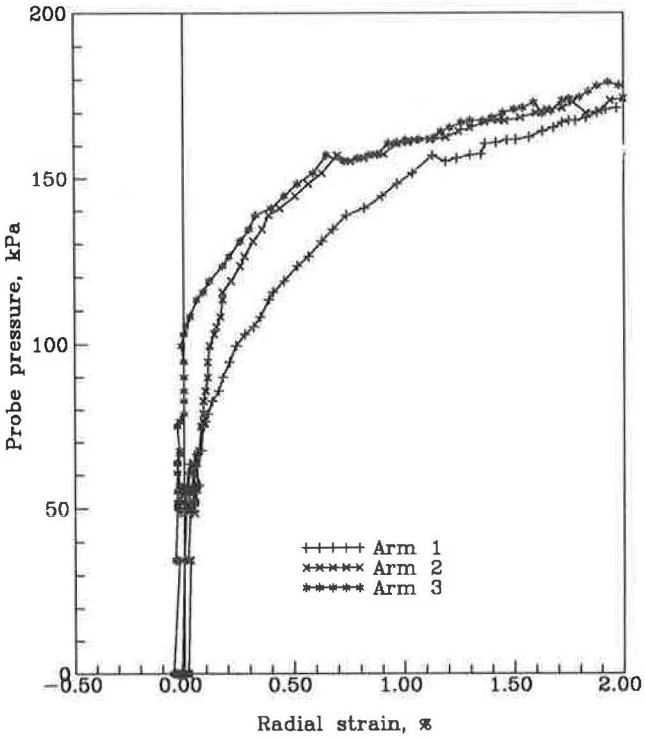

FIGURE 3 Typical SBPM expansion curves.

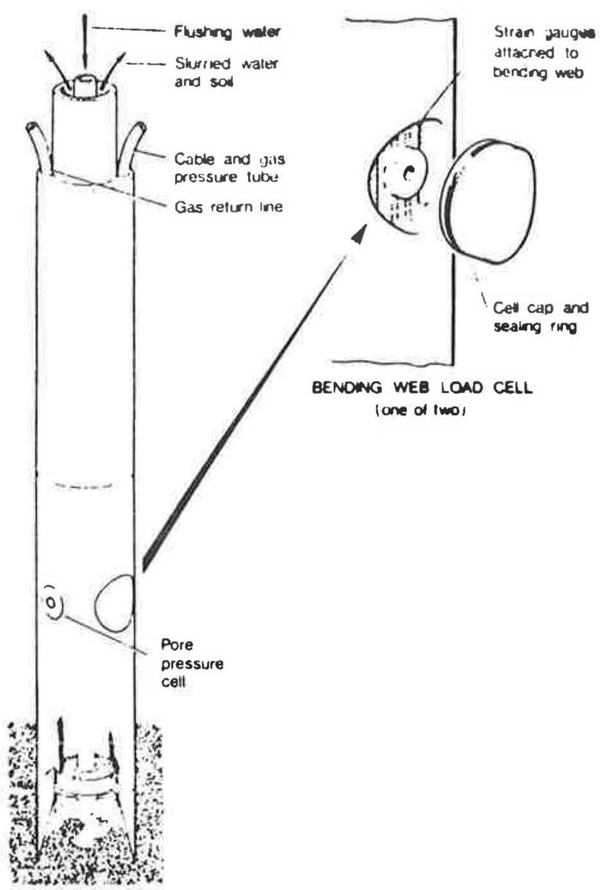

FIGURE 4 The Cambridge self-boring lateral stress cell [from Dalton and Hawkins (2)].

meter (80.4 mm). Experience on the use of SBLC has rarely been reported. The probe performs very limited expansion. The outside surface is fitted with two bending web load cells (cells C and D) located on the opposite sides near the midpoint of the instrument. The load cells are 44.4 mm in diameter. A pair of pore water pressure transducers are located between the two load cells at the same level. Any difference between the external stress on the load cells from the soil and the applied internal gas pressure would cause the load cells to deflect. The electrical output (in bits using a computer data logging system) is proportional to the load cell deflection. At the maximum allowable pressure difference of 280 kPa, the load cell deflection is 19 microns according to Dalton and Hawkins (2). The control unit was calibrated so that at zero pressure difference the output was zero bits. No inside pressure was applied during the SBLC insertion, and the soil pressure pushed the load cells inward. The "expansion" test is performed by increasing the internal pressure while monitoring the outward deflection of the load cell. The internal pressure at which the load cell reaches its neutral position (zero bits) is an indication of the lateral earth pressure. The SBLC can be thought of as a "passive" measuring device because it allows an inward movement of the soil/load cell to occur. The at-rest lateral earth pressure is reinstated upon expanding the load cells to their neutral position.

Insertion of the SBLC follows the same procedure as insertion of the SBPM. Two profiles of the SBLC tests were performed from depths of 3.5–7.5 m. The expansion started after the excess pore pressure dissipated, as was indicated by the pore pressure transducers. Figure 5 presents the typical results of SBLC expansion tests and the technique for deducing the lateral earth pressure. The probe was rotated 60 degrees clockwise upon deflation, and the test was repeated after stabilization of the pore pressure. By rotating the probe twice, a total of six lateral earth pressure readings can be taken to encompass 360 degrees. Experience indicated that rotating the SBLC probe did cause some variations of the lateral stress measurements. However, the variations were random and within the accuracy of the measurements. An additional evidence for this is that the data from SBLC and SBPM showed similar lateral earth pressure anisotrophy and its relationship with depth, as to be presented later.

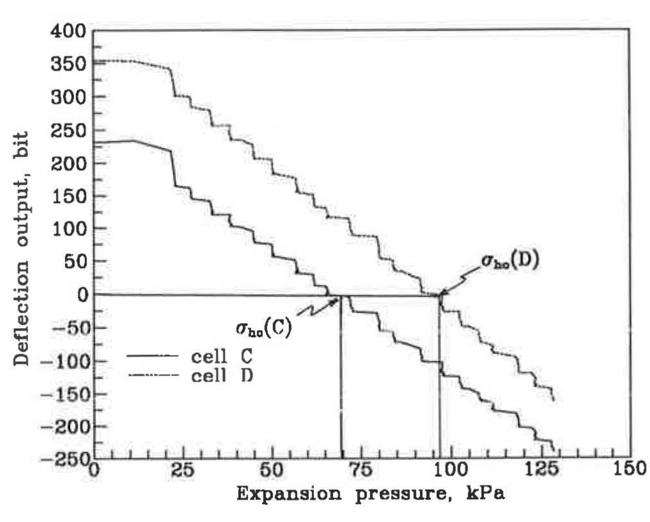

FIGURE 5 Typical SBLC expansion curves.

DMT Tests

A total of five profiles of the Marchetti (*3*) flat DMT tests were performed from 1 to 10 m at the test site. In each profile, the DMT blade was oriented to a different direction so that the five tests would cover directions from due north to due south at 45 degree rotations counterclockwise. The tests were performed at 0.3-m intervals. Figure 6 presents the profiles of the corrected lift-off pressure, P_0 and 1 mm expansion pressure, and P_1 from all the DMT tests.

TEST RESULTS AND INTERPRETATION

There are at least eight published methods for deducing σ_{ho} (*11*) from pressuremeter tests. All methods involve some subjective judgement, and none of them should be considered as measurements of σ_{ho}. Most of those methods are not applicable to SBLC tests because of the lack of significant probe expansion. To maintain consistency, the SBPM lift-off pressure is used to deduce σ_{ho}, because this method is similar to that used for SBLC tests. However, the design differences between the SBPM and SBLC can have significant effects on the deduction of σ_{ho}. Jefferies et al. (*12*) indicated that in stiff clays the lift-off pressure from SBPM tests could correspond to the soil lateral yield stress σ_{hy}, where the probe pressure starts to induce large, plastic deformation in the surrounding soil. The strain sensing arms movement at σ_{hy}, which is significantly higher than σ_{ho}, could be very small and difficult to detect. The same is not likely to occur for SBLC tests because it has a "passive" sensing system, as was described previously, and it does not involve any lift-off pressure.

Figure 7 presents the deduced σ_{ho} values from SBPM and SBLC tests. The SBLC readings came from tests (cell C facing north and cell D facing south) in the same bore hole. Table 1 summarizes the limit pressures P_1, undrained shear strengths s_u, initial shear moduli G_i, shear moduli from unload reload loops H_σ, and σ_{ho} values from all the SBPM tests. The simplex method developed by Huang et al. (*13*) was used in the interpretations of SBPM tests. The σ_{ho} values from SBPM tests are based on the average of the three strain arm readings. The results substantiate the argument by Jefferies et al. in that the σ_{ho} from SBPM are consistently higher than those from the SBLC tests within the stiff clay layer (see Figure 2) at depths from 3 to 4 m. From below that level and within the soft clay deposit, σ_{ho} values from both tests agree fairly well. Within the soft clay layer, the σ_{ho} from SBPM and SBLC correspond to K_o values on the border of 0.5 to 0.65, which is consistent with the oedometer test results (Figure 2).

The σ_{ho} values from load cells (i.e., C and D) located on the opposite sides of the same SBLC probe were different (Figure 7) by as much as 40 percent. There was significant and different levels of soil disturbance around the load cells. The same should also occur for the SBPM tests, as was indicated by Huang and Haefele (*14*).

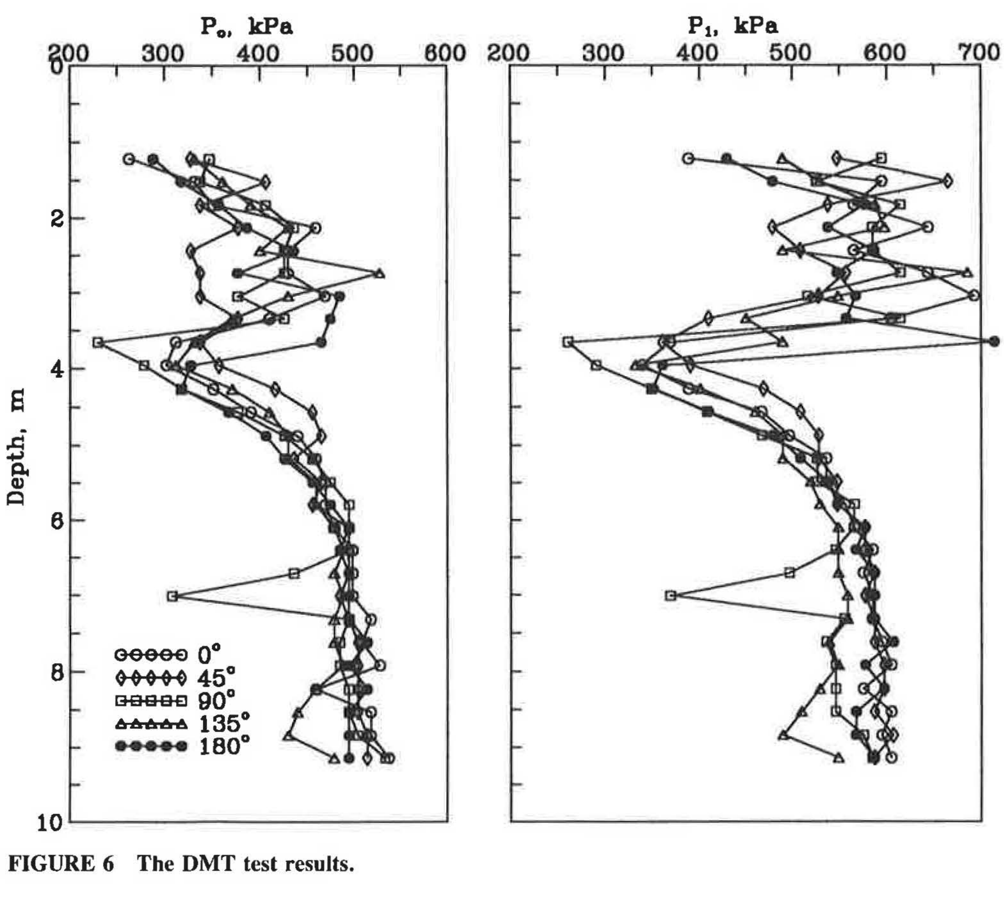

FIGURE 6 The DMT test results.

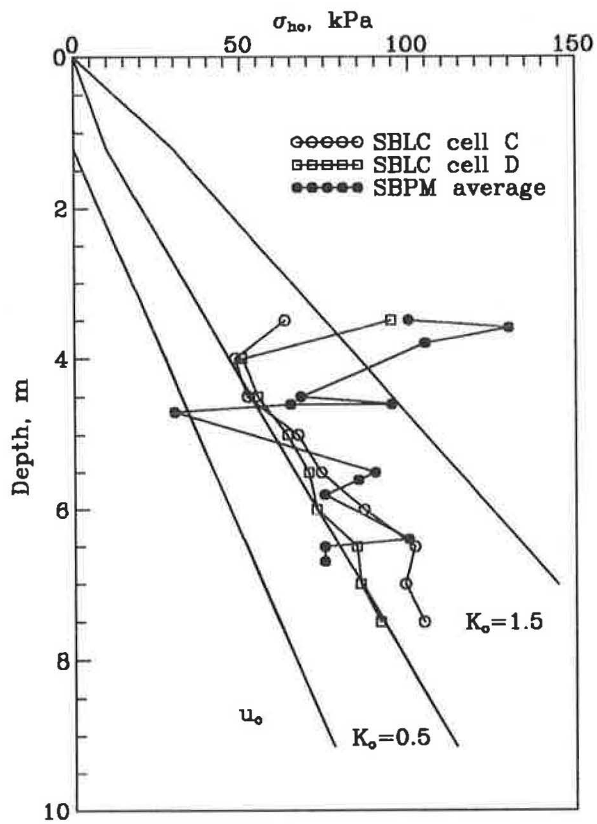

FIGURE 7 Deduced σ_{ho} from SBPM and SBLC tests.

TABLE 1 SUMMARY OF THE SBPM TEST RESULTS

Test	Depth	P_o	P_l	Su	G_i	G_r
	m	kPa			MPa	
Strain Controlled Tests						
SBPM4	3.5	100	450	71	56.5	–
SBPM8	3.8	105	400	49	59.7	14.4
SBPM5	4.5	68	240	28	53.9	7.3
SBPM9	4.6	95	350	46	57.7	11.7
SBPM1	4.7	30	410	93	31.4	10.1
SBPM10	5.5	90	425	61	52.4	11.9
SBPM2	5.8	75	250	35	24.3	5.4
SBPM11	6.4	100	440	60	79.5	14.6
SBPM3	6.7	75	360	50	73.9	11.8
Stress Controlled Tests						
SBPM12	3.6	130	480	65	64.4	8.3
SBPM13	4.6	65	310	48	50.6	8.0
SBPM14	5.6	85	360	47	56.1	11.8
SBPM15	6.5	75	365	59	64.5	13.3

A direction index D_i is used to provide a quantitative indication of the lateral stress variations.

$$D_i = \frac{\sum_{d=1}^{nd}\left[\frac{(\sigma_{ho})_d}{(\sigma_{ho})_{avg}}\right]}{nd} \tag{3}$$

and

$$(\sigma_{ho})_{avg} = \sum_{i=1}^{6}\frac{(\sigma_{ho})_i}{6} \tag{4}$$

where nd is the number of depths where σ_{ho} was measured (nd = 4 for SBLC, nd = 8 for SBPM).

A higher D_i value, therefore, indicates greater σ_{ho} measurement in that direction. According to the D_i values, σ_{ho} in different directions for both SBPM and SBLC tests (Figures 8 and 9) seem to indicate a consistent axis of major lateral stress despite the existence of disturbance. The direction of the major lateral stress is approximately parallel to the creek adjacent to the test site (see Figure 1). There was no geological reason for an anisotropic stress field at the test site other than the erosion created by the creek. If indeed this was the case, then the test results are consistent with the direction of the creek. In any case, the results are not very convincing because the differences in lateral earth pressures are generally within the accuracy of the measurements.

Most of the available empirical methods assume an exponential relationship between K_o and K_D in analyzing the DMT data. For example, on the basis of his statistical analyses, Marchetti (*3*) suggested that

$$K_o = (K_D/1.5)^{0.47} - 0.6 \tag{5}$$

appears to be a reasonable approximation of such a relationship. P_0 represents the average normal stress on the expandable diaphragm at the end of DMT penetration. The normal stress, as inferred from strain path analysis (*15*), undergoes a monotonic loading followed by a slight unloading before the soil element reaches the DMT diaphragm (Figure 10). If Equation (5) is rearranged as

$$\sigma'_{ho} = \sigma'_{vo}\,[(K_D/1.5)^{0.47} - 0.6] \tag{6}$$

then this implies that for given σ'_{vo} and u_o there is an exponential relationship between $(P_0 - u_o)$ and σ'_{ho}, regardless of the state of stress, stress history prior to the DMT insertion, and the soil stress strain relationship. The authors are not aware of any studies in soil mechanics that would substantiate such a premise.

The deduced lateral earth pressure, using Equation (6), showed for the DMT data at the test site that the corresponding K_o values (Figure 11) are mostly higher than 1.5, even within the soft clay layer (between 4 and 7 m). They correspond to OCRs of 10 and higher according to Mayne and Kulhawy (*16*), which are much higher than those from oedometer tests (see Figure 2).

Figure 12 presents a plot of σ_{ho} normalized with respect to the average of all the σ_{ho} values in five directions and at the same depth. Except for a few rogue data points, there does not appear to be any noticeable anisotropy of lateral stresses. The results from the five DMT bore holes are extremely repeatable (see Figures 6 and 11). The repeatability is partly due to the large strains induced during the DMT insertion and compatible with the experience in pressuremeter tests where repeatable limit pressures (i.e., pressure readings at large strains) can be obtained regardless of the level of bore hole disturbance. The large strains might also have masked

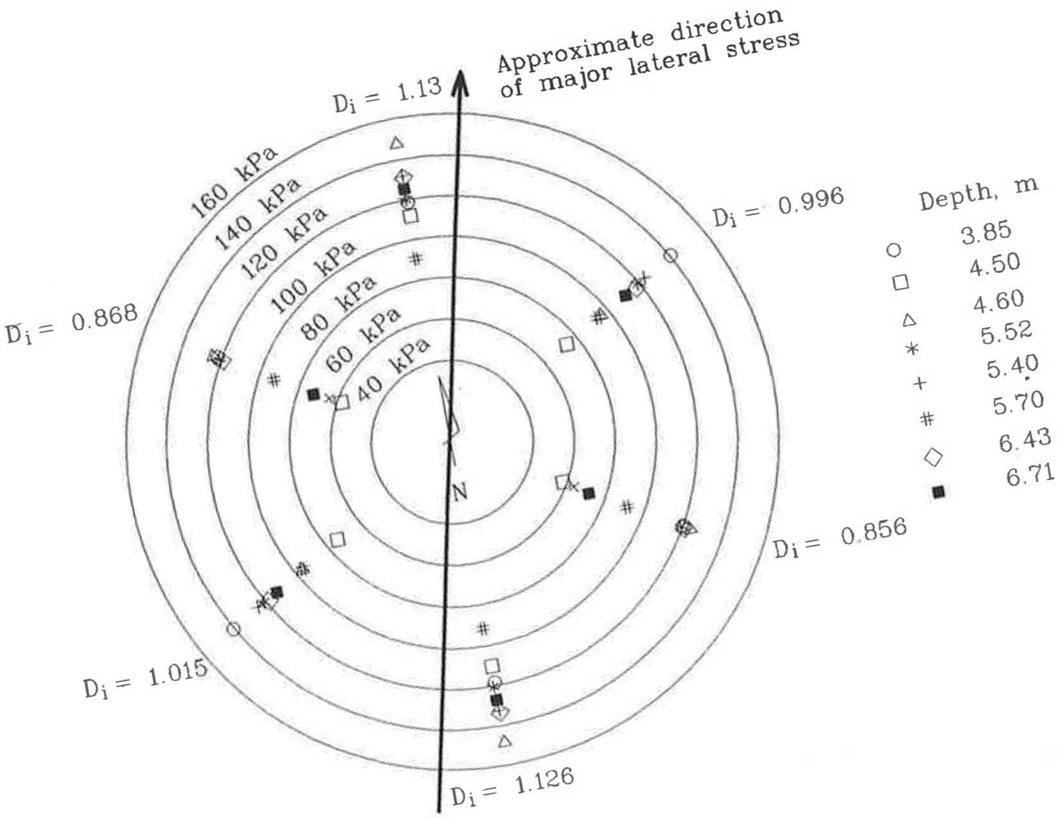

FIGURE 8 Results from SBPM tests.

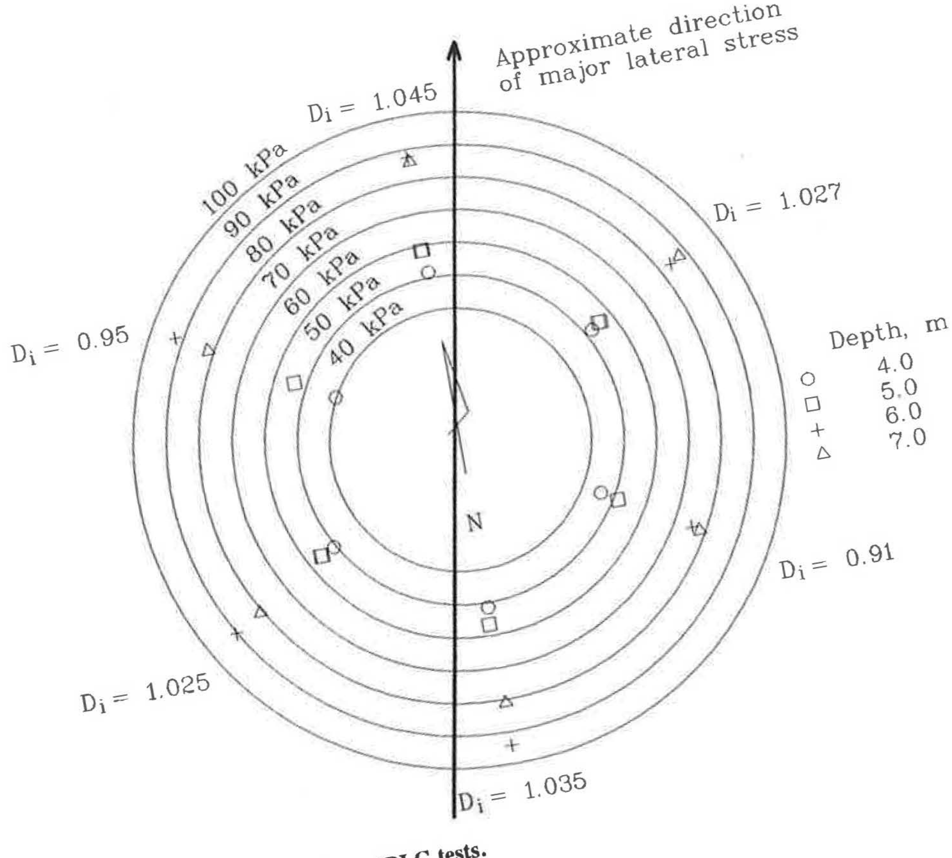

FIGURE 9 Results from SBLC tests.

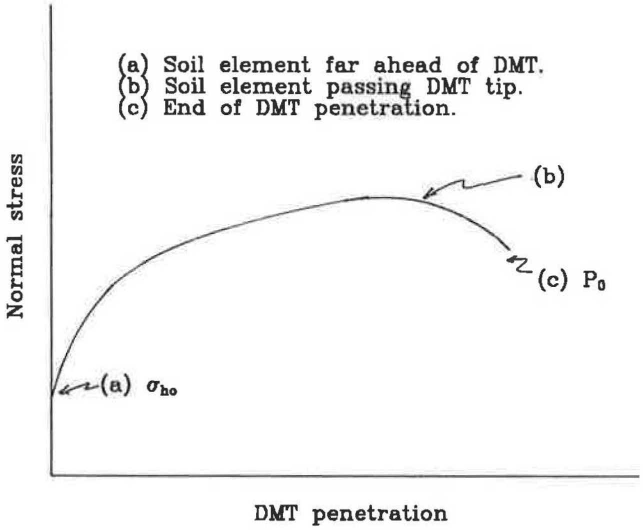

FIGURE 10 Inferred stress path during DMT penetration.

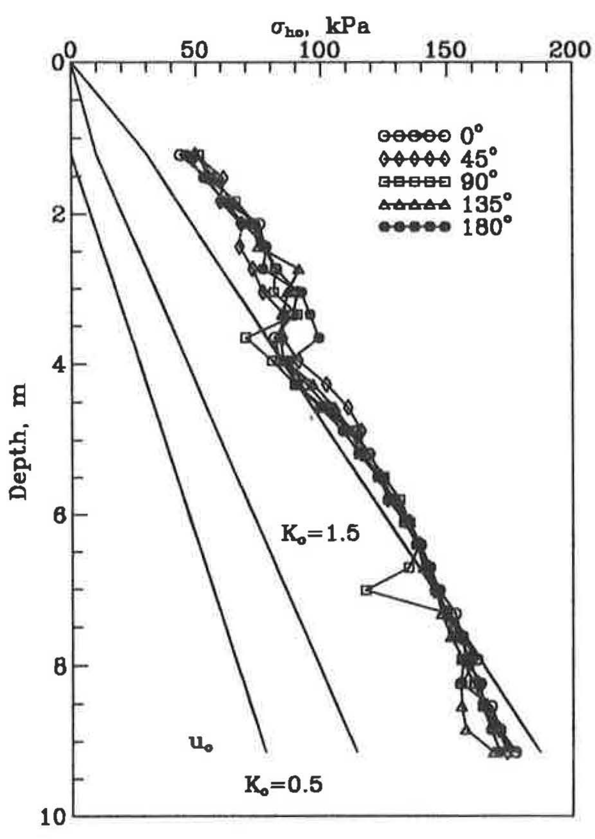

FIGURE 11 Deduced σ_{ho} from DMT tests.

the anisotropy in lateral earth pressures, if this indeed were the case.

CONCLUDING REMARKS

In the context of the study presented here, the following conclusions are drawn:

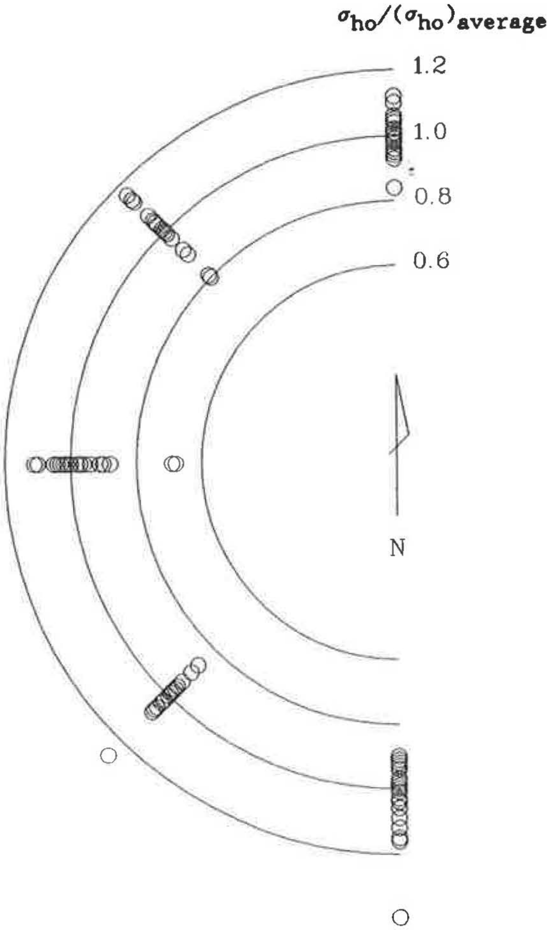

FIGURE 12 Normalized σ_{ho} from DMT tests.

1. In a stiff soil deposit where σ_{hy} is significantly larger than σ_{ho}, a passive measuring device such as the SBLC is likely to provide more reliable measurements of σ_{ho} than the SBPM.
2. Disturbance does occur even when self-boring probes (e.g., SBPM and SBLC) are used for lateral earth pressure measurements. However, the results should still be reasonable, provided the tests are properly performed.
3. Despite the soil disturbance, a limited number of SBPM and SBLC tests showed consistent directions of the major lateral stress. However, more studies are required to substantiate this finding.
4. The soil element is likely to experience a complicated strain path before reaching the DMT diaphragm where P_0 and P_1 readings are taken. By using DMT to estimate σ_{ho} based on an exponential relationship between K_D and K_o may therefore be premature.

ACKNOWLEDGMENTS

The data shown in Figure 2 were based on tests performed by A. J. Lutenegger. The research was sponsored in part by the National Science Foundation and in part by the U.S. Air Force Office of Scientific Research.

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Publication of this paper sponsored by Committee on Soil and Rock Properties.