Dilatometer Lateral Stress Measurements in Soft Sensitive Clays

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Results from self-boring pressuremeter (SBPM) and dilatometer (DMT) tests at sites in Portsmouth, New Hampshire, and at Hamilton Air Force Base, California, are compared in terms of total lateral stresses. Site-specific correlations for soft sensitive clays between the dilatometer initial lift-off pressures and the range of self-boring pressuremeter horizontal stresses are observed, and it appears that the SBPM can be successfully used to calibrate the DMT. Results from lateral stresses measured at the end of DMT total stress dissipation tests are in close agreement with upper bound results from the SBPM.

Measurement of lateral stresses in the ground is best accomplished in situ by using the self-boring pressuremeter (SBPM). However, the high potential of the SBPM is somewhat overshadowed by its relatively low production testing and the complexity of its drilling and testing operations. In response to some of those difficulties, the dilatometer (DMT) was introduced in the mid-1970s (*1*) as a fast and simple tool having the capability to yield an empirically derived in situ lateral stress. The lateral stress from the DMT is based on the pressure necessary to initially move the flexible circular steel membrane from the face of the instrument into the soil. However, empirical correlations are only as good as the reference tests used for their development. To this end, extensive programs of self-boring pressuremeter and dilatometer testing have been carried out at two soft sensitive clay sites in an attempt to correlate the results from those in situ devices. The test sites are the Portsmouth I-95 Interchange in New Hampshire and Hamilton Air Force Base in California. Those sites were chosen because of the wealth of documentation available concerning the engineering properties of the soil deposits and because of ongoing research programs that use a unique nine-arm self-boring pressuremeter and the flat plate dilatometer.

This paper summarizes the lateral stress results obtained from the SBPM and the DMT at both sites. Comparisons are made between the measured horizontal stress from the SBPM, the initial lift-off pressure reading p_0 from the DMT, and the pressure at the end of DMT total stress dissipation tests. Assessment of the potential of the DMT as a primary tool to evaluate lateral stresses in the ground by using the SBPM for calibration is discussed.

SITE CHARACTERISTICS

The New Hampshire test site is located in Portsmouth and is adjacent to the test embankment investigated by Ladd (*2*) during the construction of the surrounding I-95 highway embankments. The site, situated on the premises of the Pease Air Force Base (PAFB), is a shallow swamp with the water table varying from the ground surface to more than 2 ft above ground. Beneath a surficial organic layer lies the silty clay deposit. Underlying 5 to 8 ft of stiff mottled silty clay is a layer of very soft and highly sensitive marine gray silty clay. Within this clay layer of thickness up to 19 ft are occasional silt and sand lenses. Glacial till underlies the deposit.

The California site is located in Novato at Hamilton Air Force Base (HAFB). Soil conditions at the site consist of 15 to 20 ft of gray stiff silty clay underlaid by a soft to medium gray clay known as Young Bay Mud. Occasional shells and silt lenses may be found within this medium sensitive clay, which extends to a depth of approximately 50 ft. The water table fluctuates from the ground surface to as low as 12 ft below ground.

Table 1 summarizes some of the basic engineering soil properties at the PAFB and HAFB test sites. Both soft clay deposits are slightly overconsolidated below the dessicated crust. The highly sensitive clay at PAFB is of low plasticity, with a liquidity index that suggests very viscous liquid behavior during shearing. The soft clay at HAFB is highly plastic and not nearly as sensitive as the PAFB clay. Natural water contents of the Young Bay Mud are approximately twice those of the Portsmouth clay. The normalized strengths range from 0.13 to 0.30 for the PAFB clay, and it is significantly higher for Young Bay Mud at 0.29 to 0.38.

TESTING PROGRAM

Flat Plate Dilatometer

The dilatometer tests at PAFB and HAFB were conducted in accordance with the suggested ASTM standard D18.02.10. The blade was generally pushed at a rate of 2 cm/sec. Figures 1 and 2 present typical profiles of DMT indices versus depth for both sites. For the PAFB profile in Figure 1, the material index I_d varies between 0.15 and 0.3 for the very soft portion of the deposit. The presence of silt and fine sand lenses observed in undisturbed tube samples obtained from an adjacent borehole is clearly shown by increases of the index. The lateral stress index K_d indicates a decreasing trend with depth and is higher than usually observed for soft, nearly normally consolidated clays. A similar trend is noticed in the preconsolidation pressures obtained from oedometer tests, which also indicate a decrease with depth relative to the assumed effec-

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TABLE 1 TYPICAL SOIL PROPERTIES AT PEASE AIR FORCE BASE HAMILTON AIR FORCE BASE SITES

Test Location	Soil Description	Water Content (%)	Plastic Limit (%)	Liquid Limit (%)	Plasticity Index (%)	Liquidity Index (%)	Normalized Strength* (s_u/σ'_{vo})	Sensitivity	References
Portsmouth I-95 New Hampshire (Pease Air Force Base)	Soft marine grey silty clay with occasional silt and sand lenses	35-50	20-25	25-40	10-15	1.3-2.3	0.13-0.30	10-15	2,3
Hamilton Air Force Base California	Soft grey clay with some shells and silt lenses	86-90	38-40	85-88	45-50	1.0-1.1	0.29-0.38	6-8	4,5

*The normalized strengths are shown as a range from various laboratory tests using different stress paths

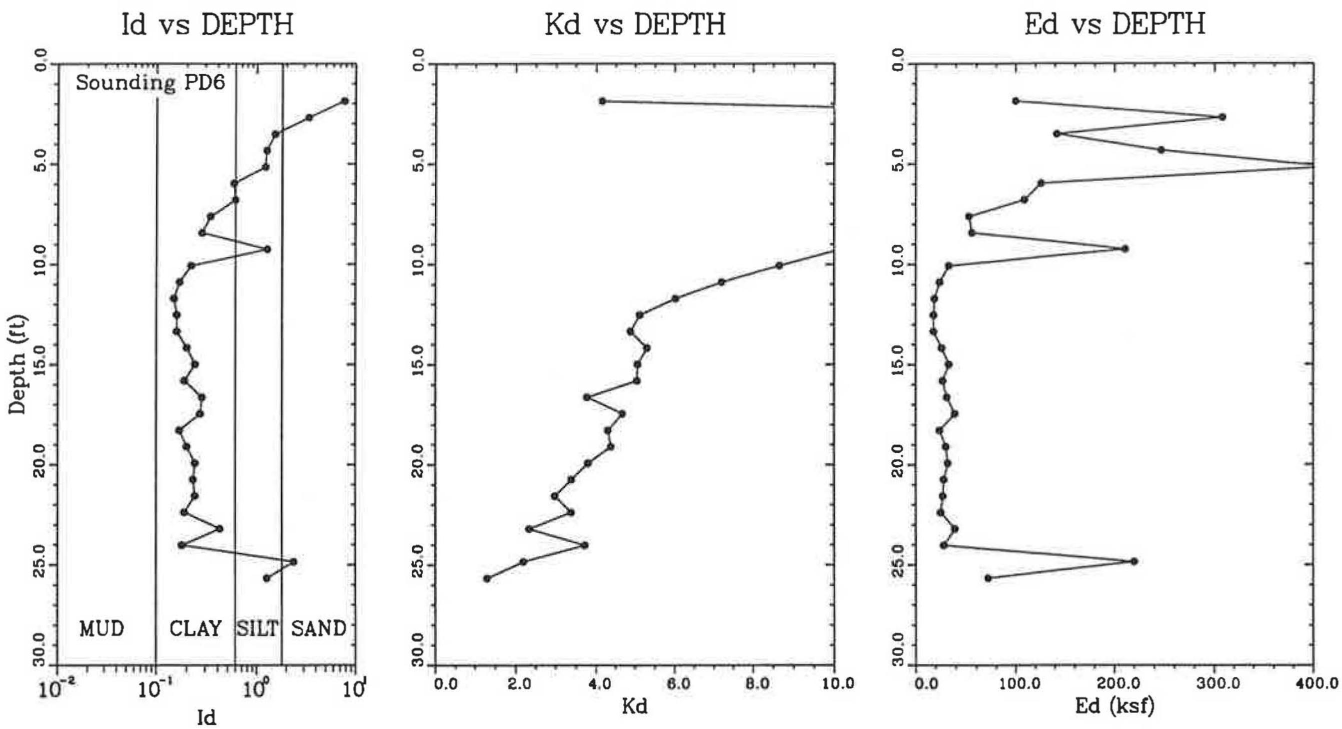

FIGURE 1 Typical profile of dilatometer indices at Pease Air Force Base, New Hampshire.

tive vertical stress. Although the water pressures at the site were measured as hydrostatic, the vertical stress may be more complex than simply geostatic because of the shape of the underlying bedrock. The dilatometer modulus E_d is nearly constant at 30 ksf for the soft material.

The HAFB index profiles are less variable with depth than those from PAFB. The material index varies from approximately 0.1 to 0.15 throughout the normally consolidated clay. The lateral stress index is approximately constant at 2.3, typical of normally consolidated clays. The dilatometer modulus increases slightly with depth from about 10 ksf at 20 ft to 30 ksf at 50 ft.

The indices determined from the DMT tests at each of the two sites are strikingly different. The material index is generally lower for the less-sensitive HAFB deposit. Although this contradicts expected soil behavior, it is consistent with test results in the Onsøy and Drammen clay deposits by Lacasse and Lunne (*6*). There, they observed a lower I_d for the less sensitive Drammen clay. Lutenegger (*7*) also suggests that I_d may be a function of sensitivity. From this testing program and that of Lacasse and Lunne, I_d may be related to both sensitivity and strength. The trends for lateral stress index show the same type of variability observed in results of lateral stress from SBPM tests, which will be discussed later. The

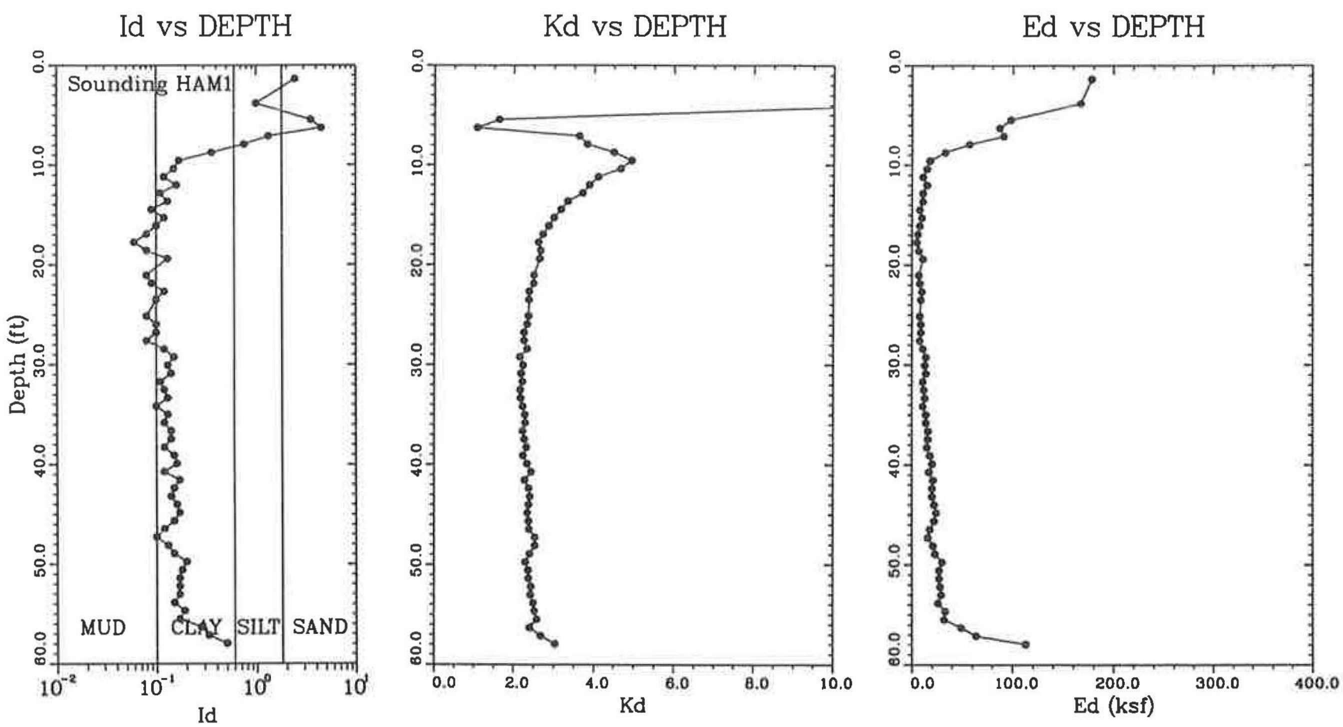

FIGURE 2 Typical profile of dilatometer indices at Hamilton Air Force Base, California.

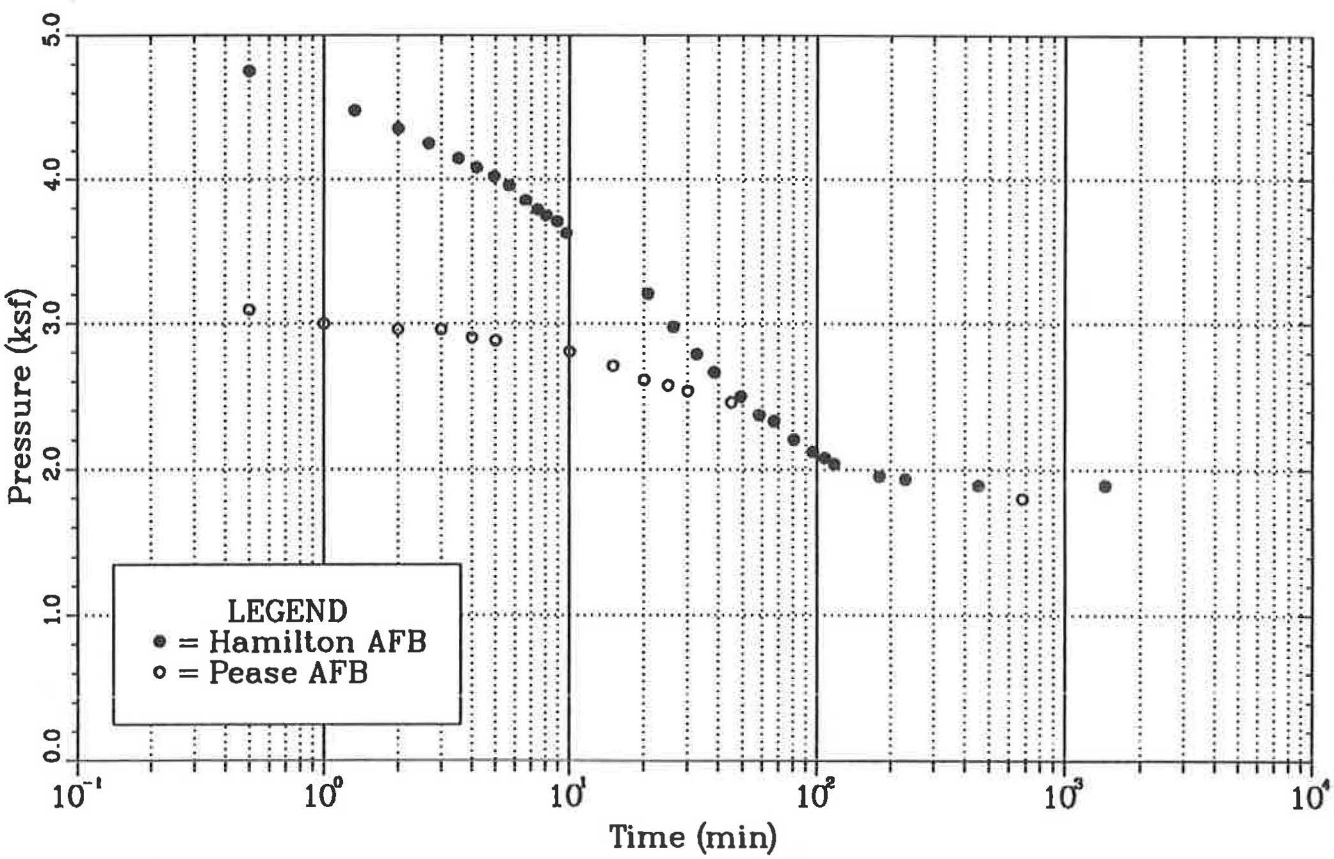

FIGURE 3 Typical dilatometer total stress dissipation tests at Hamilton and Pease Air Force Base sites.

DMT modulus is lower for the more plastic HAFB deposit. As was stated by Lacasse and Lunne (*6*), the sensitivity of the DMT for soft clays may be insufficient for shallow deposits, because the membrane corrections account for a major portion of the field pressure readings. For those testing programs, a very soft membrane was used, and several calibrations were carefully conducted prior to and after each sounding.

Special dilatometer tests designed to evaluate the coefficient of consolidation were performed at both sites. Typical total stress-type dissipation tests (DMTA) are presented in Figure 3 for both sites. The test involves taking initial pressure readings with time without ever deflecting the membrane beyond the plane of the blade. The pressure at the end of dissipation is taken as a total stress without the effects of excess pore pressures, yet it still includes remolding effects.

Self-Boring Pressuremeter

Different self-boring pressuremeters were used for the PAFB and the HAFB investigations, although both probes were fabricated by the firm Cambridge Insitu, England. The SBPM used at HAFB is of the conventional type and is equipped with three strain feeler arms at the midsection of the probe set 120 degrees apart to monitor cavity expansion. The probe used at PAFB was designed by the principal author and differs from the HAFB device in that it is specially equipped with three levels of strain arms. The three levels are located at the top fourth, midsection, and bottom fourth of the inflatable section of the probe. Each level has three arms also set 120 degrees apart. The increased number of strain arms tracking the expandable membrane allows for the entire cavity expansion to be monitored more accurately. The SBPM results presented in this paper are from tests where the conventional cutting method of insertion was used [following the procedure described in Benoit and Clough (*5*)]. Determination of lateral stresses was made in all of the SBPM tests conducted at both sites by using an enhanced visual inspection method. This method, described in Benoit and Clough (*8*), consists of magnifying the portion of the pressuremeter expansion curve associated with the "lift-off" pressure, and this allows a more accurate assessment of the in situ lateral stress. Appropriate corrections were made for the stiffness of the flexible membrane. The SBPM tests at PAFB also were corrected for excess pore pressures generated during insertion and which had not completely dissipated at the time of initial lift-off. Pore pressures were continuously monitored by using two pressure transducers located near midprobe, 180 degrees apart. Figures 4 and 5 present typical profiles of the lateral stress with depth for both sites and for each of the strain-monitoring arms. All nine measurements of lateral stress per test are shown in Figure 4. The PAFB stresses for each of the three levels of arms seem to indicate an inherent horizontal stress anisotropy that is more pronounced than that previously observed at HAFB (*8*).

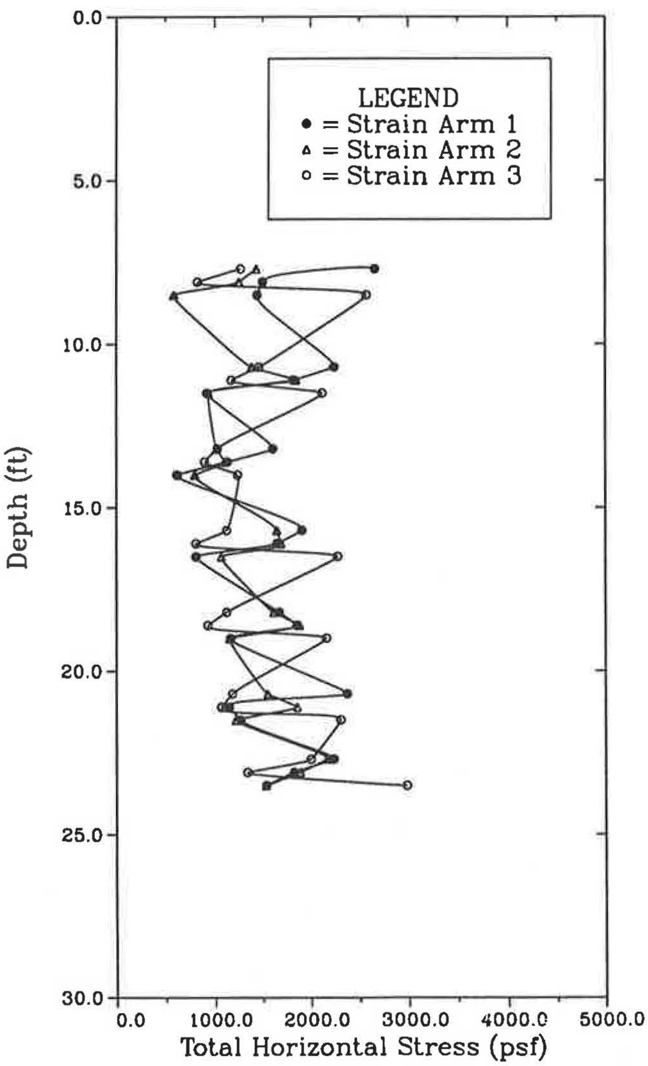

FIGURE 4 Total horizontal stresses from self-boring pressuremeter tests at Pease Air Force Base.

COMPARISON OF SBPM AND DMT LATERAL STRESS MEASUREMENTS

Lateral stresses from SBPM, DMT, and DMTA tests at PAFB and HAFB are presented in Figures 6 and 7. The SBPM horizontal stresses presented are the lower and upper bounds of the values presented in Figures 4 and 5. The DMT results are plotted in terms of initial lift-off pressures p_0 and in terms of total stress at the end of the DMTA dissipation tests, as was previously indicated in Figure 3.

The results seem to indicate that at PAFB and DMT p_0 pressures follow a trend similar to the range embraced by the minimum and maximum lateral pressures measured by the SBPM. The total stress at the end of the DMTA dissipation tests is midway between the minimum and maximum SBPM values in the overconsolidated clay but is in very close agreement with the maximum SBPM stresses in the normally consolidated clay. Similar trends are observed for the HAFB horizontal stresses. The DMT p_0 readings also follow the trend of the range of SBPM lateral stresses in both the overconsolidated and the normally consolidated clay. The total stress at the end of the DMTA dissipation tests are, as with PAFB, in excellent agreement with the maximum values of lateral stress measured by the SBPM. Owing to field time constraints, only the test presented in Figure 3 at 18.9 ft was conducted

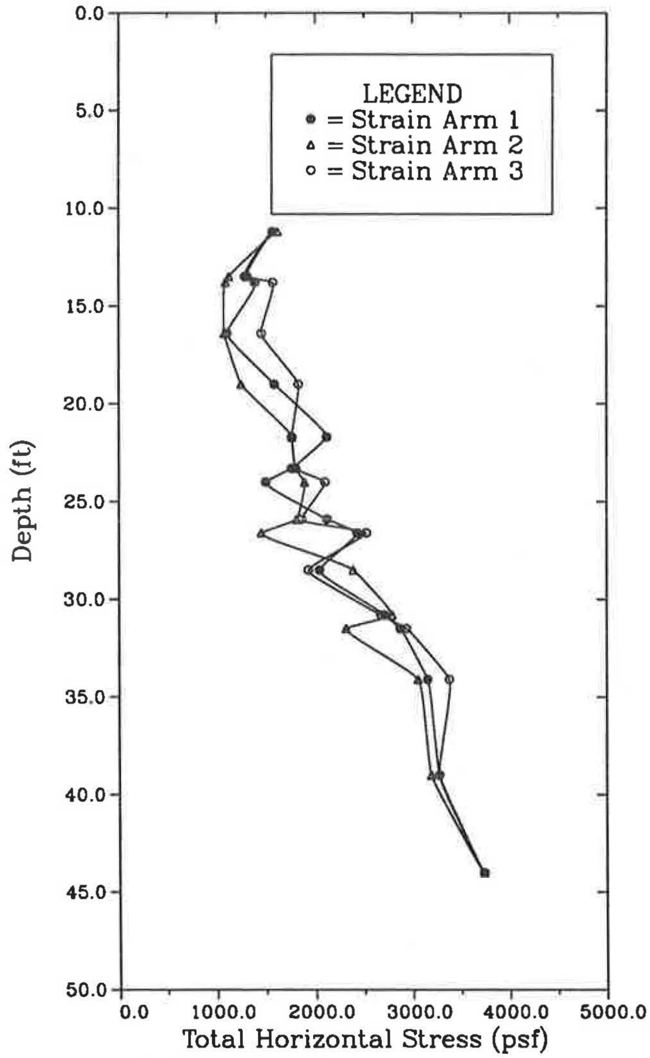

FIGURE 5 Total horizontal stresses from self-boring pressuremeter tests at Hamilton Air Force Base.

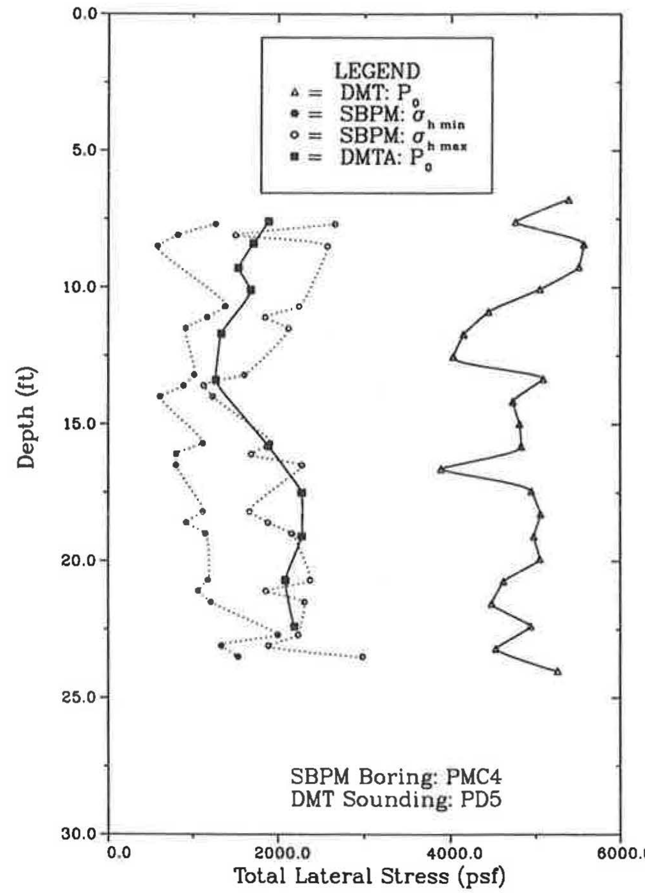

FIGURE 6 Comparison of dilatometer and self-boring pressuremeter total lateral stress test results at Pease Air Force Base.

overnight until dissipation had fully occurred. The other two DMTA tests were monitored for 2 hours, which is beyond the time for 50 percent consolidation, t_{50}. The pressure at 100 percent dissipation was estimated for those two tests based on the time for 50 percent consolidation of the fully dissipated test. It should be noted that t_{50} for the fully dissipated test is in very close agreement with the SBPM holding tests previously performed at this site (*9*).

Clarke and Wroth (*10*) compared results from DMT and SBPM tests at eight different sites in the United Kingdom. An attempt was made to correlate the change in pressure from lift-off to the 1-mm expansion for the DMT test ($p_0 - p_1$) with the difference between the pressuremeter limit pressure and the measured horizontal stress ($p_L - \sigma_h$). Their correlation seems to show a linear relationship over a wide range of stresses. This relationship was examined by using the results from the PAFB and HAFB sites, as is shown in Figure 8. For clarity, only the average strain channel for the HAFB tests and the three middle arms for the PAFB tests are plotted. Also shown are SBPM results from tests at HAFB that showed disturbance caused by the oversizing of the cutting shoe or probe clogging. A relationship similar to that suggested by Clarke and Wroth appears to exist for the results from those two sites. However, the gradient of the relationship greatly differs for those low pressures, and, furthermore, disturbance does not seem to affect the correlation that suggests that limit pressure is a dominating factor.

SUMMARY AND CONCLUSIONS

Lateral stress results from self-boring pressuremeter and dilatometer tests are compared for two sensitive soft clay sites: Pease Air Force Base and Hamilton Air Force Base. The results seem to indicate that the p_0 readings from the DMT may be calibrated by using the SBPM because they follow very similar trends. Results of DMT p_0 readings at Pease Air Force Base are approximately 5 times greater than those from the minimum SBPM lateral stress values. At Hamilton Air Force Base, the DMT results are approximately 2.5 times greater than those from the SBPM tests. Clearly, DMT and SBPM lateral stress measurements can be correlated but should remain site specific at this time. Once calibrated, the more

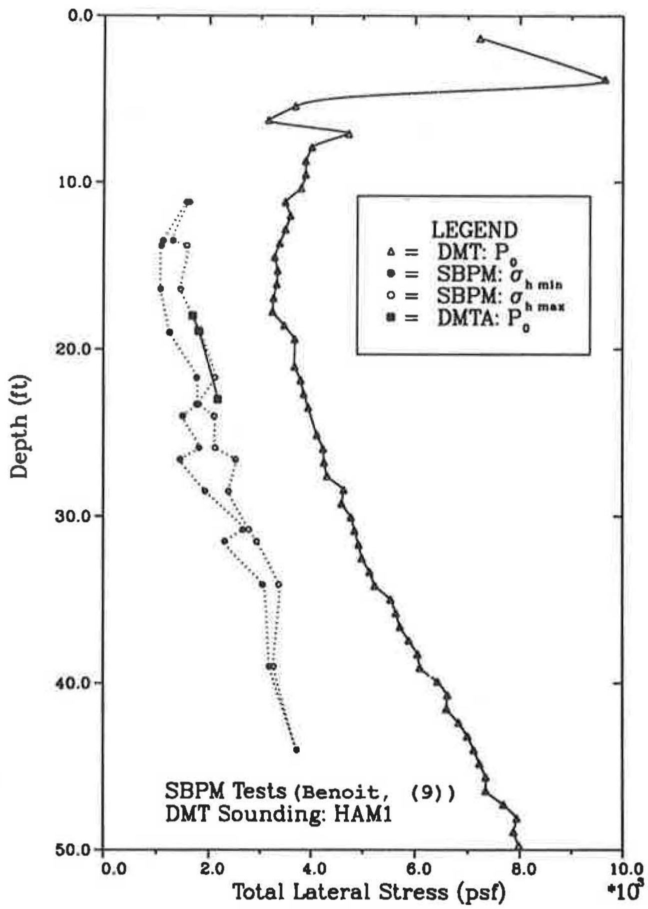

FIGURE 7 Comparison of dilatometer and self-boring pressuremeter total lateral stress test results at Hamilton Air Force Base.

cost-effective dilatometer may be used to investigate spatial variability. Lateral stresses from DMTA dissipation tests are in very close agreement to the maximum values of horizontal stress measured with the SBPM and may be used to estimate the upper bound of in situ lateral stresses.

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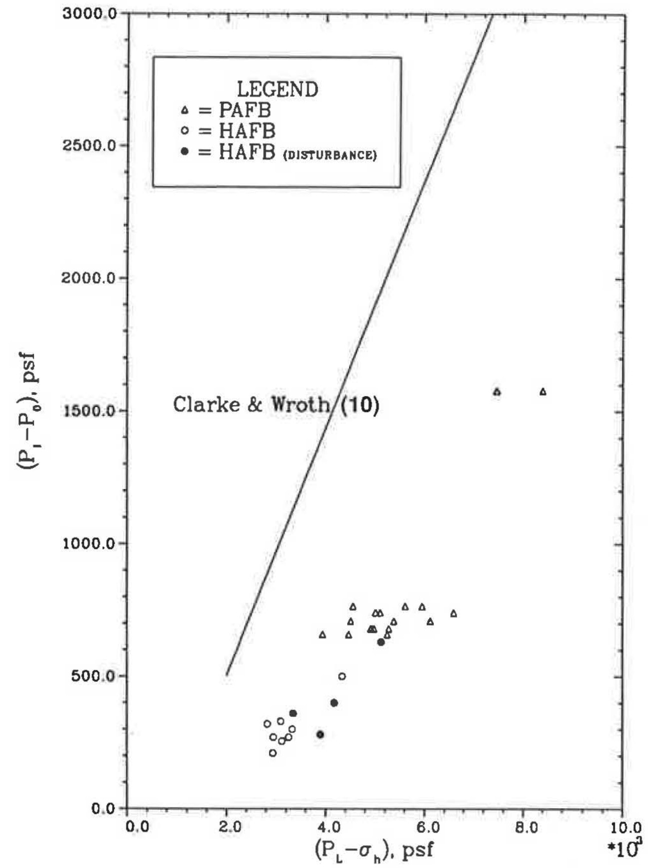

FIGURE 8 Comparison between DMT ($p_1 - p_0$) and SBPM ($p_l - \sigma_h$) for Pease and Hamilton Air Force Base test results.

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