Determination of Horizontal Stress in Normally Consolidated Sands by Using the Dilatometer Test: A Calibration Chamber Study

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The results of dilatometer tests (DMTs) performed in a calibration chamber on normally consolidated Cape Fear sand are presented and are interpreted with respect to both relative density and state parameter and are compared with those from calibration chamber tests on normally consolidated Hokksund and Ticino sands. The relationship between the amplification factor K_D/K_o and state parameter data for the Cape Fear sand tested and the combined data from the three sands discussed resulted in best-fit equations of the form $K_D/K_o = a{\cdot}e^{m\Psi}$. In an effort to improve the ability of a single function to describe the amplification factor-state parameter relationship for the entire data base, normalization of the state parameter by the difference between the maximum and minimum void ratio and by the steady state void ratio at 10 kPa was investigated. However, neither of those normalizing factors produced a higher correlation coefficient for the best-fit relationship. The addition of the Cape Fear sand to the existing trend lines for the K_o^{DMT}/K_o relative density relationship developed from data on Hokksund and Ticino sands suggests a limiting value of K_o^{DMT}/K_o between 0.5 and 1.0 at low relative densities. At higher relative densities, a significant difference exists between the current data and that data obtained previously on the Hokksund and Ticino sands. Further study is needed to evaluate the potential influence of calibration chamber diameter on the measured results.

Penetration testing was developed as a method to obtain soil characteristic information from soils where undisturbed sampling was difficult or impossible. The flat dilatometer developed in the 1970s (*1*) is a penetration device that has been shown to provide reliable soil characteristic information. As with all penetration tests, the determination of the change in the in situ stress state created by the insertion of the dilatometer is a complicated boundary value problem. Therefore, the index parameters obtained from the dilatometer test have been empirically correlated to the actual soil properties. Recent development of large calibration chambers where penetration testing can be conducted has lead to improved correlations because of the capability of strictly controlling the stress state of the soil.

This paper presents the results of a study of existing correlations of horizontal stress index parameters obtained from the dilatometer with the actual horizontal stress applied in calibration chamber tests conducted in normally consolidated Cape Fear sand in the North Carolina State University (NCSU) calibration chamber. The results are interpreted in terms of relative density and the state parameter, introduced by Been and Jefferies (*2*), which incorporates both the void ratio and the stress level. Additional data incorporated into this study were obtained from similar calibration chamber tests performed on Hokksund and Ticino sands (*3*) (M. Jamiolkowski, personal communication).

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MARCHETTI DILATOMETER

The flat dilatometer developed by Marchetti (*1*) is essentially a penetration device capable of obtaining an estimate of lateral pressure and soil stiffness. The body of the dilatometer has an approximate width of 95 mm (3.7 in.) and a thickness of 14 mm (0.6 in.). The external surface of the approximately 60-mm (2.4-in.) diameter membrane when at rest is flush with the surrounding flat surface of the blade. The blade is usually pushed into the ground at conventional penetration test rates (2 to 4 mm/sec). When the desired test depth is reached, the membrane is inflated through a small control unit at the ground surface with pressurized gas. Readings are taken of the pressure required to initiate movement of the membrane (related to the horizontal stress existing in the ground) and the pressure required to move its center an additional approximate 1 mm (0.04 in.) into the soil (related to the soil stiffness). Both of those pressure readings are corrected for the effect of membrane stiffness. The first of those corrected pressures is called the p_0 pressure. An index parameter similar to the at-rest earth pressure coefficient K_o, termed the horizontal stress index K_D, was developed by using the p_0 pressure. The horizontal stress index is determined by the following equation:

$$K_D = \frac{(p_0 - u_0)}{\sigma'_v} \quad (1)$$

where u_0 is the hydrostatic pore water pressure and σ'_v is the in situ vertical effective stress. On the basis of field tests results in uncemented clays Marchetti (*4*) proposed the following correlation for the relationship between the horizontal stress index K_D and the in situ at-rest earth pressure coefficient K_o.

$$K_o^{DMT} = \left(\frac{K_D}{1.5}\right)^{0.47} - 0.6 \quad (2)$$

Jamiolkowski et al. (5) have suggested, on the basis of calibration chamber tests conducted on Hokksund and Ticino sands and field experience, that this empirical formula overestimates K_o in dense to very dense sands and underestimates K_o in loose sands.

STATE PARAMETER

The state parameter φ, which is embodied in critical state soil mechanics, was introduced by Been and Jefferies (2) as a rational approach to combine the effects of void ratio and stress level into a single parameter that enables the behavior of a sand to be predicted. The state parameter is defined as the difference in the initial void ratio e_A and the void ratio at "steady state" e_{ssA} at the initial stress level, as is illustrated in Figure 1. The steady state for any mass of particles has been defined as that state where the mass is continuously deforming at constant volume, constant effective stress, constant shear stress, and constant velocity (6). The steady-state void ratio e_{ss} corresponding to a mean normal effective stress of 10 kPa has been suggested as an index for comparing various sands.

The sand used in the NCSU calibration chamber was a subangular to angular sand obtained from the Cape Fear River in North Carolina. A summary of its properties and a photograph of the sand appear in Table 1 and Figure 2, respectively. To determine the steady-state line (SSL) for Cape Fear sand, a series of strain-controlled isotropically consolidated undrained triaxial tests were performed. The test specimens were prepared by compacting six 1-in. layers to the desired density. The specimens were flushed with carbon dioxide and were saturated by using desired water. A minimum B-value of 0.97 was obtained before proceeding with compression testing. The initial and steady-state points for each test are presented in Figure 3 along with the best-fit SSL determined by regression analysis. The SSL for Cape Fear sand is compared in Figure 4 with those for the Hokksund and Ticino sands as well as the Kogyuk sand with 0 percent silt used by

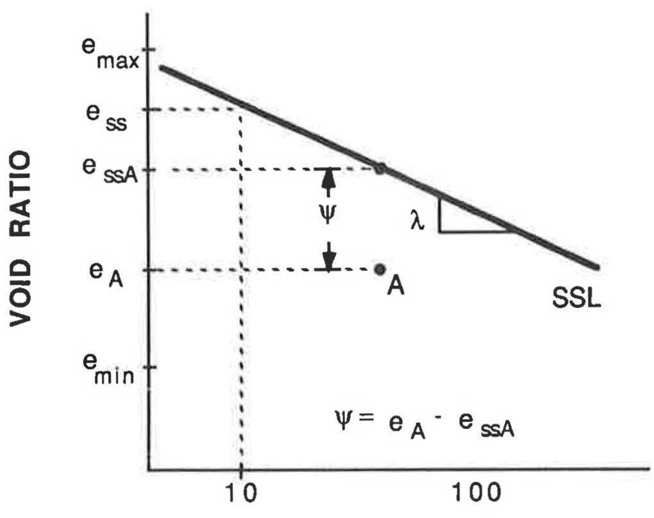

FIGURE 1 Definition of the state parameter.

TABLE 1 INDEX PROPERTIES OF SANDS USED IN VARIOUS CALIBRATION CHAMBERS

	CC TEST SANDS		
PROPERTY	CAPE FEAR SAND	HOKKSUND SAND	TICINO SAND
d_{50} (mm)	0.69	0.39	0.53
d_{10} (mm)	0.29	0.21	0.36
C_U	2.76	2.10	1.60
G_s	2.67	2.70	2.69
e_{max}	0.802	0.894	0.931
e_{min}	0.527	0.549	0.579
e_{ss}	0.858	0.934	0.986
λ_{ss}	0.074	0.054	0.056

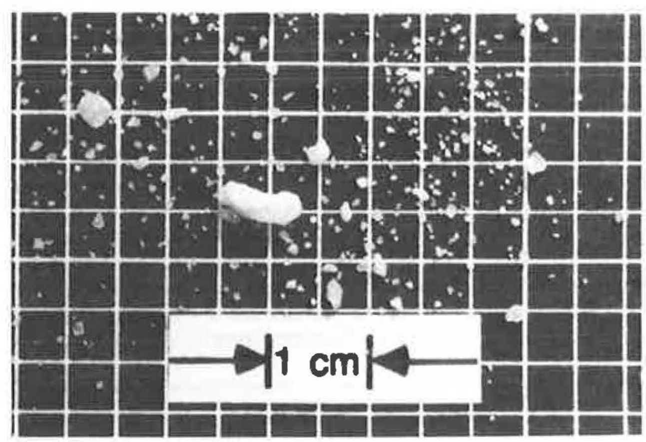

FIGURE 2 Photograph of Cape Fear River sand grains.

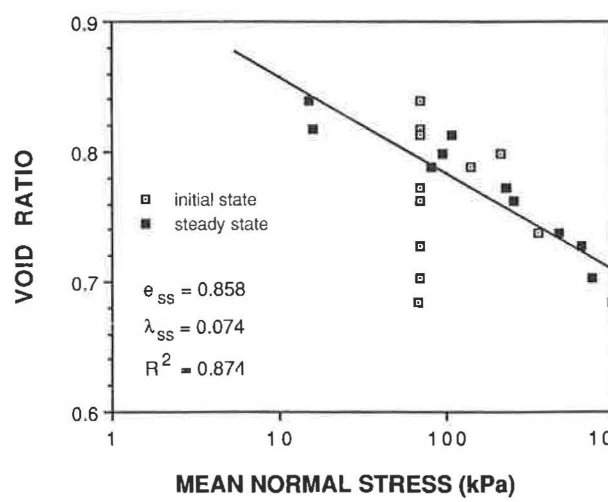

FIGURE 3 State diagram for Cape Fear sand.

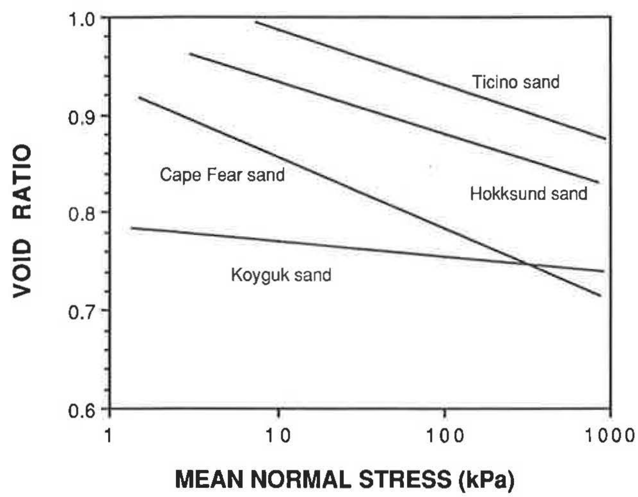

FIGURE 4 Steady state lines for calibration chambers sands.

Been and Jefferies (*2*) in their development of the state parameter. Table 1 also contains a summary of soil properties for the Hokksund and Ticino sands.

NCSU CALIBRATION CHAMBER

A diagram of the NCSU calibration chamber is presented in Figure 5. The NCSU calibration chamber is capable of accommodating a sand specimen 0.94 m (37 in.) in diameter and 0.94 m (37 in.) in height. The test specimens were prepared by pluviation in air. The specimens were then subjected to one-dimensional consolidation, from which the K_o of the sand was determined. Then, the dilatometer tests were conducted while constant vertical and horizontal stresses were maintained through a computer-controlled pneumatic pressure system. Table 2 summarizes the results of the NCSU calibration chamber tests. A detailed description of the NCSU calibration chamber, including test procedures and results, has been reported by Borden et al (*7*).

INTERPRETATION

Correlation of the K_D/K_o ratio, called the amplification factor, to the state parameter has been suggested by Jamiolkowski et al. (*5*) as a rational approach for interpreting the calibration chamber data. Jamiolkowski et al. have presented results of 57 calibration chamber tests on normally and overconsolidated Hokksund and Ticino sands (see Figure 6) and suggest fitting the two parameters with an equation of the following form:

$$K_D/K_o = a{\cdot}e^{m\Psi} \qquad (3)$$

where a and m are empirical coefficients. For the combined data from the Hokksund and Ticino sands, a and m were determined to be 1.35 and −8.08, respectively.

A similar correlation was investigated for normally consolidated Cape Fear sand. Although other functions were investigated, none provided a significantly better fit. The relationship between the state parameter and the amplification factor for those tests and for the a and m coefficients determined by regression analysis are presented in Figure 7. Sig-

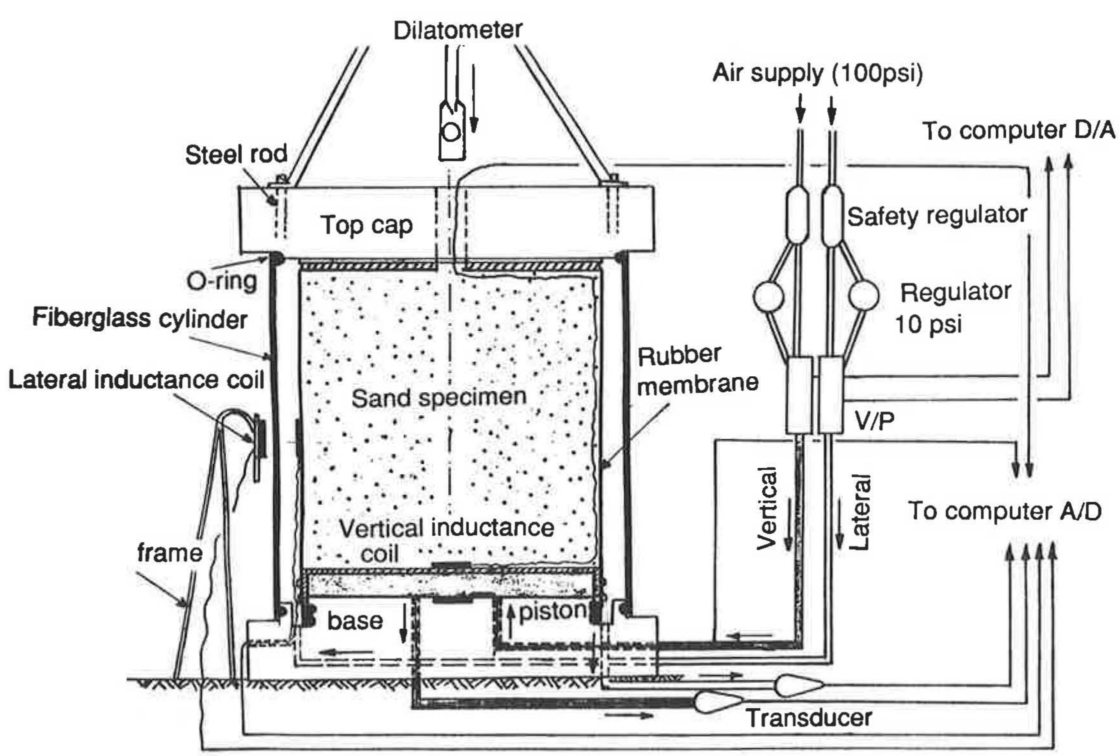

FIGURE 5 NCSU calibration chamber system.

TABLE 2 SUMMARY OF CALIBRATION CHAMBER TESTS PERFORMED ON CAPE FEAR RIVER SAND

TEST no.	σ'_v (kpa)	σ'_h (kpa)	D_R (%)	OCR	K_o	p_o (kpa)	p_1 (kpa)	K_D	Ψ
2	62.06	27.58	73.3	1.00	0.44	151.07	823.88	2.43	-0.214
4	36.54	20.00	91.5	1.00	0.55	141.07	667.31	3.86	-0.280
9	20.69	27.58	76.7	1.00	1.33	87.04	845.39	4.21	-0.238
10	20.46	13.79	58.9	1.00	0.67	47.02	542.25	2.30	-0.202
11	34.32	6.90	87.1	1.00	0.20	35.02	512.24	1.02	-0.283
12	61.14	20.69	78.8	1.00	0.34	83.04	855.40	1.36	-0.234
16	61.37	28.96	6.0	1.00	0.47	78.04	592.27	1.27	-0.021
17	61.14	39.30	15.6	1.00	0.64	85.04	868.40	1.39	-0.044
18	34.32	25.17	23.5	1.00	0.73	90.04	471.22	2.62	-0.083
19	47.73	34.96	33.3	1.00	0.73	102.05	609.28	2.14	-0.100
20	61.14	39.30	-5.3	1.00	0.64	123.06	587.27	2.01	0.016
22	34.32	22.06	-0.8	1.00	0.64	85.04	435.20	2.48	-0.016

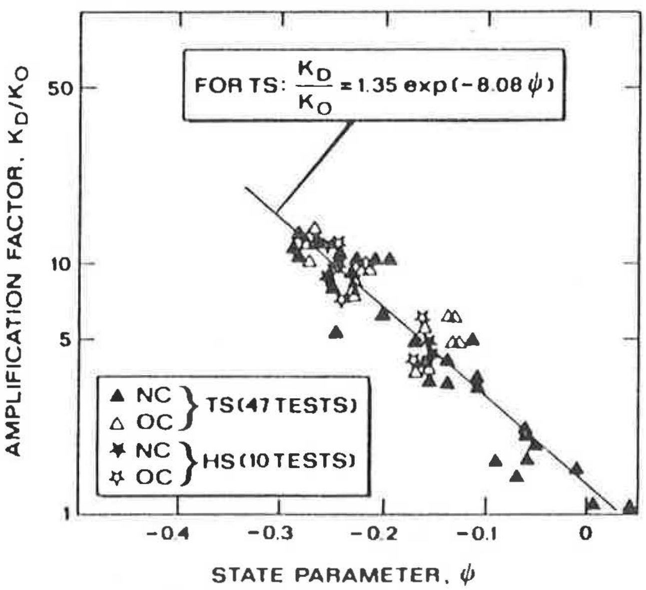

FIGURE 6 Dilatometer amplification factor for Hokksund and Ticino sands (5).

nificant scatter exists, and the resulting R^2 value is 0.58. Data for tests on the normally consolidated Hokksund and Ticino sands are presented in Figures 8 and 9, respectively. The corresponding R^2 values for those relationships are 0.77 and 0.76. Figure 10 illustrates a composite of the data from the three sands with the best-fit line determined according to Equation (3) ($R^2 = 0.66$). A comparison of those figures indicates that the slope of the state parameter verses amplification factor relationship for the Hokksund and Ticino sands appears to be steeper than that of the Cape Fear sand. This may suggest the influence of particle mineralogy, grain shape, and grain-size distribution of the individual sands on the state parameter.

It has been suggested (8–10) that the state parameter be normalized, with respect to the difference between the maximum and minimum void ratio, to account for this influence. This normalization procedure, and normalizing with respect to the steady state void ratio at 10 kPa, was investigated and was found not to influence the relationship of the trend lines for individual sands. The addition of the Cape Fear sand to the existing trend lines for the K_o^{DMT}/K_o relative density relationship presented by Jamiolkowski et al. (5) suggests that

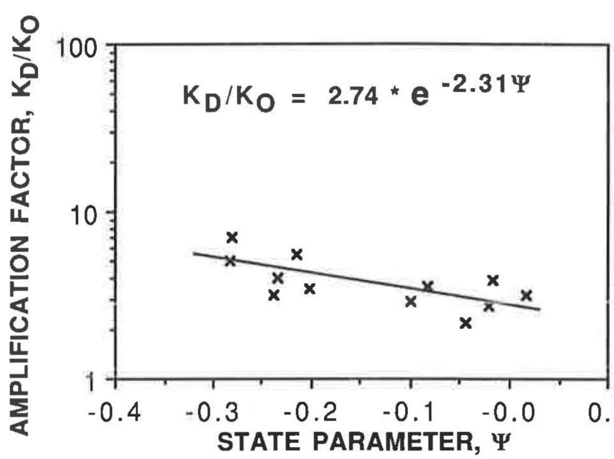

FIGURE 7 Dilatometer amplification factor for normally consolidated Cape Fear sand.

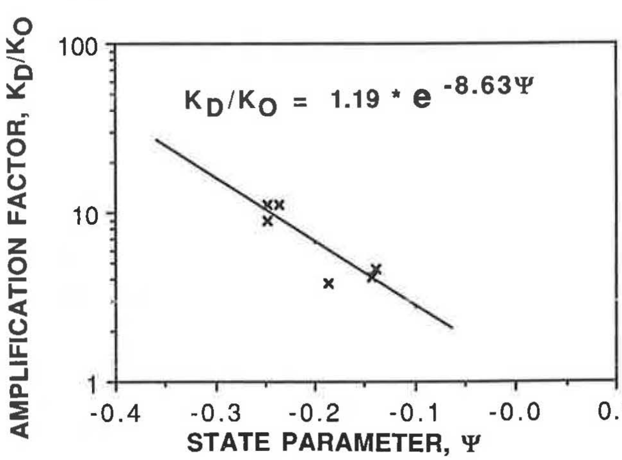

FIGURE 8 Dilatometer amplification factor for normally consolidated Hokksund sand.

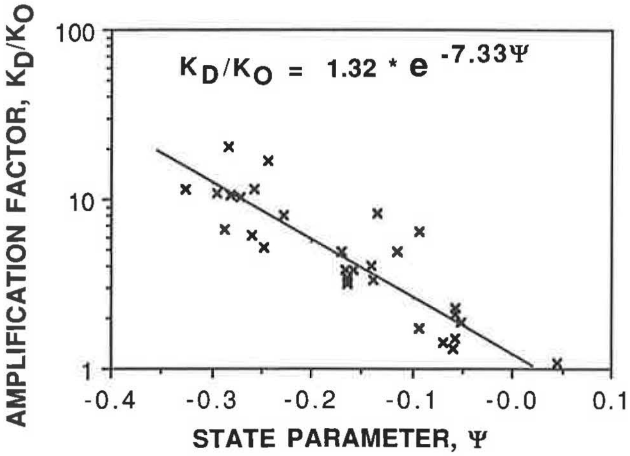

FIGURE 9 Dilatometer amplification factor for normally consolidated Ticino sand.

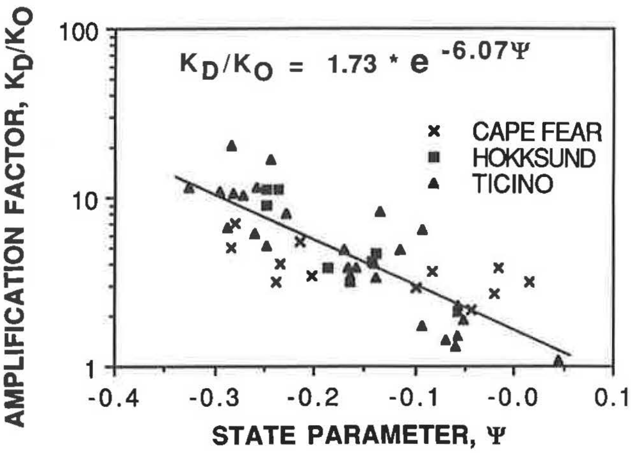

FIGURE 10 Dilatometer amplification factor for normally consolidated calibration chamber sands.

the trend line approaches a limiting value of K_o^{DMT}/K_o between 0.5 and 1.0 at low relative densities.

At the higher relative densities, corresponding to lower state parameter values, the K_o^{DMT}/K_o values are significantly lower for the Cape Fear sand than for either the Hokksund or Ticino sands. The latter tests were performed in a 1.5-m (59 in.) diameter chamber while the NCSU chamber is 0.97 m (37 in.) in diameter. It is possible that the difference in results in the more dilatant soils is related to the development of a plastic zone during penetration into the smaller chamber that extends to the boundary. In the more contractive materials, it would be expected that the plastic zone would be considerably smaller and thus would minimize the influence of chamber diameter. This concept would support the good agreement observed between the data obtained on medium density samples for all three soils.

As was stated previously, Jamiolkowski et al. have suggested that the empirical formula for K_o^{DMT} overestimates K_o in dense to very dense sands and underestimates it in loose sands. The results of the calibration chamber tests on Hokksund and Ticino sands presented in Figure 11 indicate this trend. Examination of the results from the tests on Cape Fear sand

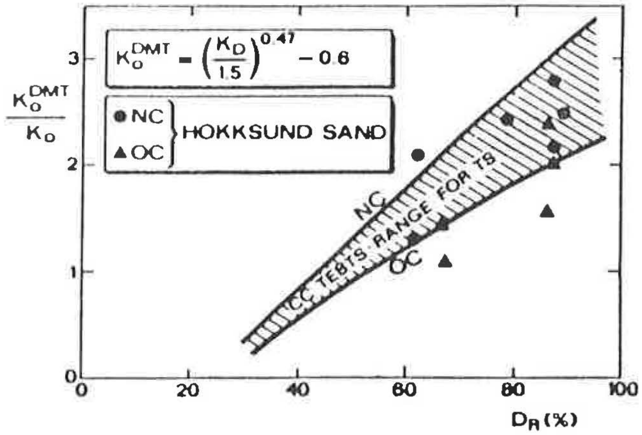

FIGURE 11 K_o^{DMT}/K_o for Hokksund and Ticino sands, using the original Marchetti correlation (5).

(Figure 12) suggest that at lower relative densities the trend is toward a K_o^{DMT}/K_o ratio of 0.5 to 1.0. As was previously suggested, Marchetti's correlation tends to overestimate K_o for dense sands and underestimates it for loose sands but to a smaller degree than for the Hokksund and Ticino sands.

When the K_o^{DMT}/K_o ratio is interpreted in terms of the state parameter, which includes the influence of the stress level, it appears that there is no significant reduction in the scatter of data. Similar data for the Hokksund and Ticino sands are presented in Figures 13 and 14, respectively. As with the K_D/K_o analysis, the slopes of the K_o^{DMT}/K_o verses D_R and Ψ relationships for the Hokksund and Ticino sands are again similar and again steeper than those for the Cape Fear sand. The trend lines for combined data from the three sands are presented in Figure 15. The data from several of the tests on Cape Fear sand at low relative densities suggest that the K_o^{DMT}/K_o ratio approaches a limiting positive value in the range of 0.5 to 1.0.

SUMMARY AND CONCLUSIONS

The relationship between DMT horizontal stress index parameter and existing horizontal stress was evaluated on the basis

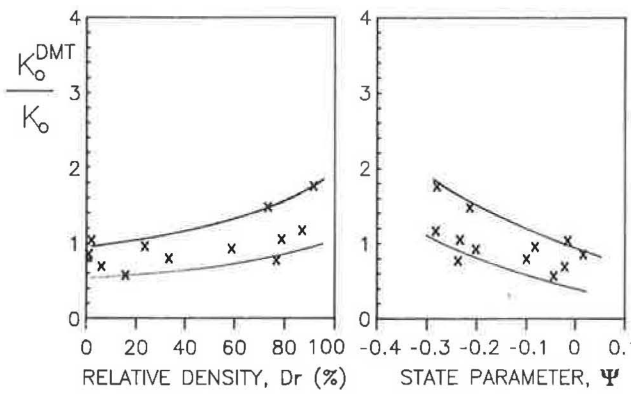

FIGURE 12 K_o^{DMT}/K_o for normally consolidated Cape Fear sand, using the original Marchetti correlation.

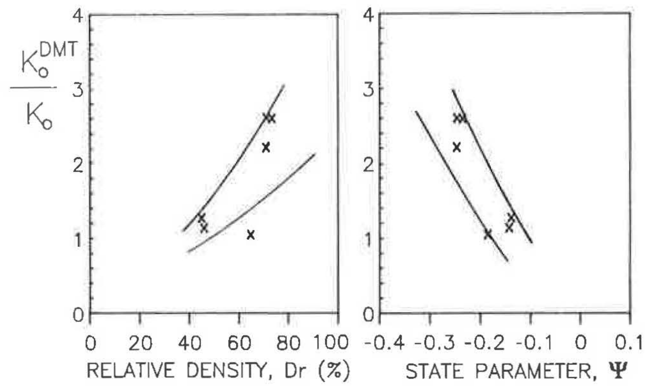

FIGURE 13 K_o^{DMT}/K_o **for normally consolidated Hokksund sand, using the original Marchetti correlation.**

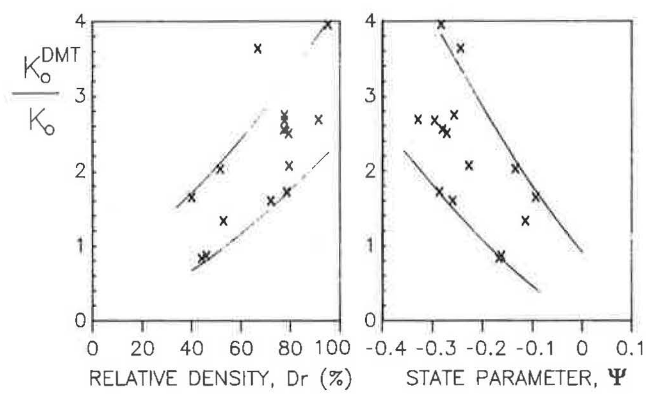

FIGURE 14 K_o^{DMT}/K_o **for normally consolidated Ticino sand, using the original Marchetti correlation.**

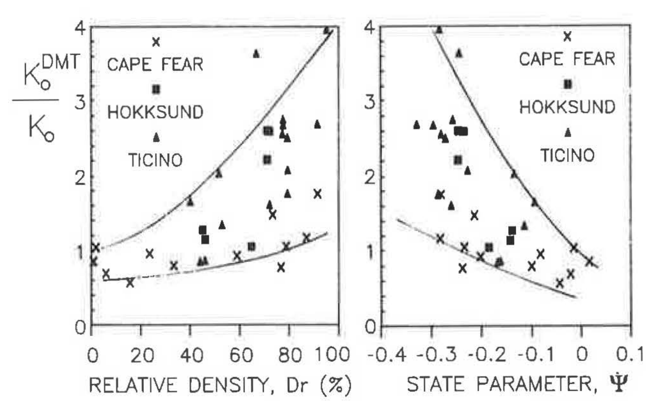

FIGURE 15 K_o^{DMT}/K_o **for normally consolidated calibration chamber sands, using the original Marchetti correlation.**

of dilatometer tests performed in calibration chambers on normally consolidated sands. The results are interpreted in terms of the existing lateral stress index parameter K_D and the original Marchetti correlation of K_D and K_o with respect to both relative density and state parameter.

Interpretation of the amplification factor-state parameter data for the Cape Fear sand tested in this study and the combined data from the three sands discussed resulted in best-fit equations of the form

$$K_D/K_o = a{\cdot}e^{m\Psi}$$

The addition of the Cape Fear sand to the existing trend lines for the K_o^{DMT}/K_o relative density relationship presented by Jamiolkowski et al. (5) suggests that the trend line approaches a limiting value of K_o^{DMT}/K_o between 0.5 and 1.0 at low relative densities.

Normalization of the state parameter by the difference between maximum and minimum void ratio did not result in better agreement between those functions for the three sands. It is possible that the difference in results between the Cape Fear sand and the Hokksund and Ticino sands at higher relative densities could be related to calibration chamber size. Further research is needed to evaluate the required chamber diameter as a function of relative density for dilatometer penetration such that the plastic zone does not extend to the boundary.

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