Direct and Indirect Determinations of In Situ K_o in Clays

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For natural clays encountered in the field, the in situ effective horizontal stress ($\bar{\sigma}_{ho}$) may be evaluated from the interpretation of direct measurements by using the self-boring pressuremeter test (SBPMT) or total stress cells (TSC) or may be evaluated indirectly from other tests such as the dilatometer test (DMT) and piezocone penetration test (CPTU). A review of K_o data summarized from 56 different sites tested by the SBPMT demonstrates that stress history (OCR) is a predominant factor affecting the magnitude of the in situ geostatic state of stress. For clay deposits that have developed their K_o profile primarily from stress history effects (i.e., mechanical overconsolidation), a simplified cavity expansion theory is used to express K_o in terms of the cone tip resistance (q_c) and penetration pore water stress (Δu) obtained during CPTU soundings and the DMT contact stress (p_o). Data derived from 17 sites tested by the SBPMT and CPTU and 12 sites tested by the SBPMT and DMT are used to verify the approach.

The geostatic state of stress in the ground can develop as a combination of a number of factors and processes that have occurred during the geologic history of the deposit (*1–3*). Variables potentially affecting the development of horizontal stress ($\bar{\sigma}_{ho}$) in situ may include, for example, stress history, geologic origin, mineralogy, cementation, aging, desiccation, pore water fluid, passive failure, strain history, temperature, wet-dry cycles, wave loading, degree of saturation, or weathering. For a given soil it is unlikely that a completely accurate scenario of all of the relevant factors and their chronology can be developed with a high level of confidence. Furthermore, the significance and effect of each variable may not be fully understood. However, dominant variables such as stress history usually can be estimated reasonably well. Alternatively, one can bypass evaluating those variables and attempt to measure σ_{ho} in situ when possible.

Laboratory triaxial and oedometer data on clays, silts, and sands indicate a rather strong relationship between the horizontal stress coefficient ($K_o = \bar{\sigma}_{ho}/\bar{\sigma}_{vo}$) and overconsolidation ratio (OCR $= \bar{\sigma}_p/\bar{\sigma}_{vo}$) (*4*). However, a recent study (*5*) has suggested that the in situ geostatic state of stress at one site in the Beaufort Sea may be independent of stress history. This opinion is contrary to K_o test data obtained on natural and remolded soils in laboratory triaxial cells and instrumented oedometers. For soils that experience virgin loading and simple rebound, the following expression appears appropriate:

$$K_o = (1 - \sin \bar{\phi})\ \mathrm{OCR}^{\sin \bar{\phi}} \quad (1)$$

where $\bar{\phi}$ is the effective stress friction angle of the material.

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Therefore, it is of interest to examine whether direct field measurements of in situ K_o by self-boring pressuremeter test (SBPMT) are consistent with K_o-OCR trends observed in the laboratory.

SBPMT is one of the few devices capable of obtaining a direct measurement of horizontal stress in situ. Recent advances with the flat dilatometer, the stepped blade, and special cone penetrometers outfitted with horizontal stress sensors appear to be promising, but they are dependent on extrapolation procedures or empirical correlations for their estimation of σ_{ho}. Since the advent of the SBPMT, almost 2 decades of experience have been acquired, allowing for an overall assessment of the device for characterizing soil properties. In this paper, a brief review of the trend of K_o with OCR is examined, both from laboratory studies and from available field data acquired with the SBPMT.

As an alternative to the SBPMT, a direct measurement of σ_{ho} may be obtained by using total stress cells (TSC) or hydraulic fracturing (HF). Experience with the TSC has shown reasonable success in profiling horizontal stresses, although a considerable waiting time (i.e., several days or more) often is required for the dissipation of excess pore water stresses caused by insertion of the blade. Conversely, the hydraulic fracturing technique appears to be hampered by several difficulties, and the method may actually be restricted to measuring σ_{ho} in soils with K_o less than 1 (*6*).

Of additional interest is the notion that all in situ tests reflect, to some degree, the ambient geostatic state of stress in the ground. Traditionally, the cone tip resistance (q_c) has been used to provide an index of the undrained shear strength (s_u) of clay deposits. Because it has been well established that a relationship exists between s_u and OCR, logically it may be assumed that K_o also is reflected in the measured value of q_c. In this paper, approximate cavity expansion relationships are presented for determining K_o from piezocone measurement and dilatometer readings.

SBPMT DATA BASE

A data base of soil properties measured by SBPMT has been compiled from 56 separate clay sites that have been described in the geotechnical literature. A listing of the sites, sources of data, index properties, and identifying symbols is given in Table 1. Thirty-seven of the sites were tested using Cambridge-type probes (Camkometer) and are denoted by solid and partially darkened symbols. Eighteen sites were tested using the French-type probe (PAFSOR) and are shown by open symbols. Two sites (Boston Blue clay and Porto Tolle)

were tested by both the Camkometer and the PAFSOR probes. In addition, three of the open symbols are used to denote sites (Tokyo, Oyo, and Hachinohe) that were tested by using the Japanese Oyo monocell probe.

The data base includes sites from worldwide sources. Index properties summarized in Table 1 represent mean values or typical values for the deposits. Plasticity indices ranged from 10 to 73 percent for those clays, and sensitivities varied from 2 to 500. Stress states were reported to vary from normally consolidated (OCR = 1) to heavily overconsolidated (OCR ≈ 80). One site from the Beaufort Sea was not included in the data base because of an apparent controversy over the interpreted profile of stress history (*7*).

Values of the soil parameters for each site were digitized at the specific test depths at which the SBPMT were conducted. Usually, the companion series of oedometer tests were not performed on samples taken at the same depths, thereby requiring interpolation of OCR values. Also, some errors likely may have been incurred in the scaling of data and measurements from the original sources.

To provide as consistent a comparison as possible, values of σ_{ho} from the SBPMT generally were defined by the lift-off method (*8*), although not all sources of data actually specified the method of interpretation used. The conventional Casagrande technique of defining $\bar{\sigma}_p$ was used most often in interpreting the results of the consolidation data. Obviously, those methods of defining $\bar{\sigma}_{ho}$ and $\bar{\sigma}_p$ are subject to errors in judgment, scaling, and bias by the various researchers who presented the data.

The observed relationship between the in situ K_o from the SBPMT and OCR is presented in Figure 1, indicating a strong trend between K_o and stress history of the deposit. Adopting

TABLE 1 LIST OF CLAY SITES TESTED BY SELF-BORING PRESSUREMETER

TYPE PROBE	SITE SYMBOL	SITE	SUMMARY OF INDEX PROPERTIES w_n	w_L	PI	CF	S_t	REMARKS	REFERENCE
Camkometer		ADGO FIELD	30	35	12	5	na	stiff OC	Kack, et al., 1986
		BACKEBOL	95	90	60	na	28	soft NC	Massarsch & Broms, 1976
		BELL COMMON	25	63	39	45	na	fissured HOC	Tedd, et al., 1984
		BOSTON BLUE	43	41	22	44	7	OC to NC	Ladd, et al. 1980
		BOTANIC PARK	na	na	na	na	na	stiff OC	Arnold, 1981 (30)
		BURNT FEN	na	na	na	na	na	soft NC	Wroth, 1980 (33)
		CANVEY ISLAND	80	75	45	na	na	soft NC	Windle & Wroth, 1977a
		CHINA BASIN	95	na	na	na	na	soft LOC	Clough & Denby, 1980
		COWDEN	17	38	20	35	na	OC till	Powell & Uglow, 1985
		DRAMMEN	54	54	28	47	7	aged NC	Lacasse, et al., 1981
		DUNTON GREEN	33	85	58	na	na	fissured HOC	Clarke & Wroth, 1984; Samuels, 1975
		ESSEX	27	61	38	45	na	fissured HOC	Tedd & Charles, 1981
		FREDERICTON	27	30	10	50	na	sensitive	Landva, et al., 1988 (22)
		GLOUCESTER	80	55	28	80	60	sensitive aged NC	Konrad & Law, 1987
		GOTHENBERG	85	83	30	na	20	aged NC	Wroth & Hughes, 1974
		GRANGEMOUTH	65	75	40	35	na	soft NC	Clarke et al., 1979 (23)
		HAGA	35	40	15	45	6	sensitive OC	Aas, et al., 1986
		HAMILTON AFB	92	90	50	na	7	aged NC	Benoit & Clough, 1986
		HENDON	28	70	42	52	na	fissured HOC	Windle & Wroth, 1977b
		KINGS LYNN	65	95	57	na	3.5	organic LOC	Wroth & Hughes, 1973 (24)
		LA SPEZIA	52	75	55	50	5.5	soft NC	Ghionna, et al., 1982
		MADINGLEY	26	72	47	92	na	fissured HOC	Windle & Wroth, 1977b
		MASSENA	60	50	25	60	10	sensitive aged NC	Huang & Haefele, 1988 (25)
		MATAGAMI	70	80	47	na	na	sensitive NC	Eden & Law, 1980
		MELBOURNE	na	na	na	na	na	soft LOC	Ervin, 1983 (26)
		MERCER ISLAND	28	53	24	41	na	stiff OC	Denby, et al., 1981 (27)
		NRCC	80	60	35	70	200	aged NC	Law & Eden, 1980; Konrad & Law, 1987
		ONSOY	62	65	28	60	7.5	aged NC	Lacasse, et al., 1981
		OTTAWA	70	55	30	66	500	sensitive aged NC	Konrad & Law, 1987
		OXFORD	na	72	40	na	na	fissured HOC	Clarke & Wroth, 1988 (28)
		PADDLE RIVER	17	36	25	na	na	clay core	Ramage et al., 1986 (29)
		PANIGAGLIA	60	72	47	na	5	soft NC	Ghionna, et al., 1981, 1985
		PORT AUGUSTA	na	na	na	na	na	stiff OC	Arnold, 1981 (30)
		PORTO TOLLE	36	52	30	34	3	soft NC	Ghionna, et al., 1981, 1985
		SEA ISLAND	36	35	10	20	5	soft NC	Konrad, et al., 1985
		TARANTO	23	60	27	na	na	cemented HOC	Ghionna, et al., 1981, 1985
		UPPER LIAS	na	62	32	na	na	fissured HOC	Clarke & Wroth, 1988 (28)
Oyo	⊖	HACHINOHE	45	85	67	na	na	OC	Moroto & Muramatsu, 1987
		OYO	na	na	na	na	na	soft NC	Ohya, 1980
	⊕	TOKYO	52	38	28	35	na	aged NC	Mori, 1981

(*continued on next page*)

TABLE 1 (*continued*)

TYPE PROBE	SITE SYMBOL	SITE	w_n	w_L	PI	CF	S_t	REMARKS	REFERENCE
PAFSOR		BANDAR ABBAS	28	44	22	27	2.5	LOC	Ghionna, et al., 1981
		BEAUMONT	30	65	40	na	na	desiccated OC	Mahar & O'Neill, 1983
		BOSTON BLUE	43	41	21	44	7	OC - NC	Ladd, et al. 1980
		CRAN	80	95	55	na	na	aged NC	Juran, et al. 1983
		CUBZAC LES PONTS	85	95	54	55	na	organic NC	Blondeau et al., 1977 (31)
		FLANDERS	na	na	na	na	na	soft silt	Baguelin et al., 1978 (32)
		GUASTICCE	68	88	63	52	na	NC	Ghionna, et al., 1981
		LANESTER	120	120	73	na	na	aged organic NC	Baguelin, et al., 1974
		MARE ISLAND	80	92	52	na	2	soft NC	John, 1980
		MONTALTO	26	52	34	38	na	intact OC	Ghionna, et al., 1981
		NEW ORLEANS	64	78	51	na	na	soft NC	Canou & Tumay, 1986
		PLANCOET	40	40	20	na	na	soft NC silt	Baguelin et al., 1978 (32)
		PORTO TOLLE	36	52	30	34	3	soft NC	Battaglio, et al., 1981
		RIO VISTA	200	180	30	na	3.5	soft NC	John, 1980
		SACRAMENTO	40	45	13	na	2	soft NC	John, 1980
		ST. ALBAN	75	45	22	38	15	sensitive aged NC	Roy & Chi Thien, 1987
		ST.ANDRE CUBZAC	100	70	35	na	na	soft NC	Baguelin, et al., 1972
		TRIESTE	50	71	47	46	na	soft NC	Battaglio, et al., 1981

Notes: NC = normally consolidated
LOC = lightly overconsolidated
OC = overconsolidated
HOC = heavily overconsolidated
na = not available

w_n = natural water content (%)
w_L = liquid limit (%)
PI = plasticity index (%)
CF = clay fraction (% < 2μ)
S_t = sensitivity by field vane

References not followed by reference number may be found in an earlier paper by Mayne and Kulhawy (7).

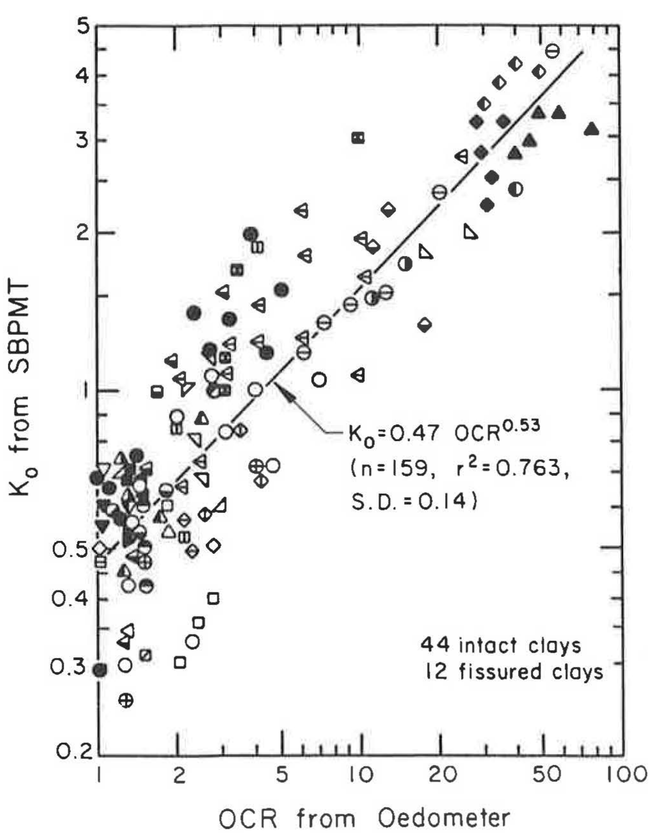

FIGURE 1 Observed trend between in situ K_o from SBPMT and overconsolidation ratio.

a format in terms of a power function, regression analyses for the SBPMT data give a best fit line (n = 159, r^2 = 0.763, S.D. = 0.14 for logarithmic scale):

$$K_o = 0.52\ \mathrm{OCR}^{0.51} \tag{2a}$$

where n is the number of data points, r^2 is the coefficient of determination, and S.D. is the standard deviation of the independent variable. For comparison, a least-squares regression assuming arithmetic relationships between K_o and OCR indicated an r^2 of only 0.562, and, therefore, the choice of the assumed power function relationship in Figure 1 appears more statistically significant. In addition, the power function has been adopted by many researchers (*6,9,10*) as a convenient and simple means of relating K_o to stress history.

The observed range of values about the statistical best-fit line in Figure 1 is likely caused by a number of factors not considered in this review. For one, by visual inspection, it can be seen that at low values of OCR the PAFSOR device consistently gives lower values of K_o than does the Camkometer. This result may be caused by differences in the length to diameter (L/d) ratios of the probes (L/d = 2 and 4 for the PAFSOR, 6 for the Camkometer, and L/d = 5 for the Oyo type). In concept, the SBPMT minimizes disturbances to the ground during installation. In reality, however, some disturbance is inevitable, and this may influence the interpreted value of K_o. In addition, the various environmental and geologic factors previously mentioned may have had some influence on the overall development of $\bar{\sigma}_{ho}$.

For comparison, it is of interest to summarize the apparent connection between K_o and OCR from laboratory studies. In

laboratory test series, the K_o condition is defined strictly by one-dimensional consolidation with zero lateral strain. In the field, the true imposed boundary conditions are not known, and the term K_o is used to infer the geostatic state of stress. In the laboratory series, specimens were subjected to vertical stresses sufficient enough to reach an OCR = 1 and then were unloaded to known values of OCR. A statistical analysis of laboratory K_o test data on 48 different clays unloaded in simple rebound has been summarized by Kulhawy and Mayne (*11*) and is presented in Figure 2. The average trend from regression analyses of the laboratory K_o data indicates

$$K_o = 0.54\ \mathrm{OCR}^{0.44} \tag{2b}$$

where $n = 174$, $r^2 = 0.88$, and S.D. = 0.17. Figure 2 also indicates the specific trends for the K_o-OCR relationships by accounting for the influence of $\bar{\phi}$ as given by Equation 1. Whereas this effect of $\bar{\phi}$ has been justified for laboratory K_o relationships (*4*), it may also be taken as significant for field values of K_o, although values of $\bar{\phi}$ were mostly unavailable for the SBPMT data base. For soils reloaded after rebound, it is important to note that the relationship between K_o and OCR is different.

CAVITY EXPANSION THEORY FOR K_o

Although the SBPMT appears to be capable of providing direct measurements of the in situ K_o, the device has not gained sufficient popularity in practice because of its high cost and low productivity. In addition, the sophisticated nature of the device requires a high level of technical expertise in the field so that proper results are obtained. Moreover, the presence of dense sands, old fills, and gravelly layers often causes difficulties in the installation of the SBPMT for routine testing. Consequently, considerable interest exists in estimating K_o from more conventional and robust tests such as the CPT and DMT, even though those represent indirect approaches to the problem.

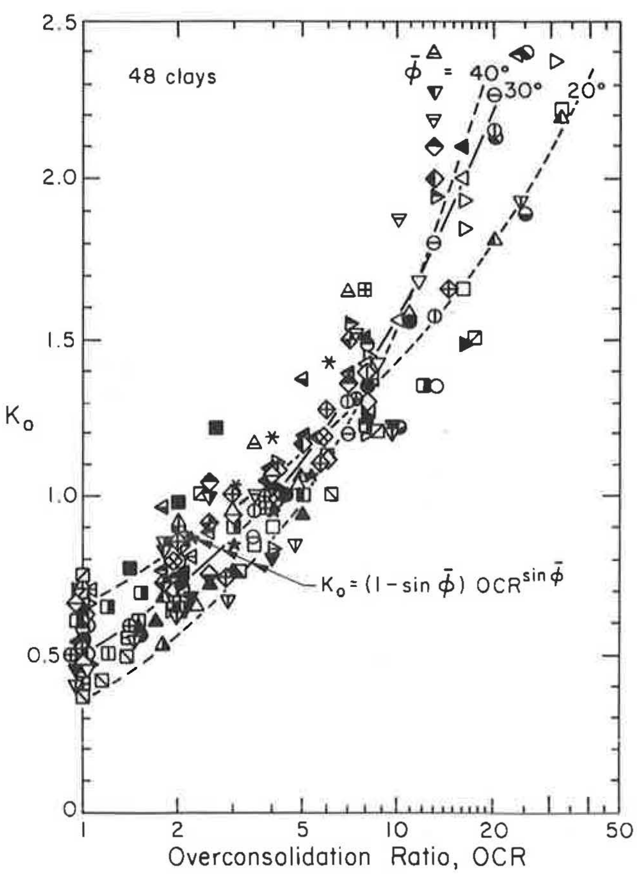

FIGURE 2 Observed and predicted relationships between K_o and OCR from laboratory test data [data compiled from work by Mayne and Kulhawy (*4*)].

Commonly, the cone tip resistance (q_c) measured during the CPT is used to determine the undrained shear strength (s_u) of clay deposits. Technically, a corrected cone tip resistance (q_T) should be used because pore water stresses act on unequal areas of the cone (*6*). Therefore, piezocone penetration tests (CPTU) are the preferred means of testing. The value of s_u is calculated from q_T according to

$$s_u = (q_T - \sigma_{vo})/N_k \tag{3}$$

where σ_{vo} is total overburden stress and N_k is the cone tip bearing factor.

The variation of normalized undrained strength ($s_u/\bar{\sigma}_{vo}$) with OCR is well documented and assumes a power law form

$$(s_u/\bar{\sigma}_{vo})_{\mathrm{OC}} = (s_u/\bar{\sigma}_{vo})_{\mathrm{NC}}\ \mathrm{OCR}^{\Lambda} \tag{4}$$

where OC is overconsolidated, NC is normally consolidated, and Λ is plastic volumetric strain potential (*12*). For most natural clays, $\Lambda \approx 0.8$ for triaxial and direct simple shear modes of failure. If the strength corresponding to direct simple shear is assumed to be relevant, then the expression for the NC normalized strength is simply (*12*)

$$(s_u/\bar{\sigma}_{vo})_{\mathrm{NC}} = \sin\bar{\phi}/2 \tag{5}$$

By combining Equations 1 and 3, Kulhawy et al. (*3*) were able to effectively remove the OCR term, resulting in

$$K_o = (1 - \sin\bar{\phi})\left[\frac{(s_u/\bar{\sigma}_{vo})_{\mathrm{OC}}}{(s_u/\bar{\sigma}_{vo})_{\mathrm{NC}}}\right]^{\sin\bar{\phi}/\Lambda} \tag{6}$$

Adopting the cavity expansion theory of Vesić (*13*), the cone-bearing factor for tip resistance is

$$N_k = (4/3)\,[\ln I_r + 1] + \pi/2 + 1 \tag{7}$$

where $I_r = G/s_u$ is the rigidity index of the clay and G is the shear modulus. Keaveny and Mitchell (*14*) have substantiated the relevance of this cavity expansion expression for N_k for CPT results in clay. The apparent difficulty with the cavity expansion approach is its reliance on I_r. Because the stress-strain behavior of clay is known to be nonlinear, the relevant value of G (and I_r) depends on strain level and stress history and is not known a priori. Fortunately, however, the expression for N_k is in terms of the natural logarithm of I_r, and therefore only a first-order assessment of I_r is needed.

Generally, I_r decreases with OCR and increases with plasticity index of the soil (*9,14*). Alternatively, the modified Cam clay model can be used to provide an estimate of the undrained rigidity index ($I_r = G/s_u$). By using conventional soil param-

eters, the original Cam clay model may be utilized to evaluate I_r for normally consolidated clays (*15*):

$$(G/s_u)_{NC} = \frac{2\,M\,(1 + e_o)\ln 10}{3\,C_c\,\Lambda\,(1 - \Lambda)\exp(-\Lambda)} \tag{8}$$

where $M = 6 \sin \bar{\phi}/(3 - \sin \bar{\phi}) \approx \bar{\phi}/25.4$ degrees, e_o is the void ratio, and C_c is the virgin compression index. Wroth and Houlsby (*10*) further showed that the effect of OCR on I_r may be represented by using the following equation:

$$\frac{(G/s_u)_{OC}}{(G/s_u)_{NC}} = [1 + C \ln \text{OCR}]\ \text{OCR}^{-\Lambda} \tag{9}$$

where C is an experimentally determined constant between 0 and 2. A value of $C = 1$ appears to typify the trends observed from laboratory test data. By combining Equations 8 and 9 and adopting a typical value of $\Lambda = 0.8$, Kulhawy and Mayne (*11*) developed a simple approximation for I_r in terms of conventional soil parameters:

$$I_r = \frac{5\,\bar{\phi}}{6}\,\frac{(1 + e_o)}{C_c}\,\frac{(\ln \text{OCR} + 1)}{\text{OCR}^{0.8}} \tag{10}$$

Figure 3 presents the parametric effect of OCR, $\bar{\phi}$, and C_c on the calculated value of I_r for an assumed constant value of $e_o = 1$.

By combining Equations 3, 5, 6, and 7, K_o can be expressed as

$$K_o = (1 - \sin \bar{\phi}) \left[\frac{(q_T - \sigma_{vo})/\bar{\sigma}_{vo}}{(2/3) \sin \bar{\phi}(\ln I_r + 2.925)}\right]^{1.25 \sin \bar{\phi}} \tag{11}$$

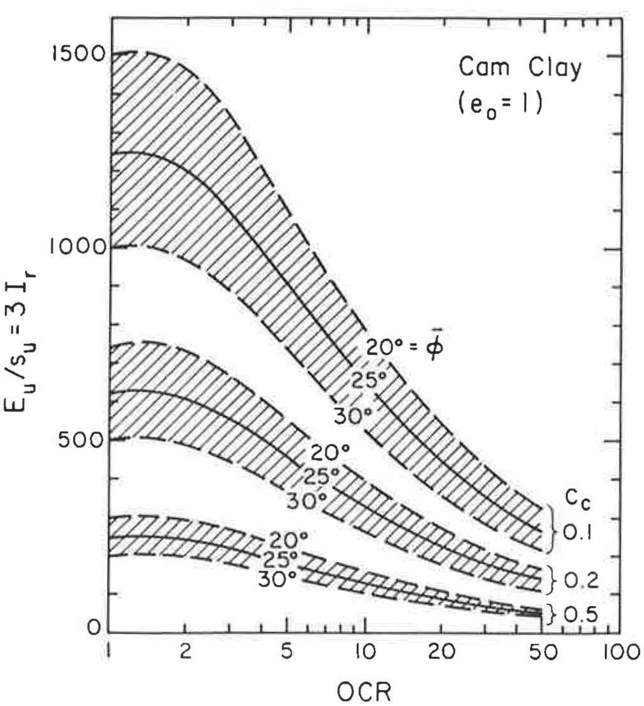

FIGURE 3 Parametric effects of effective friction angle ($\bar{\phi}$), compression index (C_c), and overconsolidation ratio (OCR) on calculated rigidity index ($I_r = G/s_u$).

which demonstrates that K_o is related to the normalized cone tip resistance, $(q_T - \sigma_{vo})/\bar{\sigma}_{vo}$, in terms of basic soil parameters ($\bar{\phi}$, C_c, and e_o). By using Equations 10 and 11, the parametric effect of compression index (C_c) on the theoretical relationship between K_o and normalized cone tip resistance is illustrated in Figure 4.

Cavity expansion theory also provides an evaluation of the excess pore water stresses (Δu) induced by a penetrating cone. For piezocones with porous elements located on the cone tip, Δu is caused primarily by changes in octahedral stresses, such that (*16*)

$$\Delta u = (4/3)\, s_u \ln I_r \tag{12}$$

which applies to spherical cavities. In accordance with Equations 4 and 10, Δu for piezocones with porous elements on the cone tip is always positive. By a similar combination of previous results, the derived expression for K_o in terms of the normalized excess pore water stress ($\Delta u/\bar{\sigma}_{vo}$) from piezocones with tip measurements becomes

$$K_o = (1 - \sin \bar{\phi}) \left[\frac{(\Delta u/\bar{\sigma}_{vo})}{(2/3) \sin \bar{\phi} \ln I_r}\right]^{1.25 \sin \bar{\phi}} \tag{13}$$

Figure 5 illustrates the parametric influence of $\bar{\phi}$ on the theoretical relationship between K_o and $\Delta u/\bar{\sigma}_{vo}$.

An approximate methodology for the DMT also can be formulated. The increase in total horizontal stress caused by a penetrating probe in cohesive ground may be estimated by using cylindrical cavity expansion theory (*16*):

$$\Delta\sigma_h = s_u\,[1 + \ln I_r] \tag{14}$$

Again, the previously mentioned approach yields

$$K_o = (1 - \sin \bar{\phi}) \left[\frac{(\Delta\sigma_h/\bar{\sigma}_{vo})}{(1/2) \sin \bar{\phi}\,(\ln I_r + 1)}\right]^{1.25 \sin \bar{\phi}} \tag{15}$$

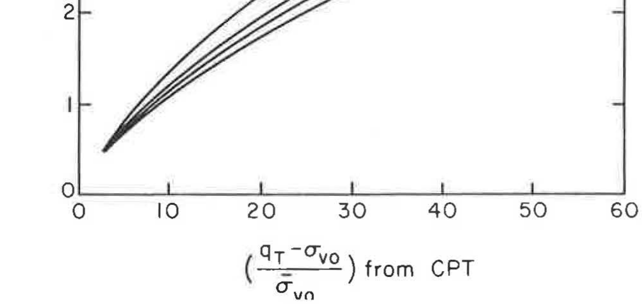

FIGURE 4 Theoretical relation for K_o in terms of normalized cone tip resistance.

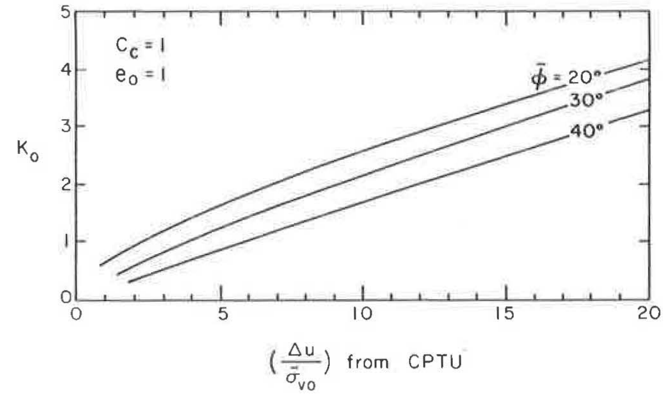

FIGURE 5 Theoretical relation for K_o in terms of normalized penetration pore water stress.

The dilatometer provides measurements of total horizontal stress after penetration by a flat blade. For purposes of correlating DMT results with estimated profiles of K_o, Marchetti (*17*) defined the horizontal stress index (K_D) as a dimensionless parameter

$$K_D = (p_o - u_o)/\bar{\sigma}_{vo} \qquad (16)$$

where p_o is the initial total contact stress and u_o is the hydrostatic pore water stress. No specific cavity expansion theory exists for a penetrating flat blade having the same geometry as the dilatometer and using the precise definition of K_D. However, as a first approximation, the index K_D may be taken as the change in total horizontal stress, represented by the normalized term ($\Delta\sigma_h/\bar{\sigma}_{vo}$) in Equation 15. Figure 6 presents the effect of the normalized total horizontal stress change on the calculated value of K_o. The empirical relationship for K_o in terms of K_D given by Marchetti is also shown in Figure 6. Apparently, the empirical approach matches the theoretical curves for a soil with $\bar{\phi} \approx 30$ degrees, $C_c \approx 0.4$, and $e_o \approx 1$.

A preliminary assessment of OCR is required to calculate I_r from Equation 10. Because I_r depends roughly as a function of the natural logarithm of OCR, only a preliminary estimate of OCR is required for calculating I_r from Equation 10. This preliminary estimate of stress history may be made by using empirical correlations between the effective preconsolidation stress ($\bar{\sigma}_p$) and in situ test results from the cone penetration test, piezocone, and dilatometer (*18,19*) given by the following expressions:

CPT

$$\bar{\sigma}_p = 0.4\,(q_T - \sigma_{vo}) \qquad (17a)$$

CPTU

$$\bar{\sigma}_p = 0.5\,\Delta u \qquad (17b)$$

DMT

$$\bar{\sigma}_p = 0.5\,(p_o - u_o) \qquad (17c)$$

For heavily overconsolidated fissured clays, these correlative trends provide conservative estimates (*19*).

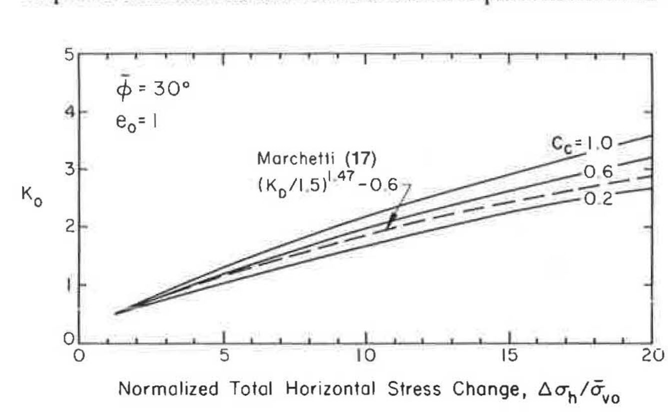

FIGURE 6 Theoretical relation for K_o in terms of normalized total horizontal stress change. Empirical correlation for DMT by Marchetti (*17*) also shown.

DATA BASE TRENDS FOR K_o

The compiled SBPMT data base permits the development of direct correlations between K_o and normalized in situ test parameters. A total of 17 of the SBPMT sites cited in Table 1 also were tested by CPTU, allowing for a direct trend between K_o and the normalized cone-tip resistance $(q_T - \sigma_{vo})/\bar{\sigma}_{vo}$, as in Figure 7. The observed trend from the field data is consistent with the theoretical relation indicated previously in Figure 4. As was expected, the highest values of K_o and $(q_T - \sigma_{vo})/\bar{\sigma}_{vo}$ are associated with heavily overconsolidated and fissured clays [London, Gault, and Cowden (*20*)], as well as with the upper fissured crust of Haga clay (*21*). Very high values of K_o also are associated with Taranto clay, which is reported to be cemented and microfissured (*8*).

Because fissured clays have likely undergone passive failure, they do not behave as a true continuum. Consequently,

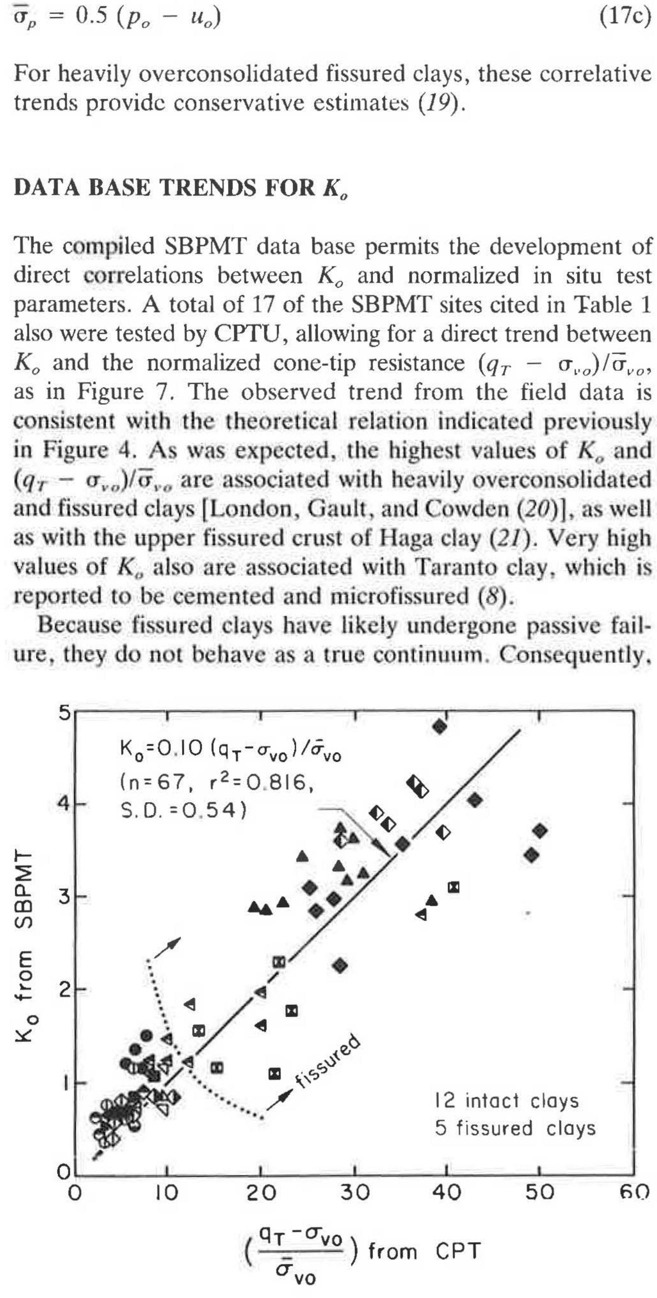

FIGURE 7 Observed trend between K_o from SBPMT and q_T from cone penetration tests.

measurements from in situ probes such as the cone penetrometer also reflect the effects of the secondary structure; that is, q_T reflects both the nature of the intact blocks of heavily preconsolidated clay and the degree, extent, and spacing of fissures. The result is that in heavily overconsolidated fissured clays measured values of q_T are high because of the stress history effects, but they are not as high as theoretical considerations because fissures allow for stress relief during cone penetration.

A similar trend is observed between the SBPMT value of K_o and the normalized excess pore water stress ($\Delta u/\bar{\sigma}_{vo}$) taken from piezocone soundings (Figure 8). Measurements of Δu are primarily from piezocones with tip or face elements. Again, observed trends for K_o are in line with theoretical curves shown in Figure 5. However, fissuring evidently affects the piezocone measurements of Δu in a manner described previously for q_T readings. For piezocones with porous elements located just behind the tip, the observed relationship does not hold in general, because at this location pore water stresses occur as a combination of shear- and octahedral-induced stress changes. Consequently, Δu for heavily overconsolidated and fissured clays tends to be zero or negative for those types of piezocones.

The direct correlation between the SBPMT value of K_o and the DMT index K_D is presented in Figure 9. The original correlation between K_o and K_D presented by Marchetti (*17*)

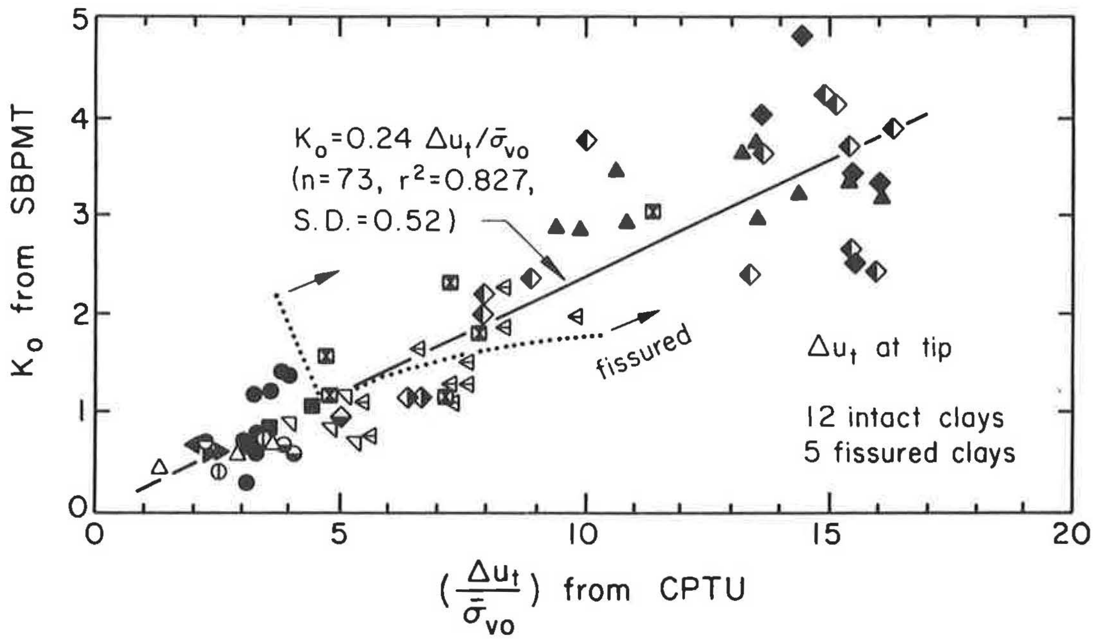

FIGURE 8 Observed trend between K_o from SBPMT and Δu from piezocone soundings with tip elements.

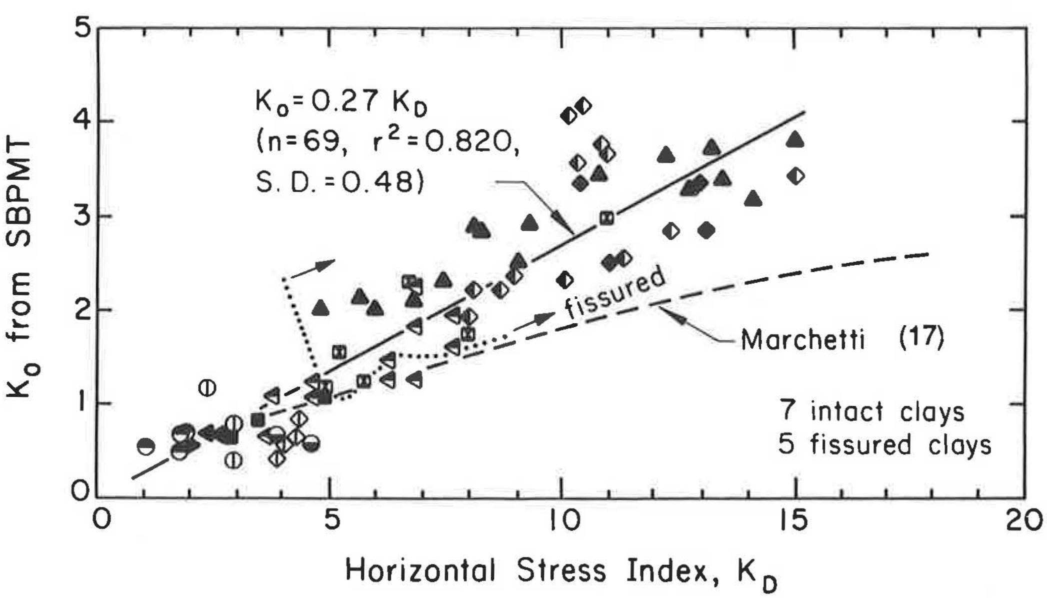

FIGURE 9 Observed trend between K_o from SBPMT and K_D from dilatometer soundings.

was, in fact, based largely on estimated values of K_o for the sites considered. In contrast, data presented in Figure 9 use values of K_o measured in situ by using the SBPMT. By comparing Figures 6 and 9 it is apparent that fissuring also affects the DMT lift-off pressures.

From a practical standpoint, only a first-order estimate of the in situ K_o may be required for geotechnical analysis. Often, the necessary values of $\overline{\phi}$, C_c, e_o, Λ, and OCR for the theoretical approach will be unavailable. Because the methodology is indirect and only approximate in nature, simplified statistical trends may be adopted that relate K_o directly to the normalized in situ test measurements. The best-fit lines from regression analyses indicate

CPT

$$K_o = 0.10\ (q_T - \sigma_{vo})/\overline{\sigma}_{vo} \quad (18a)$$

CPTU

$$K_o = 0.24\ (\Delta u/\overline{\sigma}_{vo}) \quad (18b)$$

DMT

$$K_o = 0.27\ K_D \quad (18c)$$

Summaries of the statistical results and best-fit lines forced through the origin are presented in Figures 7–9 for the CPT, CPTU, and DMT data.

CONCLUSIONS

A systematic approach to the study of K_o in situ leads to the following conclusions:

1. Direct measurements of in situ horizontal stress obtained from 56 clay sites tested by self-boring pressuremeter indicate a K_o-OCR relationship consistent and congruous with previous trends derived from laboratory data.
2. For clay deposits that have been subjected to relatively simple load-unload stress history, indirect assessments of K_o by cone penetration, piezocone, and dilatometer tests appear feasible. A simplified theoretical framework is formulated for this purpose in terms of basic soil parameters ($\overline{\phi}$, C_c, and e_o) by using cavity expansion theory.
3. Observed trends between SBPMT values of K_o and the normalized cone tip resistance ($q_T - \sigma_{vo}/\overline{\sigma}_{vo}$), excess pore water stress at the tip ($\Delta u/\overline{\sigma}_{vo}$), and DMT horizontal stress index (K_D) are consistent with theoretical relationships.
4. In situ penetration tests in heavily overconsolidated fissured clays also are influenced by secondary structure effects.

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