Correlation of Dilatometer Readings with Lateral Stress in Clays

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Published methods of predicting in situ lateral stress from the dilatometer test are reviewed. A data base containing high-quality information from clay test bed sites mainly in Norway and the United Kingdom has been established. Reference K_o values have been evaluated from a number of methods including self-boring pressuremeter, hydraulic fracture, total stress cells, laboratory measurements, and empirical correlations. A new correlation between the dilatometer parameter K_D and K_o is proposed for young clays.

The in situ horizontal stress σ_h (or the lateral stress ratio K_o) is an important parameter that needs to be assessed for many geotechnical problems:

- Input in engineering analyses (e.g., skin friction of piles, pressures on walls, fracturing of dams);
- Selection of consolidation stresses for laboratory tests (e.g., triaxial test consolidated to in situ stresses);
- Evaluating borehole stability, designing mud program; and
- Input for interpretation of in situ tests [e.g., K_o required in several methods for computing strength from cone penetration tests (CPTs)].

Schmertmann (*1*) discussed those points in more detail and, in addition, these items: natural causes for K_o variation in the ground, how K_o can be measured in the laboratory and in the field, and sources of error when attempting to measure K_o.

After the standard penetration test (SPT), the CPT is probably the most widely used in situ test. Interpretation of the CPT in several cases requires that the in situ horizontal stress σ_h is known. Even though methods of finding σ_h from CPT results have been presented in the literature, including the incorporation of a lateral stress sensor in the friction sleeve, the ability at present to estimate reliable values of σ_h is still far from satisfactory (*2*).

One of the reasons that the authors advocate the use of the dilatometer test (DMT) is the potential of the test to yield a more reliable measurement of σ_h. The DMT is, therefore, an extremely valuable supplement to the CPT. However, the original Marchetti (*3*) correlation can, in some cases, be greatly in error and, therefore, need to be updated (*4–6*).

As part of a collaborative research program between the Norwegian Geotechnical Institute (NGI) and the Building Research Establishment (BRE) in Great Britain, a data base of high-quality information on in situ stresses, soil parameters, and in situ test results has been established. One of the main purposes of this work is to arrive at better methods for interpreting various in situ tests (*7*). This paper concentrates on the results of work to improve the correlations between the DMT test results and in situ horizontal stresses.

The DMT testing equipment and procedures are not described here, but reference is made to Marchetti (*3*) and Lutenegger (*8*).

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PREVIOUS CORRELATIONS

The original correlation between the DMT horizontal stress index K_D and the coefficient of earth pressure at rest K_o was given by Marchetti (*3*) (see Figure 1). The correlation

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

was based mainly on tests in Italian clays and is meant to be valid for uncemented clays with a $K_D > 0.3$.

This correlation appeared to work in some cases for soft and medium-to-stiff uncemented clays (*9*). In medium to heavily OC clays, the Marchetti (*3*) correlation can significantly overpredict and underpredict K_o, depending on soil type (*5,6*).

Lacasse and Lunne (*9*), on the basis of data in a wide range of clays, proposed a new correlation of the form

$$K_o = 0.34\ K_D^m$$

with m between 0.44 and 0.64 (Figure 2). A value of m = 0.44 is associated with highly plastic clays, and a value of m = 0.64 corresponds to low plasticity clays. Lacasse and Lunne stated that in soils with $K_D > 4$, more evaluated experience is needed but that the correlations given by Marchetti (*3*) and Lacasse and Lunne (*9*) could be used to obtain a range of K_o values.

Following a similar approach, Powell and Uglow (*6*) suggested that for "young" U.K. clays (i.e., less than 70,000 years old) the following correlation could be used:

$$K_o = 0.34\ K_D^{0.55}$$

For old U.K. clays (i.e., more than 60 million years) the experimental data fell considerably above the Marchetti correlations (see Figure 3) and tended to be more site specific.

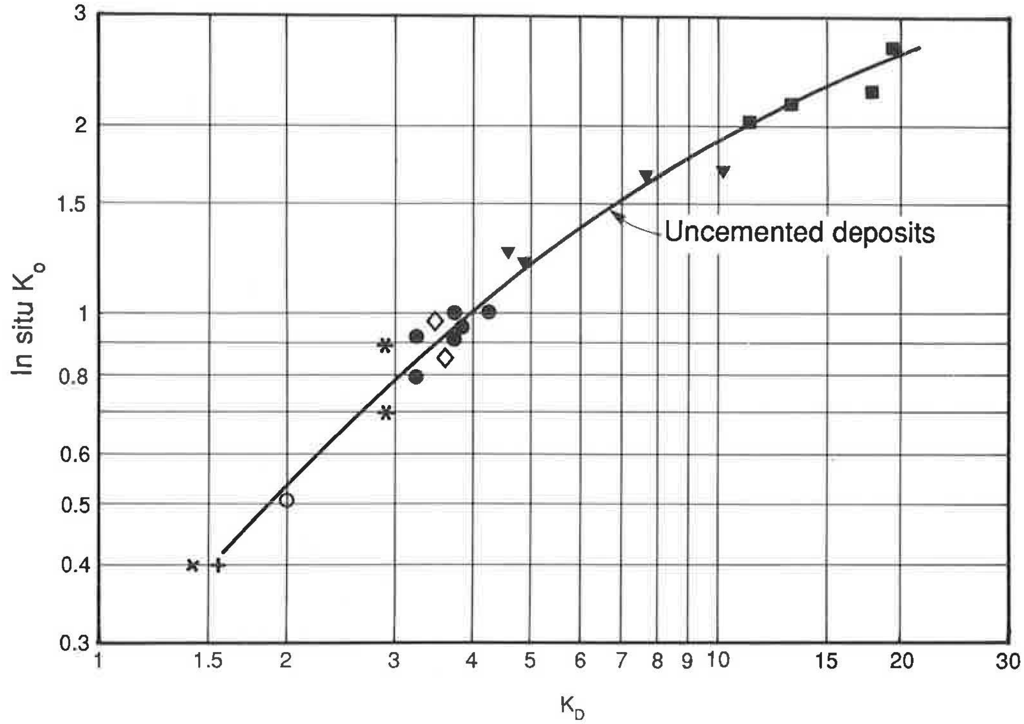

FIGURE 1 K_D **versus** K_o **after Marchetti (3).**

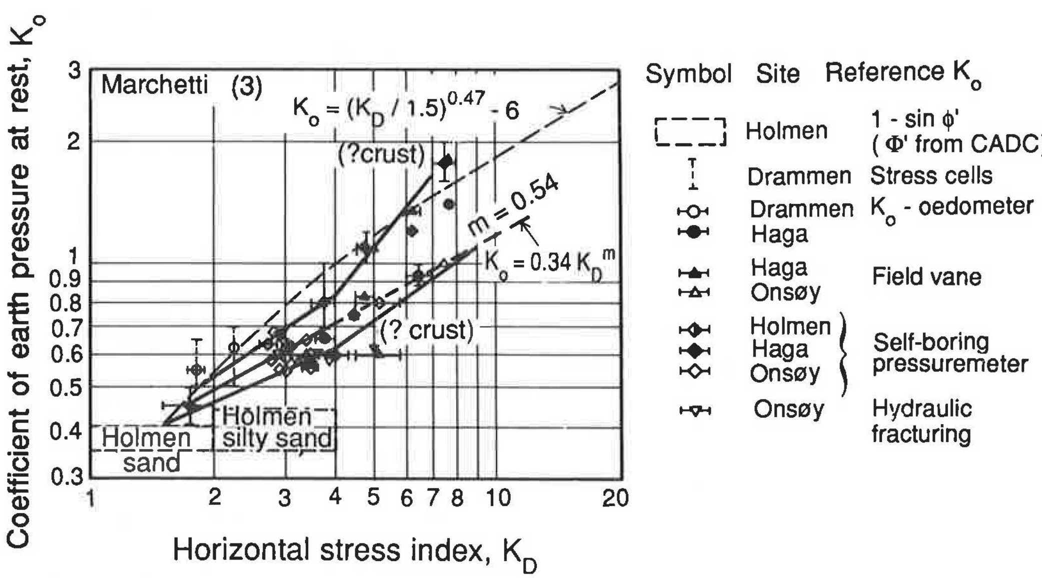

FIGURE 2 K_D **versus** K_o **after Lacasse and Lunne (4).**

Roque et al. (*10*) suggested the use of the "total horizontal effective stress" after DMT insertion to obtain a parameter, K_N:

$$K_N = \frac{(\sigma'_{h0} + \Delta\sigma'_h) + a}{\sigma'_{v0} + a}$$

where a is attraction as defined by Janbu and Senneset (*11*). The classical term cohesion (c) is related to the attraction by the expression $c = a \cdot \tan \phi'$. To obtain $\sigma'_{h0} + \Delta\sigma'_h$, it is necessary to take DMT readings with time until full dissipation of pore pressure has occurred. The in situ K_o value is then found by dividing K_N by an empirical factor. An example from the Glava clay in Norway is presented in Figure 4. Tests at other clay sites in the Trondheim area indicate that this empirical value may vary considerably from clay to clay (*10*). The necessity to wait for full dissipation, which can take several hours or days and thus becomes a costly operation par-

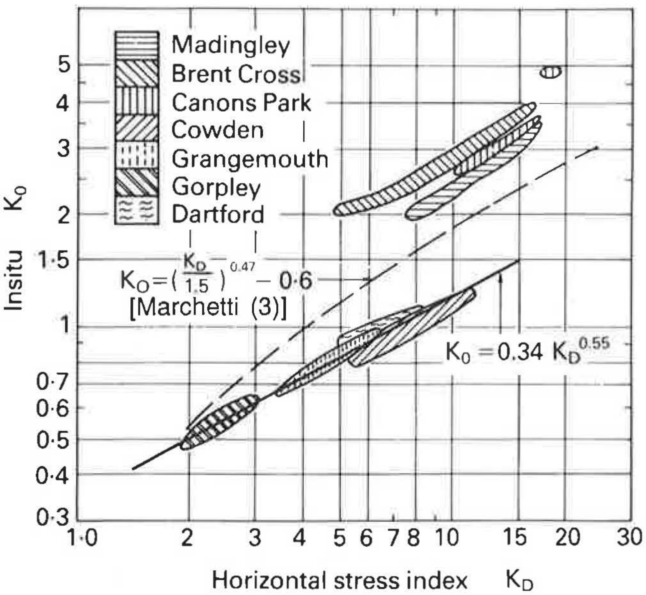

FIGURE 3 ***K_D* versus *K_o* after Powell and Uglow (*5,6*).**

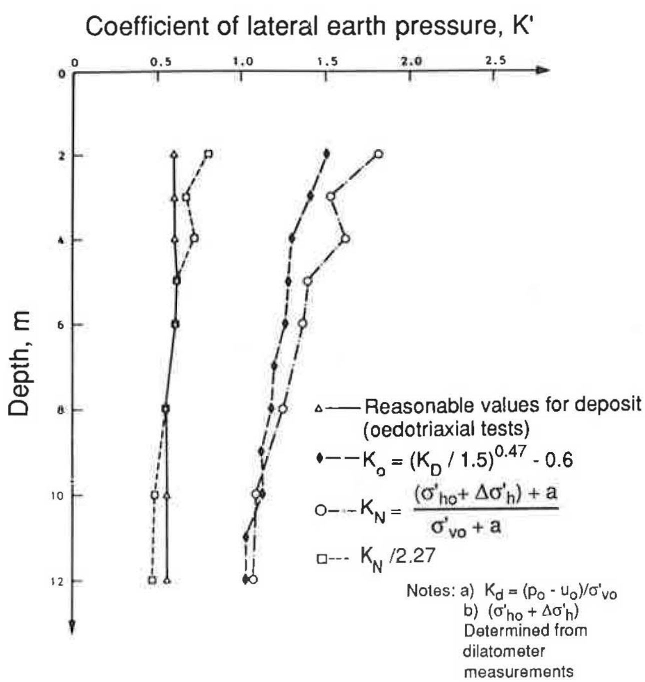

FIGURE 4 ***K* values from dilatometer and laboratory tests for Glava clay [after Roque et al. (*10*)].**

ticularly in offshore testing, is a further limitation of this approach.

Clarke and Wroth (*12*) compared results of high-quality self-boring pressuremeter tests (SBP) with DMT results and indicated that "A relationship between (p_1-p_0) and (p_1-σ_h) exists and appears to be independent of the soil type and stress level" (see Figure 5). Here, σ_h is the horizontal stress found from the SBP. This correlation may seem promising as a way of finding σ_h (and, hence, K_o) from DMT tests. However, Houlsby (*13*) rightly points out a problem with this

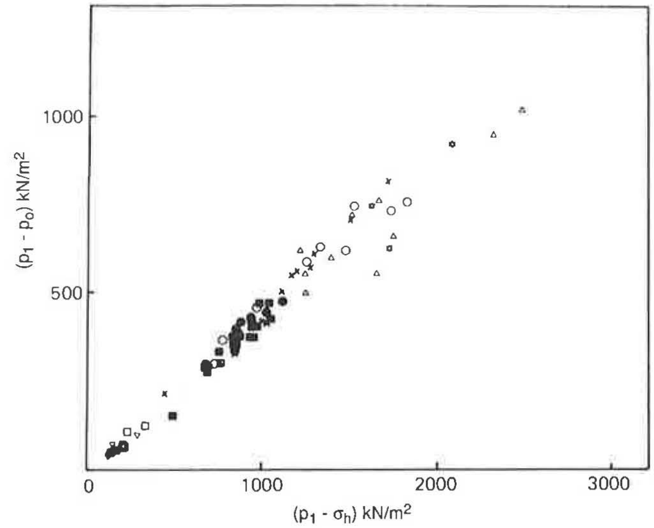

FIGURE 5 Relationship between ($p_1 - p_0$) and ($p_1 - \sigma_h$) [after Clarke and Wroth (*12*)].

correlation in that σ_h is a small quantity that has to be found as the difference between two large quantities.

ESTABLISHED DATA BASE

While the complete data base contains information from many sites, only four of NGI's test sites in Norway and five of BRE's United Kingdom test sites and the test bed site of University of California, Berkeley (Hamilton Air Force Base), are considered here.

The DMT tests were carried out with both the Marchetti standard DMT and NGI's offshore dilatometer (ODMT), which is somewhat smaller (see Figure 6) than the Marchetti because it was designed to pass inside an API drillstring (*14*). Extensive testing has indicated that the two DMTs give results that for most practical purposes are similar, as will be discussed later.

In what follows, only detailed results for one Norwegian soft clay site and one U.K. very stiff overconsolidated clay site will be shown. The method of selection of the parameters for the data base will then be discussed. For the other sites considered here, only reference data and the sources of more detailed information have been supplied.

NGI's Reference Clays in Norway

NGI's four sites presented here are Drammen, Onsøy, Haga, and Lierstranda. The Drammen and Onsøy test bed sites are among some of the most thoroughly investigated clays in the world and have been used as reference sites by NGI for 20 to 30 years.

All the four clay deposits were sedimented under marine conditions. The Haga clay is overconsolidated owing to excavation of soil, and the other three clays are only slightly overconsolidated, most likely caused by secondary compression. Plasticity indices of the clays mostly range from 15 to 40

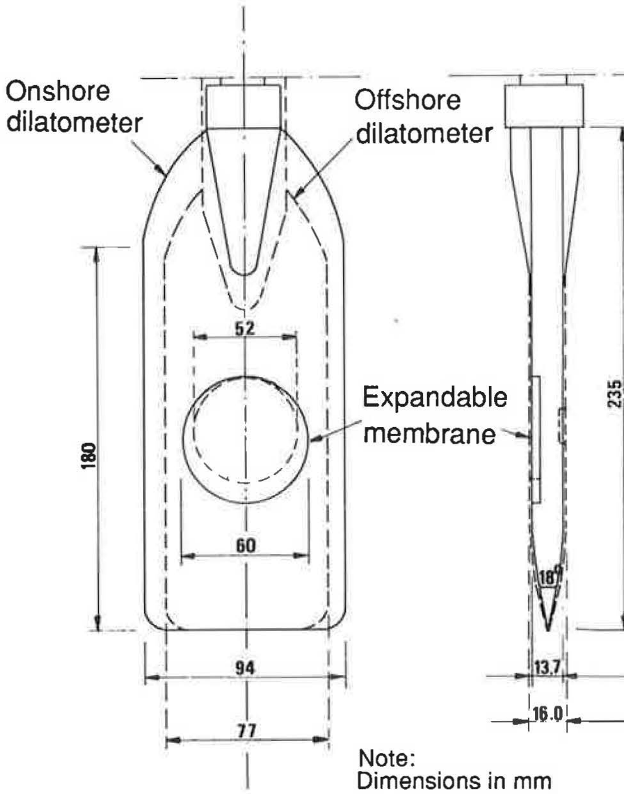

FIGURE 6 Comparison of Marchetti dilatometer and NGI's offshore dilatometer.

percent. [More information about these sites can be found elsewhere (*4,9,15*).]

As an example, Figure 7 presents the soil profile at Onsøy. The reference K_o values have been based on self-boring pressuremeter and hydraulic fracture tests (HFTs). Also presented in Figure 7 are K_o values derived from field vane test (FVT) results combined with CAU triaxial tests by using the method outlined by Aas et al. (*16*), and also laboratory correlations between OCR (from oedometer tests), plasticity index, and K_o [using Brooker and Ireland (*17*)]. Figure 8 gives dilatometer test results from both Marchetti and NGI's offshore DMTs. Here, p_0 and p_1 readings from the two devices are somewhat different at shallow depths, resulting in different Id values but that the DMT parameters K_D and E_D remain essentially similar.

Results from total stress cells and laboratory K_o oedometer tests were used for the Drammen site in addition to the SPB, HFT, and FVT to arrive at a best-estimate K_o profile. FVT, SBP, and laboratory correlations where used at the Haga site to establish the K_o profile. Results of FVT and laboratory correlations were used at Lierstranda.

BRE's Reference Clays in the United Kingdom

BRE's five sites presented here are Brent Cross, Canons Park, Madingley, Cowden, and Bothkennar. London clay, found at two of BRE's sites (Brent Cross and Canons Park), has been thoroughly investigated by BRE and others over the last 30 to 40 years. Cowden is a glacial till site and has been used by BRE for 15 years.

The Madingley site (Gault clay) has been used by Cambridge University for 15 years for several of their research programs on overconsolidated clay. BRE has had access to the site for 12 years and has carried out various in situ testing programs.

The Bothkennar clay in Grangemouth has recently been established in the United Kingdom as a national reference site on soft clay. BRE plays a central role in testing this site and has carried out in situ and laboratory programs.

The London clays (Brent Cross and Canons Park) and the Gault clay (Madingley) are very old clays (>60 million years) and are heavily overconsolidated.

The Cowden clay is a "young" (<70,000 years) consolidated glacial till, and the Bothkennar clay is a young lightly overconsolidated soft clay.

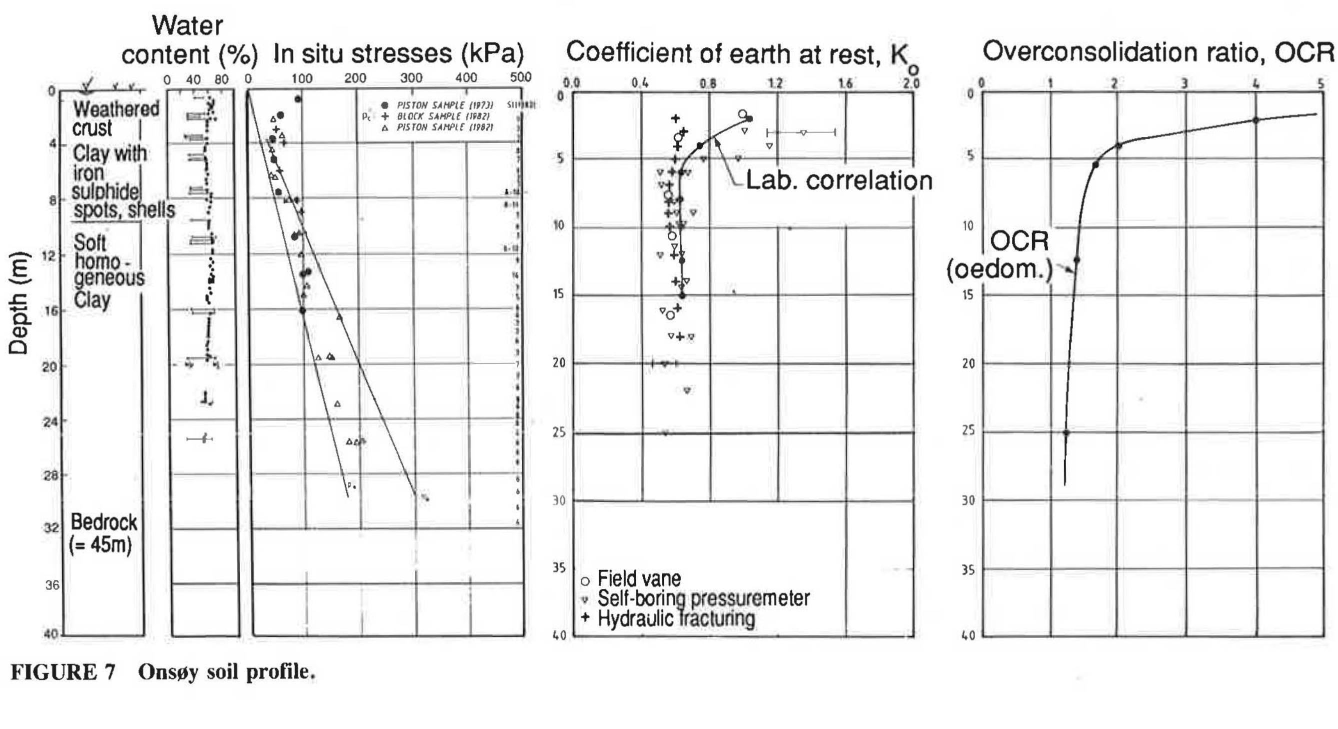

FIGURE 7 Onsøy soil profile.

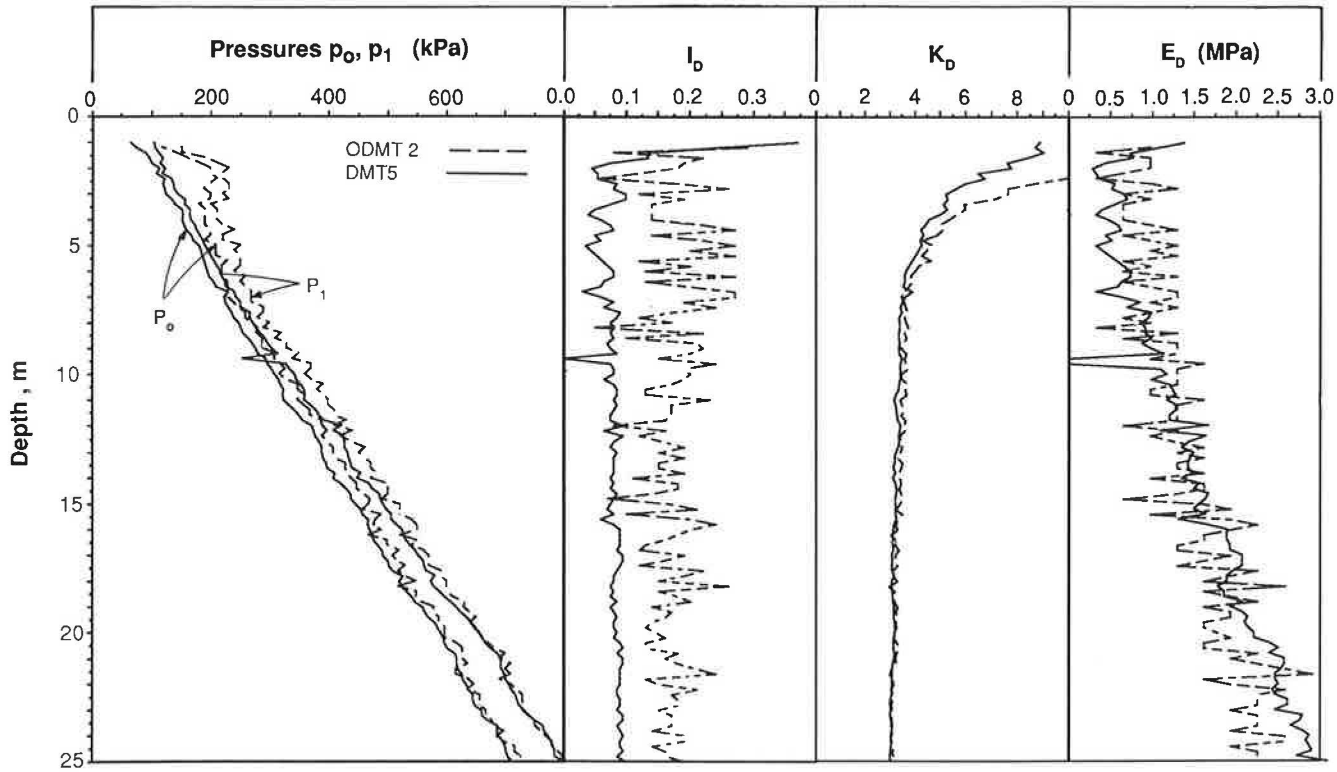

FIGURE 8 Dilatometer test results and Onsøy.

The plasticity index of those clays lies in the range 20 to 50 percent. [More information about these clays can be found elsewhere (*5,6–7*).]

As an example, Figure 9 gives the soil profile for Madingley. The K_o profile at Madingley is based on results of total stress cells and self-boring pressuremeter tests and oedometer tests by using empirical correlations (*17*). Figure 10 gives results from both Marchetti and NGI offshore dilatometers at this site. Excellent agreement between the results from the two devices can be seen.

At Cowden the K_o profiles were based on total stress cell measurements, laboratory suction tests, and laboratory correlations. At the other UK sites, pressuremeter tests, total stress cells, and laboratory correlations were used to establish K_o.

San Francisco Bay Mud

As part of a joint research program between the University of California, Berkeley (UCB) and NGI, a series of dilatometer tests were run at UCB's research site, Hamilton Air Force Base (*18*), near San Francisco.

The San Francisco Bay Mud is a marine-deposited soft clay with a plasticity index in the range 45 to 55 percent and is lightly overconsolidated. K_o values where based on self-boring pressuremeter tests, total stress cells, and laboratory correlations.

Criteria for Selecting Values for the Data Base

The soil profiles were divided into layers, and only uniform clay layers were included in the data base. Each layer was represented by one (or two, if a thick layer) point(s) normally in the middle of the layer (or equally spaced if two). The depths of those points are presented as reference depths in Table 1. The laboratory and in situ test results for each layer were then found at each reference depth.

The original data base also included a number of offshore sites. Those are not included here because of doubt as to the reliability of the values of σ_h.

All relevant data were put into a spread sheet system. Table 1 gives part of the data base. Generally, the data from the offshore dilatometer have been used. However, when results from this device were not available, the Marchetti DMT information was substituted. As was discussed, the parameters K_D and E_D, as determined from the two DMTs, are very similar.

ANALYSIS OF DATA AND NEW CORRELATIONS

In Figures 11–13, the data from the spread sheet have been plotted as K_o versus K_D on a double logarithmic scale that was originally used by Marchetti. In Figure 11, values of plasticity index I_p have been noted beside each point. Similarly, Figures 12 and 13 indicate values of DMT material index I_D and normalized shear strength s_u/σ'_{v0}, respectively, beside each point in the plots. For the U.K. clays, undrained shear strength (s_u) from UU tests have been used; and for the other sites, s_u has been determined by consolidated undrained triaxial tests (CIU or CAU). Marchetti's original correlation is also included in the figures.

The following observations can be made:

1. Marchetti's correlation appears to overpredict K_o for young clays and underpredict K_o for the very old U.K. clays (Brent

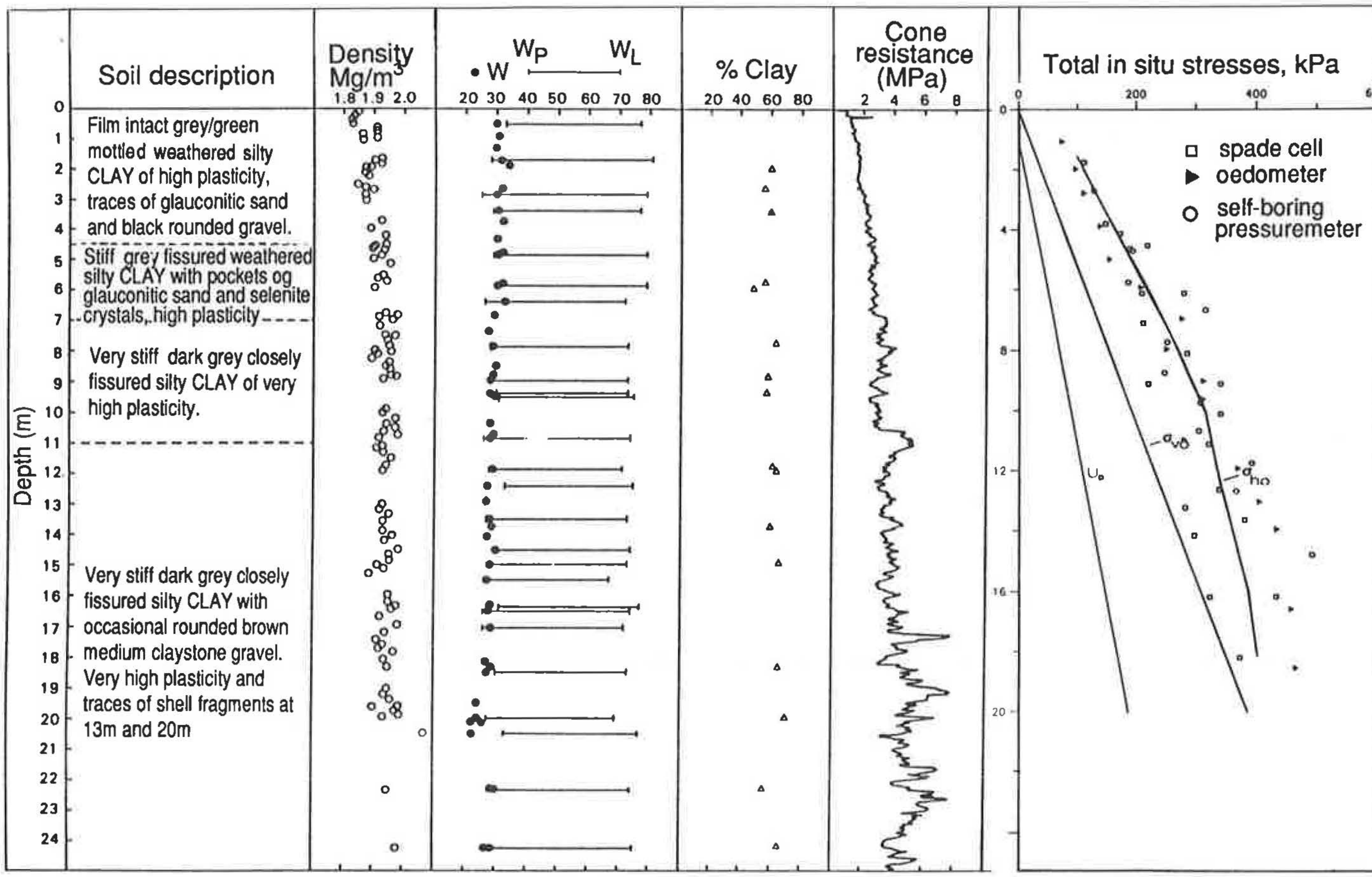

FIGURE 9 Madingley soil profile.

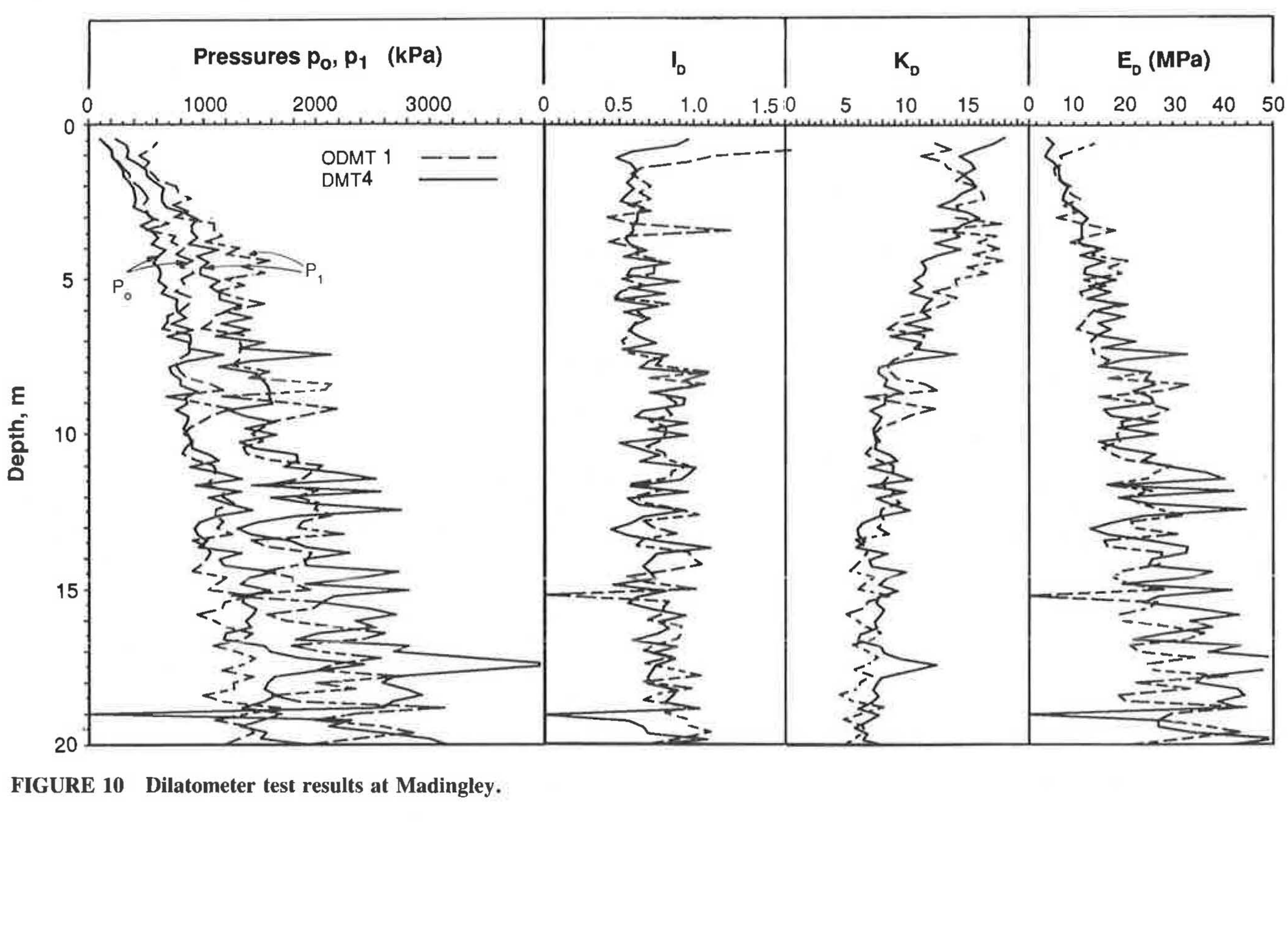

FIGURE 10 Dilatometer test results at Madingley.

TABLE 1 SUMMARY OF TEST SITES AND DILATOMETER TEST RESULTS

GENERAL				INDEX DATA					IN SITU STRESSES							DILATOMETER RESULTS						
TEST SITE	DEPTH INTERV. m	DEPTH REF. m	SOIL DESCRIPTION	wp %	Ip %	w %	Clay cont. %	Gamma kN/m³	U_o kPa	Sigma vert.eff. kPa	Sigma hor.eff. kPa	K_o	OCR	Su CAU kPa	St vane	Dilato-meter type	PO kPa	P1 kPa	ID	KD	ED MPa	REFER-ENCES
ONSOEY	4-5	5.0	CLAY, plastic clay	27	66	39	50	16.5	51	34	22	0.65	1.7	17.5	10	Offshore	201	223	0.15	4.41	0.68	4, 9
ONSOEY	5-15	7.0	CLAY, plastic clay	29	46	75	59	16.5	72	46	30	0.65	1.5	21.0	9	Offshore	228	255	0.17	3.39	0.83	
ONSOEY	15-20	16.0	Homogeneous, plastic clay	28	45	73	69	16.5	168	98	64	0.65	1.4	33.0	5	Offshore	476	525	0.16	3.14	1.51	
ONSOEY	20-40	24.0	Homogeneous, plastic clay	24	40	74	51	16.5	263	152	99	0.65	1.2	48.0	5	Offshore	667	740	0.18	2.66	2.26	
DRAMMEN	5-8	7.0	Plastic Drammen Clay	30	28	55	48	17.1	57	65	42	0.65	1.5	26.0	8	Offshore	255	275	0.10	3.05	0.62	4, 9
DRAMMEN	8-12	9.0	Plastic Drammen Clay	29	25	51	48	17.1	77	80	49	0.61	1.5	32.0	7	Offshore	305	329	0.11	2.85	0.74	
DRAMMEN	12.5-14	13.0	Lean Drammen Clay	23	17	34		19.1	116	113	62	0.55	1.2	38.4	5	Offshore	372	384	0.05	2.27	0.37	
DRAMMEN	14-16	15.0	Lean Drammen Clay	23	10	30		19.1	135	131	72	0.55	1.2	44.5	3.5	Offshore	411	421	0.04	2.11	0.31	
HAGA	1-2	1.5	Lean O.C. Clay	25	13	36	45	18.2	0	30	47	1.55	12.0	59.5	5	Onshore	241	333	0.38	8.03	2.84	15
HAGA	2-4	3.5	Lean O.C. Clay	27	16	40	50	18.0	0	70	69	0.98	4.5	63.0	4.5	Onshore	419	507	0.21	5.99	2.72	
HAGA	4-5	4.5	Plastic O.C. Clay	29	35	49	68	17.5	0	88	89	1.01	4.0	65.0	7	Onshore	547	699	0.28	6.22	4.70	
HAGA	5-6.5	6.0	Plastic O.C. Clay	25	17	36	45	18.4	0	118	85	0.72	2.2	65.5	4.5	Onshore	507	578	0.14	4.30	2.19	
HAGA	6.5-7.5	7.0	Plastic O.C. Clay	21	12	31	42	19.0	0	135	90	0.67	2.0	66.0	4	Onshore	520	584	0.12	3.85	1.98	
LIERSTR.	6-10	8.0	Plastic Drammen Clay	25	25	41	34	18.0	85	65	49	0.75	2.5	32.0	5.5	Offshore	345	383	0.15	4.00	1.17	Unpub-lished
LIERSTR.	10-15	12.5	Plastic Drammen Clay	24	25	42	34	18.1	140	93	60	0.65	1.8	35.0	4.5	Offshore	490	535	0.13	3.76	1.39	
LIERSTR.	15-25	20.0	Lean Drammen Clay	21	16	34	29	19.1	230	142	71	0.50	1.0	57.0	3.5	Offshore	648	672	0.06	2.94	0.74	
LIERSTR.	25-35	30.0	Lean Drammen Clay	20	12	27	20	19.1	341	220	99	0.45	1.0	85.0	3.5	Offshore	820	910	0.06	2.44	0.93	
BAY MUD	3-6	4.4	Soft, silty Clay	40	50	90	46	14.6	30	34	19	0.55	2.5	16.0	4	Offshore	131	177	0.46	2.97	1.42	18
BAY MUD	6-11	8.6	Soft, silty Clay	38	48	92	46	14.5	72	54	30	0.55	2.5	22.0	8	Offshore	198	240	0.33	2.33	1.30	
BAY MUD	11-16	13.4	Soft, silty Clay	39	48	94	46	14.4	119	77	54	0.70	1.2	32.0	6	Offshore	315	360	0.23	2.55	1.39	
BRENT	0-6	4.0	London weathered clay	26	54	30	54	19.1	26	50	182	3.64	> 60	66 [1]		Onshore	700	980	0.42	13.48	9.7	5, 6, 7
CROSS	6-9	8.0	London weathered clay	27	54	29	58	19.0	60	93	280	3.01	50	92 [1]		Onshore	930	1310	0.44	9.35	13.1	
	9-16	13.0	London unweathered clay	28	50	28	57	19.5	106	144	349	2.42	30	118 [1]		Onshore	1000	1640	0.72	6.21	22.1	
		16.0		28	45	27	60	19.5	133	175	393	2.25	25	136 [1]		Onshore	1250	1950	0.63	6.38	24.2	
COWDEN	0-5	3.0	Weathered Glacial till	21	20	18	30	21.4	20	44	130	2.95	11.5	141 [1]		Offshore	1138	3850	0.64	25.41	22.0	5, 6, 7
	5-10	7.0	Weathered Glacial till						30	55	80	1.45	6.5			Offshore	787	1110	0.44	7.30	10.0	
	10-12	11.0	Unweathered Glacial till	18	17	17	32	21.8	50	101	95	0.94	5	85 [1]		Offshore						
BOTHKENNAR	0-3	3.0	Soft black silty clay	27	35	58	36	16.0	25	23	20	0.87	1.6	17 [1]		Onshore	148	196	0.39	5.35	1.7	5, 6
	3-6	6.0		29	39	64	32	15.5	50	45	25	0.56	1.3	25 [1]		Onshore	222	274	0.30	3.82	1.8	
	6-9	9.0	Soft dark grey micaceous	31	44	68	26	15.2	80	60	35	0.58	1.3	34 [1]		Onshore	296	363	0.31	3.60	2.3	
	9-12	12.0	clay with thin silt	32	38	64	20	15.7	110	77	50	0.65	1.2			Onshore	385	474	0.32	3.57	3.1	
	12-15	15.0	laminations, more silty	32	41	54	28	16.2	140	96	60	0.63	1.2	53 [1]		Onshore	460	570	0.34	3.33	3.8	
			with depth																			
MADINGLEY	0-4	3.0	Firm intact silty clay	30	50	30	60	18.5	20	35	108	3.09	> 50	105 [1]		Offshore	550	900	0.66	15.14	10.8	5, 6, 7
	4-7	5.0	Stiff grey fissured clay	29	49	31	59	18.8	37	56	135	2.41	40	152 [1]		Offshore	780	1200	0.57	13.27	13.0	
	7-11	9.0	Very stiff fissured clay	29	44	30	61	19.0	72	96	188	1.96	25	130 [1]		Offshore	900	1500	0.72	8.63	18.5	
	11-20	15.0	Very stiff fissured silty	29	43	29	62	19.0	124	139	276	1.99	18	208 [1]		Offshore	1000	1700	0.80	6.30	21.6	
		20.0	clay. Very high plasticity.	28	43	28	65	19.1	168	191				220 [1]		Offshore	1600	2600	0.70	7.50	30.9	
CANONS	0-2	1.0	Gravel in a clay matrix					19.2		19												
PARK	2-4	3.0	Firm silty fissured clay	30	46	27	43	19.4	20	38	163	4.29		72 [1]		Offshore	500	723	0.67	12.63	10.0	5, 6
	4-7	6.0	Stiff silty fissured clay	28	40	28	42	19.6	43	73	287	3.93		115 [1]		Offshore	1234	1575	0.56	16.32	20.6	
	7-10	9.0	Blue London clay	28	44	29		19.6	66	109	274	2.51		120 [1]		Offshore	1128	1617	0.68	9.74	22.3	

[1] UU tests

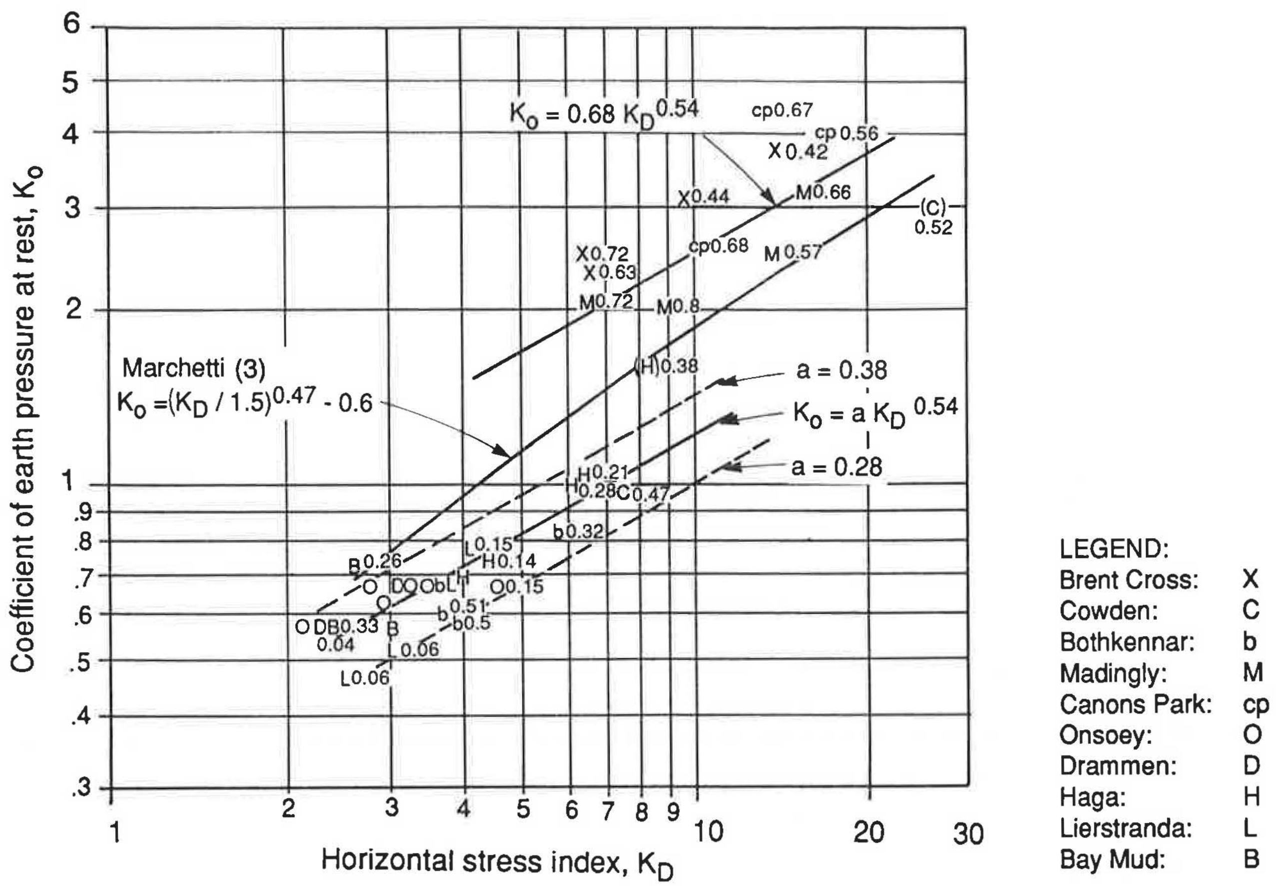

FIGURE 11 K_D **versus** K_o **with values of** I_p.

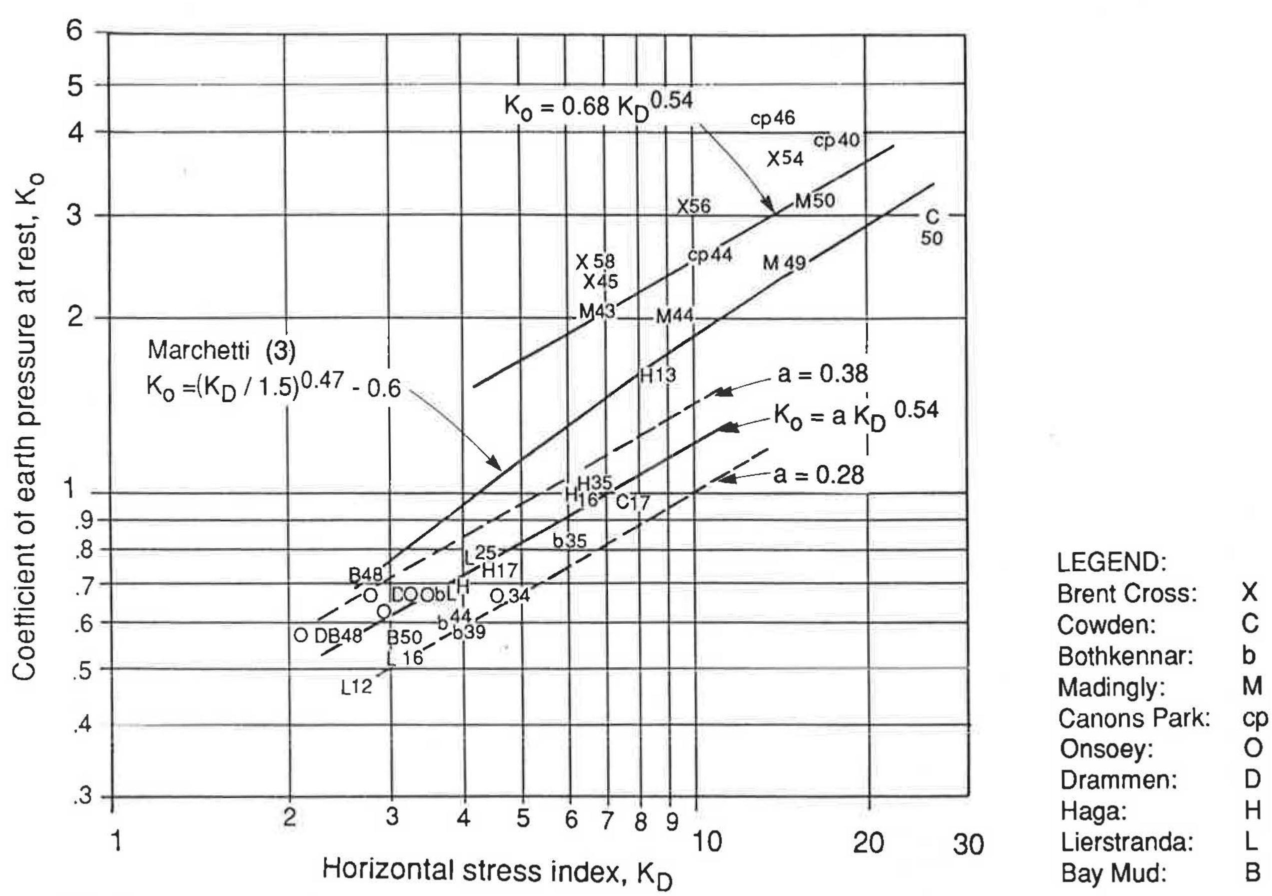

FIGURE 12 K_D **versus** K_o **with values of** I_D.

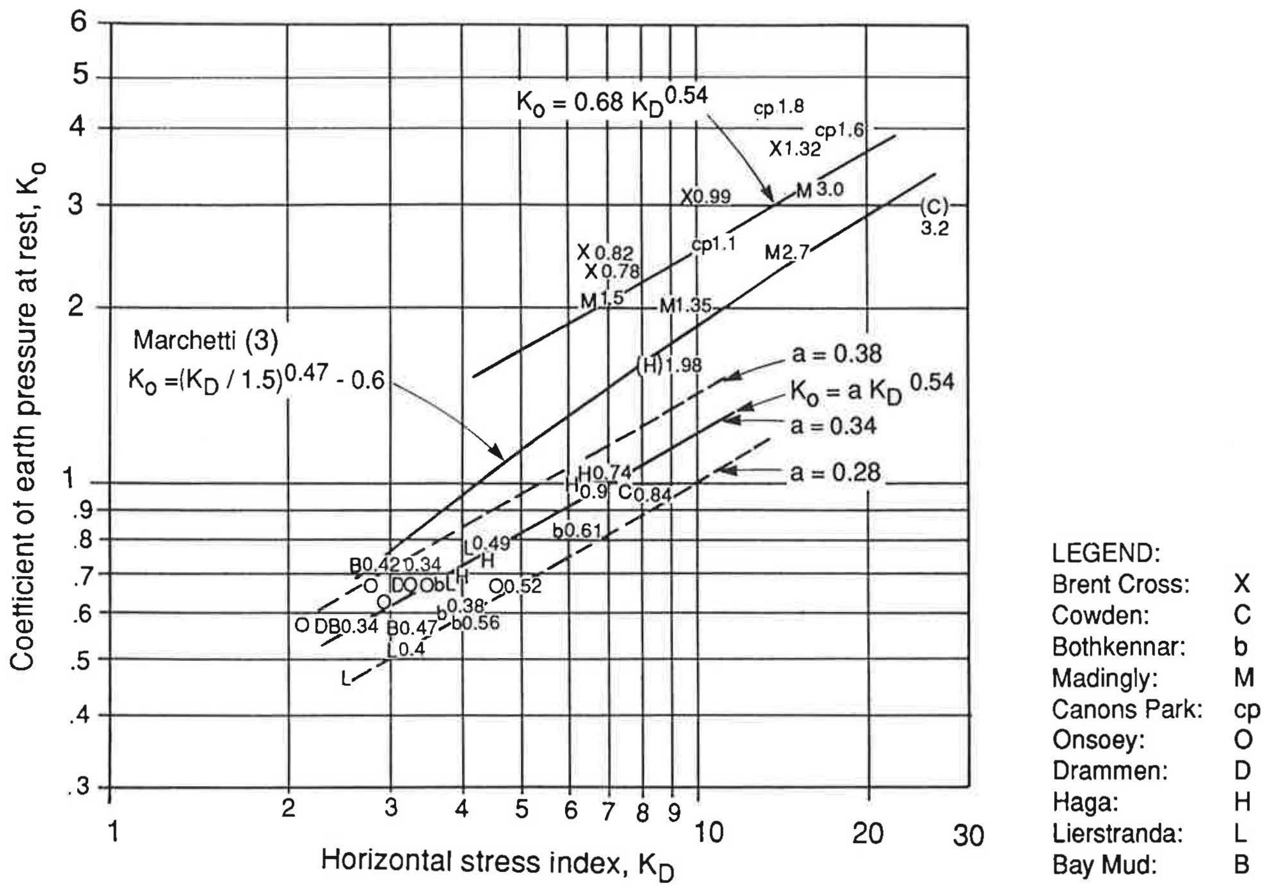

FIGURE 13 K_D **versus** K_o **with values of** s_u/σ'_{v0}.

Cross, Madingley, and Canons Park). This confirms the finding of Powell and Uglow (*6*).

2. Young clays fall within a relatively narrow band, which can be expressed as

$$K_o = a \cdot K_D^{0.54}$$

where a on the average is 0.34, but it varies between 0.38 and 0.28.

3. Referring to Figures 11 and 12 and the band for the "young" clays, there does not appear to be any systematic trend with I_p or I_D, and neither is it possible to differentiate between the "old" and the "young" clays on the basis of those two parameters.

4. Although not completely conclusive, Figure 13 indicates that s_u/σ'_{v0} may be used to separate the old from the young clays. Here, the way of measuring s_u is very important (test method and sample size, particularly in the older fissured clays).

5. Referring to Figure 13, on average, K_o for the "old" clays is related to K_D as $K_o = 0.68 \cdot K_D^{0.54}$ with a wide scatter band. However, for any one site and clay layer a site-specific correlation would appear to exist.

Figure 14 plots p_1-p_0 versus p_1-σ_h as proposed by Clarke and Wroth (*12*). The figure also includes the correlation found by Clarke and Wroth. Especially for low values of p_1-p_0, there is too much scatter for this approach to be useful, and, furthermore, it falls away from the original correlation line (*12*).

On the basis of this, what follows is recommended:

1. Use s_u/σ'_{v0} or general geological evidence to group the clay as "old" or "young." Young clays generally have $s_u/\sigma'_{v0} < 0.7$ and old clays generally > 0.7.

2. If the clay is young, then use the correlation $K_o = 0.34 \cdot K_D^{0.54}$. The uncertainty associated with this correlation is unlikely to exceed ±20 percent.

3. For old clays, either use has to be made of existing experience on that soil type to establish a correlation or, if some information on K_o and OCR is known for the site (1 or 2 values), then those should be plotted against K_D on Figure 13 and a new correlation drawn through them parallel to the $K_D = 0.68 \cdot K_D^{0.54}$ line.

Most clays are "young" clays.

Obviously, the new correlations do not fit with Marchetti's data. One likely explanation is that Marchetti (*3*) determined K_o based on OCR from laboratory oedometer tests and then used the empirical correlation of Brooker and Ireland (*17*). Thus, the K_o values may not be representative of the in situ condition.

The new data, for a wide range of clays from different parts of the world, are all based on direct in situ measurements by using self-boring pressuremeter, hydraulic fracture, total stress cells, and other relevant tests. There are also uncertainties

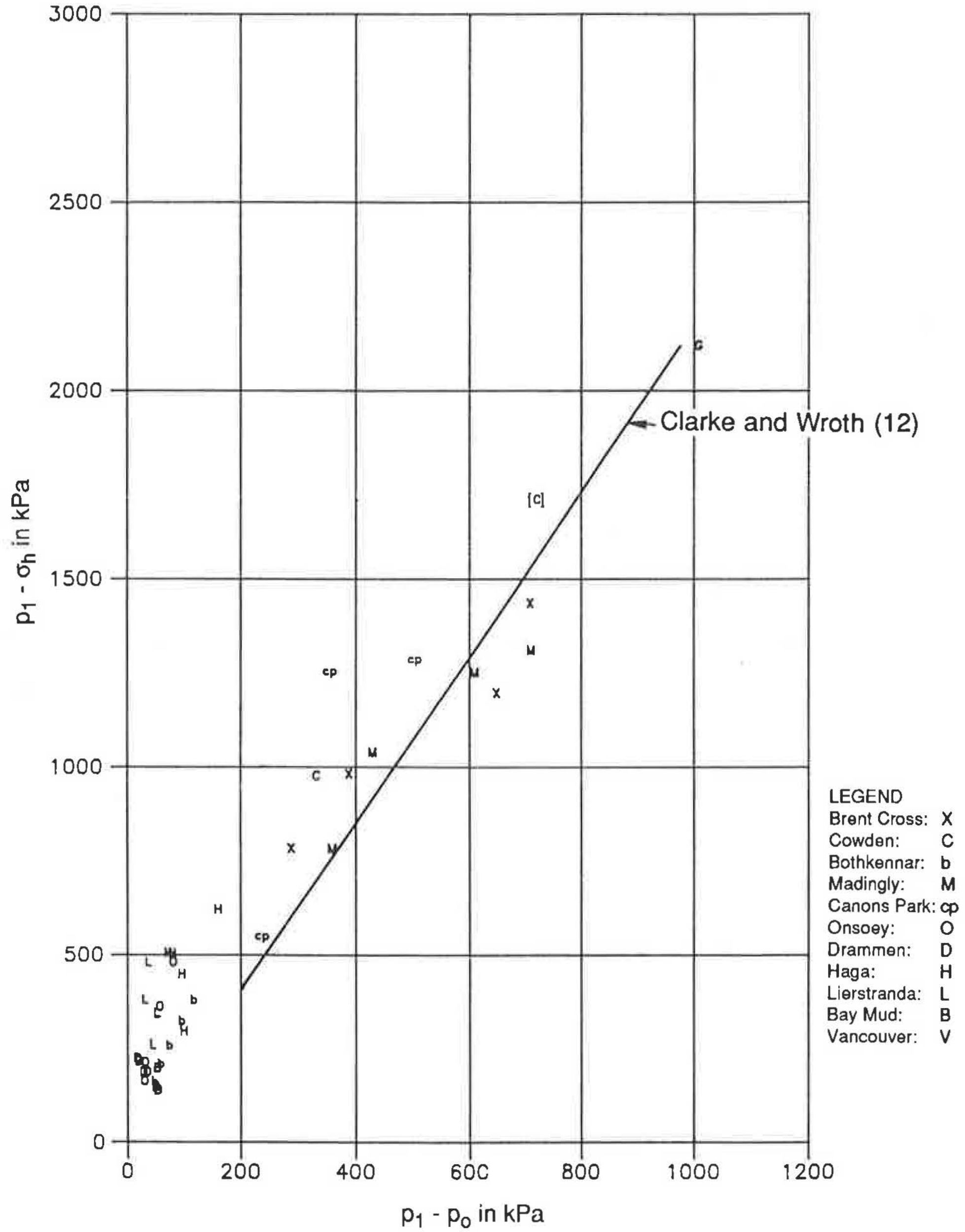

FIGURE 14 $p_1 - p_0$ **versus** $p_1 - \sigma_{h0}$.

associated with those values but much less so than those determined from empirical correlations.

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