d11. The in situ determination of an "extended" over-consolidation ratio

Sur la détermination in situ du rapport de surconsolidation "apparente"

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A method is presented for obtaining information on the profile of OCR with depth based on the K_D values determined in situ by flat dilatometer. It is shown that, for the uncemented, simply unloaded deposits ("normal" deposits) investigated, a well defined correlation exists between OCR and K_D ("normal" OCR vs K_D correlation). In the "abnormal" deposits (deposits in which the horizontal stresses are in excess of those corresponding to simple unloading and/or in which cementation/attraction effects exist) investigated, the K_D values have been found to be higher than those found in "normal" deposits subjected to the same geological OCR. These higher K_D values, entered into the "normal" OCR vs K_D correlation, supply "extended" OCR values (EOCR) that are higher than the geological OCR. Evidence is presented which suggests that EOCR: (1) increases both with the "free" horizontal stresses and with the "attraction" stresses; (2) monitors soil behavioural characteristics which have significant influence on its engineering behaviour and which, in "abnormal" deposits, are not reflected by OCR; (3) bears a definite correlation with several frequently used geotechnical parameters.

INTRODUCTION

The overconsolidation ratio OCR (ratio of the maximum past pressure σ'_{vm} to the vertical geostatic stress σ'_v) does not enter directly in normal engineering computations. However its value significantly affects most soil engineering properties (see, e.g., Figs. 18, 20, 26, 27, 28, 31 of Ladd et al, 1977). Therefore information on OCR is essential for selecting proper soil parameters for design purposes. A method is presented in the paper for obtaining information on the OCR profile with depth based on the values of the "horizontal stress index" K_D determined in situ by flat dilatometer (Marchetti, 1978). For reasons which will be discussed in the paper, separate consideration will be given to "normal" and to "abnormal" deposits, defined as follows:

"Normal" deposits: deposits in which the horizontal stresses between soil particles are those corresponding to simple one-dimensional unloading ("normal" horizontal stresses).

"Abnormal" deposits: deposits in which the horizontal stresses between soil particles, including the attraction stresses, are in excess (positive or negative) of the "normal" horizontal stresses.

In the "normal" deposits investigated a well defined correlation has been found to exist between OCR and K_D ("normal" OCR vs K_D correlation). In the "abnormal" deposits investigated the K_D values have been found to be higher than those found in "normal" deposits subjected to the same geological OCR. These higher K_D values, entered in the "normal" OCR vs K_D correlation, supply "extended" OCR values (EOCR) higher than the geological OCR. The significance of EOCR and its use as a correlation parameter with soil engineering properties will be examined in some detail.

The present paper is concerned primarily with clay deposits. When results referring to sands are presented, this will be pointed out specifically.

DESCRIPTION OF THE IN SITU TESTS

The "horizontal stress index" K_D from which EOCR is calculated, is determined in situ by the flat dilatometer. A detailed description of the instrument and comments on the correlations between test results and some geotechnical parameters are presented elsewhere (Marchetti, 1978). A brief summary will be included herein. The flat dilatometer (Fig.1) consists of a stainless steel blade carrying on one side a thin flat circular expandable steel membrane, 60 mm in diameter. When at rest the external surface of the membrane is flush with the surrounding flat surface of the blade. The blade is jacked into the ground at 20 cm depth intervals and the membrane is inflated by means of pressurized gas. Readings are taken of p_o, the pressure at which the membrane starts to expand against the soil, and p_1, the pressure at which the membrane centre deflection reaches 1.00 mm. Field readings are reducted into the "material index" I_D, the "horizontal stress index" K_D and the "dilatometer modulus" E_D through the following equations:

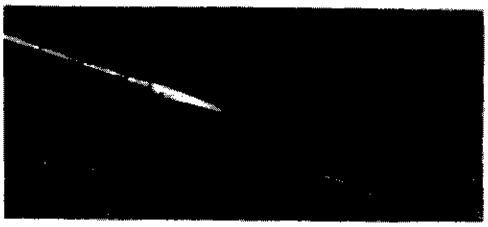


Fig.1 Flat dilatometer.

$$I_D = (p_1-p_0)/(p_0-u_0) \tag{1a}$$

$$K_D = (p_0-u_0)/\sigma'_v \tag{1b}$$

$$E_D = 38.2\ (p_1-p_0) \tag{1c}$$

where u_0 and σ'_v are,respectively,the pore water pressure and the vertical effective geostatic stress prior to the blade insertion at the depth concerned,and have to be known,at least approximately.E_D is the value of $E/(1-\mu^2)$ of the medium surrounding the blade,worked out through the theory of elasticity by (p_1-p_0),by assuming that,during the membrane expansion,the medium behaves as linearly elastic (E=Young's modulus,μ=Poisson's ratio).The numerical value 38.2 is valid for the specified diameter and deflection of the membrane.

Based on dilatometer tests performed in over 30 sites,many of which geotechnically well documented,empirical correlations have been set up betwen the three parameters I_D,K_D,E_D determined by flat dilatometer and some geotechnical parameters. The origin,the significance and the limits of these correlations are commented upon in detail elsewhere (Marchetti,1978).Therefore the correlations are reproduced in Figs.2,3,4,5 and Table I without comments.The correlations are mentioned and discussed in the paper when they become relevant.

Table I Proposed soil classification based on the I_D value.

	CLAY		SILT			SAND	
		SILTY	CLAYEY		SANDY	SILTY	
I_D VALUES	.35	.6	.9	1.2	1.8	3.3	

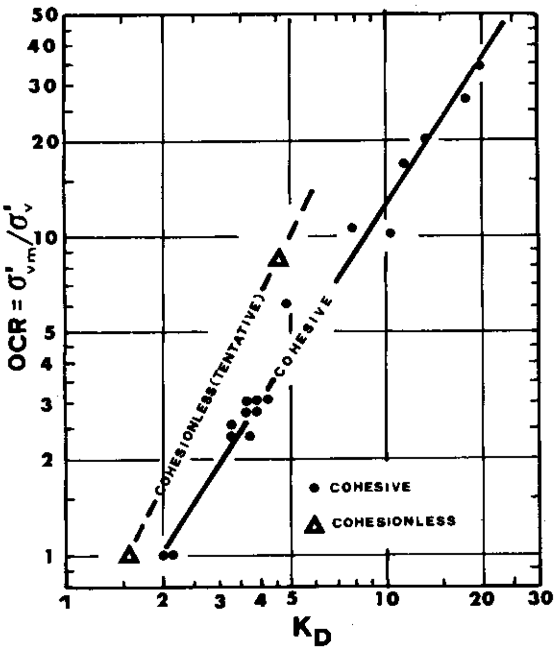


Fig.2 Correlation between OCR and K_D in "normal" deposits.

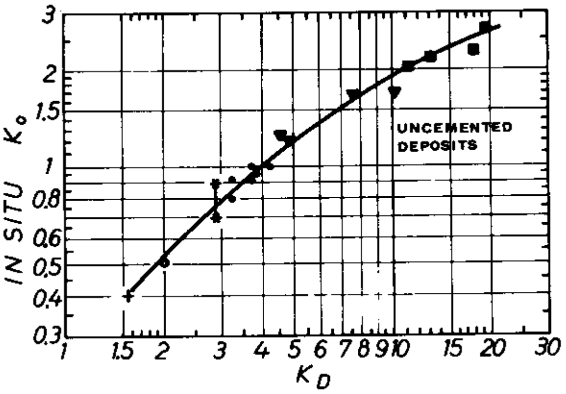


Fig.3 Correlation between K_o and K_D in uncemented deposits.

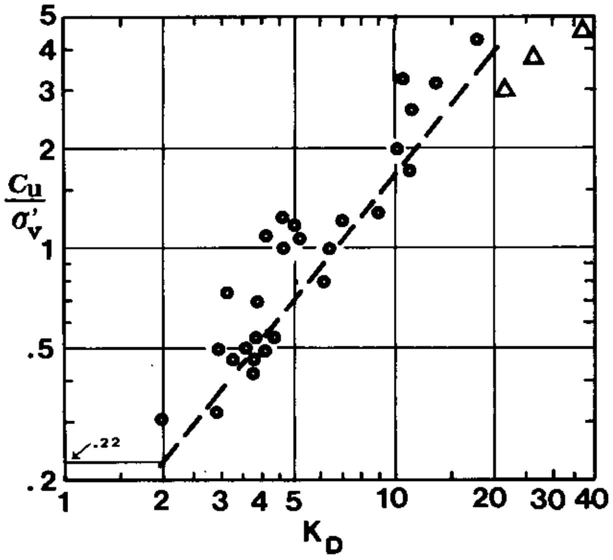


Fig.4 Correlation between the ratio c_u/σ'_v and K_D (cohesive soils , "normal" and "abnormal").

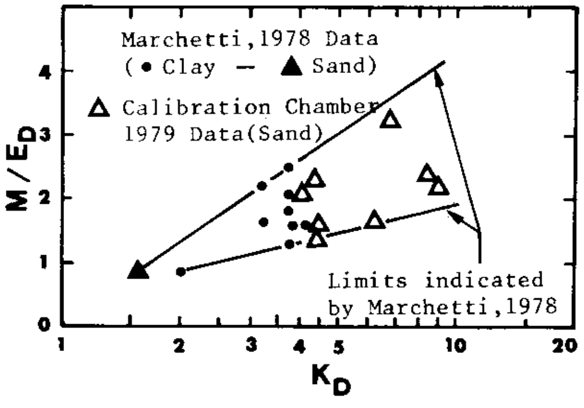


Fig.5 Correlation between the ratio M/E_D and K_D ("normal" and "abnormal" cohesive and cohesionless deposits).
NOTE: M=vertical drained constrained modulus ($=1/m_v$) corresponding to σ'_v.

OCR EVALUATION IN "NORMAL" DEPOSITS

Fig.2 displays data points of coordinates OCR (evaluated by oedometer tests) and K_D (determined by flat dilatometer tests).The data points (circles) refer to:

two"young" normally consolidated clays (in which $p_c \cong \sigma'_v$, p_c being the oedometer-determined critical pressure and σ'_v the vertical effective geostatic stress)

three overconsolidated simply unloaded uncemented clays.The absence of substantial cementation effects and the state of simple unloading in these deposits were inferred from the nearly constant value with the depth of the difference $(p_c - \sigma'_v)$ and by the geological history (see the relevant References in the Bibliography of Marchetti,1978).

All five deposits are "normal" according to the definition stated previously.It is seen that, for the "normal" sites investigated,a well defined correlation exists between the geological OCR and K_D.The equation of the continous line interpolated through the data points ("normal" OCR vs K_D correlation) is

$$OCR = (0.5\ K_D)^{1.56} \qquad (2)$$

An implication of the unique relation between OCR and K_D expressed by Eq.2 is the similarity,in "normal" deposits,of the K_D and of the OCR profiles with depth.This similarity is observed indeed in the "normal" K_D profiles shown in Fig.6,that are commented upon hereunder.

Fig.6(a) and 6(b): These K_D profiles refer to the normally consolidated young deltaic clays at Porto Tolle and Fiumicino(Italy).OCR has the value one,constant with depth.K_D is also constant with depth,its value being approximately 2 for both deposits.In general the K_D values in young NC cohesive deposits range from 1.8 to 2.3,with a round average of 2.It may be noted that the K_D values in the desiccated crusts are considerably greater than 2.

Fig.6(c): This K_D profile refers to the NC underwater-deposited loose sands at Torre Oglio.OCR has the value 1,constant with depth.K_D is also constant with depth (if local scatter is ignored). Its average value is approximately 1.5.Similar K_D values have been found in other NC loose submerged sands.It may be noted that $(K_D)_{NC,SAND} < (K_D)_{NC,CLAY}$.

Fig.6(d),6(e),6(f): In these simply unloaded deposits (Montalto,Sciacca,Numana respectively) K_D exhibits a typical shape decreasing with depth. The higher the magnitude of the eroded overburden q,the more distant is the profile from the vertical line K_D=2.

The "normal" K_D profiles of Fig.6 relative to cohesive deposits have been replotted in Fig.7, suppressing local scatter.The vertical axis displays σ'_v rather than the depth.Fig.7 can provide guidance for evaluating the magnitude of the removed overburden q in "normal" deposits similar to the investigated ones for which the K_D profile with depth has been determined.The similarity between the "normal" K_D profiles and the OCR profiles (OCR can be calculated as: $1+q/\sigma'_v$) is apparent.

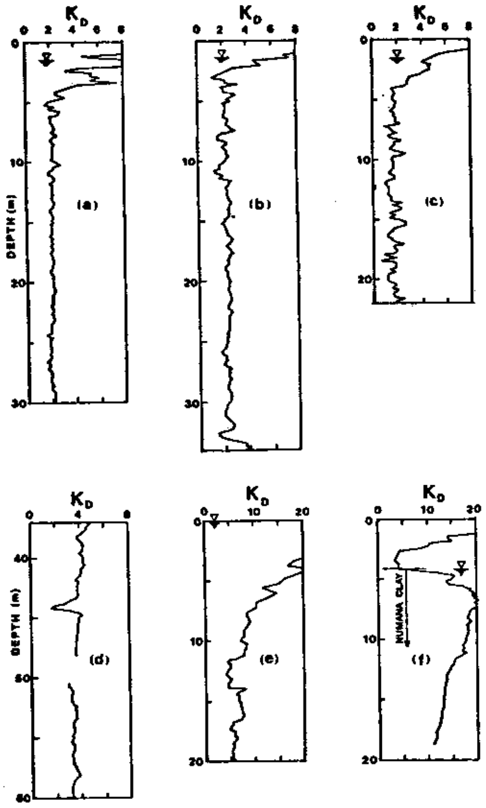


Fig.6 "Normal" profiles of K_D
(a),(b) : NC uncemented cohesive deposits.
(c) : NC uncemented underwater deposited loose sand.
(d),(e),(f) : Simply unloaded uncemented cohesive deposits.

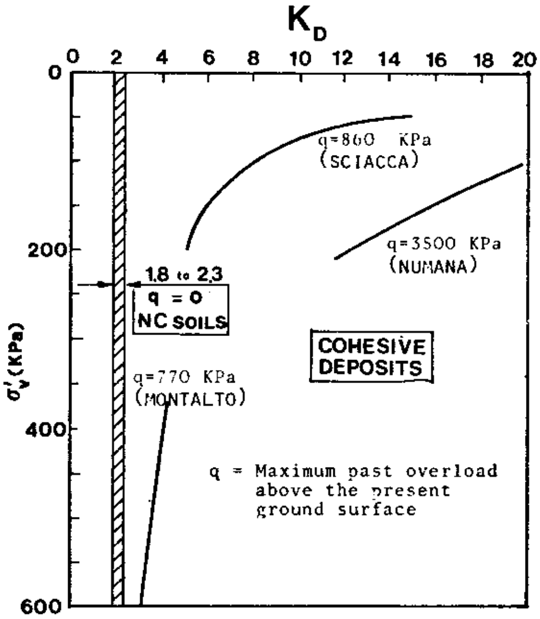


Fig.7 Idealized "normal" profiles of K_D vs geostatic effective vertical stress.

Another implication of the unique relation OCR vs K_D expressed by Eq. 2 is that, in "normal" deposits, K_D should be as effective as OCR as a correlation parameter with geotechnical soil properties. This appears broadly supported by the fact that K_D plays a dominant role in the experimental correlations displayed in the previous section.

DETERMINATION AND SIGNIFICANCE OF EOCR IN "ABNORMAL" DEPOSITS

In "abnormal" deposits (see definition in the introduction) the horizontal stresses may be "abnormal" for a variety of reasons, some of which are listed hereunder:

(a) Tectonic activity
(b) Loading cycles after the first unloading
(c) Conditions other than one dimensional during loading or unloading
(d) Attraction between soil particles, due to various kinds of cementation processes (aging, thixotropic hardening, electro-chemical phenomena etc.)

In the (d) deposits (for brevity referred to collectively in this paper as "cemented" deposits) the horizontal stresses between soil particles can be regarded as the sum of the "attraction" stresses and of the "free" horizontal stresses. In cemented deposits the global horizontal stresses are different (except in fortuitous cases) from those corresponding to simple unloading in a deposit of similar characteristics but lacking the "attraction" term. In practice all the cemented deposits are "abnormal".

In general the K_D values determined in "abnormal" deposits have been found to be higher than those found in "normal" deposits subjected to the same geological OCR. These higher values, entered in the "normal" OCR vs K_D correlation (Eq.2) supply "extended" OCR values (EOCR) higher than the geological OCR. In "abnormal" deposits EOCR is then defined as the value given by

$$EOCR = (0.5\ K_D)^{1.56} \qquad (3)$$

Note that, because of this definition, EOCR and K_D are interchangeable parameters: whatever statement is made in terms of EOCR, it can be also made in terms of K_D and vice-versa. Several profiles of K_D vs depth relative to "abnormal" deposits are now illustrated.

Site Conca del Fucino (Central Italy)

Soil type: lacustrine normally consolidated aged silty clay; c_u/σ'_v measured by field vane is ≈ 0.5. This site is "abnormal" for the reason (d). Dilatometer test results are shown in Fig.8. It is seen that K_D is nearly constant with depth, being $K_D \approx 2.9$ throughout. Eq.3 supplies EOCR ≈ 1.9, which is a value considerably higher than the geological OCR(=1). It may be of interest to note that the ratio $c_u/\sigma'_v = 0.5$ entered in Bjerrum's (1973) Fig.2, supplies OCR ≈ 1.8. Note also that the K_D profile at this site is incompatible with the "normal" K_D profiles displayed in Fig.7.

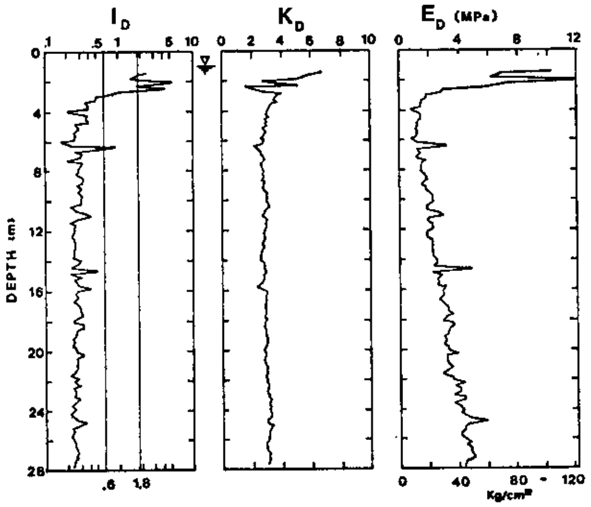
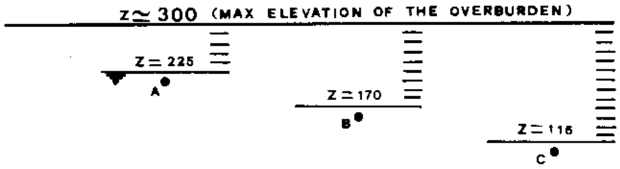


Fig.8 Dilatometer test results at Conca del Fucino.



	Point A	Point B	Point C
x(m)	26600	26420	26050
y(m)	9200	10050	10400
z(m a.s.l.)	215	160	106
σ'_v(KPa)	80	170	170
σ'_{vm}(KPa)	1230	1650	2050
OCR	15.4	9.7	12.1
K_D	37.6	21.8	26.5
EOCR	97	42	56
K_D(OCR)	11.5	8.6	9.9
c_u/σ'_v	4.8	3.0	3.8

Fig.9 Soil data and dilatometer test results at Santa Barbara.

Site Santa Barbara (Arezzo)

Soil type: heavily OC stiff fissured pliocenic lastrine clay. The clay has a very marked structure (Esu and Calabresi, 1969). An abrupt collapse is observed in the oedometer samples at the critical pressure p_c. The critical pressure is somewhat in excess of the maximum past pressure σ'_{vm} (which is fairly well known from the geological history of the Valdarno basin). Esu and Calabresi suggest that this excess may be due to delayed consolidation. This hypothesis appears supported by the relative high value of the ratio $c_u/\sigma'_{vm} = 0.31$ (average figure). Esu and Calabresi also produce evidence suggesting the existence of "high" horizontal stresses. According to the above information the deposit is markedly "abnormal".

The exploitation of the coal seam underlying the lacustrine clay has required a deep excavation. Dilatometer tests were performed starting from benches at different elevations (Fig.9), in locations chosen in the central part of each bench. Full dilatometer test results are not displayed here. It is only mentioned that, after the first 2 to 4 m, the field readings p_o and p_1 are very stable with depth.

The Table in Fig.9 refers to points A,B and C and provides,besides other information:the determined K_D,the EOCR worked out from K_D through Eq. 3,$K_{D,OCR}$ = the K_D expected based on the geological OCR and on the assumption that the deposit was "normal",i.e. worked out from OCR through Eq.2.The values of K_D determined in situ are ~3 times higher than those calculated based on the assumption the deposit was "normal".EOCR is ~5 times higher than the geological OCR.The values of σ'_v,K_D,q ($=\sigma'_{vm}-\sigma'_v$) relative to A,B and C are definitely incompatible with the "normal" K_D profiles displayed in Fig.7.All these elements indicate that the deposit is markedly "abnormal". The Table in Fig.9 also displays the ratios c_u/σ'_v for points A,B and C.These ratios are plotted vs K_D in Fig.4 (triangular symbols).It is seen that the agreement is not too bad,though the triangles fall somewhat on the "unsafe" side of the dash-line.It is believed that this deviation is connected with the brittle nature of this material.On the other hand with materials whose c_u/σ'_v is so high (say for $c_u/\sigma'_v>3$) a considerable scatter in correlations such as the one in Fig.4 is probably inevitable.

In more ductile materials the dash-line represents a lower boundary for almost all the experimental data.It is pointed out that many of the data points in Fig.4 refer to sites where only c_u measurements and dilatometer determinations were performed,so that no elements are available for evaluating the "normality" of the deposit.Probably many of these deposits are cemented,to some extent.Nevertheless the dash-line appears as a conservative average for all the data points,irrespective of the reasons which have determined K_D.

Site Budapest-Nagykovacsi

Soil type:heavily OC desiccated marl ($17\le\%CaCO_3\le 30$),above the water table.The high $CaCO_3$ content and the desiccation state suggest that the deposit is highly "abnormal".Dilatometer test results are shown in Fig.10.It is seen that the K_D profile is incompatible with the "normal" K_D profiles of Fig.7.

Site Madingley (Cambridge,U.K.)

Soil type:heavily OC stiff fissured glacial Gault clay (Windle and Wroth,1977).Glacial deposits exhibit in this region "wide variation in composition,fabric and stress history which result from the complexity of depositional and post depositional processes" (Marsland,1977).According to this

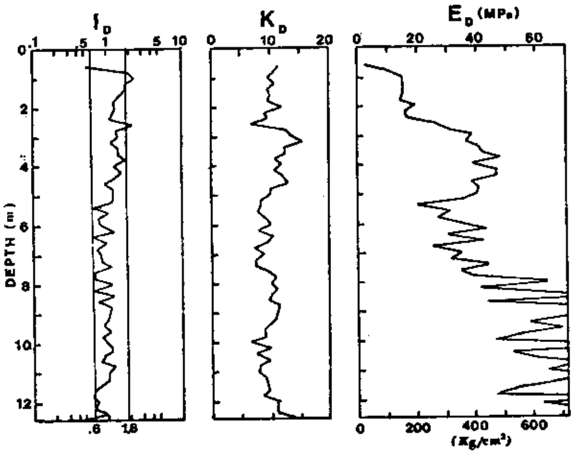


Fig.10 Dilatometer test results at Budapest Nagykovacsi.

information the deposit is "abnormal".Dilatometer test results are shown in Fig.11.Comments:

(a)A pronounced layering is observed in the readings p_o,p_1 and in all the derived parameters.

(b)Even ignoring local scatter,K_D does not seem to tend to an asymptotical value in the vicinity of 2.

Both features (a) and (b) render this K_D profile incompatible with the "normal" K_D profiles of Fig.7 (though the "abnormality" appears in this case less marked than in most deposits considered in this section).

Fig.11 also shows the profiles of EOCR and of the interpreted parameters M ($=1/m_v$) and c_u according to the correlations in Figs.4 and 5.The interpreted c_u values are generally comparable with the c_u values displayed in Fig.4 of Windle and Wroth (1977) which however are limited to the top layers.Addtional information relative to this deposit,which is presently being further investigated by several researchers,will provide an opportunity of evaluating the quality of the interpreted parameters shown in Fig.11.

Tests in the calibration chamber

Large triaxial pluvially deposited dry sand specimens,subjected to a known stress history,have been tested in a calibration chamber,then penetrated and tested by flat dilatometer.Some of the results, presented in more detail in a paper presented to this Conference by Bellotti et al (1979) ,are

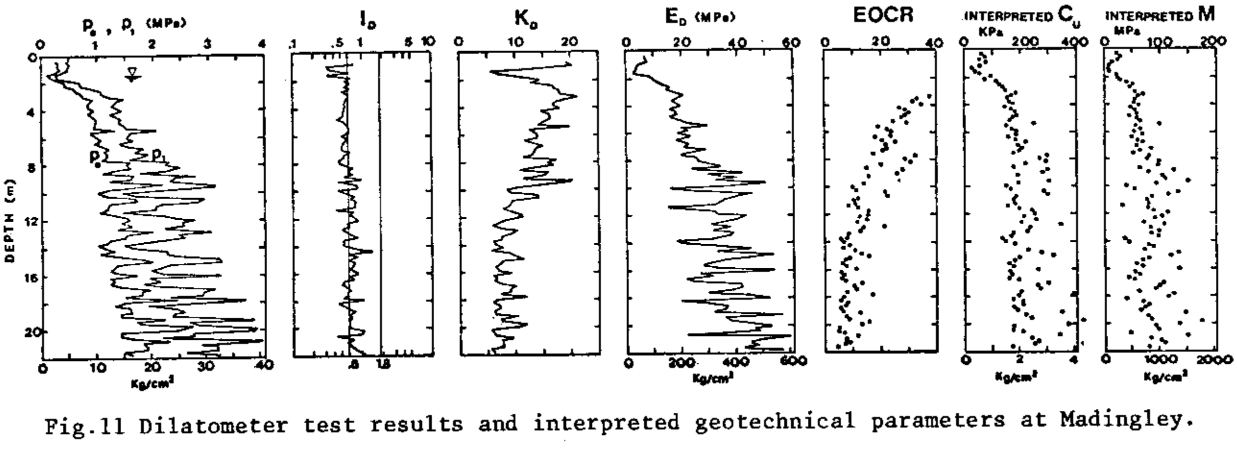


Fig.11 Dilatometer test results and interpreted geotechnical parameters at Madingley.

quoted hereunder:

1. In NC specimens K_D values in the range 4 to 4.5 have been found. These values are considerably higher than the typical value ($K_{D,NC} \simeq 1.5$) found in natural underwater-deposited NC sands. For K_D = 4 to 4.5, the dash-line in Fig.2 supplies EOCR$\simeq$7. This figure must be regarded as indicative, due to the tentative nature of the dash-line in Fig.2. However it strongly suggests the existence of "overconsolidation effects". Since true mechanical overconsolidation does not exist and cementation/attraction effects have to be excluded, the reason of the "abnormality" of this sand, denounced by EOCR >> OCR(=1), is not understood. Perhaps the next point has some connection with this question.

2. Several responses of the pluvially deposited NC specimens (such as M=1/mv, the "Young's modulus", the cone resistance) have been observed to exhibit a definite intercept on the vertical axis when plotted against the square root of the consolidation stress.

3. If the determined M/E_D ratios are plotted vs the determined K_D, all data points (triangular symbols in Fig.5), referring both to NC and to OC specimens, fall within the limits indicated by Marchetti (1978).

4. If for the NC specimens predictions of the ratios M/E_D had been made, based on Fig.5 entered with $K_{D,NC}$=1.5 (which is, as already mentioned, a typical value for NC underwater-deposited natural sands) M would have been considerably underestimated. This suggest that "higher than normal" K_D values witnesses a soil state responsible of "higher than normal" M values.

5. In tests in which during the dilatometer penetration the lateral expansion was prevented, K_o (monitored by the chamber facilities) increased appreciably during the penetration. The K_o increase was accompanied by a comparable increase of K_D.

Indications emerging from the data relative to "abnormal" deposits:

1. The "abnormality" due to aging of the Fucino clay is revealed by EOCR>1 (or K_D>2). The value of the geological OCR (=1), instead, is inherently unable to convey information about the existence of aging.
2. "Abnormal" deposits can be recognized by the incompatibility of their K_D profile with the "normal" profiles shown in Fig.7.
3. K_D (or EOCR) increase both with the "free" horizontal stresses and with the "attraction" stresses.
4. K_D (or EOCR) monitors soil behavioural characteristics which have significant influence on its engineering behaviour and which are not reflected by OCR.
5. K_D (or EOCR) bears a definite correlation with several frequently used geotechnical parameters.

It is believed that the physical parameter to which K_D (or EOCR) is more directly related is the sum of the in situ horizontal "free" stresses and of the "attraction" stresses.

SUMMARY AND CONCLUSIONS

1. Investigations performed in uncemented, simply unloaded deposits ("normal" deposits) have shown that, for the investigated deposits, a well defined correlations exists between the geological OCR and the value of K_D determined in situ by flat dilatometer (Fig.2).
2. In "normal" deposits K_D exhibits a typical shape decreasing with depth, very similar to the shape of OCR with depth (Fig.6).
3. In "normal" deposits Fig.7 can provide guidance for evaluating the magnitude of the removed overload based on the K_D profile.
4. In "abnormal" deposits (cemented and/or horizontally overstressed deposits) the K_D values have been found to be higher than those corresponding to the geological OCR according to Eq.1. These higher K_D values, entered into the "normal" OCR vs K_D correlation, supply "extended" OCR values (EOCR) higher than the geological OCR.
5. "Abnormal" deposits can be recognized by the incompatibility of their K_D profile with the "normal" K_D profiles displayed in Figs.6 and 7.
6. K_D (or EOCR) increases both with the "free" horizontal stresses and with the "attraction" stresses.
7. The presented evidence relative to "abnormal" deposits suggest that, in these deposits, K_D (or EOCR) monitors soil behavioural characteristics which have significant influence on its engineering behaviour and which are not reflected by OCR.
8. K_D (or EOCR) bears a definite correlation with several frequently used geotechnical parameters.
9. There is indication that, when $K_D > 2$, reaching values say from 2.5 to 3 (corresponding to EOCR values in the range 1.4 to 1.9) some quasi-preconsolidation (or light overconsolidation) can be already relied upon. This may be an important element of information in foundation problems.

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