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# FLAT DILATOMETER TESTS IN CALIBRATION CHAMBERS

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## ABSTRACT

This paper presents the results of a series of Flat Marchetti's Dilatometer Tests (DMT's) performed in a large Calibration Chamber (CC) on dry Ticino (TS) and Hokksund (HS) sands. These results, together with those of similar earlier tests discussed by Marchetti (19), are evaluated to assess the capability of DMT for determining the coefficient of earth pressure at rest, $K_o$, and deformation parameters of the natural sand deposits.

## INTRODUCTION

The flat dilatometer was developed in Italy during the seventies by Marchetti (16). It consists of a flat blade shaped tip having a thin expandable circular steel membrane 60mm in diameter on one face.(see fig.1). The test involves pushing the blade vertically into the ground at a rate of 10 mm to 20mm per second; every 100mm to 200mm, penetration is stopped and the DMT is performed. This consists of the following steps.

- First, the internal pressure causing lift-off of the membrane is determined. This value, after a number of appropriate corrections, yields the "first corrected reading" $p_o$.
- Second, the internal pressure required to expand the central point of the membrane by ≅ 1,1mm is determined. This value, after appropriate correction, yields the "second corrected reading" $p_1$.

Based on these two readings, the following three index parameters are determined:

Material or Deposit Index $I_D = \dfrac{p_1 - p_o}{p_1 - u_o}$

Lateral Stress Index $K_D = \dfrac{p_o - u_o}{\sigma'_{vo}}$

Dilatometer Modulus $E_D = 34.7\ (p_1 - p_o)$

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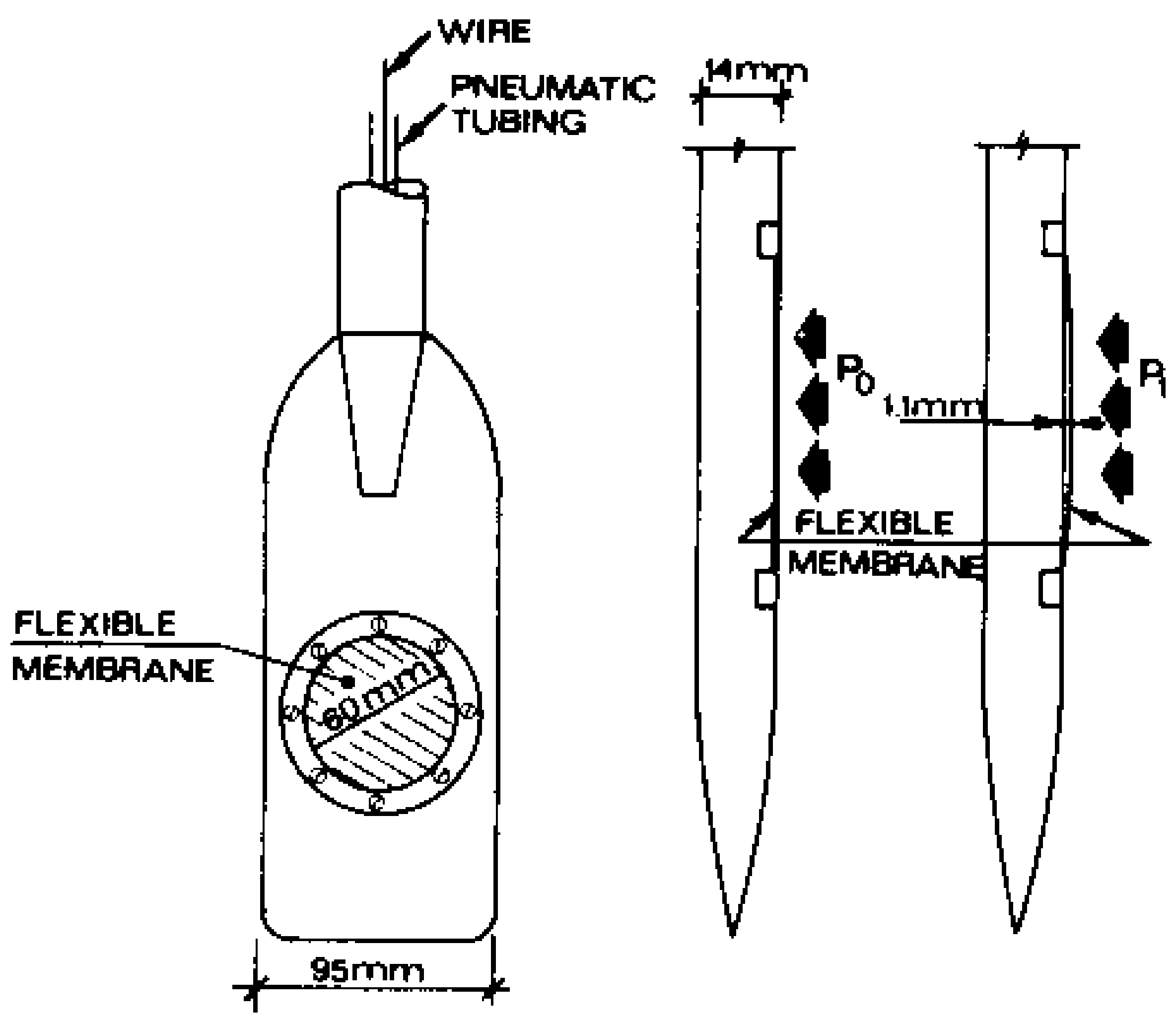


FIG.1: Marchetti Dilatometer

where: $u_o$ = in situ hydrostatic pore pressure,

$\sigma'_{vo}$ = in situ effective overburdern pressure.

For further details, see Marchetti (17) and Marchetti and Crapps (20). Based on $I_D$, $K_D$, and $E_D$, Marchetti (17,18), Schmertmann (22,23) and Campanella and Robertson (9,21) have developed empirical correlations with geotechnical parameters.

## CALIBRATION CHAMBER TESTS

CC Tests have been performed at ENEL CRIS (Milano) and ISMES (Bergamo). Details of the equipment are described by Bellotti et al. (6). Both chambers accomodate cylindrical specimens of sand 1.2m in diameter and 1.5m in height. The typical sequence of CC test consists in the following steps:

. sand specimen preparation;
. one dimensional compression of the specimen;
. execution of the "in situ" test.

The specimen is prepared by means of the pluvial deposition using a gravity mass sand spreader described by Jacobsen (12); Kildalen and Stenhamar (14) and Battaglio et al (4).

Then the specimen is subjected to one dimensional straining in order to assign the desidered stress history. During this stage the $K_o$ and the constrained modulus M of the tested sand are obtained.

Finally the "in situ" test is performed; the dilatometer is pushed into the CC specimen, with one of four possible boundary conditions (BC), imposed on boundary stresses and/or strains, showed in fig.2. Every 100mm penetration is stopped and DMT is carried out.

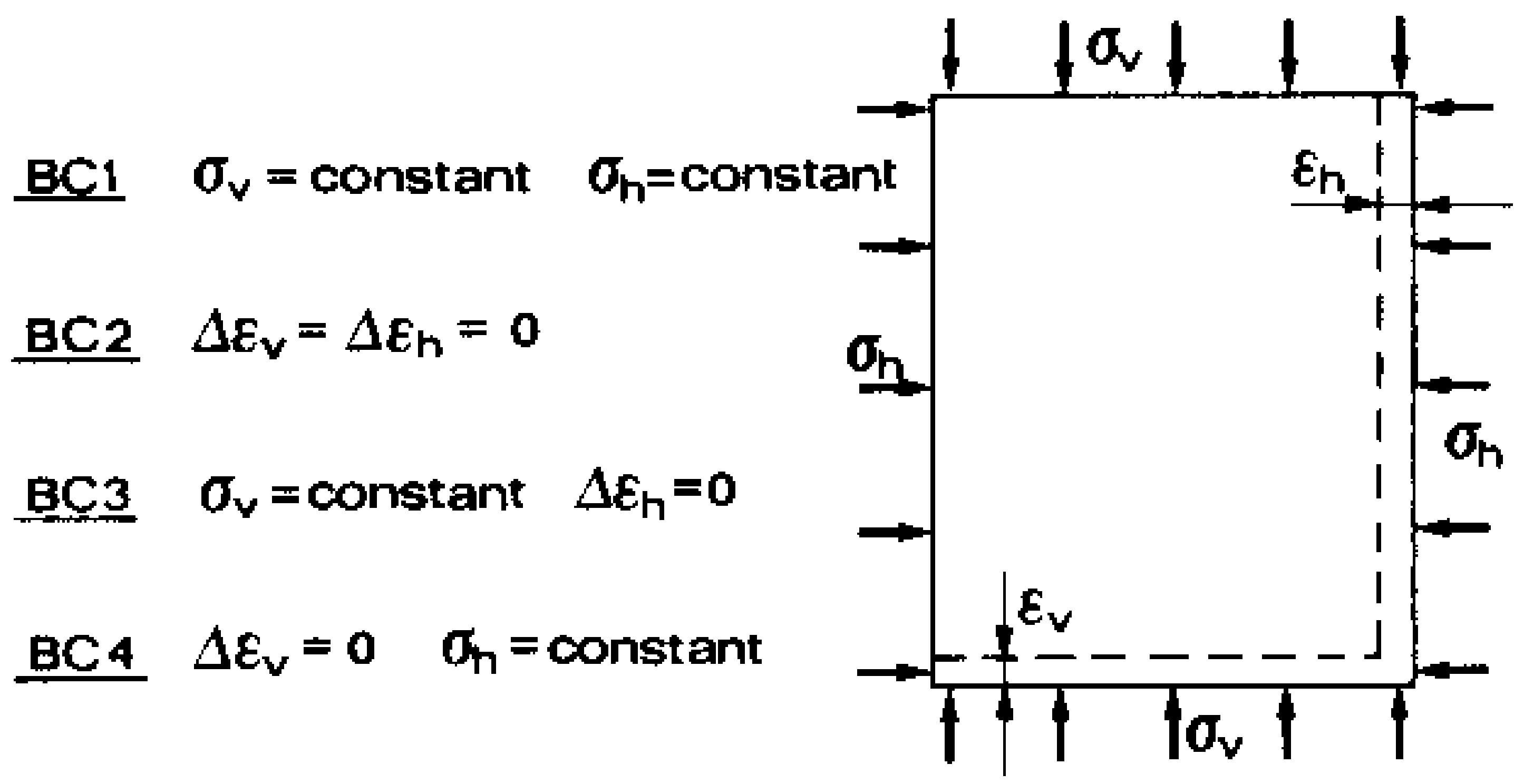
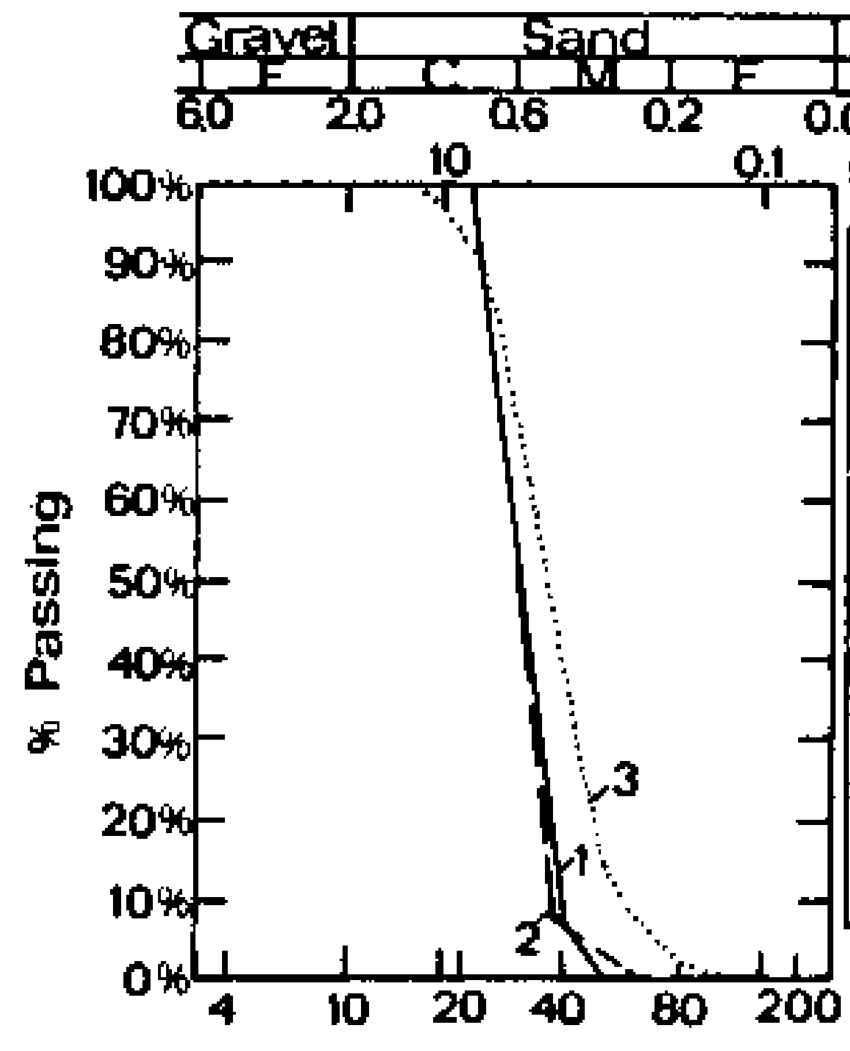


FIG.2 : CC test. Boundary conditions that can be applied during in "situ tests"



| SAND | N°1 and N°2 TICINO | N°3-HOKKSUND |
|---|---|---|
| DOMINANT MINERAL | QUARTZ (30 %) | QUARTZ (35 %) |
| ANGULARITY (LESS CHART) | 8÷9 | 6÷8 |
| MICA | -5 % | -10 % |
| $\gamma_{max}$ (KN/m³) | 16.67 | 17.16 |
| $\gamma_{min}$ (KN/m³) | 13.64 | 13.87 |

FIG.3 :Characteristics of the tested sand

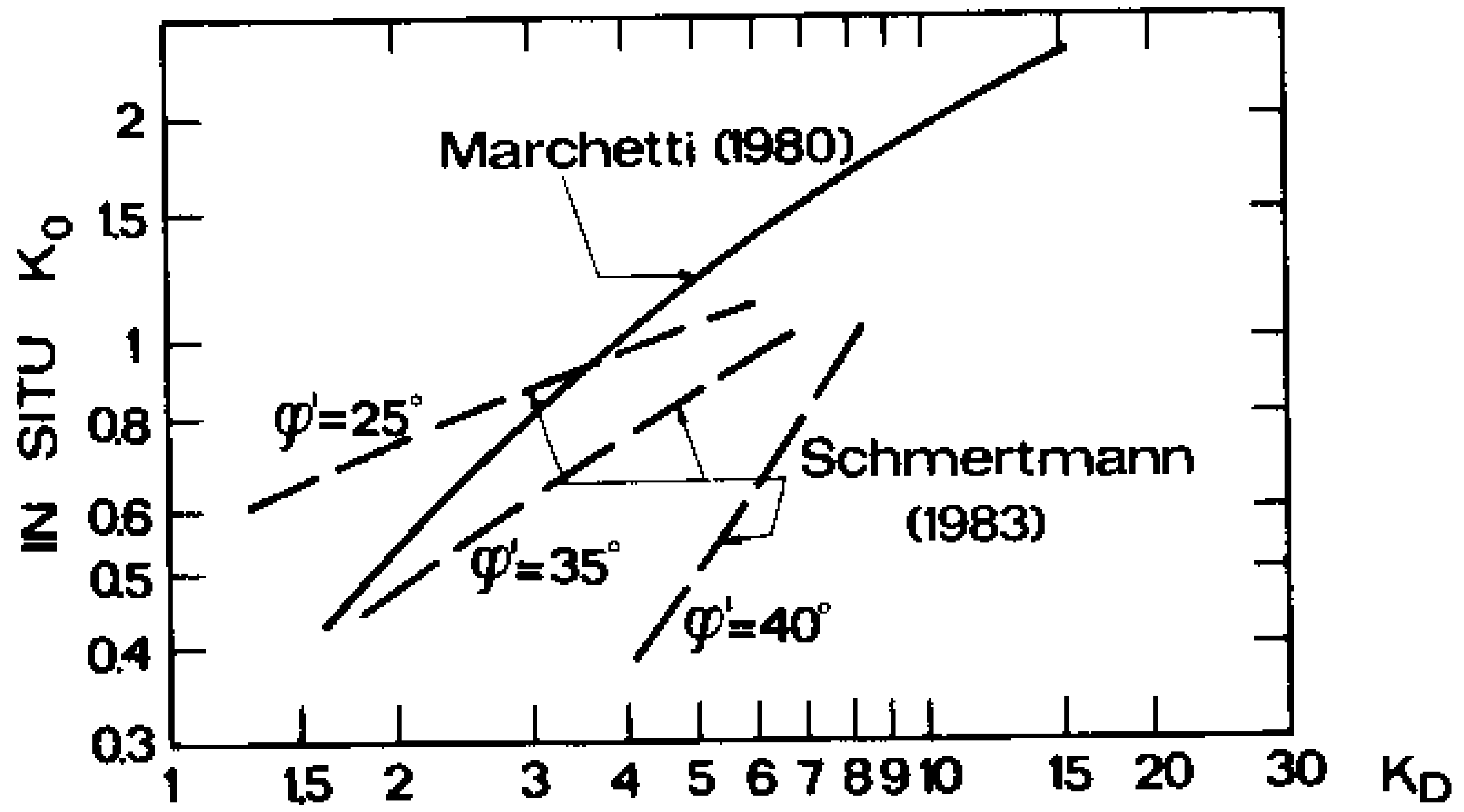


FIG.4 :Correlations of $K_0$ vs $K_D$

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The same sands have been subjected to static cone penetration (CPT) and self boring pressuremeter (SBP) tests whose results are reported by Baldi et al. (1,2,3) and Bellotti et al (7).

TEST SANDS

The main characteristics of the two sands used in the CC can be deduced from fig. 3. These two sands are quite well documented from the geotechnical point of view in reference 3.

DMT'S RESULTS

Tables 1 and 2 summarize the available DMT's results including the three basic index parameters. The same tables give

TABLE 1. TICINO SAND, DILATOMETER TESTS IN CC

| TEST | BC | $\sigma'_v$ | $\sigma'_h$ | $D_R$ | OCR | $K_o$ | M | $P_o$ | $P_1$ | $I_d$ | $K_d$ | $E_D$ | $M_D$ | $q_c$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| - | - | [kpa] | | % | - | - | MPa | [kpa] | | - | - | [MPa] | | |
| 41 | 3 | 111.80 | 41.19 | 66.7 | 1.00 | .37 | 76.98 | 685.50 | 1912.60 | 1.79 | 6.13 | 45.41 | 92.46 | 9.99 |
| 42 | 3 | 311.85 | 121.60 | 77.6 | 1.00 | .39 | 105.32 | 1394.50 | 3555.90 | 1.55 | 4.47 | 80.02 | 138.00 | 24.39 |
| 43 | 1 | 112.78 | 45.11 | 77.3 | 1.00 | .40 | 76.20 | 472.70 | 1455.90 | 2.08 | 4.19 | 36.48 | 61.73 | 13.76 |
| 44 | 1 | 212.81 | 88.26 | 79.3 | 1.00 | .41 | 94.25 | 911.10 | 2551.10 | 1.80 | 4.28 | 60.70 | 102.99 | 20.96 |
| 47 | 1 | 63.74 | 24.52 | 77.6 | 1.00 | .39 | 61.29 | 269.70 | 997.90 | 2.70 | 4.23 | 26.97 | 46.82 | 10.01 |
| 97 | 1 | 113.76 | 50.99 | 79.4 | 1.00 | .45 | 65.32 | 341.27 | 1204.26 | 2.53 | 3.00 | 29.94 | 42.44 | 15.09 |
| 98 | 1 | 114.74 | 50.01 | 91.4 | 1.00 | .44 | 73.77 | 580.56 | 1808.36 | 2.11 | 5.06 | 42.59 | 79.62 | 21.05 |
| 102 | 1 | 111.80 | 58.84 | 39.9 | 1.00 | .53 | 43.90 | 378.54 | 1232.70 | 2.26 | 3.38 | 29.66 | 44.66 | 5.19 |
| 105 | 1 | 312.83 | 152.98 | 52.8 | 1.00 | .49 | 80.92 | 755.12 | 2010.37 | 1.66 | 2.41 | 43.55 | 49.72 | 12.98 |
| 106 | 3 | 111.80 | 52.96 | 51.5 | 1.00 | .47 | 50.99 | 431.49 | 1349.40 | 2.12 | 3.86 | 31.83 | 51.56 | 6.96 |
| 109 | 3 | 113.76 | 50.01 | 79.3 | 1.00 | .44 | 62.06 | 409.92 | 1277.81 | 2.12 | 3.60 | 30.12 | 46.83 | 14.97 |
| 112 | 3 | 112.78 | 47.07 | 94.9 | 1.00 | .42 | 65.07 | 949.29 | 2431.08 | 1.56 | 8.42 | 51.42 | 120.01 | 22.72 |
| 117 | 1 | 112.78 | 51.98 | 72.0 | 1.00 | .46 | 61.59 | 314.80 | 1083.64 | 2.45 | 2.79 | 26.69 | 35.89 | 12.31 |
| 118 | 1 | 111.80 | 51.98 | 45.0 | 1.00 | .46 | 26.63 | 164.75 | 746.29 | 3.54 | 1.47 | 20.19 | 17.16 | 5.79 |
| 119 | 1 | 111.80 | 51.98 | 45.0 | 1.00 | .46 | 28.79 | 167.69 | 675.68 | 3.02 | 1.50 | 17.61 | 15.04 | 5.79 |
| 45 | 1 | 112.78 | 97.09 | 81.0 | 5.50 | .86 | 140.82 | 958.9 | 2560.3 | 1.67 | 8.5 | 59.43 | 139.35 | 19.23 |
| 46 | 1 | 113.76 | 82.38 | 77.3 | 2.80 | .73 | 167.30 | 765.0 | 2096.3 | 1.81 | 6.73 | 51.19 | 108.80 | 16.45 |
| 49 | 1 | 110.82 | 106.89 | 79.6 | 5.60 | .96 | 131.02 | 987.7 | 2600.6 | 1.63 | 8.91 | 59.43 | 142.00 | 19.07 |
| 99 | 1 | 112.78 | 84.34 | 93.3 | 2.80 | .75 | 261.89 | 997.94 | 2521.30 | 1.53 | 8.84 | 52.88 | 125.94 | 25.82 |
| 100 | 1 | 111.80 | 84.34 | 79.9 | 2.82 | .75 | 235.60 | 603.11 | 1679.89 | 1.79 | 5.39 | 37.37 | 71.56 | 17.73 |
| 101 | 1 | 110.82 | 60.80 | 79.3 | 1.47 | .55 | 211.87 | 454.05 | 1388.63 | 2.06 | 4.09 | 32.44 | 54.17 | 15.69 |
| 103 | 1 | 110.82 | 64.72 | 51.2 | 1.46 | .58 | 181.83 | 294.20 | 991.46 | 2.37 | 2.66 | 24.19 | 31.30 | 7.30 |
| 104 | 1 | 111.80 | 88.26 | 50.5 | 2.80 | .79 | 188.78 | 381.48 | 1230.74 | 2.23 | 3.41 | 29.48 | 44.55 | 7.93 |
| 107 | 4 | 110.82 | 86.30 | 52.1 | 2.83 | .78 | 195.96 | 512.89 | 1456.29 | 1.84 | 4.63 | 32.72 | 58.03 | 8.22 |
| 108 | 3 | 110.82 | 86.30 | 51.5 | 2.84 | .78 | 196.34 | 525.64 | 1528.86 | 1.91 | 4.75 | 34.80 | 62.63 | 8.08 |
| 110 | 3 | 111.80 | 84.34 | 80.2 | 2.80 | .75 | 215.49 | 640.38 | 1750.50 | 1.73 | 5.73 | 38.52 | 75.88 | 17.89 |
| 111 | 4 | 112.78 | 89.24 | 94.4 | 2.81 | .79 | 246.49 | 1104.23 | 2873.36 | 1.60 | 9.79 | 61.39 | 152.23 | 27.14 |
| 114 | 3 | 112.78 | 78.45 | 97.3 | 2.80 | .70 | 254.53 | 1020.88 | 2715.48 | 1.66 | 9.05 | 58.81 | 141.42 | 28.19 |
| 115 | 1 | 112.78 | 127.49 | 97.9 | 8.08 | 1.13 | 292.30 | 1292.52 | 3320.55 | 1.57 | 11.46 | 70.39 | 185.03 | 34.12 |
| 116 | 4 | 103.95 | 125.53 | 99.0 | 8.77 | 1.21 | 296.95 | 1631.43 | 3737.33 | 1.33 | 15.41 | 74.11 | 215.60 | 34.49 |

TABLE 2. HOKKSUND SAND , DILATOMETER TESTS IN CC

| TEST | BC | $\sigma'_v$ | $\sigma'_h$ | $D_R$ | OCR | $K_o$ | M | $P_o$ | $P_1$ | $I_d$ | $K_d$ | $E_D$ | $M_D$ | $q_c$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| - | - | [kpa] | | % | - | - | MPa | [kpa] | | - | - | [MPa] | | |
| 123 | 1 | 311.85 | 134.35 | 64.7 | 1 | 0.43 | 73.55 | 519.75 | 1505.33 | 1.9 | 1.67 | 34.19 | 29.07 | 17.88 |
| 191 | 3 | 114.74 | 49.72 | 45 | 1 | 0.43 | 46.93 | 231.44 | 784.54 | 2.39 | 2.02 | 19.19 | 20.07 | 5.86 |
| 195 | 3 | 117.68 | 50.99 | 72 | 1 | 0.43 | 67.86 | 561.92 | 2216.31 | 2.95 | 4.77 | 57.42 | 106.5 | 12.94 |
| 199 | 1 | 61.78 | 27.45 | 71 | 1 | 0.44 | 50.31 | 246.15 | 1059.12 | 3.31 | 3.98 | 28.22 | 47.95 | 8.88 |
| 203 | 1 | 62.76 | 28.44 | 71 | 1 | 0.45 | 52.66 | 320.68 | 1309.19 | 3.08 | 5.11 | 34.30 | 65.74 | 9.01 |
| 204 | 1 | 112.77 | 49.03 | 46 | 1 | 0.43 | 48.03 | 204.96 | 946.34 | 3.62 | 1.82 | 25.72 | 26.21 | 5.98 |
| 197 | 4 | 62.76 | 56.88 | 72 | 7.43 | 0.91 | 182.69 | 626.65 | 2186.89 | 2.49 | 9.99 | 54.13 | 135.27 | 11.47 |
| 198 | 3 | 62.76 | 44.13 | 72 | 3.03 | 0.7 | 159.06 | 387.36 | 1833.85 | 3.74 | 6.17 | 50.20 | 104.43 | 10.53 |
| 200 | 1 | 60.8 | 42.17 | 70 | 1.58 | 0.69 | 148.47 | 512.89 | 1789.72 | 2.49 | 8.44 | 44.31 | 103.97 | 9.73 |
| 202 | 1 | 61.78 | 54.92 | 70 | 7.44 | 0.89 | 182.6 | 394.23 | 1696.56 | 3.31 | 6.38 | 45.19 | 95.34 | 10.67 |
| 205 | 1 | 111.79 | 94.14 | 50 | 8.3 | 0.84 | 224.67 | 520.74 | 3481.38 | 5.68 | 4.66 | 102.73 | 188.68 | 8.15 |
| 206 | 1 | 108.85 | 71.59 | 50.5 | 3.3 | 0.66 | 174.36 | 268.7 | 1211.13 | 3.5 | 2.47 | 32.7 | 42.03 | 7.51 |

he values of consolidation stresses $\sigma'_v$ and $\sigma'_h$ at the mid-eight of the specimens and the corresponding value of $K_o$. Together with OCR this data reflects the state of the sand in the CC before penetration of the dilatometer under the boundary conditions specified in Tables 1 and 2. The $q_c$ values in the last columns of Tables 1 and 2 were computed from the following empirical relationship obtained by Baldi et al (3) using a large number of CPT's performed in the CC:

$$q_c = C_o \, (\sigma'_{oct})^{C_1} \exp \, (C_2 D_R) \qquad \ldots(1)$$

where: $\sigma'_{oct}$ = mean octhaedral consolidation stress, in Kg/cm$^2$
$D_R$ = relative density as fraction of unity
$C_o, C_1, C_2$ = empirical coefficients as determined by Baldi et al (3) and given below:

| Sand | $C_o$ | $C_1$ | $C_2$ | R (*) |
|---|---|---|---|---|
| Ticino | 19.99 | 0.561 | 2.79 | 0.97 |
| Hokksund | 19.48 | 0.549 | 2.88 | 0.98 |

## COEFFICIENT OF THE EARTH PRESSURE AT REST

The assessment of $K_o$ (or initial in-situ total horizontal stress $\sigma_{ho}$) using any push-in device faces the problem of disturbance in the surrounding soil caused by insertion of the device. In sands, where the penetration occurs under fully drained conditions, the horizontal stress acting on the device is the sum of the $\sigma_{ho}$ plus the increment $\Delta\sigma'_h$ caused by the insertion of the device. The main problem for the interpretation of these tests is the lack of even approximate solutions allowing the estimate of $\Delta\sigma'_h$.It is generally assumed that in sands the value of $\Delta\sigma'_h$ should be linked to its relative density [Huntsman (11)], dilatancy angle [Campanella and Robertson (9,21)] and state parameter [Been et al.(5)].Despite at present all the above mentioned attempts at rationalizing the interpretation of push-in devices for evaluating $K_o$ or $\sigma_{ho}$, they are substantially of an empirical nature.
The first attempt to evaluate $K_o$ from DMT's was by Marchetti (16), who proposed the following empirical relationship:

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

This expression has been derived mainly from data available for clays, with only a few data for sands. Successive experience shows that this relationship overestimates $K_o$ in both natural sand deposits and in the CC tests.
To improve the estimate of $K_o$, Schmertmann (22) proposed a new procedure, based on results of a limited number of CC tests,which has been summarized by Jamiolkowski et al (13).A comparison between the original correlation by Marchetti (17) and that proposed by Schmertmann (22) is shown in fig.4. It is possible to observe that in Schmertmann's correlation $K_o$ depends on the angle of shearing resistance $\phi'$.
Marchetti (19) examined the Schmertmann relationship and concluded that:

- it might be more convenient to use a dimensionless parameter $q_c/\sigma'_{vo}$ rather than $\phi'$;
- this correlation still overestimates the coefficient of earth pressure at rest for the well documented Po river sand deposit, for which the "best estimate" of $K_o$ from laboratory and SBP tests is $K_o \cong 0.55$ to $0.65$;see Bruzzi et al (8);
- to obtain a good agreement between $K_o$ of the Po river sand and that predicted by the Schmertmann correlation it is necessary to translate $K_o = f(K_D, q_c/\sigma'_{vo})$ as shown in fig. 5.

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(*) correlation coefficient

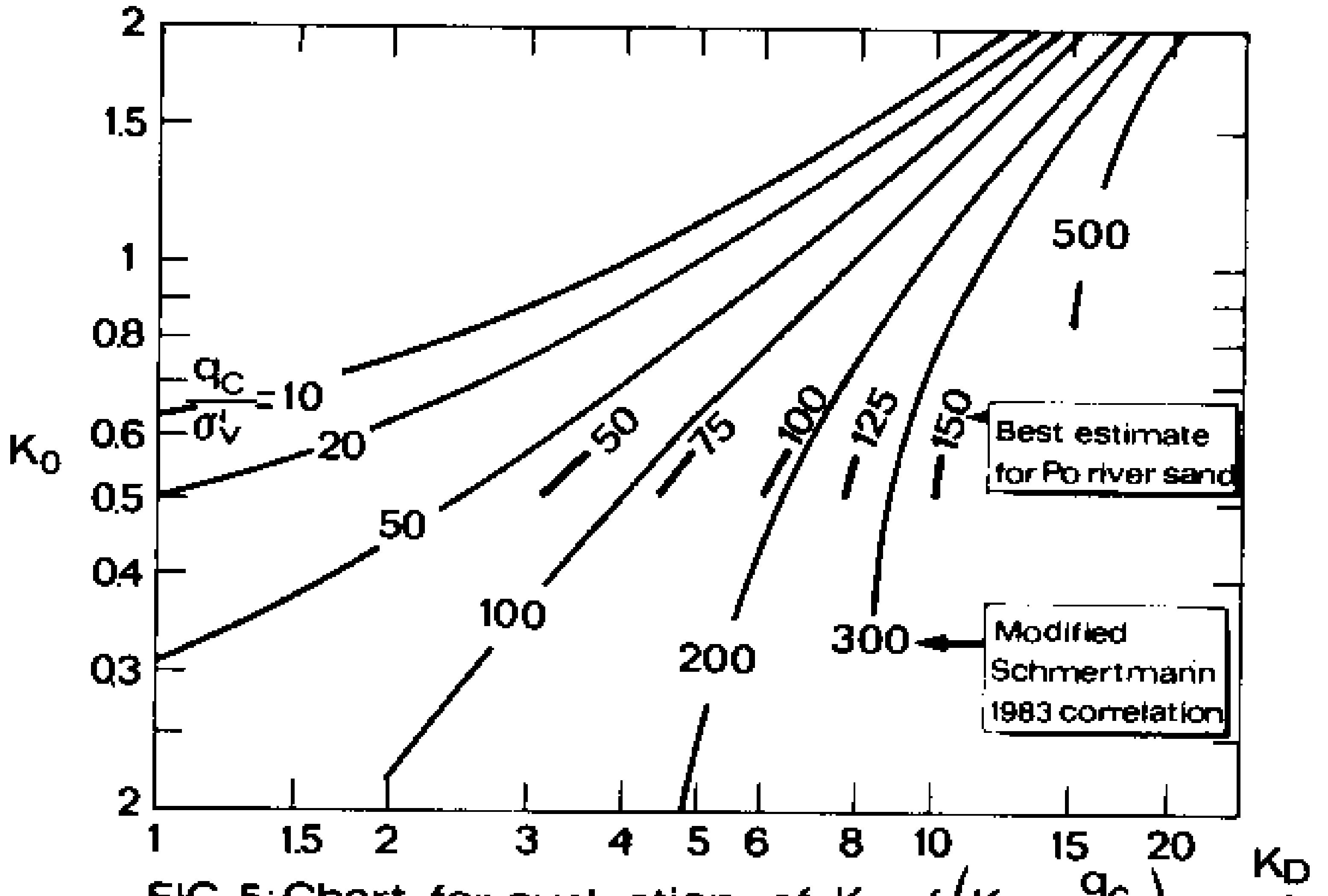

FIG. 5: Chart for evaluation of $K_0 = f\left(K_D, \frac{q_c}{\sigma'_v}\right)$ MARCHETTI (1985)

The curves $K_o = f(K_D, q_c/\sigma'_{vo})$ shown in fig. 5 were obtained by converting the $\phi$= constant curves in Fig. 4 into $q_c/\sigma'_v$= constant curves, using the Durgunoglu and Mitchell equations,as explained by Marchetti (19).
In view of what has been summarized above it was decided to search for a correlation $K_o = f(K_D, q_c/\sigma'_v)$ using all the currently available CC-DMT's data.In this search reference was made to the following fitting function:

$$K_o = D_1 + D_2K_D + D_3 \cdot \frac{q_c}{\sigma'_v} \qquad \ldots(3)$$

The use of equation...(3) when applied to the available data points (number of test: n=42) led to the following results:

$D_1 = 0.359$, $D_2 = 0.071$, $D_3 = -0.00093$ and $R = 0.746$

Using the equation:

$$K_o = 0.359 + 0.071K_D - 0.00093\, \frac{q_c}{\sigma'_v} \qquad \ldots(4)$$

one can predict $K_o$ measured in the CC with a standard error of estimate $S_d = 0.142$.

A comparison between $K_o$ estimated using eqn...(4) and that measured during the consolidation stage of the CC tests is shown in fig.6.From this figure one can deduce that the tests run under the boundary condition BC3 tend to exhibit a larger scatter than other types of BC; moreover the predicted values of $K_o$ from BC3 tests are, usually overestimated.This may be explained by the penetration of the DMT dilatometer blade causing a substantial increase of $\sigma'_h$ which leads to the horizontal stress ratio $\sigma'_h/\sigma'_v$ being higher during DMT than that existing during the consolidation stage in CC.

Considering only the tests (n=27) run under BC1, which corresponds to constant boundary stresses during DMT insertion, a fitting of the data using eqn...(3) gives:

$D_1 = 0.376$, $D_2 = 0.095$, $D_3 = -0.00172$; $R = 0.802$, $S_d = 0.119$

Fig.7 shows a comparison between measured valued of $K_o$ during the CC and those obtained using the Schmertmann procedure: despite some scatter the agreement is reasonably good.

Correlations of $K_o = f(K_D, q_c/\sigma'_v)$ have also been attempted using log $(q_c/\sigma'_v)$ or $(q_c/\sigma'_v)^n$ as reference parameter instead of $q_c/\sigma'_v$ and refering to exp $(D_2K_D)$ in place of $D_2K_D$. However the refinements obtained in terms of R and $S_d$ are too small to justify the use of a more complex fitting equation.

The equation:

$$K_o = 0.376 + 0.095K_D - 0.00172\ q_c/\sigma'_v \qquad \ldots(5)$$

determined from CC tests run under BC1 conditions overpredicts $K_o$ for Po river sand. In order to correctly predict $K_o$ for the Po river site the above given relationship should be modified.This was achieved by searching, by trial and error,for a multiplier of $D_3$ so that the $K_o$ obtained from the equation ...(3) coincided with the "best estimate" of in situ $K_o$.

This operation led to the following relationship:

$$K_o = 0.376 + 0.095K_D - 0.00461\ q_c/\sigma'_{vo} \qquad \ldots(6)$$

which according to the writers represents the best available

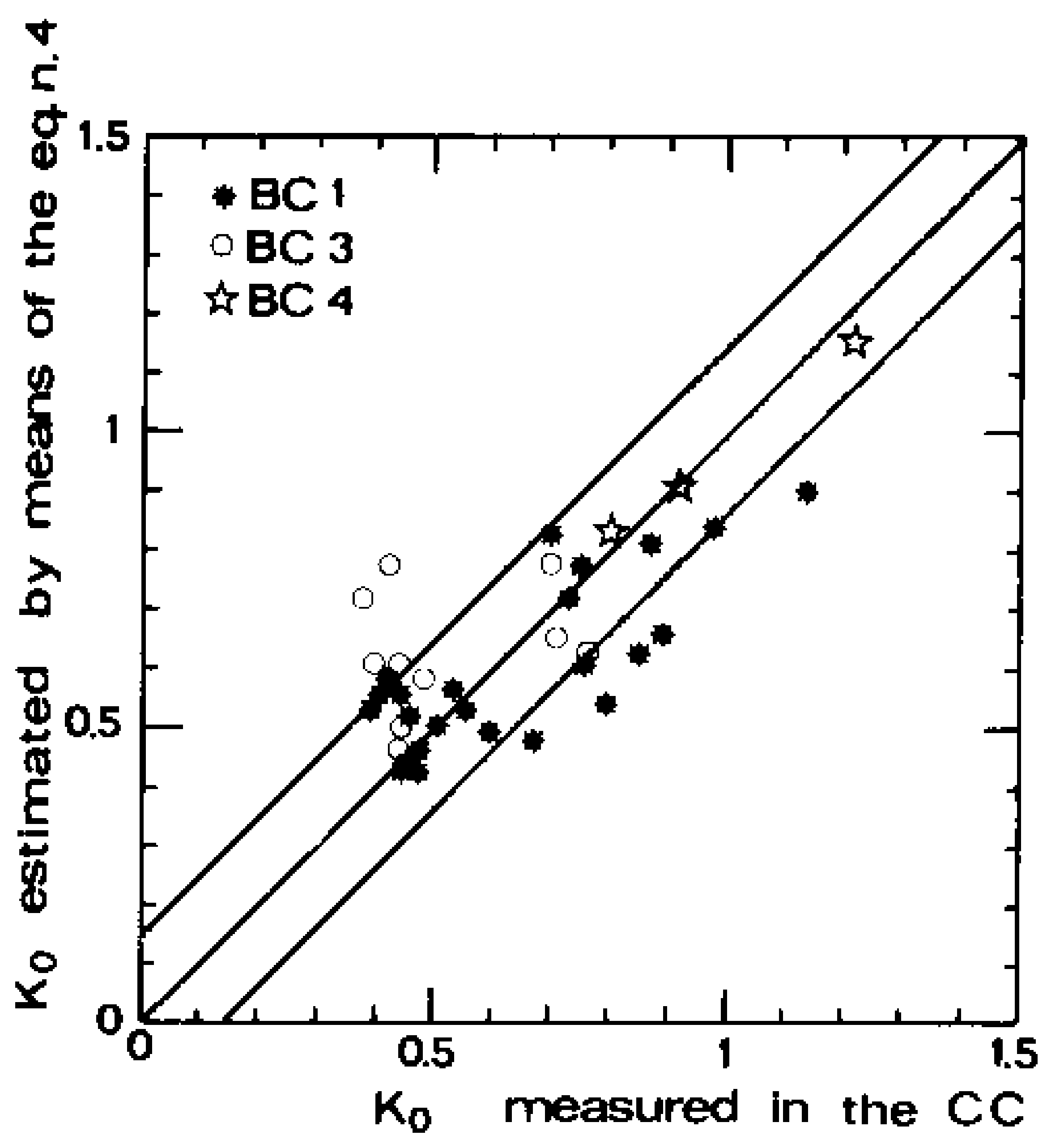

FIG. 6

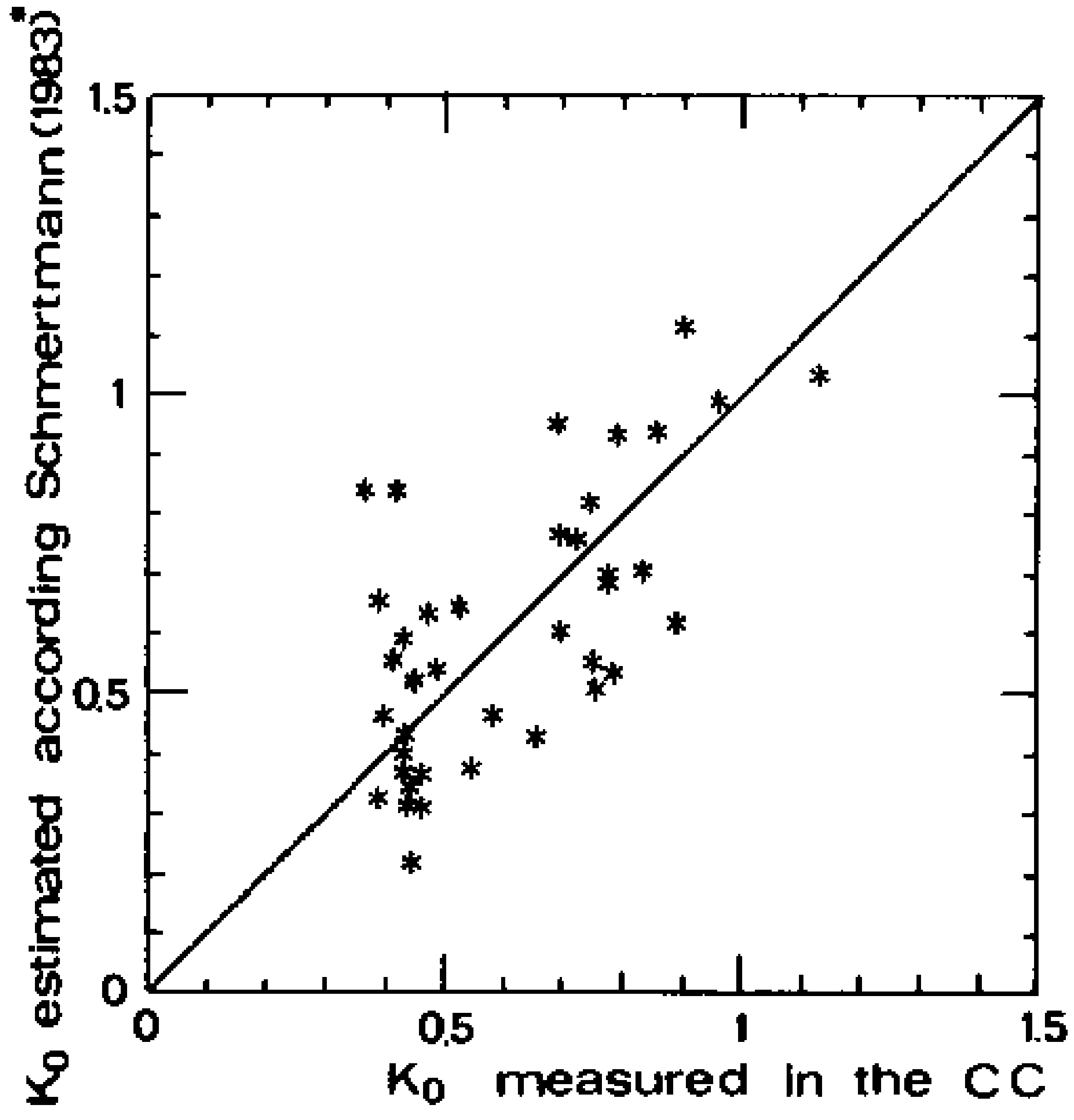

FIG.7

(•)Making reference to $\varphi' = f(q_c)$

FIG. 6-7

Comparision between calculated and measured $K_0$

tentative procedure at present for estimating $K_o$ from DMT's in natural, prediminantly quartz,uncemented sand deposit.Any further improvement of the procedure will require:

- comparison against other field data like that available for the Po river sand;
- theoretical and experimental investigation of the influence of CC size and BC on the measured $p_o$;
- additional CC tests run on sands having different grain size and mineralogical composition.

## DEFORMATION PARAMETERS

The dilatometer modulus,$E_D$,was obtained by Marchetti (17)supposing that the membrane of the device expands in isotropic homogeneous elastic half-space.For the given geometry and boundary conditions [see also Finn (10)]the following formula is obtained

$$E_D = \frac{E}{(1-\nu^2)} = 34.7(p_1-p_o) \quad ; \text{ being: } E= \text{Young modulus}$$
$$\nu = \text{Poisson coefficient}$$

Marchetti (17) proposed to correlate the $E_D$ to the tangent constrained modulus,M,throught the factor $R_M= f(K_D,I_D)$.
The main ideas behind this correlation, whose details may be found in the works by Marchetti (17) and Marchetti and Crapps (20),are: a) M versus $E_D$ correlation should depend on the soil type; hence the deposits index must be included in the correlation; b) even for the same soil, no unique relation can exist between M and $E_D$;in cohesionless soil it must depend on the existing in situ lateral stress and on the soil relative density, both reflected in $K_D$ which therefore should be considered in the correlation.
The CC tests give a possibility to verify the validity of M vs $E_D$ correlation proposed by Marchetti(17),hence during the first stage of CC tests M is assessed and it can be directly compared to the value of $M_D=f(E_D,K_D,I_D)$,where $M_D$= constrained modulus as obtained from DMT's.The tables 1 and 2 show the value of M an $M_D$ as obtained from the CC tests.
In these tables the values of M refer to:tangent constrained modulus obtained for the last small load increment,in the case of the NC specimens, and to secant constrained modulus corresponding to the entire unload loop in the case of the OC specimens.
In Table 3 the measured M are compared to those obtained from DMT's. It can be deduced that $M_D$ from Marchetti's correlation tends,on average, to underestimate the constrained modulus in NC sands by 30 to 50%. The same trend is more pronounced in OC sands, where the prediction of the M throungh DMT gives value from one half to one third of the measured M.

TABLE 3. Measured M versus $M_D$

| SAND | OCR | BC | RANGE of $D_R$% | NUMBER OF TEST n | $M/M_D \pm S_d$ |
|---|---|---|---|---|---|
| NC TICINO | 1 | BC1 | 40 to 94 | 11 | 1.48 ± 0.484 |
| NC TICINO | 1 | all | 40 to 95 | 18 | 1.29 ± 0.508 |
| NC HOKKSUND | 1 | all | 45 to 72 | 5 | 1.33 * |
| OC TICINO | ≤ 8.1 | BC1 | 50 to 98 | 8 | 2.91 * |
| OC TICINO | ≤ 8.8 | all | 50 to 99 | 14 | 2.68 ± 1.37 |
| OC HOKKSUND | ≤ 8.3 | all | 50 to 72 | 5 | 1.93 * |

(*) for n < 10 Standard Deviation is not shown
M = constrained modulus measured during the one dimensional compression of the specimen in CC test
$M_D$= constrained modulus obtained from DMT's carried out in CC

These findings are aligned with those of Lambrechts and Leonards (15) which proved that the static cone resistance in sands is much less sensitive to the stress and strain history of the deposit than any deformation parameter is.This phenomenon, confermed by Jamiolkowski et al (13) Baldi et al (2,3) by means of CC tests,is responsable for the $E/q_c$ ratio found for OC sands to be 3 to 6 times greater than the one obtained for NC sands.
The same trend, but attenuated, is observed in case of the DMT suggesting that this, despite of the unavoidable disturbance caused by the blade insertion, preserves a higher sensitivity as regards the soil deformability than the static cone penetration test.
The fig. 8 and table 4 report the results of special CC•tests performed in the attempt to evaluate the DMT sensitivity to the assigned strain history of the sand specimen. In these tests the CC specimens have been subjected to a one-dimensional straining up to the consolidation stress $\sigma'_{vc}$ showed in fig.8. Then the dilatometer blade has been pushed into the specimen down to the dephts of 500 and 600mm and DMT performed. Successively the specimens have been subjected to a number of load-unload cycles along the three different effective stress paths showed in fig. 8. After the load-unload cycles the specimens have been brought back to the former consolidation stresses $\sigma'_{vc}$ and $\sigma'_{hc}$. At this point the dilatometer penetration into the CC specimens has been completed by perfor

| TEST N° | TYPE OF PRESTRAINING | Δ-STRESS KPa | NUMBER OF CYCLES | $\sigma'_{vc}$ KPa | OCR - |
|---|---|---|---|---|---|
| 118 | ■ | 200 | 1 | 100 | 1 |
| 119 | ■ | 30 | 10 | 100 | 1 |
| 123 | ■ | 200 | 3 | 513 | 1 |
| 127 | ✱ | 200 | 3 | 313 | 1 |
| 128 | ★ | 30 | 3 | 312 | 1 |

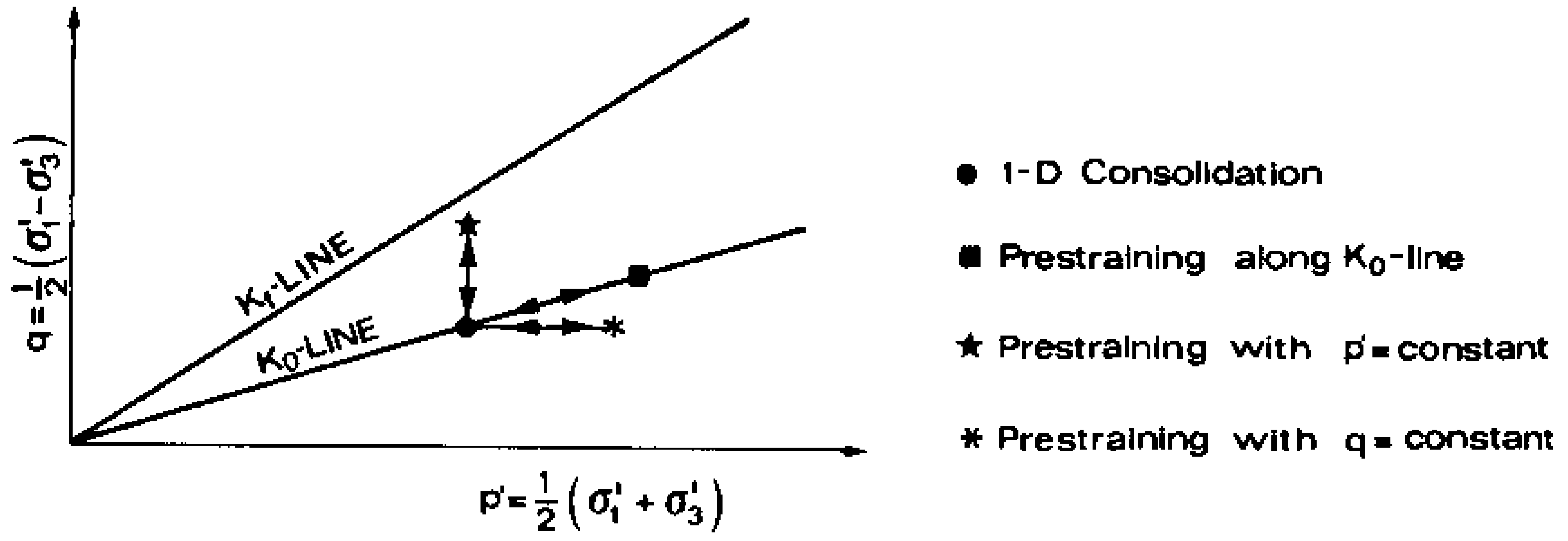

FIG.8: DMT's CC tests with prestraining

| Test n° | $D_R$ % | PRE-STRAINING | $p_o$ kPa | $p_1$ kPa | $K_D$ - | $E_D$ MPa | $M_D$ MPa | $E_t$ MPa | Depth cm |
|---|---|---|---|---|---|---|---|---|---|
| 118 | 37 | BEFORE | 105.6 | 505.2 | 0.98 | | | 19.5 | 50 |
| | | BEFORE | 161.5 | 725.9 | 1.48 | 19.9 | 17.9 | 19.5 | 60 |
| TS | | AFTER | 334.1 | 1084.0 | 3.00 | 26.4 | 36.7 | 118.3 | 80 |
| | | AFTER | 404.6 | 1221.3 | 3.55 | 28.8 | 44.2 | 118.3 | 90 |
| 119 | 40 | BEFORE | 126.5 | 603.3 | 1.17 | 16.8 | 10.7 | 20.7 | 50 |
| | | BEFORE | 164.7 | 662.2 | 1.50 | 17.5 | 14.9 | 20.7 | 60 |
| TS | | AFTER | 246.6 | 878.0 | 2.21 | 22.3 | 25.5 | 114.5 | 80 |
| | | AFTER | 280.0 | 828.9 | 2.46 | 19.4 | 23.0 | 114.5 | 90 |
| 123 | 65 | BEFORE | 553.3 | 1606.0 | 1.77 | 36.4 | 31.8 | 62.4 | 50 |
| | | BEFORE | 550.7 | 1505.0 | 1.76 | 33.0 | 28.1 | 62.4 | 60 |
| TS | | AFTER | 610.9 | 1598.0 | 1.97 | 34.2 | 32.1 | 243.1 | 80 |
| | | AFTER | 644.7 | 1670.0 | 2.09 | 35.5 | 35.3 | 243.1 | 90 |
| 127 | 60 | BEFORE | 492.0 | 1402.0 | 1.58 | 31.5 | 23.9 | 60.8 | 50 |
| | | BEFORE | 593.1 | 1361.0 | 1.91 | 25.7 | 23.3 | 60.8 | 60 |
| TS | | AFTER | 569.1 | 1577.0 | 1.84 | 34.9 | 31.2 | 194.7 | 80 |
| | | AFTER | 561.2 | 1691.0 | 1.82 | 39.1 | 35.6 | 194.7 | 90 |
| 128 | 66 | BEFORE | 493.8 | 1410.0 | 1.59 | 31.7 | 24.2 | 57.6 | 50 |
| | | BEFORE | 491.6 | 1389.0 | 1.58 | 31.1 | 23.5 | 57.6 | 60 |
| TS | | AFTER | 610.6 | 1626.0 | 1.96 | 35.1 | 33.1 | 190.1 | 80 |
| | | AFTER | 624.7 | 1652.0 | 2.01 | 35.5 | 34.4 | 190.1 | 90 |

TABLE 4 : RESULTS OF DMT's WITH PRESTRAINING

ming the DMT's again at invervals of 100mm. The table 4 shows also the tangent Young modulus $E_t$ (*) determined on the CC specimens at $\sigma'_{vc}$ before and after prestraining.

From the results of the above mentioned special tests the following can be observed.

- Because of the prestraining the $E_t$ increases from 3 to 6 times, being such increase more pronunced in the looser specimens.
- At the same time prestraining determines much a more limited increase of the measured $E_D$ and of the derived $M_D$ :

$$1.05 \leq \frac{E_D \text{ (AFTER PRESTRAINING)}}{E_D \text{ (BEFORE PRESTRAINING)}} \leq 1.39$$

$$1.13 \leq \frac{M_D \text{ (AFTER PRESTRAINING)}}{M_D \text{ (BEFORE PRESTRAINING)}} \leq 2.03$$

This increase is again more pronunced for the looser specimens of sand.

- The $K_D$ appears to be more sensitive to the prestraining than $E_D$ :

$$1.05 \leq \frac{K_D \text{ (AFTER PRESTRAINING)}}{K_D \text{ (BEFORE PRESTRAINING)}} \leq 2.66$$

This sensitivity is higher in the case of specimens having lower $D_R$.

- The sensitivity of DMT parameters to prestraining, at least in sands having $D_R \geq 40\%$, is appreciably lower than the corresponding sensitivity of the measured $E_t$.

Pluvially deposited specimen of the same sands used in the here examined CC test were subjected to a number of laboratory tests (see reference 3). These tests allowed to establish empirical correlations among different soil moduli, stress history and $D_R$. All these correlations are of type:

$$\text{Soil Modulus} = B_o\ (\sigma'_{oct})^{B_1}\ \exp\ (B_2 D_R) \qquad \ldots(7)$$

which is analogous to the eqn...(1), and where the value of empirical constants $B_o$, $B_1$ and $B_2$ as obtained from different laboratory tests are shown in table 5.

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(*) As during cyclic loading, the CC specimens have not been strained one-dimensionally, so it was necessary to refer to E rather than to M, being the former calculated according to the theory of elasticity.

TABLE 5. Laboratory Moduli for Test Sands.

Modulus = $B_o (\sigma'_{oct})$ exp $(B_2 D_R)$ in $Kg/cm^2$

| Sand | Modulus | $B_o$ | $B_1$ | $B_2$ | R | n | Range of $D_R$(%) |
|---|---|---|---|---|---|---|---|
| NC Ticino | $G_o$ | 399.2 | 0.43 | 1.39 | 0.95 | 34 | 50 to 100 |
| NC TICINO | $E_{25}$ | 48.6 | 0.44 | 2.78 | 0.90 | 29 | 48 to 94 |
| OC TICINO | $E_{25}$ | 894.8 | 0.75 | 1.03 | 0.85 | 63 | 39 to 96 |
| OC HOKKSUND | $E_{25}$ | 943.0 | 0.45 | 0.73 | 0.87 | 36 | 31 to 92 |

n =number of tests R= correlation coefficient

$G_o$=maximun shear modulus from the resonant column tests

$E_{25}$= drained Young modulus evaluated from triaxial $CK_oD$-CL tests at deviatoric stress level equal to 25% of the failure stress

These data allow to compare $E_D$ versus laboratory moduli computed for the $\sigma'_{oct}$ and $D_R$ values equal to those of the CC specimens. The following ratios are obtained:

| | |
|---|---|
| NC Ticino Sand | $R_E = E_{25}/E_D = 0.88 \pm 0.27$ |
| OC Ticino Sand | $R_E = E_{25}/E_D = 4.29 \pm 0.62$ |
| OC Hokksund Sand | $R_E = E_{25}/E_D = 2.49 \pm 0.74$ |
| NC Ticino Sand | $R_G = G_o /E_D = 2.72 \pm 0.59$ |

where:

$E_{25}$ = Drained Young modulus from triaxial $CK_oD$ compression loading tests evaluated at one fourth of the deviator stress at failure.

$G_o$ = Maximun shear modulus as obtained from the resonant column tests.

The obtained results allow the following comments.

- The $E_{25}/E_D$ ratio, as obtained for NC Ticino Sand, is close to one; this confirms the similar results obtained by Campanella and Robertson (9,21).
- The difference in $E_{25}/E_D$ ratios as obtained for NC and OC Ticino sand confirms the low sensitivity of all the pushed-in devices to the stress and strain history of the deposits, which, on the contrary, strongly influences soil deformation characteristics.
- This fact suggest the opportunity to work-out $R_E$ and $R_G$ ratios both in function of $K_D$ similar to the $R_M$ proposed by Marchetti (17).

## FINAL REMARKS

Basing on the results of 42 DMT tests performed in CC in dry Ticino and Hokksund sands, a new tentative correlation allowing the evaluation of $K_o$ as function of $K_d$ and $q_c/\sigma'_{vo}$ is proposed. (see formula 5).The correlation has been forced in a way that the predicted value of $K_o$ coinceeds with that one corresponding to the "best estimate" of $K_o$ in the Po river sand, (see formula 6).This tentative correlation represents the best procedure, presently available, to assess at least qualitatively the $K_o$ from DMT's in the natural uncemented predominantly quartz sand deposits;its improvement requires:

- further validations based on field measurements;
- additional CC test;
- a deeper insight on the influence of the chamber size boundary conditions and possible moderate non uniformities of the CC specimens on the DMT's results.

The evaluation of the constrained modulus as function of $K_D$ and $E_d$, following Marchetti's (17) procedure leads to:

- a moderate underestimate of M for NC sands.
- a pronounced underestimate of M for OC sand.

The dilatometer parameters $K_D$, $E_D$ and consequently $M_D$, are only moderately sensitive to the strain history imposed on the CC specimen; this sensitivity decreases as $D_R$ increases. On the contrary, the deformation modulus $E_t$ measured during the consolidation stage of the CC test increases from 3 to 6 times as a result of the specimens prestraining.

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## APPENDIX. - REFERENCES

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