FLAT DILATOMETER TESTS IN TOYOURA SAND

ESSAIS AU DILATOMETRE PLAT SUR SABLE TOYOURA

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SYNOPSIS : The paper presents the results of 18 flat dilatometer tests performed in a large Calibration Chamber on dry Toyoura sand. These results have been evaluated to assess the capability of the device for determining the coefficient of earth pressure at rest and the stiffness of the test sand.

INTRODUCTION

The results of 18 flat dilatometer tests performed in a large Calibration Chamber (CC) on dry pluvially deposited Toyoura sand (TOS) are presented and discussed with the aim to get a deeper insight of the capabability of such devices for assessing the design parameters of sand deposits in situ.
Two types of dilatometers have been employed in this research, namely the standard Marchetti's Flat Dilatometer (DM), see Marchetti (1980) and the Research Dilatometer (RD) developed by ISMES of Bergamo and described by Fretti (1990) and Fretti et al. (1992). The two devices are identical as to shape and size but the latter has been equipped with some instrumentation which has made possible the measurement of the deflection at the centre of the membrane, the inflation pressure at the membrane and the penetration force immediately above the blade. This last measurement is also carried out during DM. A similar research device has been developed in middle eighties at the University of British Columbia in Vancouver and is illustrated in the works by Campanella et al. (1985) and Campanella and Robertson (1991).
The RD allows to obtain a continous relationship between the inflation pressure p and the deflection at the centre of the membrane δ leading to a p vs δ being similar in shape to the pressuremeter expansion curve [Campanella et al. (1985), Fretti (1990)].
However, due to length constraint, this paper focuses on the conventional interpretation of the tests as outlined by Marchetti (1980), and does not deal with the discussion of the entire dilatometer expansion curves and with the unload-reload loops that can be performed during the RDT's, see Campanella and Robertson (1991) and Fretti et al. (1992).

Calibration Chamber

All details concerning the CC used and the method for preparing the specimens can be found in works by Bellotti et al. (1982, 1988).

Test Sand

Toyoura sand is a well known Japanese test sand whose stress-strain characteristics have been throughly explored by numerous researchers, [e.g. Tatsuoka et al. (1986), Tatsuoka and Shibuya (1991)] who have remarked that the difference of the mechanical properties of Toyoura sand in dry and saturated state is negligible.
This soil is a predominantly quartz fine sand, having a mean size of 0.16 mm, the uniformity coefficient of 1.3 and the specific gravity of 25.90 kN/m^3. The maximum (e_{max}) and minimum (e_{min}) void ratio are respectively equal to 0.977 and 0.605. The slope of the Steady State Line (SSL) in log p' vs e plot, λ_{ss} = 0.021 while its intercept at the mean effective stress p' = 1 kPa gives the void ratio e_{ss} = 0.941, see Verdugo (1989).

Tests Program

18 dilatometer tests have been performed in CC specimens whose relative density (DR) ranges between 39 and 95%, see Table 1. Out of them nine have been carried out using RD while the remaining 9 by means of the conventional DM. With the exception of the RD test n°326, all CC specimens have been penetrated under constant vertical (σ'_v) and horizontal (σ'_h) effective stresses, B-1 boundary condition. Specimen 326 has been penetrated under the condition of σ'_v = const. and zero lateral strain, B-3 boundary condition.
In order to investigate the response of the dilatometers to the changes in σ'_h, six multi-stage CC tests (MST) have been carried out *(the result of RD - MST n°327 is not reported in Table 1)*. During such tests, the CC specimens were firstly penetrated to the depth of 0.6 m under a given set of σ'_v and σ'_h, thereafter, with the blade kept stopped, the σ'_h was increased, generally almost doubled, maintaining the σ'_v unchanged and the penetration was completed at the depth of 1.2 m.

Reduction of Tests Data

For all tests the following dilatometer indexes have been computed [Marchetti (1980) and Campanella and Robertson (1991)]:

Material Index : $I_D = (p_1 - p_o) / (p_o - u_o)$
Horizontal Stress Index : $K_D = (p_o - u_o) / \sigma'_{vo}$
Dilatometer Modulus : $E_D = C\,(p_1 - p_o)$
Dilatomer Wedge Resistance : $q_D = (F_D - A_\ell \cdot \tau_s) / A_b$

being:

p_o = corrected lift of pressure

p_1 = corrected pressure for the expansion of the dilatometer membrane of 1.1 mm and 1.0 mm in case of DMT and RDT respectively
u_o = hydrostatic pore pressure
F_D = thrust force measured just above the blade
τ_s = soil-blade interface friction assumed to be equal to the local shaft friction f_s measured during the Cone Penetration Tests (CPT)
A_ℓ = lateral area of the dilatometer blade $\simeq 0.0313\ m^2$
A_b = tip area of the dilatometer blade $\simeq 0.00128\ m^2$
C = constant equal to 34.6 and 38.2 for DM and RD respectively.

The results of all tests performed so far are reported in Table 1.

Table 1. Results of Dilatometer Test in Dry Toyoura Sand

Test n.	BC	z cm	e	DR %	σ'_{vp} kPa	σ'_{hp} kPa	p_o kPa	p_1 kPa	OCR
324(*)	B-1	75	0.660	85.1	113	116	904	3256	7.2
325(*)	B-1	70	0.656	86.2	113	50	434	1964	1.0
326(*)	B-3	75	0.626	94.5	112	48	593	2710	1.0
327(*)	B-1	70	0.756	59.3	111	51	430	1624	1.0
328(*)	B-1	75	0.807	45.7	111	55	239	1143	1.0
329(*)	B-1	75	0.806	46.0	112	107	340	1474	7.3
416	B-1	75	0.772	55.2	112	66	485	1579	1.9
417(**)	B-1	55	0.825	40.8	109	56	257	943	1.0
417(**)	B-1	75	0.821	41.8	115	112	389	1376	1.0
418(**)	B-1	50	0.831	39.2	108	155	457	1589	1.0
418(**)	B-4	85	0.821	41.9	115	233	618	1990	1.0
419	B-1	75	0.755	59.7	112	74	577	1971	1.0
420	B-1	75	0.760	58.3	111	50	282	1648	1.0
421	B-1	75	0.754	59.9	111	58	310	1793	1.4
422	B-1	75	0.753	60.2	115	77	420	2089	2.7
423	B-1	70	0.746	62.1	113	106	470	2515	7.0
424(*)	B-1	75	0.633	92.5	112	113	784	2309	7.0
425(*)(**)	B-1	48	0.636	91.7	113	58	443	2490	1.0
425(*)(**)	B-1	76	0.633	92.5	117	109	618	3261	1.0
426(*)(**)	B-1	48	0.633	92.5	312	158	1015	4587	1.0
426(*)(**)	B-1	70	0.627	94.1	318	307	1499	5938	1.0
428(*)(**)	B-1	48	0.801	47.3	312	158	556	2134	1.0
428(*)(**)	B-1	72	0.797	48.3	320	312	786	2879	1.0

(*) Research Dilatometer; (**) Multistage tests
σ'_{vp}, σ'_{hp} = vertical and horizontal effective stress, respectively, prior dilatometer penetration

Engineering Correlations

This paper is intended as a preliminary presentation of the acquired RDT's and DMT's data. Therefore, only minor comments concerning the engineering correlations are presented.
At the present stage of the research the following can be anticipated:

1. Coefficient of earth pressure at rest K_o

The estimation of K_o in sands from penetration tests results is, in its broad outlines, rather a complicated problem and far from being solved in a satisfactory manner. This situation is mostly linked to the fact that the penetration of any device, in the considered case of the dilatometer blade, produces the following conditions:

- a pronounced increase of the horizontal effective stress σ'_h above its initial value existing in the ground prior the insertion of σ'_{ho};
- a large straining of the sand surrounding the dilatometer blade.

This situation is reflected in the following formula linking the dilatometer amplification factor K_D/K_o to the state parameter ψ [Been and Jefferies (1985)], which fits the CC tests results obtained in TOS:

$$K_D/K_o = 1.05 \exp(-3.07\ \psi)$$

K_o = ratio of $\sigma'_{hp}/\sigma'_{vp}$ prior the RD and DM penetration from the Table 1.

The above equation shows that the ratio of K_D/K_o is a complex function of the mean effective stress and of the void ratio of the ground and not only of the σ'_{ho}. The amplification factor increases exponentially as the ψ decreases.
The complex nature of this phenomenon has been evidentiated by the MST's. Table 2 reports their results which show the variations of p_o hence of K_D due to the changes of σ'_h imposed on the CC specimens.
The following three procedures are available for obtaining K_o from dilatometer test results:

- the procedure originally suggested by Marchetti (1980) which remarkably overestimates K_o in sands;
- the procedure indicated by Schmertmann (1983) which requires the angle of friction φ' in addition to the knowledge of K_o;
- the procedure worked out by Baldi et al. (1986) which makes a clear distinction between the freshly deposited sands tested in CC and the natural sand deposit of same geological age. This approach requires the knowledge of the cone resistance q_c in addition to K_D.

Table 2. Results of Multistage Dilatometer Tests.

Test N°	1st STAGE σ'_{v1} kPa	σ'_{h1} kPa	p_{o1} kPa	2nd STAGE σ'_{v2} kPa	σ'_{h2} kPa	p_{o2}	$\frac{p_{o2}-p_{o1}}{\sigma'_{h2}-\sigma'_{h1}}$	DR %
417 DM	109	56	257	118	112	389	2.36	40.8
418 DM	109	154	451	133	229	618	2.23	39.2
425 RD	114	58	443	117	109	618	3.43	92.5
426 RD	313	157	1015	319	306	1499	3.25	92.5
427(*) RD	110	57	191	113	107	308	2.34	45.7
428 RD	311	157	556	319	312	786	1.48	47.3

σ'_v, σ'_h = vertical and horizontal stress after penetration at the elevation of the dilatometer test.
(*) not reported in Table 1

Such procedure, valid for freshly deposited silica sands, when applied to RDT and DMT results, obtained in TOS, leads to the data reported in Fig.1. On average, there is an acceptable agreement between the measured K_o and that inferred from the dilatometer tests results for NC specimens. For OC specimens the correlation by Baldi et al. (1986) greatly underestimates K_o.
The value of q_c pertinent to each dilatometer test has been obtained from the following equation fitting more than 30 CPT's performed in CC on TOS:

$$\log \frac{q_c}{\sqrt{\sigma'_h\ p'_a}} = 1.53 - 3.98\psi$$

being p_a = reference stress = 98.1 KPa

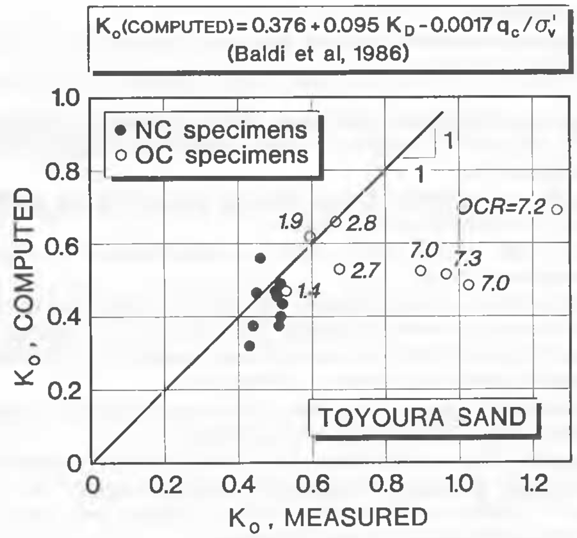
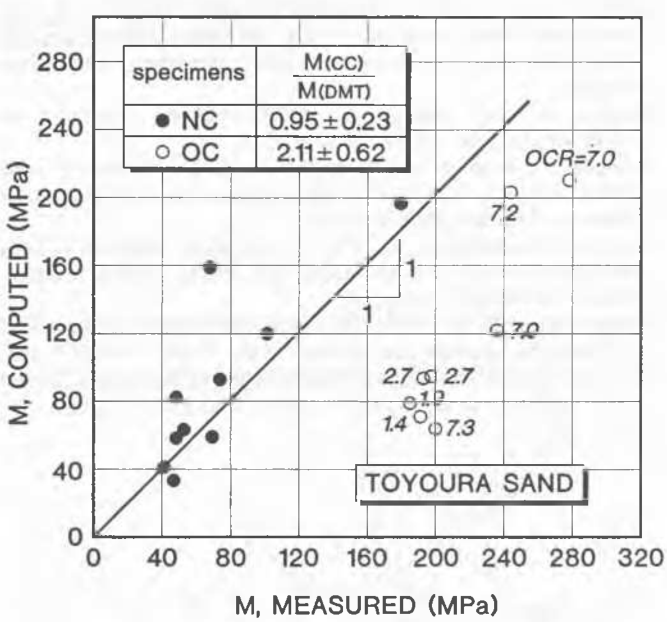


Fig. 1 - Computed versus measured coefficient of earth pressure at rest.

2. Constrained modulus M

Fig.2 shows M measured during the one dimensional compression of the CC specimens compared against the values computed from the dilatometer tests. As already observed for other silica sands tested in the CC's, the procedure suggested by Marchetti (1980) leads to a reliable prediction of M for NC consolidated sand but amply underpredicts that of the mechanically overconsolidated specimens.



(*) Computed from RDT's and DMT's following Marchetti's (1980) procedure.

Fig. 2 - Computed* versus measured constrained modulus.

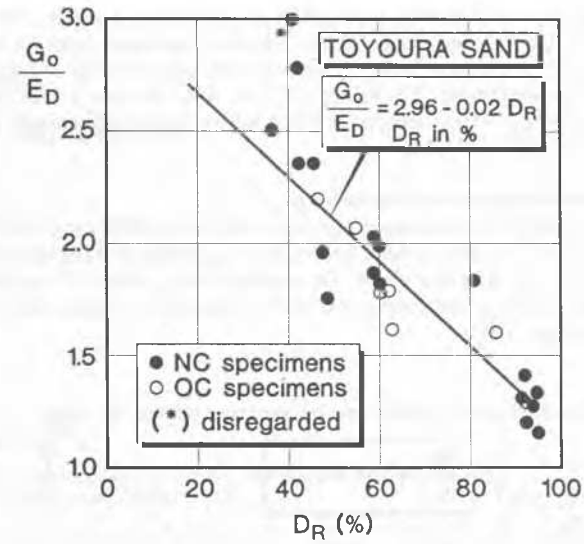


Fig. 3 - Initial shear modulus as function of E_D and D_R.

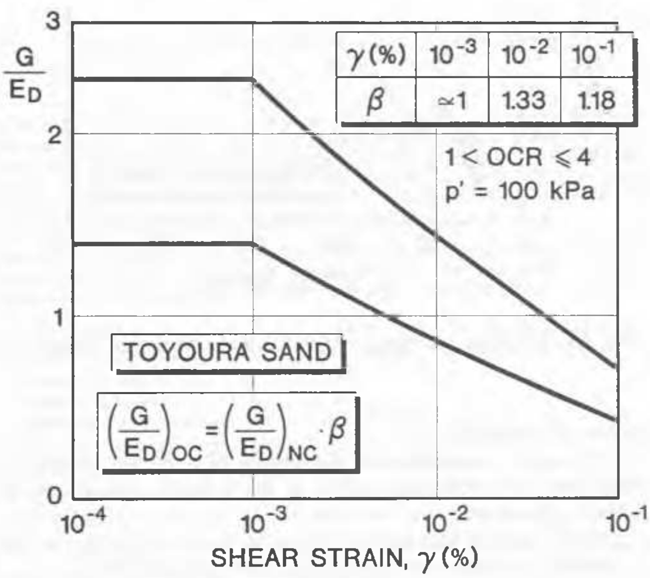


Fig. 4 - Ratio of shear to dilatometer moduli as function of strain level.

3. Shear modulus G

As already suggested by Jamiolkowski et al. (1988) and Jamiolkowski and Robertson (1988) the E_D can be reliably correlated to the initial shear modulus G_0 measured at shear strain less than to the elastic threshold strain γ_t^e ($\simeq$ 10^{-3}%), see Jamiolkowski et al. (1991), Tatsuoka and Shibuya (1991) and Shibuya and Tatsuoka (1992). An attempt of such correlation is shown in Fig.3. The observed decrease of G_0/E_D with increasing D_R is typical for all kinds of correlations between deformation moduli and parameters obtained from penetration tests, for further details see Jamiolkowski and Robertson (1988) and Baldi et al. (1989).

In Fig.4 a tentative correlation between the shear modulus G and E_D at shear strain $\gamma > \gamma_t^e$ is presented for two values of D_R. The values of G used to work out this correlation has been obtained from the monotonic torsional shear tests performed by Teachavorasinskun (1989) on NC and OC specimens of TOS. The correlation itself holds for NC sand. The correction factor β allowing the estimation of $G = f(E_D)$ in overconsolidated TOS having OCR $\leq$ 4 is also given. The two curves $G/E_D = f(\gamma)$ reported in Fig.4 for two values of e refer to the moduli at $p' = 100$ kPa.

4. Dilatometer wedge resistance q_D

Fig.5 compares the values of q_D measured during RDT's and DMT's just above the blade against the values of q_c evaluated using equation $q_c = f(\sigma'_h, \psi)$ given above. On average the q_D results 10 to 15% higher than q_c, confirming the result presented by Campanella and Robertson (1991).

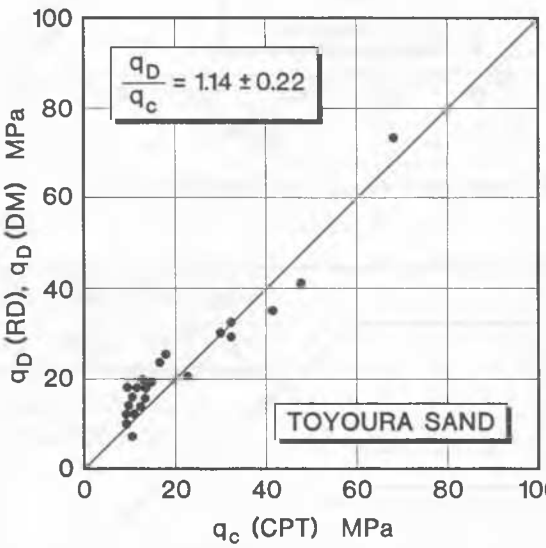


Fig. 5 - CPT cone resistance versus RD and DM wedge resistance.

FINAL REMARKS

A preliminary examination of the results of a limited number of dilatometer tests performed in CC on dry Toyoura sand allows the following comments:

- The RD and DM tests lead to very similar results in the test sand for the rank of relative density ranging between 40 and 95%.
- The evaluation of K_0 based on the results of dilatometer tests is still far from being solved mainly because of the complex nature of the amplification factor K_D/K_0 involved.
- As already observed the RDT's and DMT's allow to predict in a reliable manner the initial shear modulus G_0 of sands knowing E_D and the value of D_R.
- The procedure suggested by Marchetti (1980) allows to evaluate correctly the constrained modulus of NC sands but underestimates that of OC sands.

The above exposed comments apply only to freshly deposited sands. Much care should be paid if applied to natural sand deposits of the same geological age.

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