STIFFNESS OF TOYOURA SAND AT SMALL AND INTERMEDIATE STRAIN

RAIDEUR DU SABLE TOYOURA SOUS UN EFFORT FAIBLE OU MOYEN

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SYNOPSIS : This paper presents a limited series of laboratory tests performed on Toyoura sand using different apparatuses allowing to measure the strain down to 10^{-6}. The paper is aimed at investigating the stiffness of the test sand at small and intermediate strain, analyzing the shear moduli G as yielded by the different types of tests and comparing their results against those obtained on the same soils by a number of Japanese researchers.

INTRODUCTION

The stiffness of soils at small ($\epsilon < 10^{-5}$) and intermediate ($10^{-5} < \epsilon \leq 10^{-3}$) strain raises a number of relevant problems in geotechnical and earthquake engineering. It is accepted that within the range of strain $\epsilon < 10^{-5}$ the soil exhibits an apparently linear elastic response and after exceeding a certain threshold value the stress-strain relationship becomes highly non-linear [see as an example Hardin (1978), Jardine et al. (1984), Jardine (1985), Burland (1989), Tatsuoka and Shibuya (1991)]. The evaluation of the stiffness in the above mentioned range of strain has been recently enhanced thanks to:

- The improvements of the conventional triaxial (TX) apparatuses obtained by reducing the equipment compliance [Ladd and Dutko (1985), Tatsuoka (1988)] and by implementing a new set of sensors for the assessment of the local axial strain [Symes and Burland (1982), Goto et al. (1991)], making the value of ϵ_a measurements reliable down to the strain of the order of 10^{-6}.
- The development of a new generation of torsional shear apparatuses housing long hollow cylindrical specimens (THCS) in which the distribution of the shear strain γ is quite uniform. Thus the values of γ measured at the top of the specimens are reliable hence scarcely affected by the bedding errors.

This paper presents the results of a series of monotonic THCS, of resonant column (RC) and TX tests performed on specimens of dry, fine Toyoura sand (TOS) having different porosities and stress-strain histories. The test program has been devised with the aim to investigate the soil moduli as obtained from different laboratory tests, to clarify the influence of the mechanical overconsolidation on the shear stiffness G of TOS, and to compare the writers' results with those obtained, on the same test sand, by other researchers [e.g. Iwasaki et al. (1978), Teachavorasinskun (1989, 1992)].

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.

EQUIPMENT

The tests were performed using TX and THCS apparatuses which are available in the geotechnical laboratory at the writer's University. A TX apparatus, housing solid cylindrical specimens 70 mm in diameter and 140 mm in height and controlled by a PC through a 16 bit A/D converter, was used.
As shown in Fig.1 four independent values of ϵ_a have been measured during the early stage of the shearing phase of such tests with the aim to separate the effect of different bedding errors and of the equipment compliance [Jardine et al. (1984)]. The following measurements were involved:

a. local ϵ_a using high resolution submergible LVDT's;
b. internal to the cell ϵ_a between the pedestal and the cap using high resolution Proximeters;
c. external to the cell ϵ_a using the same Proximeter as above;
d. external to the cell ϵ_a using a conventional low resolution LVDT.

The radial deformations (ϵ_r) were all measured locally by means of said Proximeters. Furthermore, the volumetric strain (ϵ_v) has been assessed using high precision automatic system designed by Lo Presti (1987).
A fixed-free RC apparatus has been adapted to enable the execution of the monotonic torsional shear tests, see for details Lo Presti et al. (1993). This apparatus, whose schematic layout is shown in Fig.2, allows the measurements of ϵ_a, ϵ_r as well as the angular displacement of the specimen's head using high resolution Proximeters. It houses a hollow cylindrical specimen, 142 mm in height and whose outer and inner diameters are 71 and 50 mm respectively. A steel strand passing through the internal cavity of the hollow cylinder allows to transmit the

axial load to the top cap enabling the anisotropic consolidation. The maximum γ achievable in this apparatus is less than $1 \cdot 10^{-3}$.

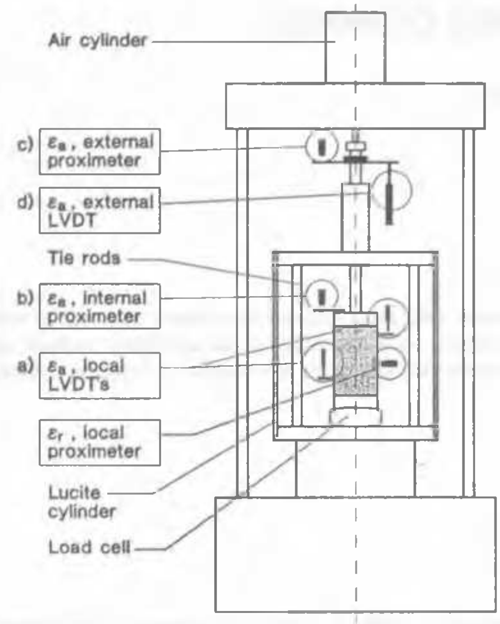

Figure 1 - Layout of triaxial cell.

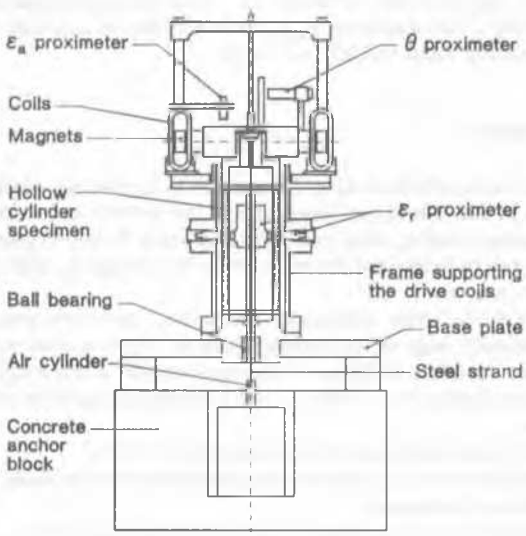

Figure 2 - Layout of torsional shear-resonant column apparatus.

TEST PROGRAM

Four anisotropically consolidated monotonic torsional shear (THCS) tests and three triaxial compression tests at radial stress σ'_r = const. (TX) have been carried out on normally (NC) and overconsolidated (OC) specimens of dry pluvially deposited TOS. Two TX tests have been performed on isotropically consolidated specimens (CID) and one on K_0-consolidated specimen (CK_0D). The THCS and TX tests were run; stress controlled ($\tau \sim$ 0.3 to 0.5 kPa/min) and strain controlled ($\dot{\epsilon}_a = 1 \cdot 10^{-4}$/min, respectively). RC tests have been performed on specimens that have been subject to THCS, after the monotonic torsional shear stage. Thereafter, the same specimens have been subject again to the monotonic torsional shear with the aim to investigate the influence of cyclic prestraining [γ_c prestraining (3.3 to 7.3) 10^{-4}] originated by the former RCT's on G. Due to length constraint this aspect of the research will not be discussed in this paper except for the inclusion of the values of the initial shear modulus G_o in the Fig.4, which for all practical purposes resulted very similar to those measured before cyclic prestraining.
The initial conditions of all tested specimens prior to shear stage are illustrated in Table 1.

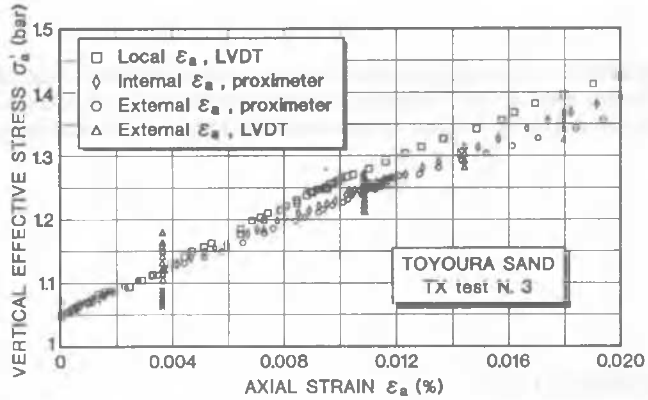

Figure 3 - Comparison of axial strain measured by different sensors during early stage of triaxial test.

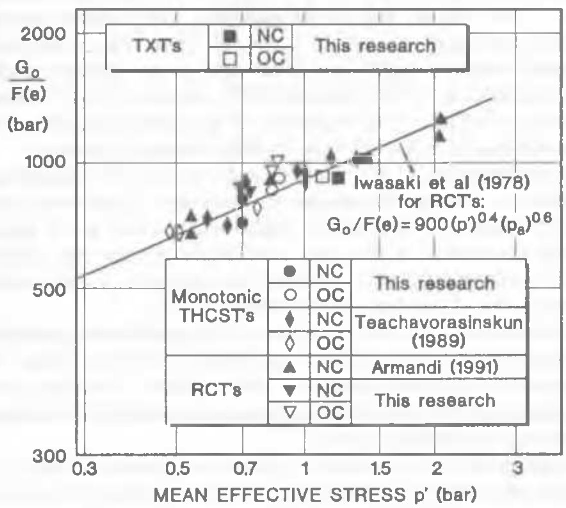

Figure 4 - Initial shear modulus of Toyoura sand from different laboratory tests.

TEST RESULTS AND RELATED COMMENTS

The analysis of the obtained experimental data is limited to a few key issues and is presented in a concise format. Within this frame the following can be anticipated:

Axial strain measured in TX tests
The discrepancies between the local ϵ_a (LVDT) and the external ϵ_a (Proximeter) resulted to be negligible at small strain ($< 5 \cdot 10^{-5}$) but

increased with increasing the strain and becoming relevant for the assessment of the stiffness in the range of strain from 10^{-4} to 10^{-3}, see Fig.3.

This is in good agreement with the findings by Goto et al. (1991) and Tatsuoka and Shibuya (1991). From Fig.3 it can also be inferred that the external ϵ_a measured using poor resolution LVDT does not allow a reliable assessement of the stiffness, at least at a strain lower than $2 \cdot 10^{-4}$, despite the quite limited compliance and bedding errors exhibited by the TX apparatus used.

Initial shear stiffness G_0

The values of G_0, obtained from different laboratory tests are plotted in Fig.4 as function of the mean consolidation stress p'.

Such values have been measured in the range of shear strains γ less than the elastic threshold (γ_t^e) strain that, in case of TOS is of the order of 10^{-5}.

To take into account the variation of the void ratio e among the different tests the measured values of G_0 have been divided by the value of void ratio function $F(e)=(2 \cdot 17\text{-}e)^2/(1+e)$ as established for TOS by Iwasaki et al. (1978) on the basis of a large number of cyclic tests. The values of G_0 relative to the results of the TXT's have been inferred from those of the measured initial Young's modulus E_0, assuming that, at a strain less than elastic threshold the isotropic elasticity holds and adopting the values of the Poisson's coefficient $0.12 \leq \nu' \leq 0.15$. This value has been inferred from the locally measured ϵ_a and ϵ_r, see the example shown in Fig.5. The data reported in Fig.4 indicate that the magnitude of G_0 of TOS for all practical purposes depends only on e, p' and on the sand fabric and is only marginally influenced by the type of loading (e.g. monotonic vs cyclic) and by the mechanical overconsolidation. What above stated is in agreement with what has been found for several predominantly silica granular soils, including the TOS, by Tatsuoka and Shibuya (1991) and Shibuya et al. (1992). In Fig.4 the values of $G_0/F(e)$ as inferred by Iwasaki et al. (1978) from RCT's and by Teachavorasinskun (1989) from THCST's are also displayed confirming the validity of the conclusions that have been drawn on the G_0 and testifying a good reproducibility of the laboratory tests examined.

Table 1. Initial Conditions of Specimens

Type of Test	Test n°	e_c -	OCR -	σ'_a bar	σ'_r bar	σ'_{amax} bar
THCS(*)	1	0.871	1	1.04	0.52	1.04
THCS(*)	2	0.751	1	1.20	0.47	1.20
THCS(*)	3	0.906	2.75	1.06	0.77	2.91
THCS(*)	4	0.758	2.75	1.08	0.71	2.97
TX-CID	1	0.783	1	1.43	1.40	1.43
TX-CID	2	0.770	3.04	1.08	1.08	3.28
TX-CK_0D	3	0.690	1	1.89	0.86	1.89

(*) specimens subject to the monotonic torsional shear followed by the RCT's and again by a monotonic torsional shear

e_c = void ratio at the end of consolidation stage

σ'_a = axial effective stress } at the starting

σ'_r = radial effective stress } of the shearing stage

σ'_{amax} = maximum axial consolidation stress

OCR = σ'_{amax}/σ'_a overconsolidation ratio

Shear stiffness G

At strains higher than the elastic threshold the stress-strain response of TOS becomes highly non-linear and the magnitude of the tangent shear modulus G_t is influenced by the type of loading and by the stress history, see Fig.6.

In Fig.7 the decay of the secant shear stiffness G_s normalized with respect to G_0 as function of the shear stress ratio f is shown, being $f(TX)=q/q_{max}$ and $f(RC) = f(THCS)=\tau/\tau_{max}$, where q_{max} and τ_{max} corresponds to the deviator and to the shear stress at failure, respectively. It can be noticed that the hyperbola can very hardly reproduce the observed soil non-linearity for monotonic loading conditions. On the contrary, this kind of fit of experimental stress-strain curves seems to work quite well in case of cyclic loading e.g. the RCT's.

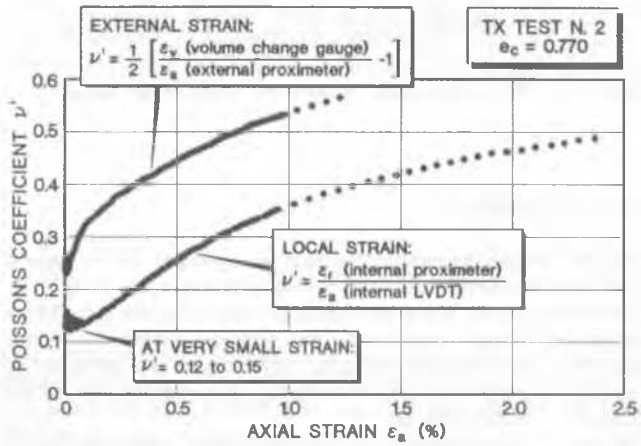

Figure 5 - Poisson's coefficient of Toyoura sand.

	Test	N.	e_c	σ'_a bar	σ'_r bar	OCR
▲	RC K_0-cons.	2	0.751	1.23	0.47	1
△		4	0.758	1.08	0.71	2.75
●	TX CID (*)	1	0.783	1.43	1.40	1
○		2	0.770	1.08	1.08	3.04
♦	TX (*) CK_0D	3	0.690	1.89	0.86	1

$\gamma(RC, THCS) = \sqrt{3}\, \varepsilon_a(TX)$; $G = K_G\,(p')^{n(\gamma)}\,(p_a)^{1-n(\gamma)}$

$p_a = 98.1$ kPa = 1 bar

$n(\gamma) = 3.738 + 1.795 \log\gamma + 0.326 (\log\gamma)^2 + 0.02005 (\log\gamma)^3 \leq 0.75$

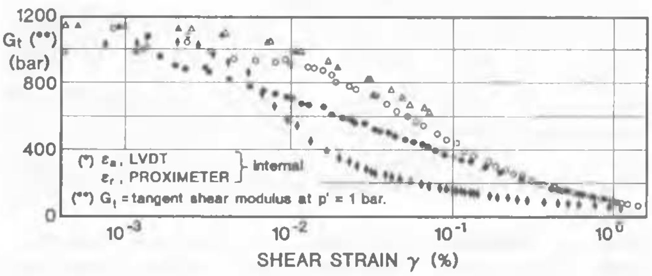

Figure 6 - Shear stiffness of Toyoura sand vs. shear strain.

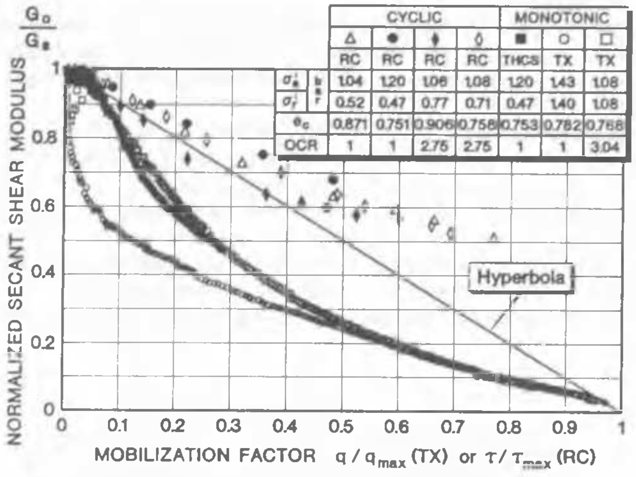

Figure 7 - Normalized shear modulus vs. mobilization factor.

FINAL REMARKS

- The sensors used to measure the local strain during TXT's allow a reliable assessment of the TOS stiffness at strains up to $5 \cdot 10^{-6}$.
- In the triaxial cell, where bedding errors and equipment compliance have been largely minimized, the differences between locally (LVDT's) and externally measured axial strains are negligible at $\epsilon_a \leq 10^{-5}$ but increases with increasing ϵ_a, becoming relevant for the assessment of the stiffness.
- The initial shear stiffness G_0 of TOS is scarcely influenced by the type of loading and by the mechanical overconsolidation.
- Exceeding the elastic threshold strain $\approx 10^{-5}$, the TOS exhibits a highly non linear behaviour that for monotonic loading cannot be fit by a hyperbola.

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