Maximum Shear Modulus Measurement Using Bender Elements in Oedometer Tests

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ABSTRACT. This paper refers to the results obtained during oedometer tests equipped with bender elements. The influence of void ratio, stress history and anisotropy on the maximum shear modulus Go has been investigated for two Italian clays, such as Fucino and Panigaglia. The first is a lightly overconsolidated, CaCO3 cemented, clay of lacustrine origin. The second is a very soft, normally consolidated silty clay.

1. Introduction

The great number of papers concerning the use of seismic laboratory techniques, applicabile to both large and small size specimens, testifies the increased interest in this approach to measure the initial stiffness of soils [WOODS and HENKE, 1979; STOKOE *et al.*, 1985; LO PRESTI and O'NEIL, 1991; ROESLER, 1979; SCHULTEISS, 1981; DYVIK and MADSHUS, 1985; DYVIK and OLSEN, 1989; THOMANN and HRYCIW, 1990; BRIGNOLI and GOTTI, 1991; DE ALBA and BALDWIN, 1991; AGARWAL ISHIBASHI, 1991; GOHL and FINN, 1991; VIGGIANI, 1991; SANTAMARINA *et al.*, 1991]. The use of this techniques, initiated in late sixties [LAWRENCE, 1965], improves the knowledge of soil behaviour making possible the selection of initial shear modulus appropriate for the solution of the relevant boundary value problems.

This paper refers to the results obtained from oedometer tests equipped with bender elements (BE) and performed on undisturbed and remoulded specimens of two clays.

BE have been developed at NGI [DYVIK and MADSHUS 1985; DYVIK and OLSEN 1989]. Be piezoceramics are widely used in the laboratory to measure the shear wave velocity by means of vibration of small amplitude and thus to compute the maximum shear modulus Go.

The tests presented here are part of a research project undertaken at the Politecnico di Torino.

The project involves the use of several apparatuses such as triaxial (internal strain measurement and BE equipped), monotonic and cyclic torsional shear, resonant column as well as Ko-IL oedometer equipped with BE.

The main objects of the research project are the following:

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- assessing the influence of void ratio e, stress history and soil fabric on Go;
- comparing Go obtained from static (monotonic or cyclic) and dynamic (cyclic) tests.

2. Soil types

The overall project involves investigation of several Italian clays such as, Fucino, Panigaglia, Pisa, Taranto, Garigliano. The significative results, concerning Fucino and Panigaglia undisturbed clay specimen are here reported.

Fucino clay

It is a medium to stiff, homogeneous, highly structured, CaCO3 cemented, quaternary, lacustrine clay. The test specimens were sampled from two different locations at a depth ranging from 15 m to 30 m in overconsolidated strata. The geological age of the strata ranged from 30000 to 64000 years. The site is located about 80 km east of Rome in the Appennines. A detailed geotechnical characterization can be found in [PANE and BURGHIGNOLI, 1988] and AGI [1991].

Panigaglia silty clay

This is a nearshore site located in the gulf of La Spezia. The sea level is on average 6-7 m above the ground level. It is a very soft, normally consolidated silty clay. For a detailed geotechnical characterization of Panigaglia site refer to JAMIOLKOWSKI *et al.*, [1985].

Index properties of the tested specimens are reported in Table 1.

3. Test program and equipment

Two different Ko incremental loading oedometers, both equipped with BE, have been used in this re-

TABLE I

SITE	DEPTH	TEST	W_L	W_n	PI	CaCO3	G_s
—	(m)	—	%	%	%	%	—
Fucino	15.00 15.55	19V	39	48	14	91	2.674
		18H		46			
Fucino	30.00 30.60	3V	116	68	81	51	2.578
		4H		70			
Panigaglia	6.35 7.20	5H	71	64	44	12	2.757
		17V		66			

search. One of them has a thick wall stainless steel ring of square cross-section with rounded edges housing a 20 cm^2 soil sample. The lateral faces of such ring are equipped with flush pressure transducers allowing to measure the total horizontal stress σ_h. The second one consists of a stainless steel ring, 0.8mm thick, equipped with strain gauges to measure the horizontal stress.

The following test conditions were adopted:

- the excitating signal had a square wave form with a frequency of 100 Hz and a voltage of 20 Volts peak to peak;
- during a loading step measurements were taken at different consolidation times.

More details about equipment, test procedure and test interpretation can be found in CONTI *et al.*, [1992]. For each sample two different oedometer tests have been performed. One specimen was cut vertically, the other horizontally (see Fig. 1). Thus, it was possible to measure the shear moduli referring respectively to vertical (Gvh) and horizontal (Ghh) planes.

It was also decided to repeat the same tests on remoulded specimens, in the case of cemented clays. Tests are still underway.

4. Results and comments

In total six tests results are presented in this paper. Four of them have been performed on samples of Fucino clay taken at two different locations. The sample taken at a depth of about 30 m. below G.L. has higher plasticity PI = 81% and lower CaCO3 = 51 % content, while that retrieved at the depth of 15.3 m has much lower PI = 14% and higher CaCO3 = 92%. The remaining tests have been performed on two specimens of Panigaglia clay.

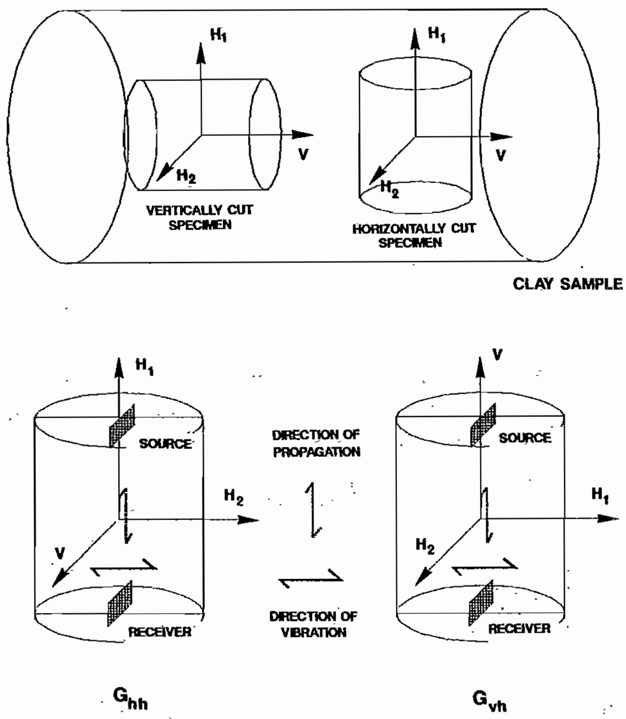


FIG.1 : CLAY SPECIMENS

4.1 *Void Ratio Function*

According to JAMIOLKOWSKI *et al.*, [1991], the shear modulus at small strain can be expressed in the following way:

$$Go = C_g F(e) \sigma_a^{2na} \sigma_b^{2nb} p_a^{(1-2na-2nb)} \quad (1)$$

where:

C_g = material constant
F(e) = void ratio function
Cg*F(e) = modulus number
2na ≈ 2nb ≈ 0.25 modulus exponents
σ_a = effective stress acting in the direction of wave propagation
σ_b = effective stress acting in the direction of particle motion

Many empirical or semiempirical expressions are available for F(e) in literature but they do not have a general validity. Recently JAMIOLKOWSKI *et al.*, [1991] proposed the following empirical formula filling a large number of experimental data:

$$F(e) = 1/e^{1.3} \quad (2)$$

A regression analysis of the experimental data was carried out. The analysis showed that the following formula:

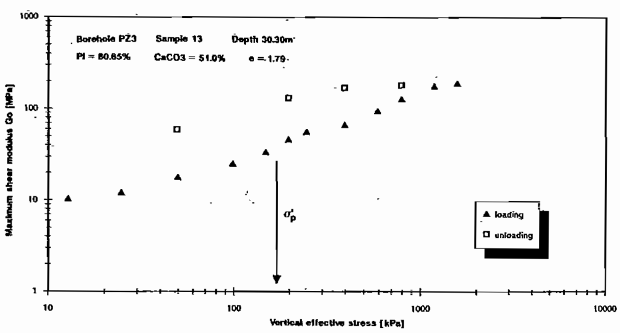
$$F(e) = 1/e^{x} \quad (3)$$

with x ranging between 1.2 and 1.6 was the best fit of the experimental data. Thus it was decided to use eq. (2) to normalize Go when making comparisons.

4.2 *Effect of OCR on Go*

In Fig. 2 the shear modulus Go is plotted vs. the vertical effective stress σ'_v. From this figure it could be inferred that OCR has a relevant influence on Go. However note that the Go values plotted in Fig. 2 were not normalized to account for changes of void ratio and confining stresses.

FIG.2 : Go VS VERTICAL EFFECTIVE STRESS
FUCINO CLAY VERTICALLY CUT SPECIMEN



Go was normalized according to Eq. 1 and 2. The normalized Go is shown in Fig. 3. From this Fig. it is possible to conclude that the effect of OCR on Go is not much relevant. Similar results were obtained in each test. The values of Go plotted in Fig. 3 are those measured after 24h of consolidation.

4.3 *Effect of anisotropy on Go*

The normalized shear modulus of the vertically cut specimen is compared to that of the horizontally cut specimen for each clay and for each depth in Figs. 4a, 4b, and 4c.

It is possible to observe the following:

FIG.3 : Go/F(e) VS CONSOLIDATION STRESSES
FUCINO CLAY VERTICALLY CUT SPECIMEN

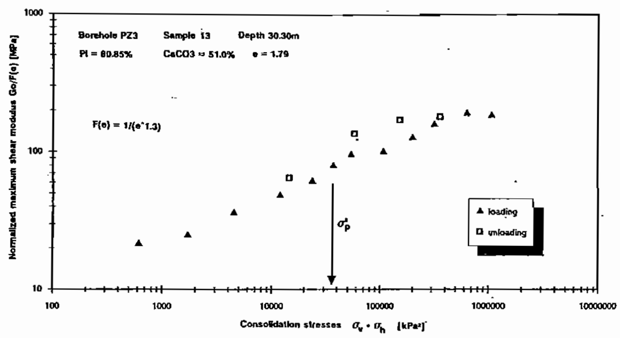


FIG.4a : Go/F(e) VS CONSOLIDATION STRESSES
FUCINO CLAY SPECIMENS

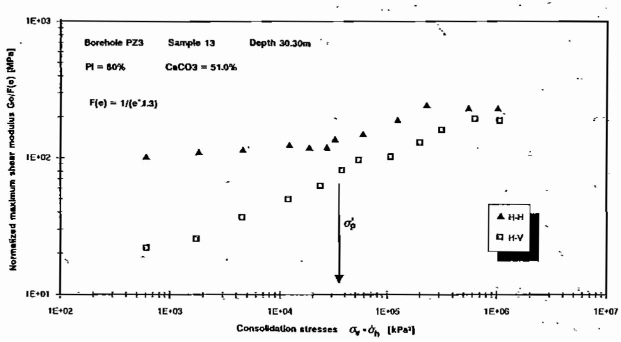


FIG.4b : Go/F(e) VS CONSOLIDATION STRESSES
FUCINO CLAY SPECIMENS

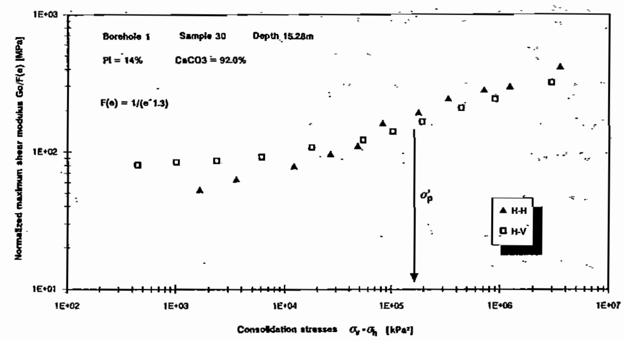
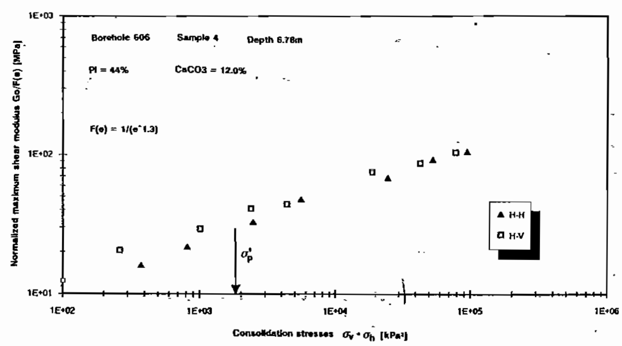


FIG.4c : Go/F(e) VS CONSOLIDATION STRESSES
PANICAGLIA CLAY SPECIMENS



- for the NC Panigaglia specimens (5H -17V) and for the overconsolidated and CaCO3 cemented Fucino (18H - 19V) G_{hh} is more or less equal to G_{vh}.
- results concerning the other two specimens of Fucino clay (3V-4H) give contradictory indications In particular:

$$G_{hh} = 4.0 - 1.2\, G_{vh} \text{ until } \sigma'_v < \sigma'_p$$

$$G_{hh} = 1.2\, G_{vh} \text{ when } \sigma'_v > \sigma'_p$$

The oedometer curves of horizontally and vertically cut specimens are compared in Figs. 5a,5b and 5c.From a qualitative point of view this comparison gives similar indications to those observed examining the shear modulus.

FIG.5a : VOID RATIO VS VERTICAL EFFECTIVE STRESS
FUCINO CLAY SPECIMENS

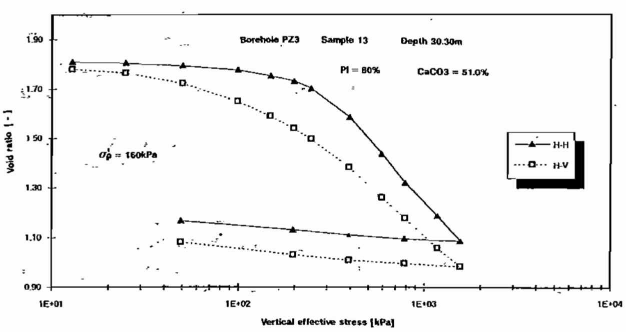


FIG.5b : VOID RATIO VS VERTICAL EFFECTIVE STRESS
FUCINO CLAY SPECIMENS

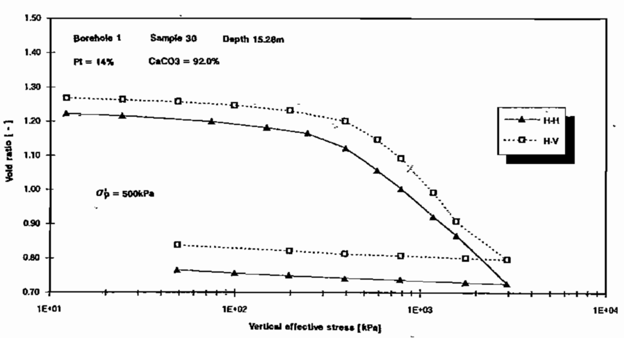
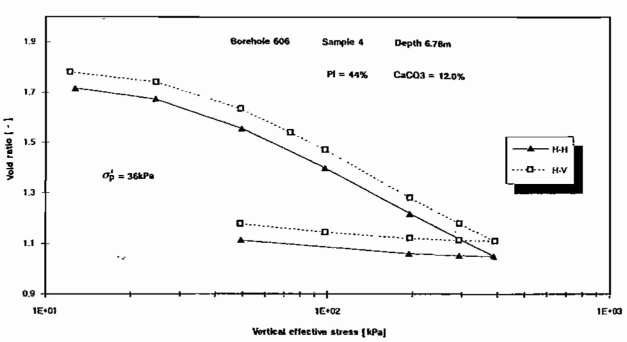


FIG.5c : VOID RATIO VS VERTICAL EFFECTIVE STRESS
PANIGAGLIA CLAY SPECIMENS



To explain such a contradictory results, further experimental research is required. However it is possible to put forward the following hypotheses.

a) the CaCO3 content alone is probably not sufficient to describe the importance of the cementing bonds and its relevance to the soil fabric.

b) Go is extremely sensible to soil disturbance [HARDIN and BLACK, 1968], therefore G_{vh} and G_{hh} should be contemporary measured on the same specimen.

c) The spatial variability of soil properties and soil fabric is another reason to avoid duplicated specimens.

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SOMMARIO

L'articolo riporta alcuni risultati, relativi alla misura del modulo di taglio a piccole deformazioni, effettuata su provini di argille italiane nel corso di prove edometriche, utilizzando la tecnica dei Bender Elements. Le apparecchiature edometriche utilizzate sono del tipo a incremento di carico con misura della pressione orizzontale.

L'indagine fa parte di un progetto di ricerca, intrapreso al Politecnico di Torino allo scopo di studiare il comportamento delle argille a piccole deformazioni per mezzo di prove di tipo statico monotono, cicliche e dinamiche.

Sono state programmate prove edometriche su campioni indisturbati delle argille di Fucino, Panigaglia, Pisa, Garigliano e Taranto.

Nell'articolo vengono riportati i risultati più significativi relativi ai provini indisturbati del Fucino e di Panigaglia. L'argilla del Fucino è sovraconsolidata e cementata per la presenza di carbonato di calcio in percentuale variabile con la profondità. I campioni dell'argilla del Fucino provengono da due diverse località e presentano proprietà indice e contenuto di carbonati molto diversi tra di loro.

L'argilla di Panigaglia è estremamente tenera e normalconsolidata.

Per ogni campione si sono ricavati due provini, uno trafilato in maniera tradizionale, l'altro perpendicolarmente all'asse verticale, in maniera tale da poter misurare il modulo di taglio nel piano verticale (G_{vh}) e quello relativo al piano orizzontale, assunto come piano di isotropia (G_{hh}). Nel caso dei terreni cementati si è voluto confrontare il comportamento del materiale intatto con quello rimaneggiato. I risultati riguardanti tale aspetto non sono ancora definitivi.

Nel corso della ricerca è stato possibile studiare l'influenza sul modulo Go a piccole deformazioni dell'indice dei vuoti,della storia tensionale e dell'anisotropia.

Le principali conclusioni del lavoro si possono così riassumere:

i) per le argille considerate è possibile esprimere la dipendenza di Go dall'indice dei vuoti, in modo soddisfacente, utilizzando la funzione $F(e) = 1/e^{1.3}$.

ii) l'effetto della storia tensionale meccanica sul modulo Go è risultata trascurabile se si tiene opportunamente conto sia dell'indice dei vuoti sia del livello tensionale.

iii) per quel che riguarda l'influenza dell'anisotropia su Go i risultati sperimentali ottenuti hanno fornito indicazioni contraddittorie. In particolare G_{hh} è risultato più o meno uguale a G_{vh} per l'argilla di Panigalia e nel caso dei campioni di Fucino con più elevato contenuto in carbonati. Invece nel caso dei campioni di Fucino di elevata plasticità e per pressioni verticali inferiori a quella di preconsolidazione il rapporto G_{hh}/G_{vh} è risultato superiore all'unità ed anche pari a 4, mentre per valori della tensione verticale superiori a quella di preconsolidazione il rapporto si è stabilizzato attorno ad 1.2.

Risulta difficile inquadrare tali risultati in un contesto razionale ed emerge la necessità di ulteriori indagini. Tuttavia appare lecito avanzare alcune ipotesi:

- il contenuto in carbonati non è in grado da solo di descrivere l'importanza della cementazione e la sua influenza sulla struttura del campione.
- la sensibilità di Go al disturbo richiede la misura contemporanea sullo stesso provino di entrambi i moduli di taglio.
- la variabilità spaziale delle proprietà dei terreni suggerisce anch'essa la necessità di operare su un unico campione.