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Paper No. 1969. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

LABORATORY AND FIELD DETERMINATIONS OF SMALL-STRAIN SHEAR MODULUS OF NATURAL SOIL DEPOSITS

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ABSTRACT

Values of the small-strain shear modulus, G_0, of three natural Italian soils deposits with age ranging from holocene to middle pliocene are presented. These values were obtained in the laboratory by using resonant column and seismic tests based on the use of piezoelectric transducers and in the field by cross-hole tests. The purpose of the paper is to compare the results of the two different laboratory testing techniques with one another and with those obtained from in situ tests. It has been found that the small-strain shear moduli obtained from resonant column tests are generally lower than those determined from laboratory seismic tests. Moreover, laboratory values are generally lower than those determined from in situ tests. The possible reasons of these discrepancies are examined and discussed.

KEYWORDS

small strains, shear modulus, resonant column, laboratory seismic test, in situ test, natural soils

INTRODUCTION

The small-strain shear modulus, G_0, is a fundamental parameter for a variety of geotechnical applications and plays a key role in all problems involving a dynamic soil behaviour response such as the study of earthquake effects, the action of wave loadings, the machines or traffic vibrations, etc. G_0 is generally evaluated using either laboratory or field tests. In the laboratory, the most common is the resonant column test in which the response of a cylindrical sample subjected to forced harmonic torsional vibrations is measured. An alternative technique is based on the use of piezoelectric transducers for the measurement of the shear wave velocity in soil samples (Dyvik and Madshus, 1985). In the field, the small-strain shear modulus is usually evaluated from the shear wave velocity using the cross-hole, the down-hole or the SASW techniques.

In the framework of a program of interdisciplinary studies called "Irpinia Project" and issued by the "ENEA (Italian National Agency for Alternative Energy Sources)-ENEL (National Electricity Board of Italy) Commission for the study of seismic problems related to the construction of power plants", a research contract was undertaken by ENEL and the Department of Structural and Geotechnical Engineering of the "La Sapienza" University of Rome. Aim of the project is to identify the main geotechnical aspects that might affect the characteristics of seismic motion recorded by the accelerometric stations of the ENEL strong motion network during the 23-11-1980 Irpinia earthquake (Southern Italy). For this purpose, an extensive geotechnical investigation comprising laboratory and field tests on the soils deposits underlying these accelerometric stations has been carried out by ISMES of Bergamo. In this paper, the results of laboratory and field tests relative to the measurements of the small-strain shear modulus performed on the soil deposits of different age of three selected accelerometric stations are examined and discussed. Resonant column and seismic tests for the measurement of the shear wave velocity were used in the laboratory while the cross-hole technique was used in the field. The values of G_0 obtained from resonant column tests are compared with those from laboratory seismic tests and both are compared with the results of in situ tests.

EXPERIMENTAL TECHNIQUES

Resonant column (RC) tests were performed by using a fixed-free type apparatus (Isenhower, 1979). In the fixed-free RC test the bottom end of the specimen is rigidly fixed against rotation at the base pedestal while the top (free end) is connected to a drive system that is used to apply the torsional excitation. The frequency of excitation is varied until resonance occurs. The resonant frequency, the weight and the dimensions of the specimens enable to determine the shear wave velocity of the soil. As it is known, G_0 is related to V_S by the expression $G_0 = \rho V_S^2$ where ρ is the density of the soil. The laboratory seismic (LS) tests involve the use of piezoelectric transducers placed at opposite ends of the soil specimen. The transducer at one end is used to generate a shear wave pulse which propagates through the specimen and is received by the transducer at the other end of the specimen. The shear wave velocity V_S is determined from the distance between the two transducers and the time required by the wave to cover this distance. The tests described in the paper were performed by using two types of piezoelectric transducers, i.e. bender elements and shear plates. A detailed description of the main differences between bender elements and shear plates can be found in Brignoli and Gotti (1992) in which the satisfactory comparability of the V_S measurements obtained with the two types of transducers is also demonstrated. The transducers were mounted in triaxial cells. Globally, 25 RC tests and 20 LS tests were performed on 24 specimens isotropically consolidated at different values of the effective confining pressure. In both RC and LS tests cylindrical specimens with a 50 mm diameter and 100 mm height were used. The effects of the time of confinement on G_0 was not investigated.

The cross-hole (CH) measurements were carried out in two 100 m long adjacent boreholes, located 5 m apart. The distance between two successive measurements was constant and equal to 1 m.

SOILS TESTED

The main relevant features of the three natural soil deposits subjected to investigation are summarised below (see also Table 1).

Garigliano

The site is located 70 km inland from the Gulf of Gaeta (about 60 km north of Naples) along the alluvial deposits of the Garigliano river of holocene to upper pleistocene age. The soil profile consists of 18 m of medium to high plasticity clayey silts, 6 m of silty sands, 16 m of gravels and 50 m of low plasticity silty sands. The results of laboratory tests refer to undisturbed samples taken between depths of 3 and 18 m, in correspondence of clayey silts, and 48 to 68 m, in correspondence of silty sands. The deposit is normally consolidated.

San Severo

It is a location about 30 km NW of Foggia, a town 30 km from the Adriatic sea coast. The deposit, of upper pleistocene to lower pliocene age, consists of an upper layer of gravel with sand, 2 m thick, overlying alternating layers of medium plasticity silty sands and sandy silts down to a depth of 100 m. The undisturbed samples were retrieved between depths of 3 and 40 m.

Benevento

It is a location in the central Apennines about 90 km NE of Naples. The deposit, of middle pliocene, consists of layers of gravels mixed with silt and sand interbedded with layers of medium plasticity clayey silts down to a depth of 78 m; from 78 to 100 m a thick deposit of stiff clay of middle pliocene is encountered. The undisturbed samples were retrieved between depths of 12 and 38 m, in correspondence of clayey silt soils. The deposit is overconsolidated, with an OCR inferred from oedometer tests of about 3.

Table 1. Main characteristics of the tested soils

Site	Geological age	Type of soil	w_L	PI	LI	CF (%)	OCR	e_0
Garigliano	holocene-upper pleistocene	clayey silts	37÷58	23÷38	0.39÷0.60	23÷42	1	0.77÷1.03
		silty sands	25÷28	10÷12	0.67	5÷22		0.74÷1.07
San Severo	lower pleistocene-upper pliocene	sandy silts and silty sands	27÷37	14÷22	0.18÷0.44	14÷33	-	0.48÷0.62
Benevento	middle pliocene	clayey silts	40÷46	24÷30	0.08÷0.18	32÷46	3	0.49÷0.60

RESULTS OF LABORATORY TESTS

It is generally recognised that the small-strain shear modulus G_0 is a function of voids ratio, effective stresses, stress history and soil properties. For isotropic conditions of confinement this dependence can be conveniently expressed in the form (Hardin, 1978):

$$G_0 = S\, F(e)\, OCR^k\, (\sigma'_0)^n\, (p_a)^{1-n} \qquad (1)$$

where S is a stiffness coefficient, F(e) is a voids ratio function, OCR is the overconsolidation ratio, k is an empirical exponent, σ'_0 is the effective confining stress, n is a stiffness index and p_a is the atmospheric reference pressure ($p_a \cong 100$ kPa). The dimensionless parameters S, k and n account for the soil nature and are usually correlated to the plasticity index of the soil, PI (Viggiani, 1992; Rampello et al., 1994). By assuming that the overconsolidation does not influence the magnitude of the small-strain shear modulus in any significant way (Jamiolkowski et al., 1994), the eq. (1) simplifies into:

$$G_0 = S\, F(e)\, (\sigma'_0)^n\, (p_a)^{1-n} \qquad (2)$$

Several empirical correlations are available in the literature to express the voids ratio function which provides the best fit for the experimental data. Jamiolkowski et al. (1991) have proposed a simple F(e) in the form:

$$F(e) = e^{-x} \qquad (3)$$

where x was found to vary between 1.1 and 1.5 with a mean value of 1.3.

On the basis of eqs. (2) and (3), a multiple linear regression analysis of the experimental data was performed. The values of parameters S, n and x are summarised in Table 2 in which the values of the correlation coefficient, r, are also reported. In Figs. 1a to 1d the values of G_0 normalised by the voids ratio function given by eq. (3) were plotted versus the effective confining stress σ'_0 in a double logarithmic plane for the three soils. For Garigliano site two different plots were considered, corresponding to the results of the clayey silt samples and the silty sand samples respectively. In all these figures the log $G_0/F(e)$ versus log σ'_0 results are very well approximated by a straight line either for RC or LS tests results. This fact is even substantiated by the values of the correlation coefficients, generally higher than 0.93. For Garigliano site (Figs. 1a and 1b) the data points inferred from RC tests are close to those determined with LS tests and, consequently, a unique linear regression line has been drawn for all the data. For San Severo site (Fig. 1c) the data points determined from RC tests are much lower than those obtained from LS tests in the whole range of σ'_0 investigated. It is interesting to note that the slope of the regression lines, which is represented by the parameter n, is practically the same from RC and LS tests; this means that the value of n is independent from the experimental technique. For Benevento site (Fig. 1d) the data points inferred from RC tests are lower than those obtained from LS tests with this difference decreasing as confining pressure increases.

The reasons for the discrepancies between RC and LS tests are not completely clear. However, it is interesting to note that a good agreement is observed for the youngest soil deposit; on the other hand, differences more or less remarkable are observed for the two older soil deposits. It cannot be excluded that these discrepancies might be related to the fundamental nature of the two testing techniques, involving different frequencies and different shear strain levels (Brignoli and Gotti, 1992; Jamiolkowski et al., 1994).

Table 2. Parameters of eq. (2) as obtained from regression analyses performed on resonant column (RC) and laboratory seismic (LS) tests

Site	Type of soil	S	n	x	r
Garigliano	clayey silts	410 (RC-LS)	0.59 (RC-LS)	1.20 (RC-LS)	0.930
	silty sands	442 (RC-LS)	0.73 (RC- LS)	1.66 (RC-LS)	0.944
San Severo	sandy silts and silty sands	358 (RC)	0. 57 (RC)	1.21 (RC)	0.966
		728 (LS)	0.60 (LS)	0.89 (LS)	0.958
Benevento	clayey silts	506 (RC)	0.42 (RC)	1.10 (RC)	0.998
		987 (LS)	0.19 (LS)	1.30 (LS)	0.664

Based on the results from RC tests, the reliability of the F(e) assumed was also evaluated. In Fig. 2 the solid lines represent, for each soil with the exception of the silty sand of Garigliano site, the relationships between G_0 and the voids ratio at σ'_0=100 kPa, which are derived from eq. (2). Also indicated in the figure is the range typical for cohesive soils determined from RC tests (Jamiolkowski et al., 1991). It can be noted that the lines relative to the soils tested fall in this range, even if a certain divergence exists for high values of void ratio for Benevento site. The $F(e)=e^{-x}$ give thus a reasonable normalisation for most of the soils investigated.

COMPARISON BETWEEN LABORATORY AND IN SITU VALUES OF V_S

The values of the shear wave velocity V_S obtained from CH tests are considered as the true field parameters. To compare these values with those obtained from laboratory tests, in situ stresses representative of the field conditions need to be computed. The mean effective stress σ'_m in the field was evaluated using $\sigma'_m=\sigma'_v(1+2K_0)/3$ where σ'_v is the vertical effective stress and K_0 is the coefficient of earth pressure at rest. Empirical correlations were used to determine the coefficient of earth pressure at rest as a function of PI and OCR (Brooker and Ireland, 1965). K_0 was assumed equal to 0.5 and 0.8 for Garigliano and Benevento sites respectively; for San Severo site K_0 was assumed equal to 0.85 for an approximate value of OCR=3. The σ'_m values calculated in this way were used to determine G_0 by means of eq. (2). These G_0 values were thus elaborated in terms of V_S. No correction for the age of the deposit was applied to the laboratory tests results.

The results of the comparisons are shown in Figs. 3 to 5 for the three sites. In these figures the stratigraphic logging, the shear wave velocity profile obtained with the CH tests and the points representative of V_S values obtained from laboratory tests are indicated. For Garigliano site (Fig. 3) it results that the V_S values obtained from laboratory tests agree well with those obtained from CH tests, with the exception of the data relative to

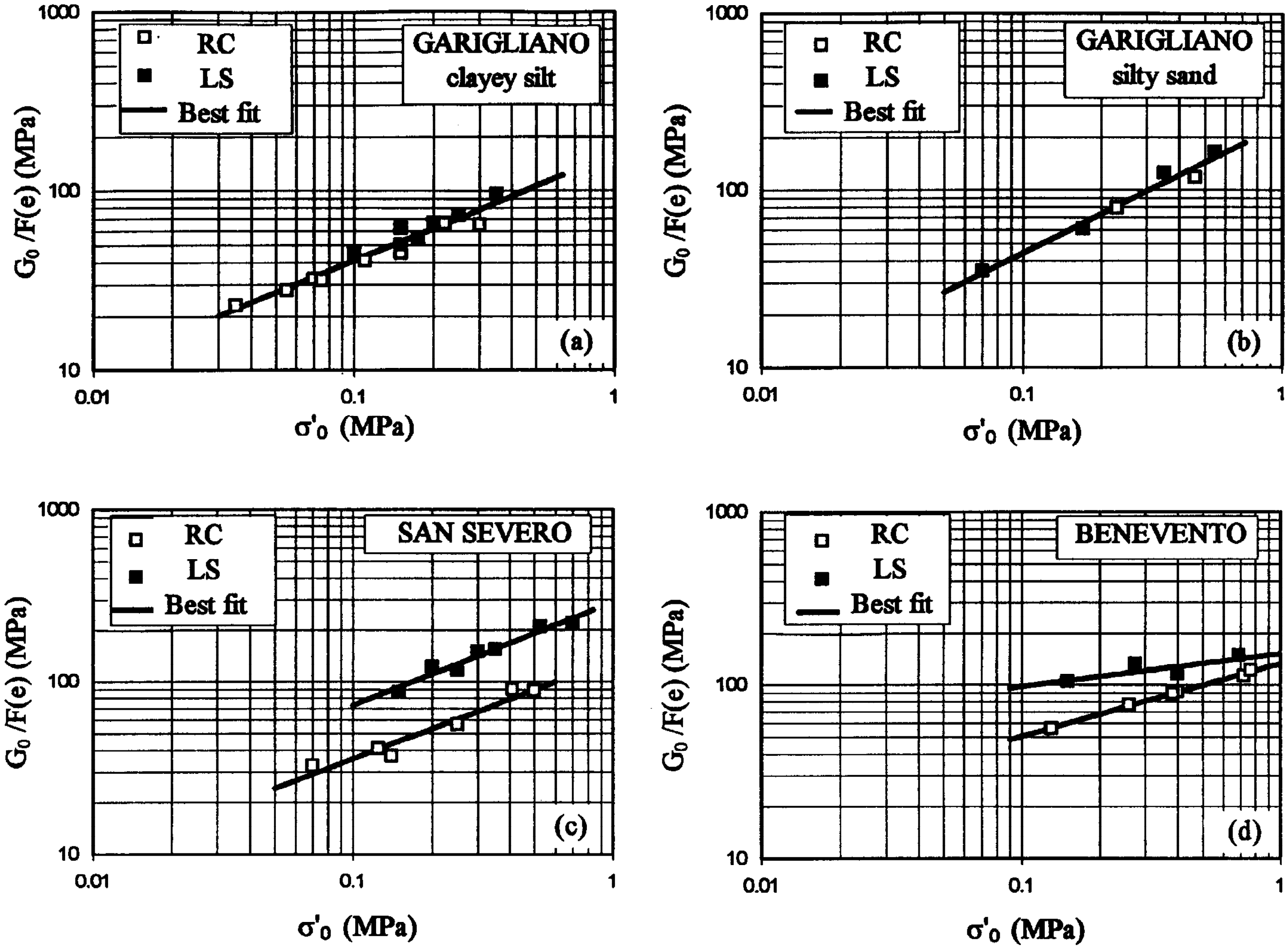

Fig. 1. Normalised maximum shear modulus versus isotropic effective confining stress

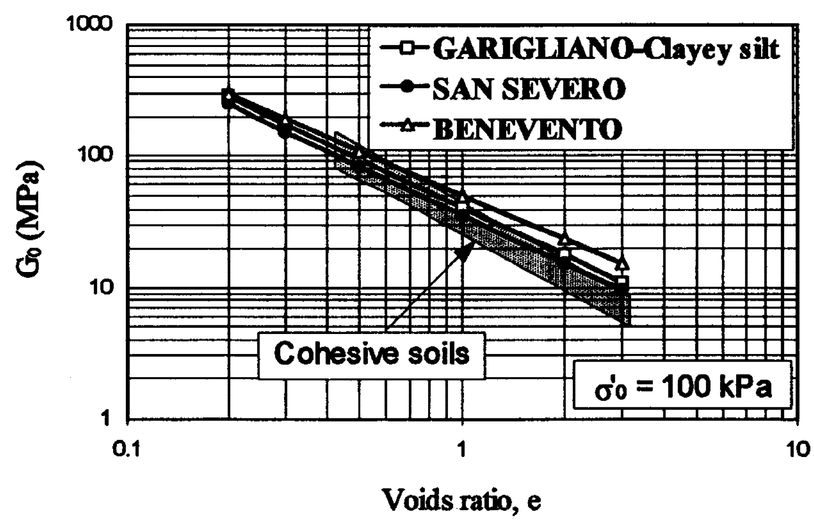

Fig. 2. Maximum shear modulus at σ'_0=100 kPa versus voids ratio

the upper 3 to 8 m desiccated crust and those at a depth of about 48 m in the silty sands. This latter inconsistency has also been found for high sand content samples of sandy silt by Jamiolkowski et al. (1994). At San Severo site (Fig. 4) the laboratory tests systematically yield Vs values lower than the CH field ones. However, laboratory and field values follow the same general trend throughout the soil profile. At Benevento site (Fig. 5), due to the probably heterogeneity of the deposit also in the horizontal direction, the information given by the stratigraphic logging do not correspond to the shear wave velocity profile. This is evident at depths between about 10 to 18 m in which the clayey silt show V_S values typical of the underlying gravel. For this reason it seems reasonable to compare V_S values determined from laboratory tests at a depth of 12 m with those obtained from CH tests at depths between 6 and 9.5 m. With this assumption the V_S value determined from the LS test agrees well with that obtained from CH field test; on the other hand the V_S value determined from RC test is slightly lower than that obtained from CH test. The same trend can be observed for the laboratory data points relative to the depths of 34 and 37 m.

From the above observations, some conclusions can be drawn. The best agreement between laboratory and field values of V_S was obtained for the youngest soil deposit of Garigliano. This fact demonstrates the good quality of undisturbed samples; furthermore, it can be deduced that there is no need to correct the laboratory values to account for the age of the deposit. The other two soil deposits, which are older than Garigliano, exhibit differences between laboratory and field values especially pronounced for San Severo site. These differences can be presumably related to the disturbance effects inevitable also for "undisturbed" samples. In fact it has been found that the effects of sample disturbance increase with the age of a soil deposit (Tatsuoka and Kohata, 1995); moreover these effects may be even greater for silty soils of low plasticity (Lefebvre *et al.*, 1994) and for those containing high percentage of sand (Jamiolkowski *et al.*, 1994). This latter fact may be responsible for the remarkable differences observed at San Severo site. Finally, it should be pointed out that the long-term time effects (Anderson and Stokoe, 1978) were not taken into account and this circumstance could also explain the existing discrepancies between laboratory and field data.

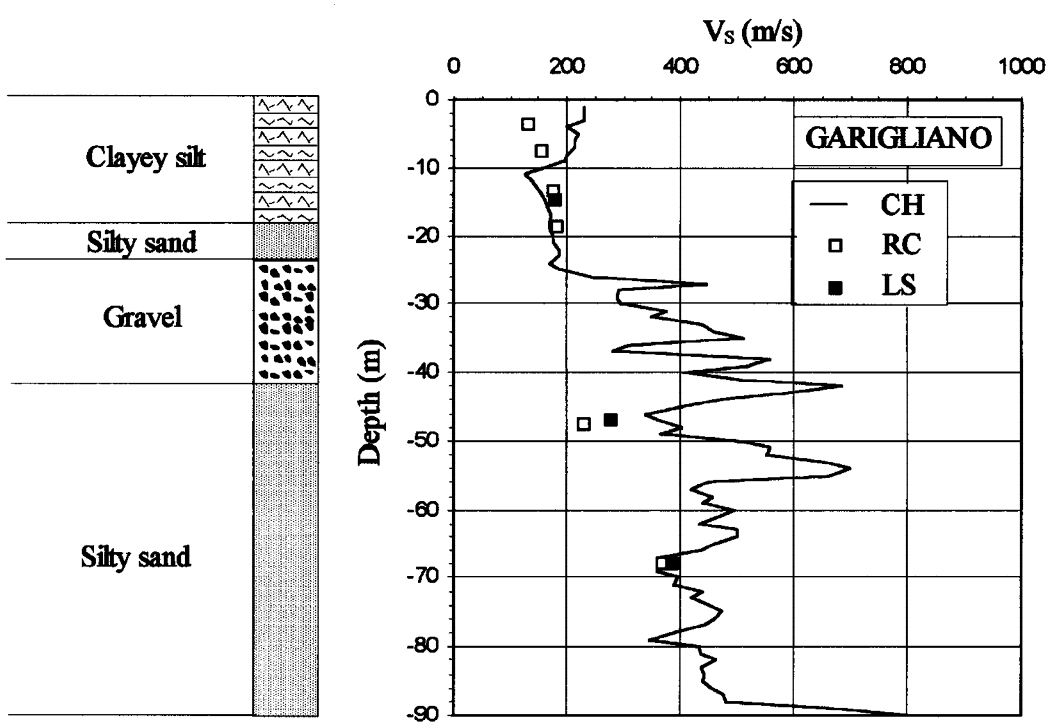

Fig. 3 - In situ versus laboratory shear wave velocity for Garigliano site

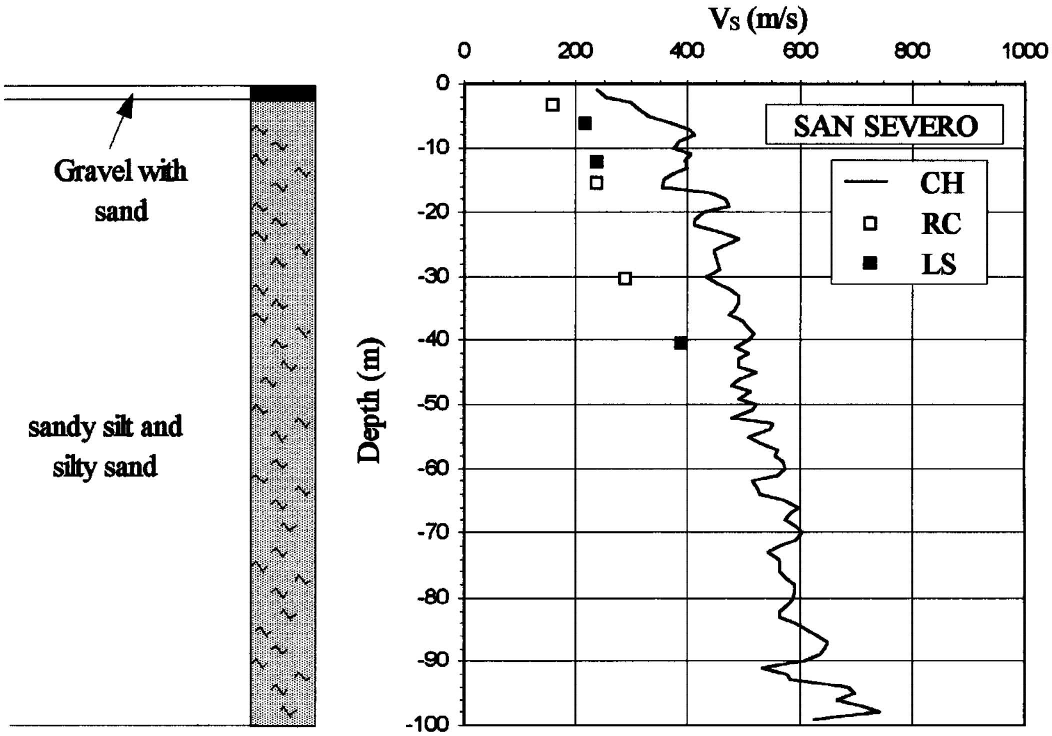

Fig. 4 - In situ versus laboratory shear wave velocity for San Severo site

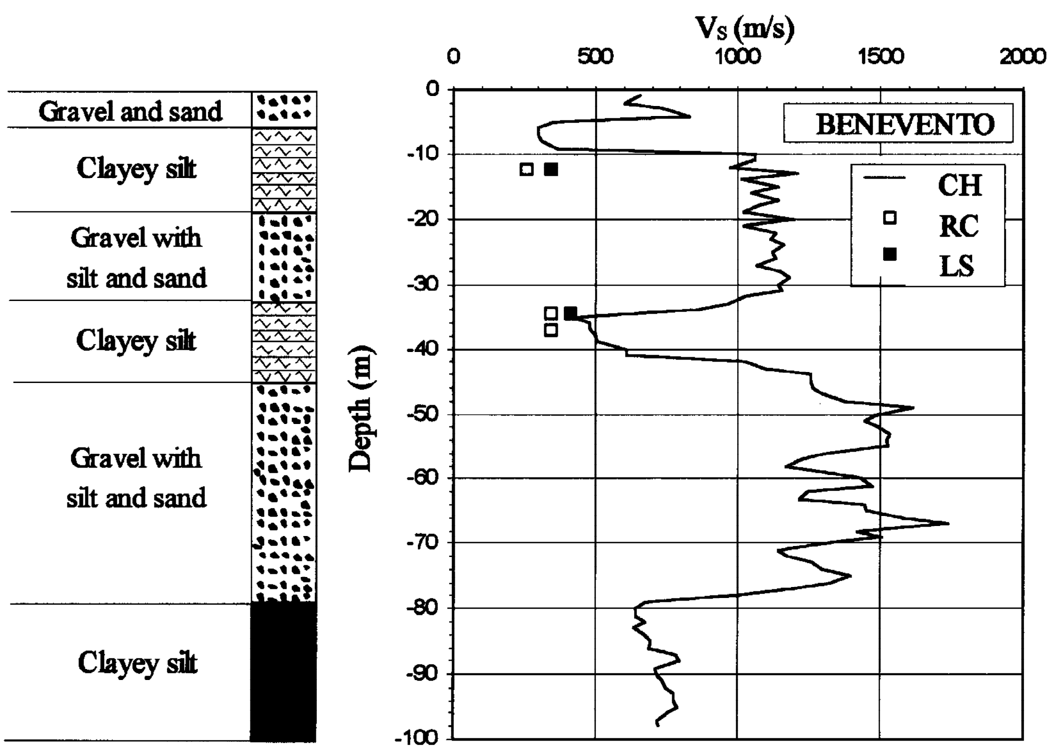

Fig. 5 - In situ versus laboratory shear wave velocity for Benevento site

CONCLUSIONS

Results of laboratory and in situ tests have been presented in order to investigate the small-strain shear modulus G_0 of three natural Italian soil deposits of ages ranging from holocene to middle pliocene. It was found that for the youngest soil deposit the values of G_0 determined from laboratory seismic tests are close to those from resonant column tests; for the other two older soil deposits the values of G_0 from laboratory seismic tests are higher than those from resonant column tests. The reasons for these discrepancies are not completely clear. It is supposed that these discrepancies might be essentially related to the fundamental nature of the two testing techniques employed, involving different frequencies and different shear strain levels.

In all the sites it was also possible to compare the values of the shear wave velocity V_S measured in situ with those obtained from laboratory tests at effective stresses comparable with those existing in the field. It resulted that for the youngest soil deposit laboratory and in situ values are in a fairly good agreement while for the oldest ones the laboratory values are generally lower than those determined from in situ tests. As in situ tests are believed to provide the most reliable measure of the shear wave velocity, the effects of sample disturbance have been invoked as a possible explanation of the underestimation of V_S determined from laboratory tests. However, it should be noted that the consideration of long-term time effects, which were not taken into account, could have also improved the agreement between laboratory and field tests.

ACKNOWLEDGEMENTS

The Authors wish to express their thanks to ENEL S.p.A. for allowing the publication of the results of laboratory and in situ tests presented in this paper.

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