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DYNAMIC SITE CHARACTERIZATION BY THE SEISMIC DILATOMETER MARCHETTI TEST IN CENTRAL ITALY

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ABSTRACT

This paper describes and compares the results of in situ and laboratory investigations performed on two Italian sites: St. Giuliano di Puglia (CB) located in the Molise region and Tito Scalo (PZ) located in the Basilicata Region. The tests were carried out to determine the variation of shear wave velocity with depth and strain level by Seismic Dilatometer Marchetti Test (SDMT), Cone Penetration Test (CPT), Noise Analysis Surface Waves (NASW), Down-Hole (DH) Test and Resonant Column Tests (RCT). Some considerations on shear modulus degradation evaluation by SDMT are proposed. The available data also enabled one to compare the shear modulus profile obtained by empirical correlations based on CPT and NASW or laboratory results with Down Hole Test and Seismic Dilatometer Marchetti Test.

INTRODUCTION

The shear wave velocity V_S and shear modulus G_o are at the base of any seismic analysis. The G-γ decay curves of stiffness with strain level are an increasingly requested input in seismic analyses and, in general, in non linear analyses. Moreover in the world increasing demand for liquefiability evaluations by direct evaluation of dynamic soil property.
In this paper the seismic flat dilatometer test (SDMT) was used to provide shear wave velocity (V_S) measurements to supplement conventional inflation readings (p_o and p_1).
The seismic dilatometer (SDMT) is the combination of the traditional "mechanical" Flat Dilatometer (DMT) introduced by Marchetti (1980) with a seismic module placed above the DMT blade. The SDMT module is a probe outfitted with two receivers, spaced 0.5 m, for measuring the shear wave velocity V_S. From V_S the small strain shear modulus G_o may be determined using the theory of elasticity ($G_o = \rho \cdot V_S$).
The SDMT equipment and test procedure are briefly described in the paper.
A comprehensive in situ and laboratory seismic investigation has been carried out to study two Italian sites: St. Giuliano di Puglia (CB) and Tito Scalo (PZ).
Soil stratigraphy and soil parameters are evaluated from the pressure readings while the small strain stiffness (G_o) is obtained from in situ V_S profiles and laboratory tests.

Moreover this paper study the experimental interrelationships between the small strain shear modulus G_o and the operative (working strain) constrained modulus M_{DMT}, investigated by use of SDMT results obtained in the Tito Scalo site.
It must be emphasized the well known notion that, while the small strain shear modulus is unique, the "working strain" modulus varies with strain. Hence, in theory, such comparison is impossible. However the term "working strain" sounds very familiar to practicing engineers, because they use it very often in design and would find useful methods providing even rough estimates of it. The price to pay is actually to accept (non negligible) approximation in the definition of the "working strain", which however maybe still useful in practice, in view of the often very large errors in estimating such modulus.

GEOTECHNICAL CHARACTERISTICS OF TEST SITES

The St. Giuliano di Puglia (CB) area is located in the Molise region in central Italy. On October 31, 2002, a M_L = 5.4 earthquake struck Molise region in Southern Italy. The strongly non-uniform damage distribution observed in the town of St. Giuliano di Puglia suggested that site amplification significantly affected the seismic response of the area.
Melidoro (2004) and Guerricchio (2005) have proposed an

interpretation of the town geological setting of St. Giuliano di Puglia area:

- the Faeto flysch (F), that is a sedimentary succession of mainly calcareous soils, either coarse or fine-grained; in particular these can be calcirudites, limestones, calcareous marls, white marls and green clays, differently fractured and fissured;
- a deep layer of Toppo Capuana marly clays (MC), whose maximum thickness has not been assessed yet; at the top, these clays are weathered down to few meters; they are overtopped by a shallow cover of disturbed soil and landslide debris;
- a chaotic complex (C) formed by Varicolored Scaly clays, limestones, calcareous marls, calcarenites and fragments of Faeto flysch.

The Toppo Capuana marly clay formation at St. Giuliano di Puglia consists of three principal units:

- a 'debris cover', of less than five meters thickness, including black organic carbonaceous elements, lumps and lenses of white powdery calcite and small calcareous litho-clasts;
- a layer, of two to ten meters thickness, of 'weathered tawny clays', characterized by medium to intense fissuring, resulting from the weathering and disturbance of the uppermost part of Toppo Capuana marly clays;
- a deep layer of Toppo Capuana marly clays, called 'grey clays' hereafter. The thickness of this layer seems to be around three hundred meters. The grey Toppo Capuana marly clays are less intensely fissured than the weathered tawny clays; in some cases the fissure surfaces are either ochraceous or covered by a black oxidation patina. The polyhedral clay elements, of 2 – 4 cm maximum size, are sharply edged and well embedded within the fissure network. Crystals of selenitic gypsum are detectable in rare lenses or in thin layers of fine sand.

For St. Giuliano di Puglia site the average values of the main physical properties are summarized in Table 1 (Cavallaro et al, 1998b).

Table 1. Physical average properties of the sites.

	γ [KN/m^3]	e [-]	G_s [-]	w_n [%]	w_l [%]	w_p [%]	PI [%]
St. Giuliano di Puglia	19.65 – 21.23	0.49 – 0.72	2.71 – 2.73	17.4 – 22.4	53.2 – 63.4	23.2 – 23.8	30 – 39.6
Tito Scalo	17.8 – 19.7	-	-	25 - 43	55.9 – 67.5	23.6 – 31.6	32.3 – 35.9

The Tito Scalo site, located near the city of Potenza in the Basilicata, is a high seismic risk area. Since 1561, the Tito Scalo area has been struck by fifteen earthquakes with an MKS intensity from III to X.

The deposit under consideration lies in the S. Loja plane. The area is confined on the North by the Li Foj mount, on the West by the Arioso mount and Pierfaone mount, on the South by the Passo della Sellata Relief, and on the North-West by the South-West border of Potenza Basin. The S. Loja basin deposit placed on the axial zone of Lucano Apennine consists of soils derived from paleogeographic Mesozoic of Lagonegro basin.

Two boreholes (20 m and 40 m) were performed to characterize the investigated area. The water level is located at few meter below the ground level. The deposit is characterized by clayey soils with insertion of silty lenses and sand. The detritus component increase with the depth. Four undisturbed samples were retrieved at the depths of 7 m (grey-green clay with high plasticity), 9.50 m (brown plastic clay), 20.50 m (grey clay) and 27.50 m (overconsolidated grey-brown clay). The general characteristics and index properties of the Tito Scalo soil are shown, as a function of depth, in Table 1 (Cavallaro et al, 1998a).

SHEAR WAVES VELOCITY FROM SDMT

The small strain ($\gamma \leq 0.001$ %) shear modulus, G_o, was determined from CPT, SDMT, NASW and a Down Hole (D-H) tests. Moreover it was attempted to assess G_o by means of empirical correlations, based either on penetration test results or on laboratory test results (Jamiolkowski et al., 1995).

The Seismic Dilatometer Marchetti (SDMT) is an instrument resulting from the combination of the DMT blade with a seismic modulus measuring the shear wave velocity V_S.

Initially conceived for research, the SDMT is gradually entering into use in current site investigation practice. The test is conceptually similar to the seismic cone (SCPT). First introduced by Hepton (1988), the SDMT was subsequently improved at Georgia Tech, Atlanta, USA (Martin & Mayne 1997, 1998, Mayne et al. 1999). A new SDMT system (Fig. 1) has been recently developed in Italy.

The seismic modulus is a cylindrical instrumented tube, located above the DMT blade (see Figure 1), housing two receivers at a distance of 0.50 m. The test configuration "two receivers"/"true interval" avoids the problem connected with the possible inaccurate determination of the "first arrival" time sometimes met with the "pseudo interval" configuration (just one receiver). Also the pair of seismograms recorded by the two receivers at a given test depth corresponds to the same hammer blow and not to different blows in sequence, which are not necessarily identical. The adoption of the "true interval" configuration considerably enhances the repeatability in the V_S measurement (observed repeatability $V_S \approx 1 – 2$ %).

V_S is obtained (Figure 1 and 2) as the ratio between the difference in distance between the source and the two receivers (S2 - S1) and the delay of the arrival of the impulse from the first to the second receiver (Δt). V_S measurements are obtained every 0.5 m of depth.

The shear wave source at the surface (Figure 3) is a pendulum hammer ($\approx$ 10 kg) which hits horizontally a steel rectangular base pressed vertically against the soil (by the weight of the truck) and oriented with its long axis parallel to the axis of the receivers, so that they can offer the highest sensitivity to the generated shear wave.

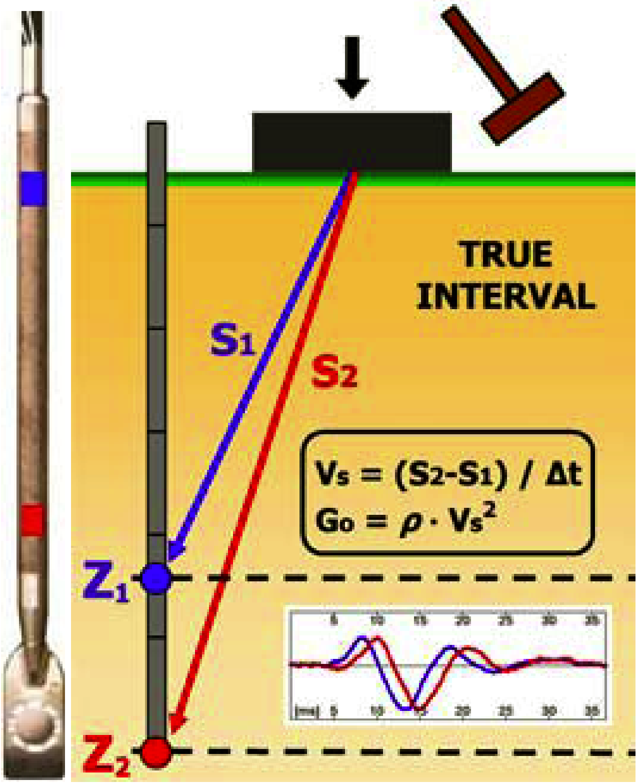

Fig. 1. DMT blade with seismic module and schematic layout of the seismic dilatometer test.

Fig. 2. Seismic dilatometer equipment.

The determination of the delay from SDMT seismograms, normally carried out using the cross-correlation algorithm, is generally well conditioned, being based on the two seismograms – in particular the initial waves – rather than being based on the first arrival time or specific marker points in the seismogram.

Fig. 3. Shear wave source at the surface.

Figure 4 shows an example of seismograms obtained by SDMT at various test depths at the site of St. Giuliano di Puglia (it is a good practice to plot side by-side the seismograms as recorded and re-phased according to the calculated delay).

Figure 5 (St. Giuliano di Puglia) is an example of the typical graphical format of the SDMT output. Such output displays the profile of V_S as well as the profiles of four basic DMT parameters − the material index I_d that gives information on soil type (sand, silt, clay), the vertical drained constrained Modulus M, the undrained shear strength c_u and the horizontal stress index K_D (related to OCR) − obtained using current DMT correlations.

The profile of K_d is similar in shape to the profile of the overconsolidation ratio OCR. $K_d = 2$ indicates in clays OCR = 1, $K_d > 2$ indicates overconsolidation.

A first glance at the K_d profile is helpful to "understand" the deposit. (Information on the mechanical DMT, not described in this paper, can be found in the comprehensive report by the ISSMGE Technical Committee TC16 2001). It may be noted in Figure 5 that the repeatability of the V_S profile is very high, similar to the repeatability of the other DMT parameters.

SHEAR MODULUS FROM IN SITU TESTS

V_S measurements by SDMT have been validated by comparison with V_S measurements obtained by other in situ seismic tests at various research sites. As an example Figure 6 shows V_S comparisons at the research site of Tito Scalo, Italy.

Values of G_o have been obtained from Down-Hole (D-H) and NASW for Tito Scalo site. The Noise Analysis Surface Waves (NASW) is based on two fundamental ideas.

The first is that common seismic-refraction recording equipment, set out in a way almost identical to shallow P-wave refraction surveys, can effectively record surface waves at frequencies as low as 2 Hz.

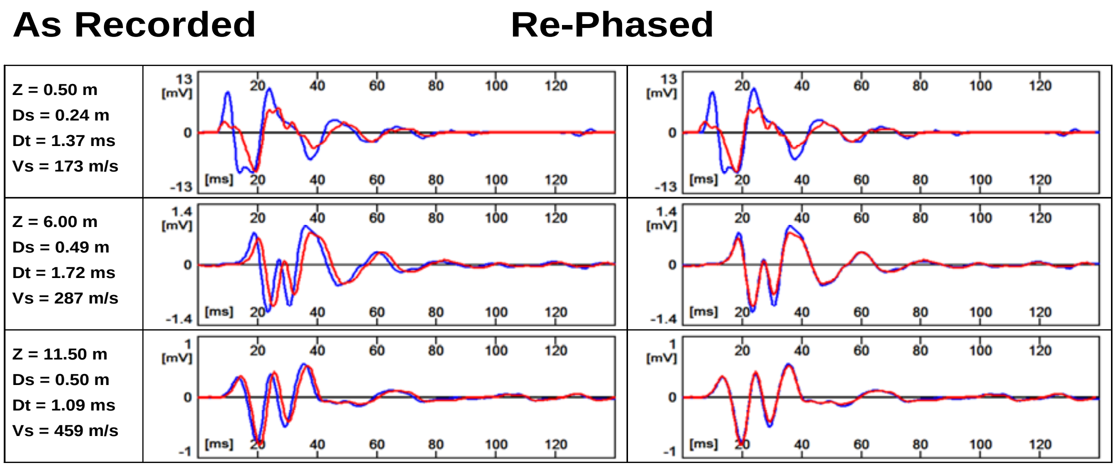

Fig. 4. Example of seismograms obtained by SDMT at the site of St. Giuliano di Puglia (Italy).

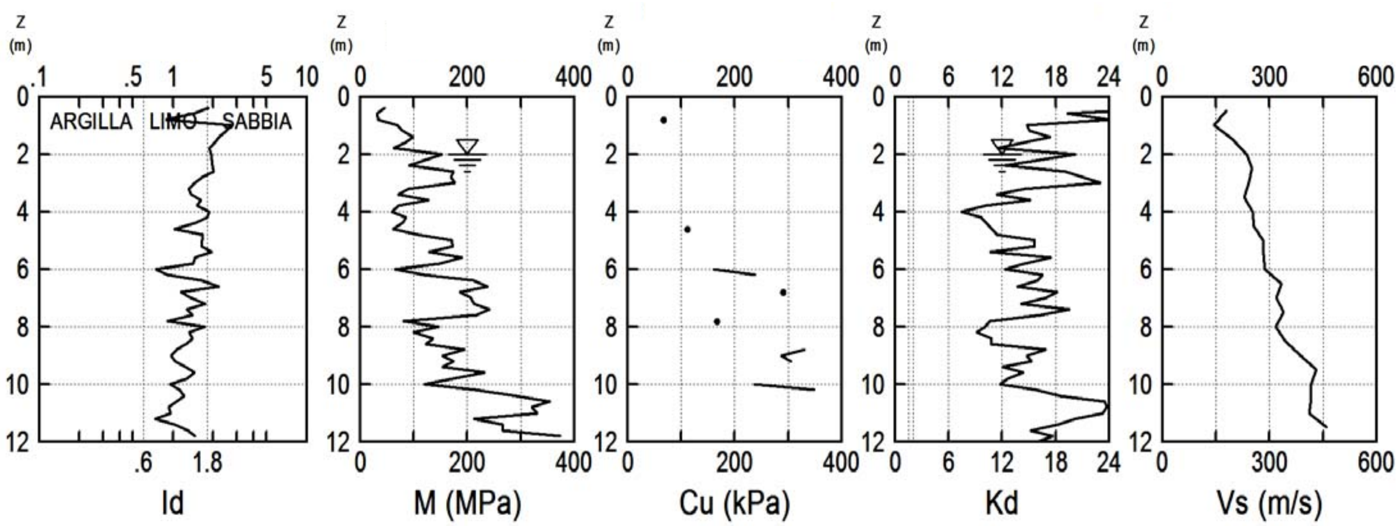

Fig. 5. SDMT profiles from two parallel soundings at the site of St. Giuliano di Puglia (Italy).

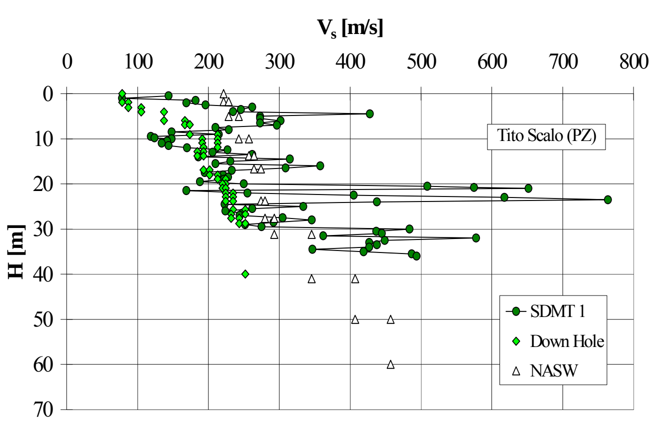

Fig. 6. Comparison of V_S profiles obtained by SDMT and by Cross-Hole and NASW at the research site of Tito Scalo.

The second idea is that a simple, two-dimensional slowness-frequency (p-f) transform of a microtremor record can separate Rayleigh waves from other seismic arrivals, and allow recognition of true phase velocity against apparent velocities. Figure 3 shows the values of Vs obtained in situ from a D-H test, NASW test and SDMT. In the superficial strata Vs by SDMT is about 250 m/s. In the deeper strata Vs values are about 450 m/s. At the depths of 20 and 24 m Vs is about 700 m/s in correspondence of sandy strata. These high Vs values by SDMT show the effect of soil disturbance during the test. The Vs values, experimentally determined during D-H and NASW tests, did not show any important variation in the transition zone at depths 20 and 24 m, where thin layers of sand exist. Values of G_o have been obtained from Down-Hole (D-H) for St. Giuliano di Puglia site.

Figure 7 shows the values of G_o obtained in situ from D-H tests and Seismic Dilatometer Marchetti Test (SDMT).

The G_o values are plotted in Figure 7 against depth. It is possible to see that quite a good agreement exists between the D-H tests results. Higher values of G_o was obtained by SDMT.

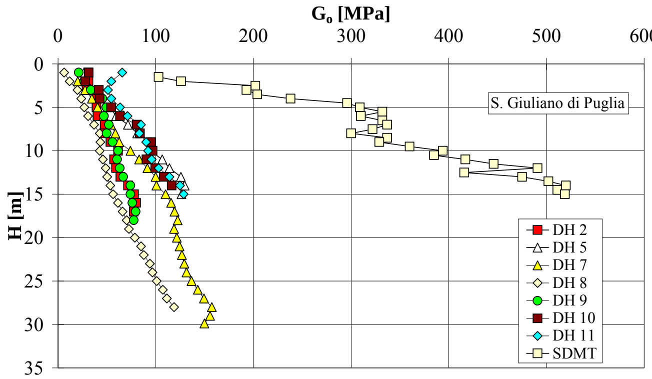

Fig. 7. G_o from in situ St. Giuliano di Puglia tests.

SHEAR MODULUS FROM EMPIRICAL CORRELATION

Because it is not always possible to perform dynamic in situ tests it was also attempted to evaluate the small strain shear modulus by means of the following empirical correlations based on in situ test results or laboratory results available in literature.

a) Hryciw (1990):

$$G_o = \frac{530}{(\sigma'_v/p_a)^{0.25}} \frac{\gamma_D/\gamma_w - 1}{2.7 - \gamma_D/\gamma_w} K_o^{0.25} \cdot (\sigma'_v \cdot p_a)^{0.5} \qquad (1)$$

where: G_o, σ'_v and p_a are expressed in the same unit; p_a = 1 bar is a reference pressure; γ_D and K_o are respectively the unit weight and the coefficient of earth pressure at rest, as inferred from SDMT results according to Marchetti (1980);

b) Mayne and Rix (1993):

$$G_o = \frac{406 \cdot q_c^{0.696}}{e^{1.13}} \qquad (2)$$

where: G_o and q_c are both expressed in [kPa] and e is the void ratio. Eq. (2) is applicable to clay deposits only.

c) Jamiolkowski et. al. (1995):

$$G_o = \frac{600 \cdot \sigma'^{0.5}_m p_a^{0.5}}{e^{1.3}} \qquad (3)$$

where: $\sigma'_m = (\sigma'_v + 2 \cdot \sigma'_h)/3$; p_a = 1 bar is a reference pressure, "e" is the void ratio by laboratory tests; G_o, σ'_m and p_a are expressed in the same unit. The values for parameters which appear in equation (3) are equal to the average values that result from laboratory tests performed on quaternary Italian clays and reconstituted sands. A similar equation was proposed by Shibuya and Tanaka (1996) for Holocene clay deposits. Equation (3) incorporates a term which expresses the void ratio; the coefficient of earth pressure at rest only appears in equation (1). However only equation (1) tries to obtain all the input data from the SDMT results.

The G_o values obtained with the methods above indicated are plotted against depth in Figure 8 for Tito Scalo site. The method by Jamiolkowski et al. (1995) was applied considering a given profile of void ratio. The coefficient of earth pressure at rest was inferred from SDMT.
All the considered methods show different G_o values of the soil for depths between 15 and 30 m. On the whole, equation (1) seems to provide the most accurate trend of G_o with depth, as can be seen in Figure 8. A good agreement exists between empirical correlations and D-H test. The SDMT material index indicated the presence of sandy layers at depth of about 20 and 24 m and at the same depths the dilatometer modulus increased. However the method by Hryciw (1990) was not capable of detecting these sandy strata as can be seen in Figure 4. It is worthwhile to point out that equation (1) underestimated G_o for depths between 20 and 30 m.

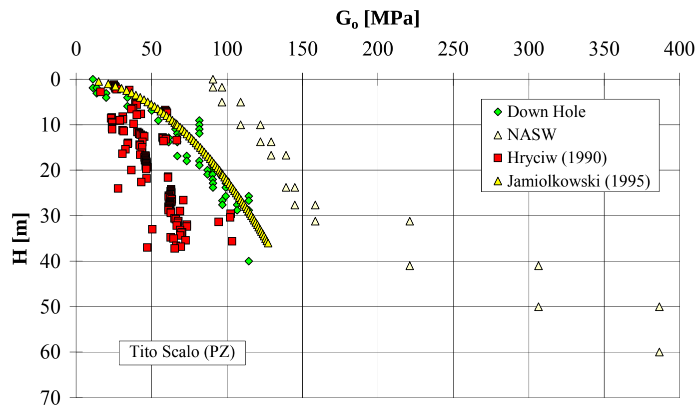

Fig. 8. G_o from different empirical correlations for Tito Scalo site.

The methods by Hryciw (1990) and Jamiolkowski et. al. (1995) show very different G_o values of the soil respect to the method by Mayne and Rix (1993). On the whole, equation (2) seems to provide the most accurate trend of G_o with depth, as can be seen in Figure 9. The DMT material index was not capable of detecting the presence of different strata at depths of about 5 and 10 m.

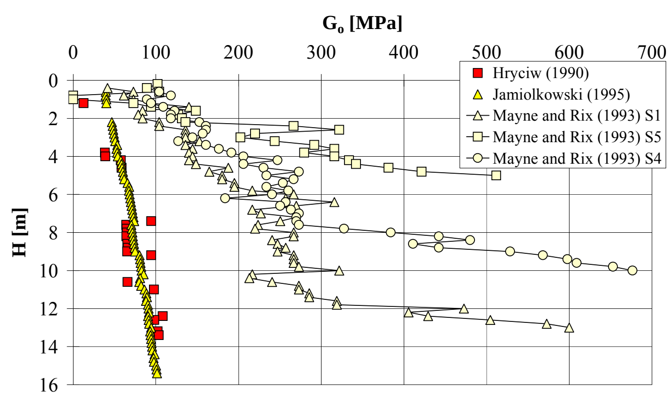

Fig. 9. G_o from different empirical correlations for St. Giuliano di Puglia site.

Moreover considering the Figures 7 and 9 it is possible to see a good agreement between the G_o results obtained by Mayne and Rix (1993) and by in situ SDMT.

SHEAR MODULUS DEGRADATION FROM SDMT

G is the unload-reload shear modulus evaluated from RCT, while G_0 is the maximum value or also "plateau" value as observed in the G-log(γ) plot. Generally G is constant until a certain strain limit is exceeded.

This limit is called elastic threshold shear strain (γ_t^e) and it is believed that soils behave elastically at strains smaller than γ_t^e. The elastic stiffness at $\gamma<\gamma_t^e$ is thus the already defined G_0. At strains greater than γ_t^e some plastic deformation occurs and the stress-strain relationship becomes non-linear. When a certain limit strain is exceeded, degradation phenomena are observed. This limit strain is called volumetric threshold shear strain (γ_t^v) and is rate dependent.

For shear at a strain rate of about 0.4 %/min γ_t^v ranges between 0.05 and 0.1 % and increases for increasing strain rates (Lo Presti 1989, Vucetic 1994).

Shear modulus G and damping ratio D of Toppo Capuana marly clay formation were obtained in the laboratory from Resonant Column tests (RCT). The laboratory test conditions and the obtained small strain shear modulus G_o are listed in Table 2.

Table 2. Test Condition for St. Giuliano di Puglia marly clay formation specimens.

Borehole No.	H [m]	σ'_{vc} [kPa]	e	PI	RCT	G_o [MPa]	ΔU_{max} [kPa]
S3C1	1.75	98	0.720	37	U	36	11
S5C2	7.15	155	0.523	30	U	144	30
S11C1	2.25	350	0.579	29	U	133	9
S11C3	11.75	397	0.464	31	U	173	2
S11C4	14.70	397	0.506	32	U	145	5

where: U = Undrained.

The undisturbed specimens were isotropically reconsolidated to the best estimate of the in situ mean effective stress. The size of solid cylindrical specimens are Radius = 25 mm and Height = 100 mm.

A key feature distinguishing SDMT from other seismic tests is that in addition to G_o, a "working strain" shear modulus, G_{ws} is determined. The availability of two data-points (G_o and G_{ws}) may help in selecting the G-γ decay curve, important in soil dynamics.

G_{ws} can be evaluated by the following equation based on M_{DMT} values:

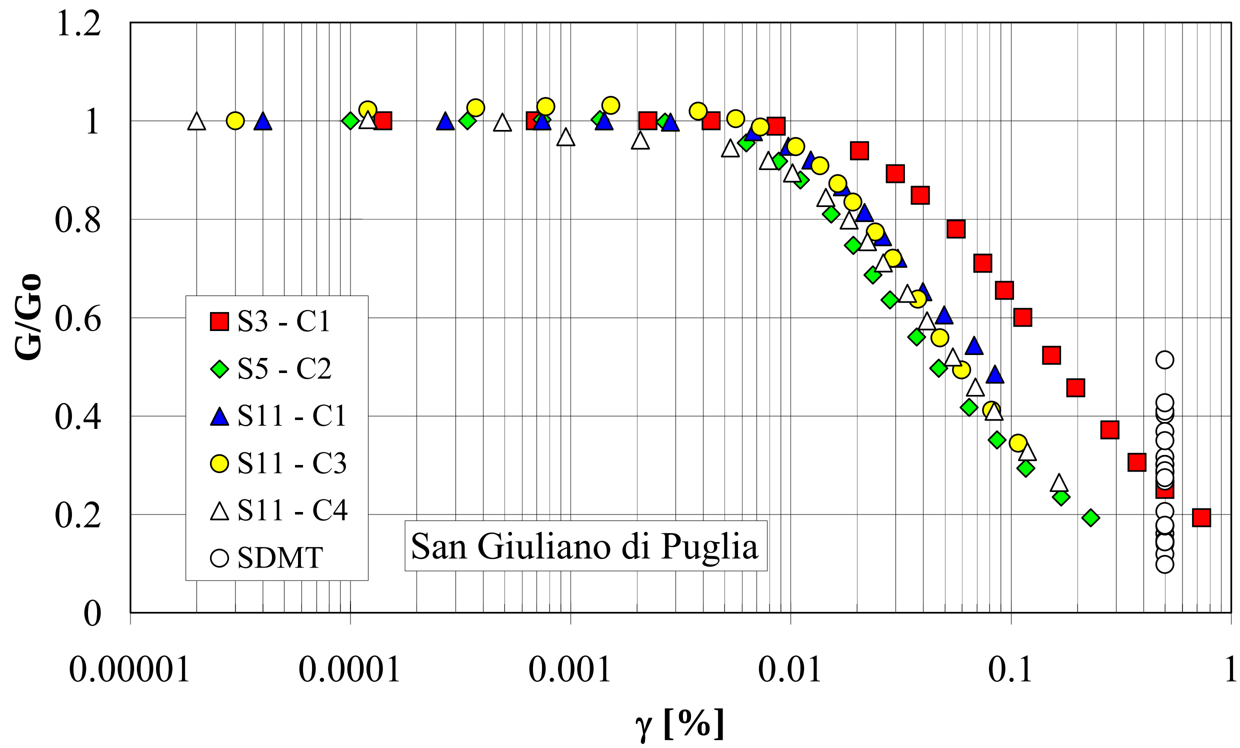

Fig. 10. G/G_o vs shear strain for for St. Giuliano di Puglia site.

$$G_{ws} = \frac{(1 - 2 \cdot \nu)}{2 \cdot (1 - \nu)} \cdot M_{DMT} \quad (4)$$

where $\nu = 0.35$ is the Poisson ratio.

As regard the evaluation of "working strain" γ_{ws}, we must distinguish the settlements predicted during the analysis of case histories (γ = 0.05 to 0.1 %) and the real strain investigated by SDMT to measure the dilatometer modulus E_D.

In the vicinity of the probe, the flat dilatometer blade is expected to produce shear similar to the cylindrical probes of the piezocone and smaller than the push-in pressuremeter (Lacasse & Lunne, 1988). Tentatively reported in Figure 10 is the comparison between RCT for different Catania site and SDMT results at large strain for St. Giuliano di Puglia area.

CONCLUSIONS

A site characterization by the seismic dilatometer Marchetti test for two Italian sites has been presented in this paper. On the basis of the data shown it is possible to draw the following conclusions:

- SDMT were performed up to a depth of 37 meters for Tito Scalo site. The results show a very detailed and stable shear wave profile.
- the small strain shear modulus measured in the laboratory for St. Giuliano di Puglia is on average 0.90 of that measured in situ by means of SDMT and DH tests;
- empirical correlations between the small strain shear modulus and penetration test results were used to infer G_o from CPT and SDMT. The values of G_o were compared to those measured with SDMT and DH tests. This comparison indicates that some agreement exists between empirical correlations and SDMT and DH test for St. Giuliano di Puglia;
- moreover SDMT measurements are much more stable and repeatable than DH test, so the SDMT is a powerful investigation tool.
- SDMT, because of three independent measurements of p_o, p_1 and V_s, gives shear modulus at small strain and large strain for detecting soil non linearity.

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