SDMT Testing for the Estimation of In Situ G Decay Curves in Soft Alluvial and Organic Soils

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ABSTRACT: One of the most stimulating research topic of SDMT testing is the possibility to estimate the in situ stiffness decay with strain level (G-γ curve). The current practice is to determine the G-γ curve by fitting "reference curves" based on two points, i.e the initial shear modulus G_0 and a working strain modulus G_{DMT}, whose location is not *a priori* known. This fact poses some uncertainties in the application of the method, especially for organic and soft cohesive soils. In this note, starting from SDMT and cyclic laboratory data collected in organic and soft alluvial clays of Tiber River deposits in Rome, an alternative approach to derive the in situ stiffness decay curve is presented and discussed.

1 INTRODUCTION

The design of geotechnical structures in both static and dynamic conditions requires knowledge of the stiffness characteristics of soils, often expressed in terms of shear moduli. The SDMT testing is widely used in evaluating these deformational properties. In fact, it provides the small-strain shear modulus G_0 and a *working strain* modulus, G_{DMT} (from the constrained modulus M_{DMT}), at a medium strain level.

A challenging issue, which the scientific community has focused in the last decade (Lehane & Fahey, 2004; Marchetti *et al*., 2008; Amoroso *et al*., 2013a), concerns the possibility of assessing the in situ decay curves of soil stiffness with shear strain (G-γ curves), based essentially on the G_0 and G_{DMT} experimental data. This approach has proven applicable to different soil types, as shown by Amoroso *et al*. (2013a and 2013b) and Monaco *et al*. (2014). However, limited data are available as to ascertain the reliability of this procedure for soft materials, especially for organic soils.

In this paper, normally consolidated alluvial and organic soil deposits, located in the northern area of Rome, were investigated in the framework of the "TIBER Project" (Report FILAS, 2013; Mancini *et al*., 2013). In this project, a comprehensive in-situ and laboratory investigation was conducted in the alluvial deposits of the Tiber River in Rome. Specifically in situ surveys comprised three boreholes (ATS1, ATS2 and S1 in Fig. 1a) as well as PMT, CPTU and SDMT tests. Laboratory tests included standard and more sophisticated cyclic tests.

Hereafter, results from cyclic laboratory and SDMT tests carried out in proximity of S1 borehole are presented and discussed, with special attention to the possibility of deriving the in situ G-γ decay curves, and a comparison with literature findings is also presented.

2 GEOLOGICAL BACKGROUND OF THE STUDY AREA

The S1 borehole, 64 m deep, is located in the centre of Rome, Prati neighborhood, within the Tiber River alluvial plain. The plain corresponds to top surface of the Upper Pleistocene-Holocene Tiber Valley infill, Recent Alluvial Deposits, and is bordered to the west and east by the Monte Mario and by Monti Parioli ridges, where the Pliocene-Pleistocene geological substratum crops out (Report FILAS, 2013) (Fig 1a). The Recent Alluvial Deposits are composed of several lithotypes, i.e. basal gravels, channel-belt sands, floodplain inorganic and organic clays and silts, that fill with aggradation the fluvial incised valley (Fig. 1b). In fact, the valley infill records, in the last 22 kyr, a very complex lateral-vertical stacking of fine grained floodplain sediments alternated with sandy-gravelly channel deposits, both aggrading in response to the concomitant sea-level rise and highstand (Mancini *et al.*, 2013, with references).

The stratigraphic sequence crossed by S1 summarizes the Tiber fluvial facies for a 58.1 m depth. The borehole reaches the basal boundary recording the unconformity between the Tiber alluvial deposits and the geological substratum, which is locally represented by the Pliocene marine clay of the Monte Vaticano Formation, from 58.1 to 64.0 m from the wellhead. Details on lithostratigraphy, sedimentary facies and palaeo-environmental interpretation of the Recent Alluvial Deposits, as well as the position of geotechnical samples, are reported in Fig. 1c. A piezometer cell has been emplaced in the basal pebbly layer (53-58 m depth). A piezometric head of about 6 m a.s.l. was recorded.

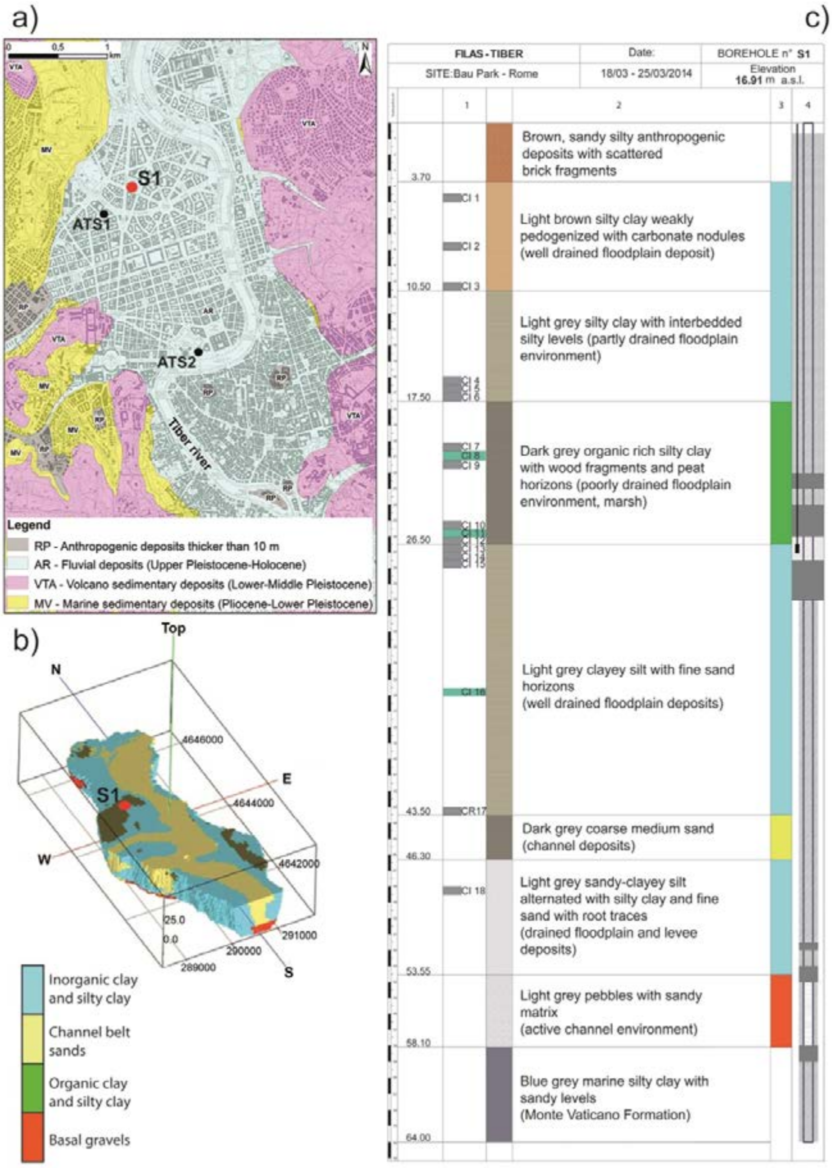

Fig. 1. a) Simplified geological map of the study area and location of S1, ATS1, ATS2 boreholes (Mancini et al., 2013); b) 3D lithotype model of the Tiber valley infill cut at about 0 m a.s.l. (Report Filas, 2013); c) stratigraphic log of the S1borehole: 1) geotechnical samples, 2) lithostratigraphy and facies, 3) lithotypes of the 3D model, 4) piezometers.

3 LABORATORY TESTS RESULTS

3.1 *Testing program*

A total of 17 undisturbed and 1 disturbed soil samples were recovered in S1 borehole (Fig. 1c). Main index properties were measured in the laboratory; moreover, oedometer and consolidated-drained, consolidated undrained and unconsolidated-undrained triaxial tests were carried out. In this paper emphasis is placed on cyclic simple shear tests carried out on selected samples as discussed hereafter.

3.2 *Cyclic tests*

Cyclic soil behaviour was investigated through the Double Specimen Direct Simple Shear (DSDSS) device (Doroudian and Vucetic, 1995; D'Elia *et al.*, 2003). The apparatus is capable of investigating, in a single test, the cyclic properties from very small to very large strains: stiffness and damping characteristics have been successfully measured for different soils in the range of strain γ_c varying between 0.0004% to more than 1% (Lanzo *et al.*, 2009). The tests are conducted on fully saturated cylindrical specimens (66 mm in diameter and 20 mm high), confined by wire-reinforced rubber membranes and consolidated under pseudo oedometer conditions (Lanzo *et al.*, 2009). After the consolidation stage, the specimens are subjected to several consecutive cyclic strain-controlled tests with cyclic shear strain amplitude equals to γ_c. Testing follows the Norwegian Geotechnical Institute (NGI) constant-volume equivalent-undrained simple shear procedure (Doroudian and Vucetic, 1995). Frequency of cyclic loading ranges between approximately 0.1 and 0.3 Hz.

The results are interpreted in terms of shear stress (τ) vs. shear strain (γ_c) curves. From these curves the standard dynamic parameters, i.e. the secant shear modulus (G) and damping ratio (D), are determined. The maximum shear modulus (G_0) is estimated by extrapolation from the G vs. γ_c curve at very small strains.

The DSDSS tests were carried out on specimens obtained from C8 (20.6-21.2 m), C11 (25.5-26.0 m) and C16 (35.5-36.0 m) samples. The first two samples were recovered in the organic clay layer (Fig. 1c) and are characterized by a plasticity index PI of 48 and 51, respectively, while the Soil Organic Matter (SOM) content determined by loss on ignition at 440°C is 12.8 and 10.9 %, respectively. The C16 sample pertains to the underlying soft clay layer; the presence of organic matter is scarce and the plasticity index is about 14.

Specimens were consolidated at the estimated vertical effective in situ stress; two additional confining pressures were also applied, respectively lower and higher than the in situ one. The cyclic shear strain amplitude γ_c varied from about 0.0004% to almost 10%.

The curves of normalized shear modulus (G/G_0) measured on the three samples are reported in Fig. 2 and compared with those proposed by Darendeli (2001) for the corresponding PI and an average confining pressure of 400 kPa. The effect of confining pressure is almost negligible in all tested soils. A satisfactory agreement of experimental data with literature curve is observed for C16 sample while organic soils exhibit a more pronounced linearity. This more pronounced linearity, as compared to fine-grained soils of similar plasticity, is confirmed by other literature experimental studies (see for instance Pagliaroli and Lanzo, 2009; Pagliaroli *et al.*, 2014).

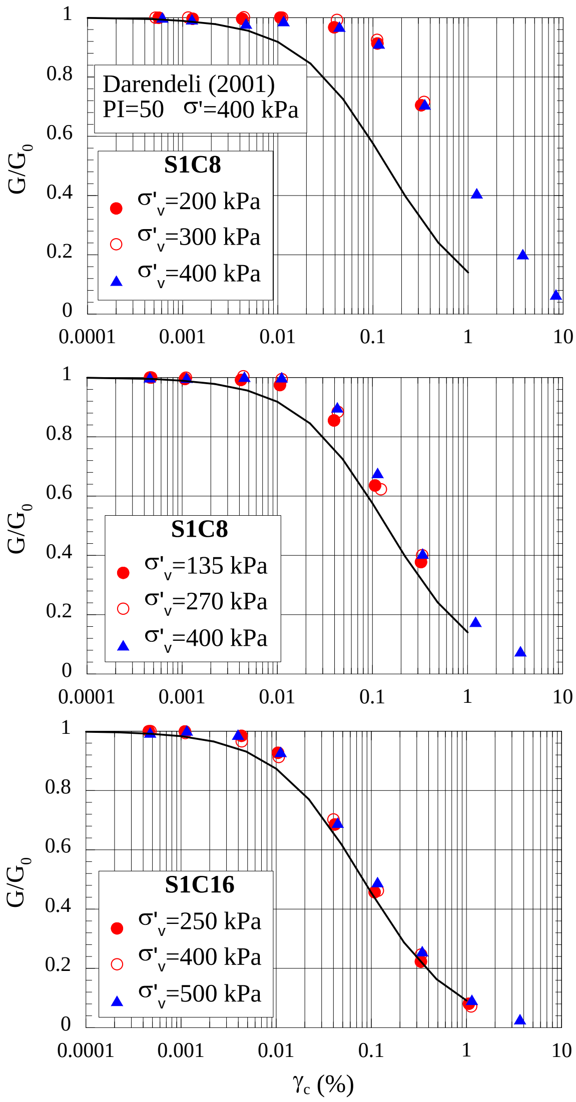

Fig. 2. Normalized shear modulus (G/G_0) versus cyclic shear strain amplitude (γ_c) curves from DSDSS tests.

4 SDMT TEST RESULTS

The SDMT tests results are summarized from Fig. 3 to Fig. 5. Material index “I_d” (Fig. 3a) is fully consistent with soil layering characteristics. The upper organic clays are correctly interpreted as “clays” (I_d<0.6), while lower soft clays with silt layers can be recognized by the scatter between the two categories (I_d=0.2-2). The underlying sandy layer, at 43.0 m b.g.l., is clearly identified by the reduction of data scattering in Id versus depth plot. Constrained Modulus “M” (Fig. 4a) is extremely low (about 5 MPa) in upper organic soils, and increases in lower soft clays, where the influence of the thin silt layers induces, again, a substantial data scattering.

Shear wave velocity “Vs” profile (Fig. 5) shows a sharp drop in organic clays where reaches very low values (V_S=150 m/s), while in lower soft clays an almost linear slight increase of V_S with depth can be recognized, being Vs always higher than 250 m/s.

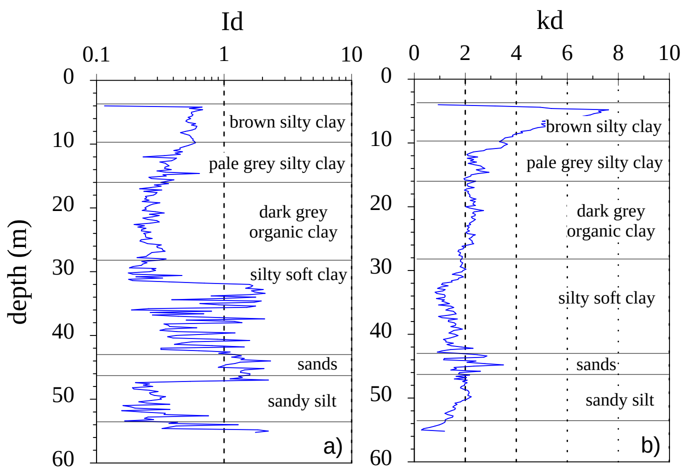

Fig. 3. DMT soil index I_d (a) and horizontal stress index K_d (b).

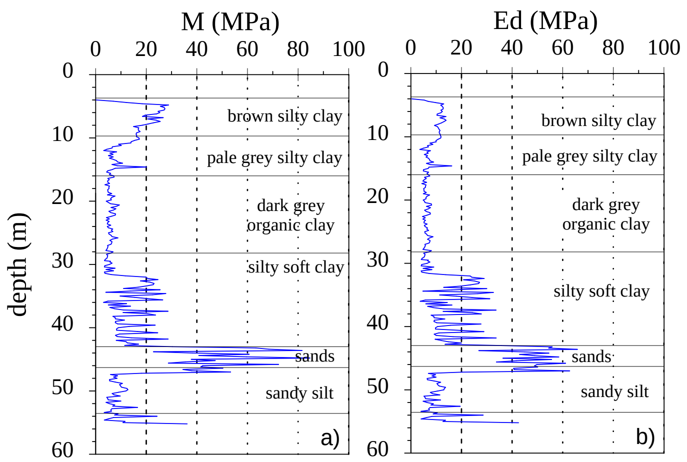

Fig. 4. DMT constrained modulus M (a) and dilatometer modulus E_d (b).

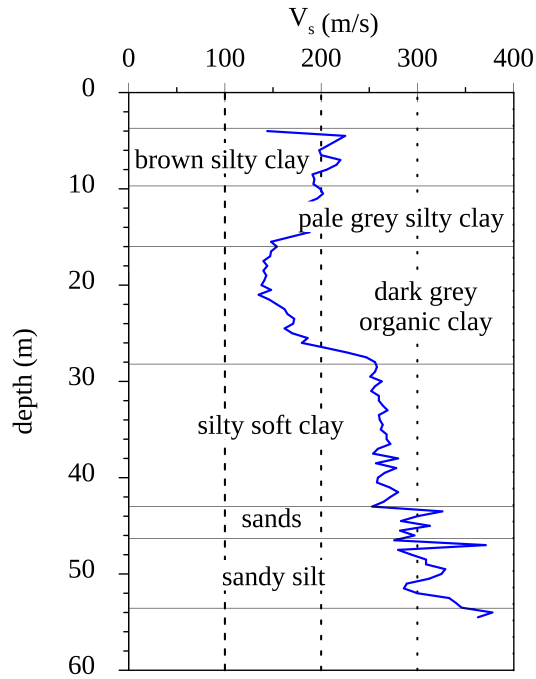

Fig. 5. Shear wave velocity profile from SDMT test.

5 IN SITU STIFFNESS DECAY CURVES FROM SDMT

5.1 *Some considerations on the construction of the G-γ curves from SDMT tests*

As outlined by Marchetti *et al*. (2008), the SDMT could be a useful tool to define the “in situ” shear modulus decay curves, as it provides indications on the small strain stiffness and an intermediate shear strain stiffness.

Such curves could tentatively be constructed by fitting "reference typical-shape" laboratory curves through two points, both obtained by SDMT: (1) the small strain modulus G_0 computed from V_S, and (2) a *working strain* modulus G_{DMT}. The small strain shear modulus is obtained from the shear wave velocity measurements as follows:

$$G_0 = \rho \, Vs^2 \quad (1)$$

being ρ the material density while the *working strain* modulus G_{DMT} can be derived from the constrained modulus $M_{DMT,}$ hypothesizing an elastic behavior of the material:

$$G_{DMT} = \frac{M_{DMT}}{2(1-\upsilon)/(1-2\upsilon)} \quad (2)$$

where ν is the Poisson’s ratio of soil. For example, for ν = 0.25, the *working strain* modulus is G_{DMT}= M_{DMT}/3. It should be remembered that the constrained modulus M_{DMT} is obtained from the dilatometer modulus E_d via the empirical coefficient

R_M, ranging mostly between 1 and 3 as a function of I_d and K_d indexes (Marchetti, 1980).

In order to construct the G-γ decay curve is necessary to locate the *working strain* modulus $G_{DMT.}$ In other words, it is necessary to know, at least approximately, the shear strain corresponding to G_{DMT}. Indications by Mayne (2001) locate the DMT moduli for sands at an intermediate level of strain (γ ≈ 0.05-0.1 %). Similarly Ishihara (2001) classified the DMT within the group of methods of measurement of soil deformation characteristics involving an intermediate level of strain (0.01-1 %). More recent studies (Amoroso *et al.*, 2013b) clearly showed that the working strain modulus depends on the soil texture: typical working strain ranges of G_{DMT} can be approximately assumed as 0.01–0.45 % in sand, 0.1–2 % in silt and clay, higher than 2 % in soft clay.

According to this procedure, if one were to define the in situ decay curve, a reference strain level has therefore to be assigned.

An alternative approach here proposed is to assign the shear strain level and estimate shear strain stiffness, at that level, starting from SDMT results. This shear strain stiffness could be estimated defining a relation between G_{DMT} and the Dilatometer Modulus (E_d). This method may imply a regionalization of the interpretation curves for DMT, i.e. specific G-E_d relationship defined at local scale. Some attempts of regional correlations have already been carried out for organic soil and soft clays by Lechowicz *et al.* (2014). The Authors for example define a specific correlation between the Dilatometer Modulus E_d and the Young modulus at 0.1 % level of strain.

The proposed procedure is illustrated hereafter with reference to the Viale Angelico test site.

5.2 *Results at the Viale Angelico test site*

The small strain modulus G_0 and the working strain modulus G_{DMT} were computed along the SDMT profile at the test site according to formulas (1) and (2). The decay ratio G_{DMT}/G_0 is shown in Fig. 6.

For matter of comparison, the decay ratios calculated from dilatometer test were compared to pressumeter (PMT) test decay ratios. For these latter tests first loading (LD) and unloading-reloading (UR) Young modulus were available, and shear modulus was calculated using elastic behaviour formula:

$$G_{PMT}= E_{PMT}/[2(1+\nu)] \quad (3)$$

where G_{PMT} and E_{PMT} are shear modulus and Young modulus from pressumeter test.

As shown in Fig. 6, in the upper silty clay layer (4-10 m b.g.l.) PMT shear strain moduli are both lower than that calculated through the SDMT test, while in the lower organic clay layer the dilatometer shear modulus lays between the first loading and the unloading-reloading pressumeter moduli.

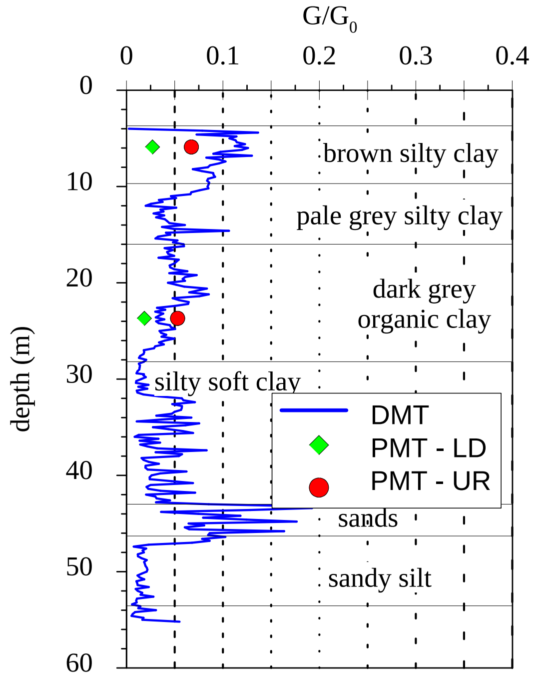

Fig. 6. G_{DMT}/G_0 profile from SMDT and PMT tests

It has to be highlighted that along all the test profile the decay ratios are always lower than 0.10 and high working shear strain levels are therefore expected.

In order to calculate the shear strains corresponding to G_{DMT}, reference was made to G decay curves measured with DSDSS laboratory tests. Following the indications of Hardin and Drnevich (1972), which proposed the use of a hyperbolic law for stiffness decay curves, the Santos and Correia (2001) expression have been chosen to interpolate experimental results:

$$\frac{G}{G_0} = \frac{1}{1+a\frac{\gamma}{\gamma_{0.7}}} \quad (4)$$

where "a" is an experimental coefficient equal to 0.385, γ is the shear strain amplitude and $\gamma_{0.7}$ its value at 70% decay ratio (G/G_0=0.7).

Sample	Depth	$\gamma_{0.7}$ (%)
-	[m]	-
C8	20.6	$2.90 \cdot 10^{-1}$
C11	25.5	$9.50 \cdot 10^{-2}$
C16	35.5	$4.50 \cdot 10^{-2}$

Table 1. Values of $\gamma_{0.7}$ for the interpolation of DSDSS results according to Santos and Correia (2001) relation

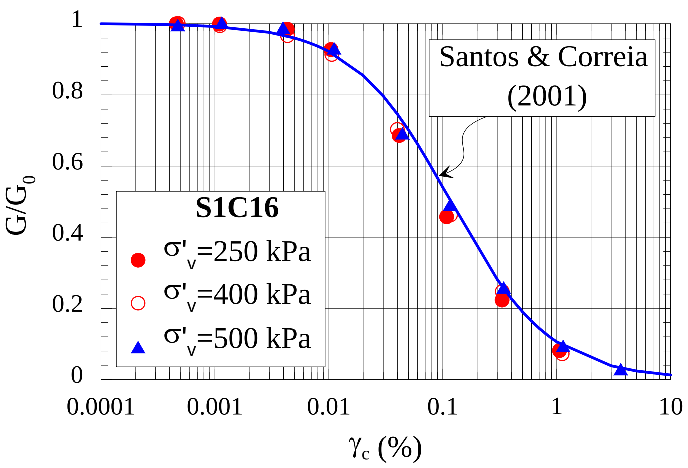

Fig. 7. Interpolation curve for DSDSS tests carried out on C16 sample

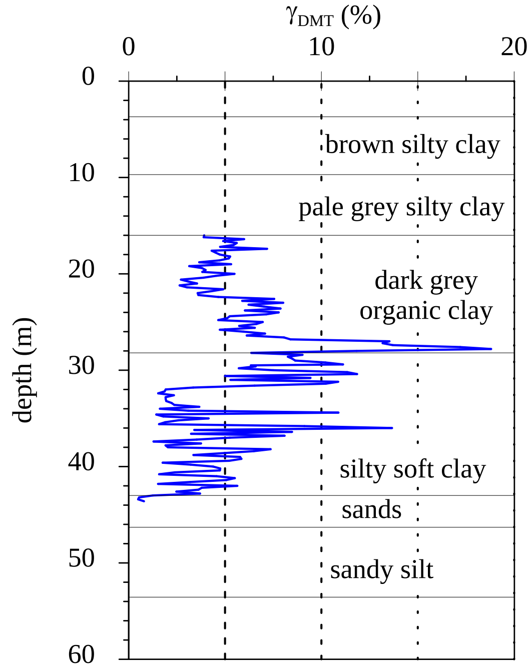

Fig. 8. Working shear strain profile.

Santos and Correia relationship has been chosen essentially for three reasons:

1. it provides excellent correlation with experimental data;
2. it is easy to manage depending only from one parameter;
3. it is implemented in one of the most common material models that takes into account the small strain stiffness (Hardening Soil Small Strain model), available in many of the most popular Finite Element commercial codes (e.g. Plaxis) and therefore the results here presented can be easily transposed in engineering practice.

The interpolation parameter $\gamma_{0.7}$ values for the three DSDSS tests are reported in Table 1 while a representative comparison between DSDSS curve and the analytical one is shown in Fig. 7. The high $\gamma_{0.7}$ value found for C8 sample seems extremely affected by the high amount of organic material and it cannot be considered representative of the soil material between 16.0 and 28.0 m b.g.l. For this layer (organic clay in Fig. 6) the value obtained for C11 has therefore been taken as a reference. The $\gamma_{0.7}$ value found for C16 has been taken as a reference for the soft clays layer between 28.0 and 43.0 m b.g.l..

Assuming the above mentioned $\gamma_{0.7}$ values, the working strains (γ_{GDMT}) were calculated at each depth from G_{DMT}/G_0 profile in organic and soft clays layers (Fig. 8) from the expression given in (4). As expected strain levels are always higher than 1%, sometimes reaching values around 10%. Higher strains are observed in the organic layer with respect to the soft clay one. Some spikes in working strain profile are probably due to the presence of sand and silt layers, for which the proposed G-γ interpolation curve is not valid.

The working strain values are consistent with those outlined by Amoroso *et al.* (2013), as shown in Fig. 9 where the blue symbols represent the working strain values associated to decay ratios for the SDMT test performed at the test site.

As stated at 5.1, an alternative approach to build possible G decay curves can be summarized as follows:

1. choose a reference typical shape curve, depending on soil texture;
2. constrain the curve to pass through G_0 and a working shear modulus referred to an assigned known shear level; this latter could be computed defining a relation between G_{DMT} and the Dilatometer Modulus (E_d) at an assigned shear level $\bar{\gamma}$.

With this method no estimation of strain level associated to G_{DMT} is needed.

In this study an empirical relation between G_{DMT} and E_d has therefore been defined at medium strains ($\bar{\gamma}$=0.1%). Following Lechowicz *et al.* (2014), the equation is the following:

$$\bar{G}_{DMT}=R_G\cdot Ed \qquad (5)$$

where $\bar{G}_{DMT}$ is G_{DMT} at $\gamma=\bar{\gamma}$ and R_G is a parameter depending on the material index I_d and horizontal stress index K_d. The relation between R_G, I_d and K_d has been defined separately for organic clays and soft clays.

The values of $\bar{G}_{DMT}$ have been calculated simply by multiplying the G_0 derived by SDMT test for the decay ratio G/G_0 measured at 0.1% strains in the DSDSS test. As stated before, the cyclic test on C11 was considered for organic layer while the DSDSS carried out on C16 was taken as representative for soft clays.

For organic clays (Fig. 10), experimental data tend to align if $R_G = \bar{G}_{DMT}/E_d$ is correlated to $Id \cdot Log(K_d)$ with acceptable correlation coefficients ($R^2 \approx 0.7$). On the contrary for soft soils (Fig. 11) a correlation has been found between R_G and $Log(K_d)/I_d$ with a satisfactory correlation coefficient ($R^2 \approx 0.85$).

It has to be recalled that the influence of I_d and K_d on the relation between E_d and G is taken into account also in standard procedure (Marchetti, 1980) to derive M_{DMT} from E_d.

For organic clays the R_G parameter can be therefore be calculated as:

$$R_G = 35.24 - 94.57 \cdot I_d \cdot \log(K_d) \quad (6)$$

while for soft clays:

$$R_G = 8.81 + 9.37 \cdot \log(K_d)/I_d \quad (7)$$

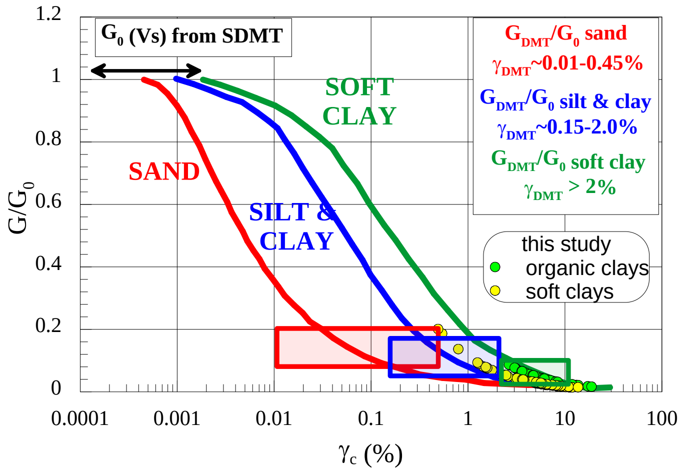

Fig. 9. Typical decay curves for different soils (modified from Amoroso *et al*., 2013b); symbols shows working strain values obtained at Viale Angelico test site

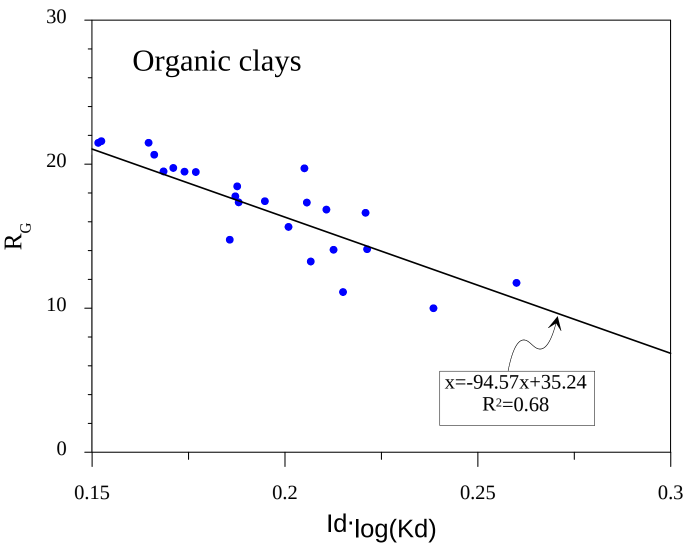

Fig. 10. Empirical coefficient R_G for organic clays.

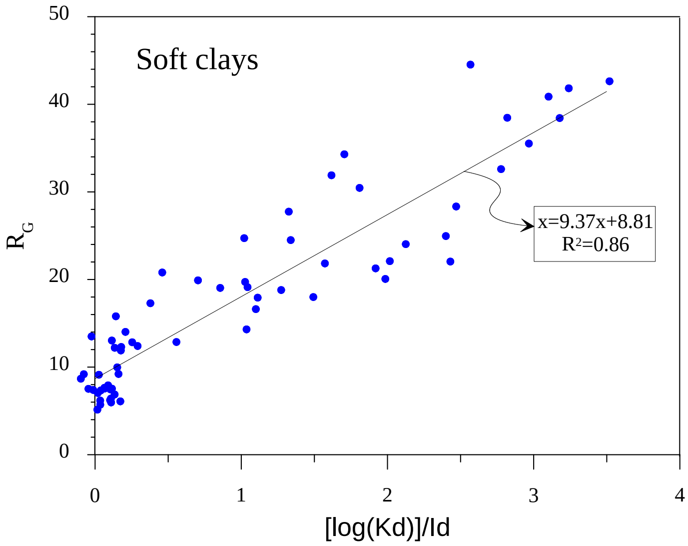

Fig. 11. Empirical coefficient R_G for soft clays.

6 CONCLUSIONS

One of the most challenging issue of the SDMT testing concerns the possibility of developing a reliable method to assess the in situ stiffness decay with strain. The proposed method in the literature is to address the G-γ curves by fitting available reference "typical shape curve", depending on physical characteristics, through two points, i.e. the starting point of the curve, that is the small-strain stiffness, that can be derived from shear wave velocity measurement, and a *working strain* modulus G_{DMT} to be derived from standard DMT results. To locate the second point it is necessary to know the shear strain associated with G_{DMT} which is affected by large uncertainties.

The paper presents the results of an experimental investigation carried out in a test area located in soft and organic alluvial deposits in Rome. In situ SDMT tests as well as laboratory cyclic simple shear tests were carried out, these latter allowing the complete definition of decay curves in a very large of shear strains.

The intersection between the laboratory G/G_0-γ curves with those estimated by SDMT showed that for the investigated soils the shear strain values related to the working DMT modulus are extremely high, between 2 and 5% (in some cases reaching even 10%) in soft clays and generally larger than 6% in organic clays.

For this reason, a different approach has been proposed in this note: a correlation between working strain shear modulus at assigned shear strain (0.1%) and DMT results (E_d, I_d and K_d) has been derived, starting from G/G_0 curves from laboratory tests.

This approach allowed the definition of the decay curve, based on the choice of the typical shape curve, without the estimation of shear strain level associated to G_{DMT}. However, the method implies the “regionalization” of the DMT formula, meaning that for each soil, specific correlations using decay curves measured by laboratory tests should be defined.

Once derived the decay curves can easily be implemented in well known geotechnical numerical nonlinear codes or used to estimate the soil stiffness at assigned strain level in more simple “elastic” calculations.

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7 REFERENCES

Amoroso S., Lehane B.M., Fahey M. (2013a). “Determining G-γ decay curves in sand from a Seismic Dilatometer Test (SDMT).” In: *Geotech. and Geoph. Site Charact. 4*, Coutinho and Mayne (eds), 447-452.

Amoroso S., Monaco P., Marchetti D. (2013b). “Use of the Seismic Dilatometer (SDMT) to estimate in situ G-γ decay curves in various soil types.” In: *Geotech. and Geoph. Site Charact. 4*, Coutinho and Mayne (eds), 489-497.

Darendeli, M. B. (2001). “Development of a New Family of Normalized Modulus Reduction and Material Damping Curves.” *Ph.D. Diss.*, Univ. Texas at Austin.

D’Elia B., Lanzo G., Pagliaroli A. (2003). “Small strain stiffness and damping of soils in a direct simple shear device.” *Pacific Conference on Earthquake Engineering*, Christchurch, New Zealand.

Doroudian M., Vucetic M. (1995). “A direct Simple Shear Device for Measuring Small-Strain Behavior.” *Geotechnical Testing Journal*, GTJODJ, 18, 1, 69-85.

Hardin, B.O. & Drnevich, V.P. (1972). “Shear modulus and damping in soils: Design equations and curves.” *J Soil Mechanics and Foundations Div.*, 98(7): 667-692

Ishihara, K. (2001). “Estimate of relative density from in-situ penetration tests.“ *Proc. Int. Conf. on In Situ Meas. of Soil Properties and Case Histories*, Bali, 17-26.

Lanzo G., Pagliaroli A., Tommasi P., Chiocci F. L. (2009). “Simple shear testing of very soft offshore clay for wide strain range.” *Canadian Geotechnical Journal*, 46(11), 1277-1288.

Lehane B.M., Fahey M. (2004). “Using SCPT and DMT data for settlemnet prediction in sand.” In a: Viana da Fonseca & P.W. Mayne (eds.), *Proc. 2nd Inter. Conf. on Site Charcterization*, Porto, 2, 1673-1679.

Lechowicz Z., Bajda M., Rabarijoely S. Wrzesinski G. (2014). “Use of SDMT for the evaluation of the geotechnical parameters of organic soils.” *Proc. 5th Int. Workshop on CPTU and DMT in soft clays and organuic soils*. Poznan, Poland, Sept. 22-23, 2014.

Mancini M., Moscatelli M., Stigliano F. et al. (2013). “The Upper Pleistocene-Holocene fluvial deposits of the Tiber River in Rome (Italy): lithofacies, geometries, stacking pattern and chronology.” *J. Med. Earth Sciences*, Special Issue (2013), 95-101.

Marchetti, S. (1980). “In Situ Tests by Flat Dilatometer.” *J. Geotech. Engrg. Div*., ASCE, 106(GT3), 299-321.

Mayne, P.W. (2001). “Stress-strain-strength-flow parameters from enhanced in-situ tests.” *Proc. Int. Conf. on In Situ Measurement of Soil Properties and Case Histories*, Bali, 27-47.

Marchetti S., Monaco P., Totani G., Marchetti D. (2008). “In Situ Test by Seismic Dilatometer (SDMT).” *ASCE GSP honoring Dr. J. H. Schmertmann, From Research to Practice in Geotech. Eng.*, GSP No. 170, 2008.

Monaco P., Amoroso S., Marchetti S., Marchetti D., Totani G., Cola S., Simonini P. (2014). “Overconsolidation and stiffness of Venice Lagoon sands and silts from SDMT and CPTU.” *Journal of Geotech. and Geoenv. Eng*., ASCE, 140, 215-227.

Pagliaroli A., Lanzo G. (2009). “Comportamento ciclico di terreni argillosi della città di Roma.” *XIII Convegno “L’Ingegneria Sismica in Italia”*, S7.19, Bologna.

Pagliaroli A., Lanzo G., Tommasi P., Di Fiore V. (2014). “Dynamic characterization of soils and soft rocks of the Central Archaeological Area of Rome.” *Bulletin of Earthquake Engineering*, 12, 1365–1381.

Report FILAS (2013). “Innovazione nel campo geotecnico per la definizione di strumenti, metodologie operative e procedure finalizzate alla realizzazione di un nuovo modello di sottosuolo (modello integrato).” *Rapporto Finale Progetto di ricerca: FILAS-CR-2011-1031* Codice CUP : F87I12000080007.

Santos J.A., Correia, A.G. (2001). “Reference threshold shear strain of soil. Its application to obtain a unique strain-dependent shear modulus curve for soil.” *Proc. XV Int. Conf. on Soil Mechanics and Geotechnical Engineering. Istanbul, Turkey*. Vol. 1, 267-270.