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Strain moduli of alluvial soils from CPT, DMT, Vs, and lab tests

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ABSTRACT: In situ and laboratory test data from normally consolidated alluvial soils, deposited along the Tevere River about 15 km from the coastline, are analyzed and compared. Attention is focused on the sandy and silty layers, for which CPTU, SCPTU, SDMT, Cross-Hole, identification and resonant column data are available. The aim is to search strain levels associated to DMT and CPT tests and also to derive moduli decay curves for practical use in soil-structure interaction analyses.

1 INTRODUCTION

A variety of geotechnical problems, such as settlement calculations and soil-structure interaction analyses under static and dynamic loading conditions, require adequate knowledge of the stiffness properties of each interacting soil layer. Because the response of soils to loading-unloading is markedly non linear, constitutive models must include decay curves in order to follow the variation of stiffness with varying strain beyond a nearly elastic state.

Following initial studies on the evaluation of soil stiffness and damping properties for use in dynamic analyses, several procedures have been proposed to derive moduli decay curves from in situ test data. To this aim, it has proven quite effective to combine laboratory results, even from few samples, with extensive seismic dilatometer and cone (SDMT, SCPTU) profiling, supplemented by Cross-Hole and Down-Hole inside the boreholes. Laboratory tests should cover identification and cyclic loading, as in triaxial, simple shear, torsional and resonant column.

In this paper only data on well graded sandy and silty soils are analysed. They are part of investigation results from two sites, North and South of the right and left banks of the Tevere River, in the outskirts of Rome. Data include SDMT, SCPTU, CPTU, Cross-Hole measures, a large set of index properties, and the results of one resonant column test.

Test results have been analysed in pursue of various objectives. These include a comparison of soil stiffness from DMT and CPT; a comparison of shear wave velocity data from the down-hole measurements in SDMT and SCPTU and from the Cross-Hole results; an evaluation of the strain levels associated to DMT and CPT; the reconstruction of moduli decay curves for sandy soils from SDMT and Vs test data.

2 INVESTIGATION AND SUBSOIL PROFILE

The results of the in situ and lab tests used in this study are a fraction of the data retrieved during an extensive investigation program performed throughout the second half of last year. As shown in Figure 1, the investigated areas extend on both sides of the river. The southern area is enclosed within a hairpin bend of the stream; the northern one is split into four smaller sites, generally close to the right bank.

The investigation completed to date includes a total of 59 boreholes extended to maximum depth of 120 m, with core recovery by rotary drilling and casing, the retrieval of several samples, the execution of some SPT tests, of 13 SDMT and 30 SCPTU-CPTU tests, and 4 Cross-Hole to maximum depth of 120 m.

The piezocone was equipped with a porous stone inside the cylindrical part of the tip, above the cone, to measure u_2. A cylindrical module equipped with two receivers, to detect arrival of shear and compression waves, was also installed above the friction sleeve. An analogous module was installed above the blade to perform SDMT tests.

Samples for laboratory tests were retrieved using thin tube sampling in boreholes (intact) and by cutting portions of the cores extracted from the subsoil (disturbed); these disturbed samples were used to implement data on index properties and prepare reconstituted samples for drained direct shear tests.

Within the investigated area the elevation of the ground surface varies between 7.0 and 10.0 m a.s.l.

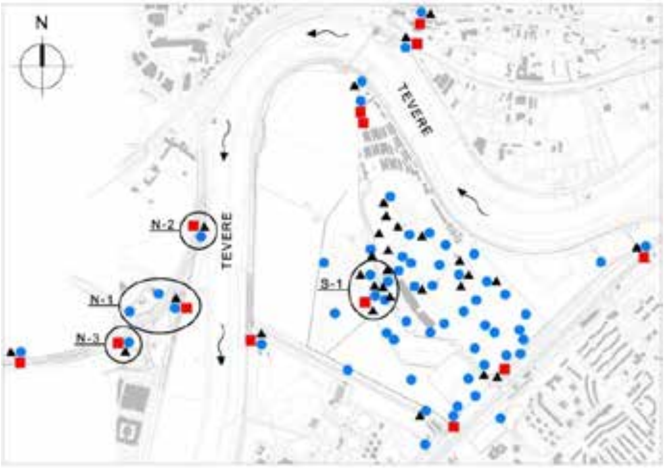

Figure 1. Investigation area and test sites used in this study

with minimal changes from the North to the South side of the river; thus the surface is essentially flat.

Data from boreholes and in situ tests reveal a thick alluvial deposit extending to depths of 55 m (North-East) and 65 m (South-West). It consists of layers of fine to medium coarse soils, silty clays and clayey silts, often mixed with organic matter, sandy silts and silty sands. In the top 20-30 m the predominantly clayey and silty soils are often mixed with organic clays and peat. At greater depths fine soils consist of horizontally layered silty clays and clayey silts containing fine sand; instead coarser strata are often interbedded with finer materials; the grain size spans from clayey silts with traces of sand to silty sands with moderate clay, and from silty sands with minor clay to slightly silty and slightly clayey sands.

The alluvial deposit covers a sandy gravel layer with thickness between 6-12 m on the northern side of the river and between 11 m (North-East) and 3 m (South-West) on the southern side. These coarse soils were deposited during the plio-pleistocene age atop a silty clay formation of comparable age; this fine soils deposit extends to great depths and includes thin layers of sandy and clayey silt.

At ground surface a thin layer of rubble, 1-2 m thick, and a layer of redeposited fine soils, 5-8 m thick, are encountered atop the alluvial deposit. The fine soils are highly overconsolidated as a result of desiccation and high suctions.

The distribution of pore water pressures with depth has been determined from measurements in standpipe and Casagrande piezometers and from recorded readings in electrical piezometers at four depths. Data agree well with the results of dissipation tests executed in the sandy layers during CPTU and SCPTU profiling. In essence a hydrostatic distribution can be assumed with a water table at an average depth of 7 m below surface.

This linear pore pressures increase and a constant unit weight of 19 kN/m^3 for soils above and below water table were used to analyse all test data.

The numerous lab tests provide a detailed identification of the different soils, with data on physical properties and also on the shear strength of the clayey and sandy soils. Combined information from borehole logs and in situ tests, allow detailed profiling and determination of shear strength and stiffness.

3 STUDY AREA NORTH OF THE RIVER

The investigation within this study area comprised a total of five boreholes, 4 of which drilled to 75 m and 1 to 85 m, the retrieval of 23 thin-tube and 16 disturbed samples from the sandy strata, three SCPTU to depths of 46, 48, 51 m, three SDMT to depths of 41, 46, 49 m, one Cross-Hole to 75 m.

One of the thin-tube samples was used for a resonant column test, to obtain a stiffness decay curve and values of damping with increasing shear strain.

Logs of boreholes show two stratigraphic conditions. At two locations (N-1, N-2) the alluvial deposit is entirely composed of sandy soils, including thin layers of fine materials and becoming finer at depths greater than about 35 m; at the third location (N-3) the top 16 m and the lower 20 m of the deposit consist of soft clayey silts and silty clays, while the central part (16-39 m) is essentially sandy in nature.

The grain size distributions of the 39 samples retrieved from the sandy layers are plotted in Figure 2. Despite the variability of the soil composition, it can be recognized that samples come from essentially sandy and silty layers with interbedded silty clays and clayey silts. In detail 11 samples contained less than 20% sand ($d > 75$ μm, retained by #200), 18 samples contained less than 50% silt and clay ($d < 75$ μm, passing #200), the remaining 10 samples are relatively well graded with a 50-70% content of particles finer than 75 μm. Accordingly 8 samples were non plastic, 6 samples had PI = 7-13%, 12 had PI = 15-24%, and 3 had PI = 29-34%.

The sample used for the resonant column contained 74% sand particles, 21% silt and 5% clay ($d <$ 2μm), and was non plastic.

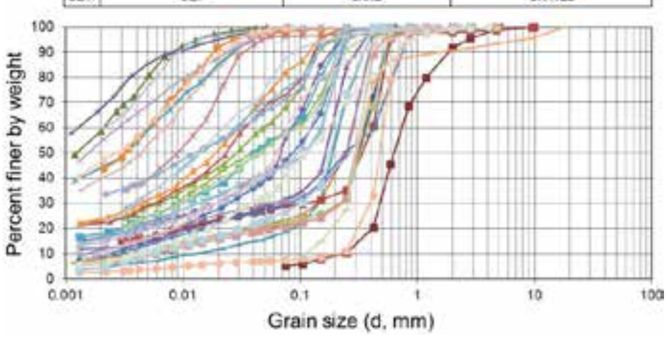

Figure 2. Grain size distributions of samples retrieved from sandy layers at the test sites on the North side of the river

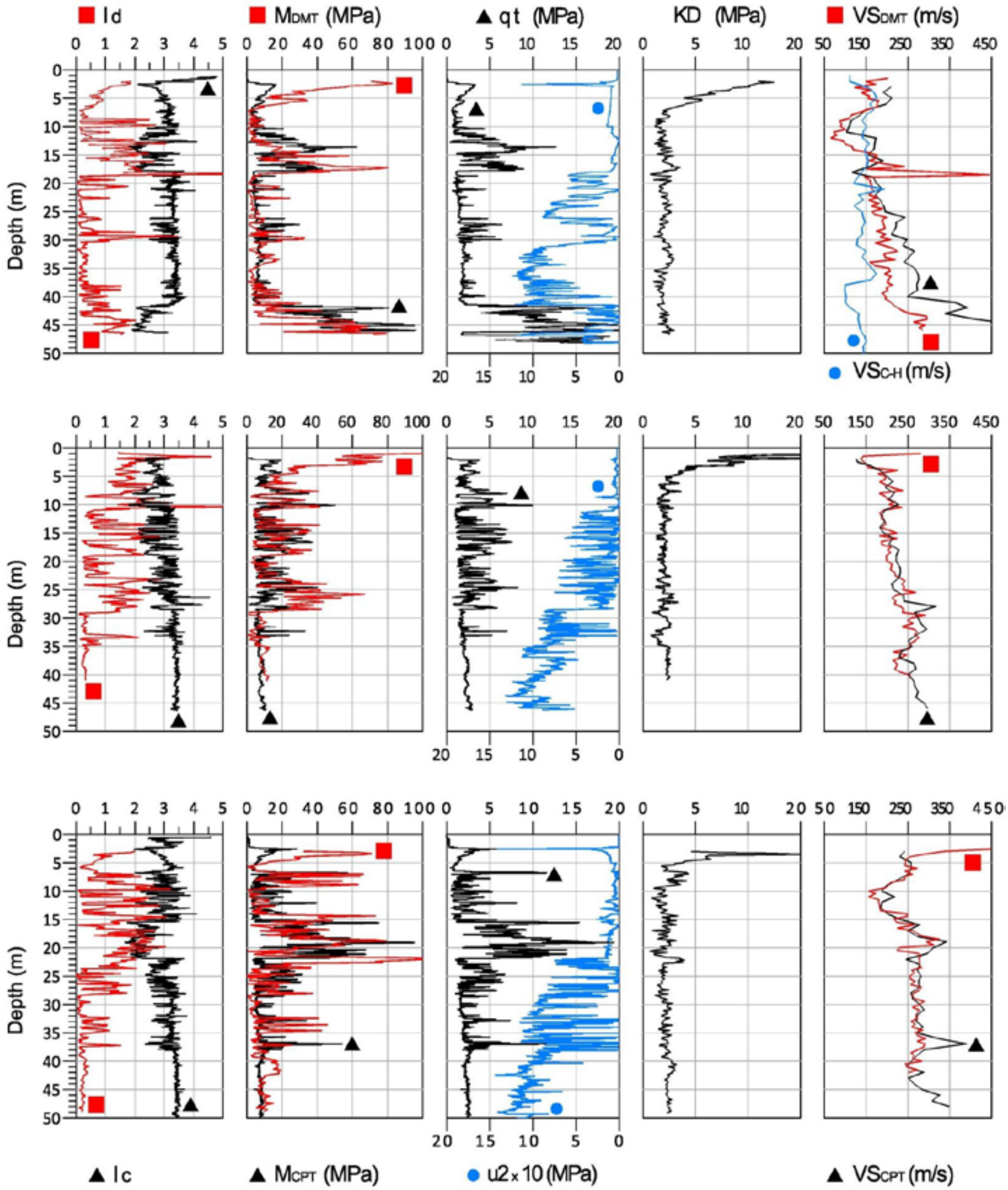

Figure 3. Comparison between values of measurements and of calculated parameters from SDMT, SCPTU, Cross-Hole tests from the three study sites on the North side of the river (N-1 top; N-2 centre; N-3 bottom)

Results of SCPTU, SDMT, Cross-Hole tests and values of calculated parameter are presented versus depth in Figure 3. The five plots of each row were drawn using data from each one of the three locations (N-1 top, N-2 centre, N-3 bottom). In each row these plots show the calculated values of I_c (Soil Behaviour Type Index from CPT-CPTU) and I_D (material index from SDMT), the constrained moduli (M_{CPT} and M_{DMT}), the data from SCPTU or CPTU (total cone tip resistance q_t, measured pore water pressure u_2 plotted by a factor of ten), the values of K_D (horizontal stress index from SDMT), and the velocities of shear waves (Vs) measured in the SCPTU, in the SDMT, and in the Cross-Hole test (only N-1). Calculations were performed using procedures described in the literature (Marchetti 1980; Robertson 1990); values of M_{CPT} have been determined using the relationship $M_{CPT} = 5\ (q_t - \sigma_{v0})$ with σ_{v0} total overburden at test depth (Mayne 2006).

The information on the type of soil, namely its behaviour with respect to drainage obtained from Ic and from Id is quite similar.

At the same time, values of the constrained modulus calculated from the cone (M_{CPT}) appear in good agreement with those obtained from the dilatometer (M_{DMT}), both in the fine and the coarse grained soils in the alluvial deposit.

A remarkably good agreement is noted between values of Vs measured along the SCPT and SDMT profiles. Instead both sets of values tend to diverge from the data obtained with the Cross-Hole test (location N-1). In this respect it shall be noted that in general the distance between the SCPT and SDMT profiles was less than 10 m; in addition, at location N-1 the two profiles are close to the borehole used for Cross-Hole testing. Thus, deviations between values of Vs measured with the two Down-Hole profiles and with the Cross-Hole test may originate from local variations in soil composition, density and resulting stiffness. It shall be noted, in fact, that in the upper 35 m all measurements agree quite well; visible minor differences may be due to local soil conditions.

4 STUDY AREA SOUTH OF THE RIVER

The investigation in the area on the South side of the river that was selected for this study (S-1) included the execution of three boreholes, 2 drilled to 60 m and 1 to 75 m, the retrieval of 21 samples from the sandy strata, 10 thin-tube and 11 disturbed samples, the execution of 4 CPTU to depths of 47, 55, 56, 59 m and 1 SDMT to a depth of 53 m.

The 3 boreholes and the 5 test profiles are enclosed within a limited area, in a radius of about 80 m. Data on shear wave velocities have been obtained from measurements along the dilatometer profile and from a Cross-Hole test; this test was performed in a borehole about 500 m away from the SDMT profile, but located within the same geological formation.

Logs of the four boreholes, including the one used for the Cross-Hole test, show similar stratigraphic conditions. The alluvial deposit comprises a top layer of soft silty clays, peaty clays, and clayey silts, extending to depths ranging from 17 m to 22 m, followed by a thick layer of sandy soils reaching an essentially constant depth of 60 m; at this depth the gravelly and sandy stratum is reached.

The grain size distributions of the 21 samples retrieved from the sandy layers are plotted in Figure 4. Once again the composition of the sampled material varies within a large interval, even if samples were retrieved from essentially sandy and silty soils. In essence, three types of material can be distinguished; in fact, 5 samples contained less than 20% sand (d > 75 μm), 10 samples contained less than 50% silt and clay (d < 75 μm), the remaining 6 samples are relatively well graded with a 50-70% content of particles finer than 75 μm. Accordingly 13 samples were non plastic, 4 had PI = 10-15%, 4 had PI = 15-24%.

In Figure 5 the results of the SDMT test are plotted versus depth and compared with data from one of the four CPTU located within the study area and with values of Vs. Shear wave velocity were obtained from the nearby Cross-Hole test.

As in the case of the three other study areas, values of I_c and I_D lead to essentially the same information with respect to soil type.

Instead, values of constrained modulus from the SDMT profile (M_{DMT}) tend to be smaller than those calculated from cone resistance (M_{CPT}), at least for the coarser portion of the sandy alluvium (depths 20 to 40 m). A better agreement is observed where the silty and clayey fractions become predominant, in the upper and lower layers of the deposit.

Values of M_{DMT} are aligned with similarly low values of K_D, comprised in the range 1-2 at depths greater than 20 m. Nonetheless, it shall be noted that K_D reflects the NC condition of the alluvial soils below the water table.

To a certain extent the differences between values of M_{CPT} and M_{DMT} may originate from thin layering and local variations of soil composition; these may produce the observed variability of q_t that shows high peaks and almost continuous oscillation between the lowest and highest range.

Such localized variations of stratigraphy and stiffness are not traced with the shear wave velocity measurements. In fact, values of Vs from SDMT and from the Cross-Hole test show a remarkably good agreement, despite the 500 m distance between the borehole and the dilatometer profile.

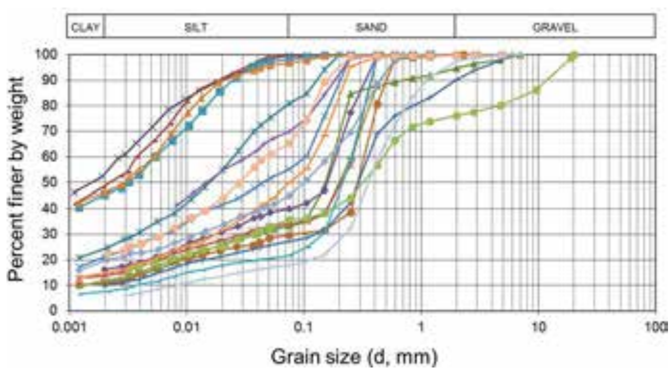

Figure 4. Grain size distributions of samples retrieved from sandy layers at the test site on the South side of the river

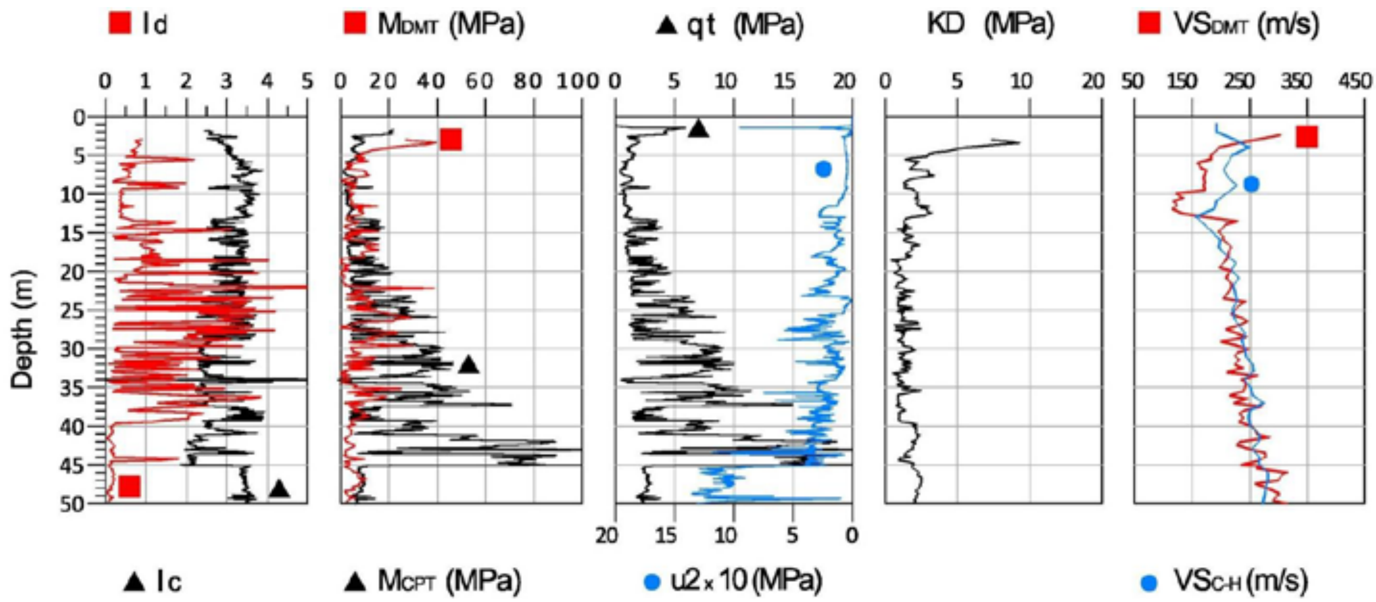

Figure 4. Comparison between values of measurements and of calculated parameters from SDMT, CPTU, Cross-Hole tests from the study site on the South side of the river

5 IN SITU G/G_0 -γ DECAY CURVES FROM SDMT

A procedure to derive in situ curves depicting elemental soil stiffness variations with strain level from SDMT was originally outlined by Marchetti et al. (2008). Such decay curves could be tentatively constructed by fitting "reference typical-shape" laboratory G/G_0-γ curves through two points, both provided routinely by SDMT: (1) the initial *small strain* shear modulus G_0, obtained as $G_0 = \rho\ V_S^2$; (2) a *working strain* shear modulus G_{DMT} derived from the constrained modulus M_{DMT} obtained by the usual DMT interpretation. As a first approximation, the two moduli may be linked using linear elasticity formulae.

The effectiveness of the M_{DMT} estimation relies on a large number of well documented comparisons between measured and DMT-predicted settlements or moduli (Monaco et al. 2006).

To locate the second point on the curve it is necessary to know, at least approximately, the elemental shear strain corresponding to G_{DMT} (hereafter denoted as γ_{DMT}) along the G/G_0 -γ curve.

Indications of values of γ_{DMT} in different soil types were presented by Amoroso et al. (2014); the Authors compared SDMT data with reference stiffness decay curves, from lab tests or back-calculated from real scale tests. The γ_{DMT} shear strains associated to the working strain moduli G_{DMT} typically range between 0.015-0.30 % in sand and 0.23-1.75 % in silt and clay.

Amoroso et al. (2014) proposed a hyperbolic stress-strain formulation (Eq. 1) for estimating the G/G_0 -γ decay curve from SDMT data:

$$\frac{G}{G_0} = \frac{1}{1+\left(\frac{G_0}{G_{DMT}}-1\right)\frac{\gamma}{\gamma_{DMT}}} \tag{1}$$

At a given site, by introducing into Eq. (1) the ratio G_{DMT} /G_0 obtained from SDMT results and a "typical" shear strain γ_{DMT} estimated for the given soil type, it is possible to plot the corresponding G/G_0 -γ curve.

Figure 6 shows the comparison between the G/G_0 -γ curve obtained in the laboratory by resonant column (RC) test on the silty sand sample from study area N-1 and the G/G_0-γ curve obtained by Eq. (1) using data from the SDMT (N-1) at the same depth.

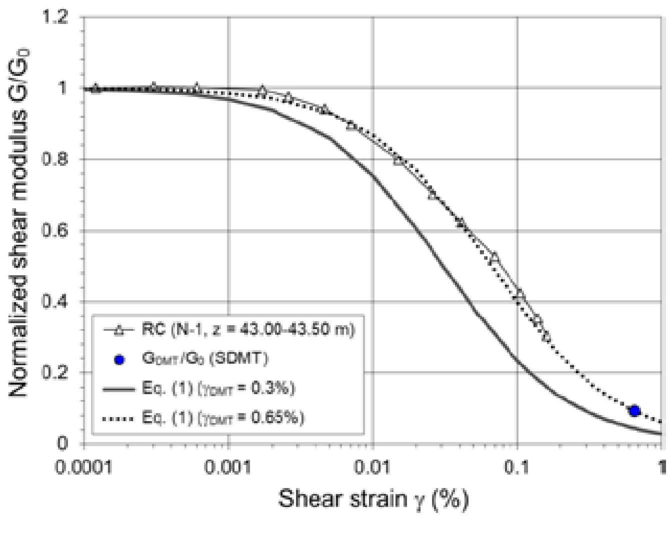

Figure 6. Comparison between G/G_0 -γ decay curves obtained in the laboratory by resonant column test and estimated from SDMT by Eq. (1)

G_{DMT} was calculated from M_{DMT} assuming a Poisson's ratio $\nu = 0.2$. As indicated by Amoroso et al. (2014) for sands it was assumed $\gamma_{DMT} = 0.30\%$.

It can be observed that the hyperbolic G/G_0 -γ curve does not fit the laboratory RC curve. Instead a much better agreement is found by introducing $\gamma_{DMT} = 0.65\%$ into Eq. (1).

6 CONCLUSIONS

An analysis and interpretation of results from an extensive investigation performed through an alluvial plain, along the Tevere River is presented herein. The examined data were obtained from SDMT, SCPTU, CPTU, Cross-Hole and laboratory tests.

With the attention focused on the sandy soils encountered within the 60-70 m thick deposit originated by the river, one of the main objectives of this study was to compare SDMT, SCPTU, and Cross-Hole test results. Test results have been analysed to check the potential of the two procedures in reconstructing the stratigraphy of the site, determining stiffness properties of well graded silty and sandy soils for small and working level strains, reconstruct stiffness decay curve for use in practical problems, such as soil-structure interaction analyses.

Based on the analyses performed herein, it can be concluded that both SDMT and SCPTU are a reliable mean of investigation, even in largely variable soil conditions, typically occurring in thinly bedded alluvial deposits. In fact, the results of the two procedures appear well aligned and coherent with respect to soil identification and evaluation of stiffness at small strains; some discrepancies have been noted, however, with respect to the constrained modulus M, which corresponds to the higher strain levels that are reached in most geotechnical problems under working conditions. Based on the information available herein, it could not be understood, however, if the observed differences (M_{DMT} vs M_{CPT}) depended on the type of relationship adopted to calculate M, on differences in soil conditions between the two test profiles, on a specific layering of fine and coarse materials, on possible errors during testing, or a combination of such factors.

With respect to reconstructing moduli decay curves from in situ tests, it appears that further studies are required; these should be aimed at defining values of γ_{DMT} related to specific and well identified soil types, to reduce the ranges in which γ_{DMT} may vary, and to provide a firm link between one soil type and corresponding narrow range of γ_{DMT} values.

7 REFERENCES

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