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G-γ decay curves in granitic residual soils by seismic dilatometer

C. Rodrigues
Polytechnic Institute of Guarda, Department of Civil Engineering

S. Amoroso
Istituto Nazionale di Geofisica e Vulcanologia, Via dell'Arcivescovado

N. Cruz & J. Cruz
Direção de Coordenação Técnica Rodoviária da Mota-Engil – Engenharia e Construção

ABSTRACT: Due to stiffness non-linearity direct application of small-strain shear modulus to evaluate deformations in most practical problems is not possible, which gave rise to the development of modulus (E_0 or G_0) degradation curves. This has been applied with success to sedimentary soils, but in residual soils the experience and available information in the international community is still scarce. Those soils are considered as structured soils, often classified as problematic soils as they do not fit into the behaviour that of remoulded or unstructured soils. In reality the role of bonding and fabric enhances the strength and stiffness of the soil. In this paper, the use of the seismic dilatometer test (SDMT) for the determination of in situ decay curves of stiffness with strain level (G-γ curves or similar) in a granitic residual soil, located in NE region of Portugal (Guarda) is illustrated, revealing its adequacy to solve this kind of problems. In situ tests and laboratory tests were performed in those granitic residual soils. The results were used for this investigation. The approach adopted relies on the ability of SDMT to provide a small strain modulus G_0 (from the shear wave velocity V_s) and a "working strain" modulus G_{DMT} (from the constrained modulus M_{DMT} by elasticity theory). Thus in situ G-γ decay curves are tentatively constructed by fitting curves through these two points. At this site the working strain modulus and the operational strain modulus are compared with same depth reference stiffness decay curves obtained by triaxial tests.

1 INTRODUCTION

The design of geotechnical structures requires knowledge of the stiffness characteristics of soils, often expressed in terms of shear moduli. However, due to stiffness non-linearity direct application of small-strain shear modulus to evaluate deformations in most practical problems is not possible, which gave rise to the development of modulus (E_0 or G_0) degradation curves. Available studies reveal that the decay in sands is much less than in silts and clays decay curves, which are very similar and in all cases the decay is maximum in the NC or lightly OC region. This has been applied with success to sedimentary soils, but in residual soils the experience and available information in the international community is still scarce.

The SDMT testing is widely used in evaluating these deformational properties, due to its ability to provide the small-strain shear modulus G_0 and a working strain modulus at a medium strain level, G_{DMT} (derived from the constrained modulus M_{DMT} by elasticity theory). Monaco et al. (2009) argued that since M_{DMT} is a working strain modulus, G_{DMT}/G_0 could be regarded as the shear modulus decay factor at working strains. The possibility of having two independent measurements of stiffness in only one test, opens a way to attempt deriving in-situ decay curves of soil stiffness with strain, as suggested by Monaco et al. (2009). To do so, it is important to locate, even if roughly, the shear strain γ_{DMT} corresponding to G_{DMT}.

2 SITE CHARACTERIZATION

2.1 *Geological background*

The climate in the studied area (Guarda, northeast of Portugal) is moist moderate, which favours the weathering of the granitic rock mass that dominates the region, turning the granite masses into a permeable sandy frame. The fluctuations of water level that go from a submerged stage in the wet season followed by drying up to depths of 5 to 6 meters during the summer, create the conditions to favour the constant weathering of the rocky substrate. As weathering progresses, the primary interparticle bonds between the grains are broken and a series of intergranular voids are created. Afterwards, weathering makes the feldspars and micas unstable, allowing leaching to occur, with the creation of a network of intragranular voids. In addition, the more stable minerals, mostly quartz grains, are bonded by highly weathered (and therefore unstable) grains of feldspars and micas to form a solid skeleton that is sometimes quite open.

2.2 *Testing program*

The testing program consisted of 6 SDMT tests, 6 SCPTu tests and 18 PMT tests distributed by 6 boreholes, as well as 3 triaxial tests with internal instrumentation performed in undisturbed and reconstituted samples, as represented in Figure 1. In this framework, emphasis is given to SDMT and triaxial tests carried out on selected samples as discussed hereafter.

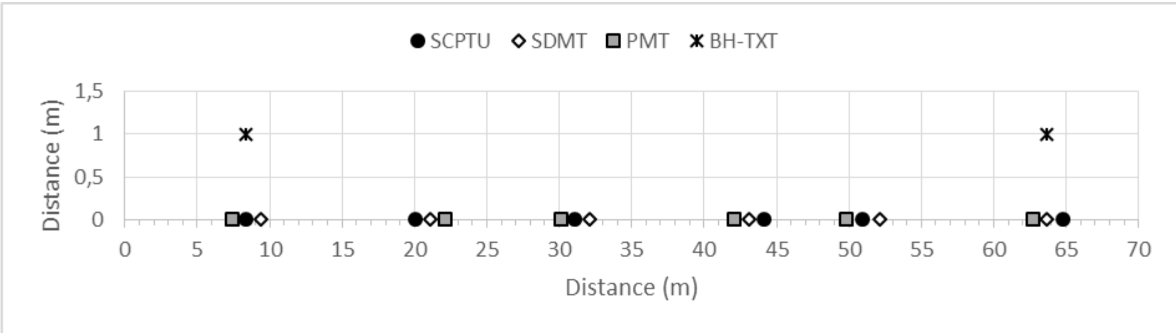


Figure 1. Spatial localization of the tests

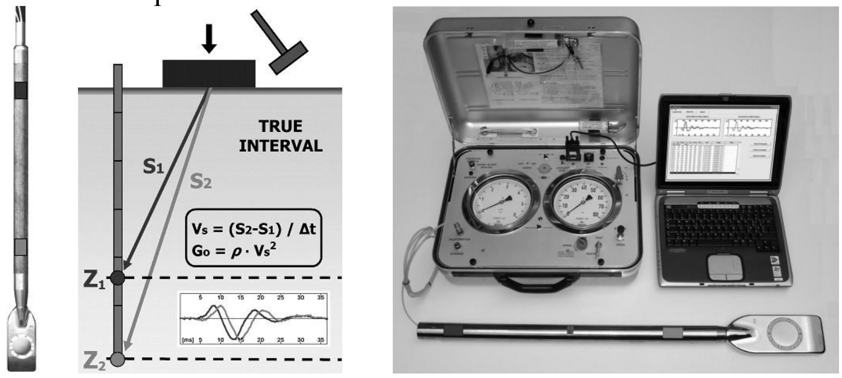
2.3 *SDMT tests*

The seismic dilatometer (SDMT) is the combination of the mechanical flat dilatometer (DMT), introduced by Marchetti (1980), with a seismic module for measuring the shear wave velocity, V_s. From V_s the small strain shear modulus G_0 may be determined using the theory of elasticity. A new SDMT system has been recently developed in Italy (Marchetti 2008), where the seismic module (Fig. 2) is a cylindrical element placed above the DMT blade, provided with two receivers spaced 0.5 m apart. The signal is amplified and digitalized at depth. The true-interval test configuration with two receivers avoids possible inaccuracy in the determination of the “zero time” at the hammer impact, sometimes observed in the pseudo-interval one-receiver configuration. Moreover, the couple 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. Hence the repeatability of V_s measurements is considerably improved. V_s is obtained (Figure 2b) as the ratio between the delay of the arrival of the impulse from the first to the second receiver (Δt) and the difference in distance between the source and the two receivers (S2−S1). V_S measurements are obtained every 0.5 m of depth, while the mechanical DMT readings are taken every 0.20 m.

The SDMT test results obtained on site are summarized in Figure 3. From the soil identification point of view material index I_D is fully consistent with grain size of these granitic residual soils, revealing once more the adequacy of the parameter to correctly identify these soils (Cruz, 2010). On its turn, horizontal stress index K_D ranges between 10 and 40, clearly pointing out to a significant cementation structure present in the soil, which seems to be confirmed by the particularly high values of the constrained modulus M_{DMT} with a mean value of 200MPa in the upper part of profile and 325MPa after 4m depth, clearly corresponding to a different weathering level. Finally, the shear modulus G_0 profile shows a linear increasing with the depth.

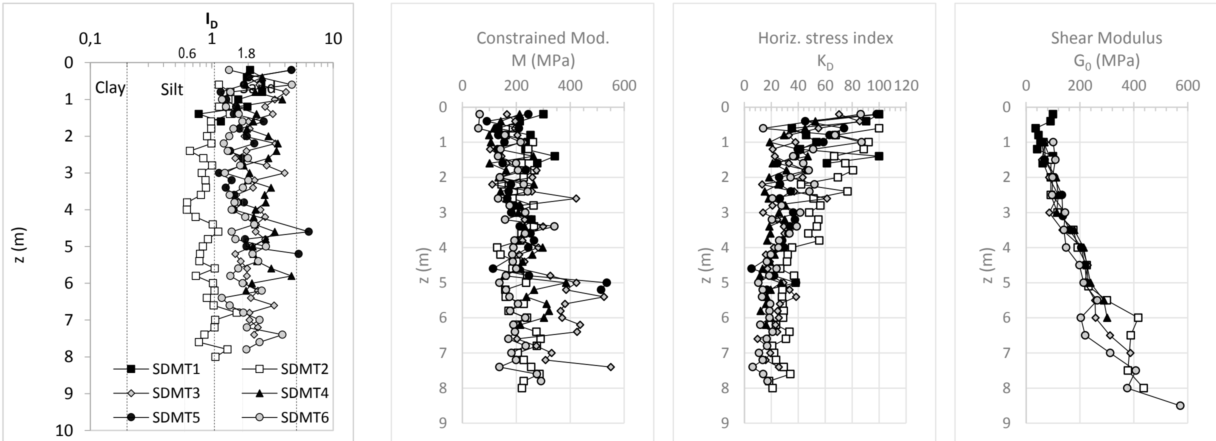
2.4 *Triaxial tests*

A set of three triaxial tests (CID), with internal instrumentation, were performed in samples taken with a Shelby sampler 1m away from SDMT1 and SDMT6. In Figure 4 the secant stiffness-strain behaviour is presented, obtained from 3 samples collected at different depths and consolidated at 50 kPa, where three discontinuities can be identified and may be considered as yield points. The first was established in $\log E_{sec}$:$\log \varepsilon_a$ space and relates to the point where the initial horizontal stretch ends, defined as first yield. This yield corresponds to the end of the linear elastic behaviour, reached for very small strains (less than ε_a=0.005%). The second discontinuity, located nearby 0.07% of axial strain, corresponds to the second yield, where it is observed an increase in the volumetric deformation in relation to the triaxial distortion. This yield was set according to Alvarado et al. (2012) and corresponds to the initial change in the relation between the volumetric deformation ε_v and the distortion ε_s. The behaviour between the first and the second yields should be elastic, but close to the second yield plastic strains and permanent deformations occur. These first two yields correspond to Y_1 and Y_2 defined by Jardine (1992). The last yield (ε_a=1% to 2%), established in logE_{sec}:logε_a space, corresponds to a point in which the structure is dramatically destroyed close to the maximum shear resistance. At this point, soils reveal large plastic strains and correspond to the Gross Yield of Coop & Wilson (2003) or the Bond Yield of Malandraki & Toll (2001).



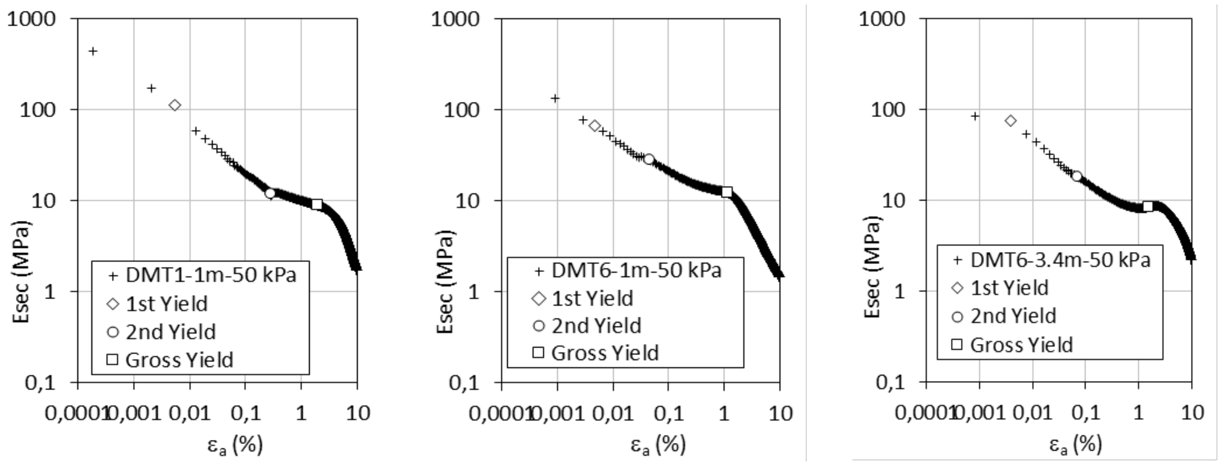
a) b) c)

Figure 2 - Seismic dilatometer test (Marchetti et al. 2008): DMT blade and seismic module (a); schematic test layout (b); seismic dilatometer equipment (c).



a) b) c) d)

Figure 3. SDMT test results



a) b) c)

Figure 4. Stiffness and yield points obtained by CID triaxial tests; a) BH 1, depth 1m, consolidation pressure 50 kPa; b) a) BH 6, depth 1m, consolidation pressure 50 kPa; a) BH 6, depth 3.4m, consolidation pressure 50 kPa.

3 IN SITU G-γ DECAY CURVES

3.1 *Seismic dilatometer*

The adopted approach relies on the ability of SDMT to provide routinely in sand at each depth both a small strain modulus (G_0 from V_S) and a "working strain" modulus (G_{DMT} from M_{DMT}) that could be tentatively used to fit in situ decay curves. The small shear strain modulus was evaluated by the SDMT ($G_0 = \rho V_s^2$) by using the shear wave velocity V_S obtained at the same depth of triaxial retrieved samples and the total mass density γ estimated by DMT unit weight results. On its turn, the working strain modulus G_{DMT} can be derived from the constrained modulus M_{DMT}, obtained from the flat dilatometer DMT (Marchetti et al. 2001) using the linear elastic formula (Eq. 1), as supported by Monaco et al. (2006) and Marchetti et al. (2008):

$$G_{DMT} = \frac{M_{DMT}}{2(1-\nu)/(1-2\nu)} \tag{1}$$

where ν = Poisson's ratio (taken equal to 0.2 in sand).

However, to use this G_{DMT} it is necessary to know the correspondent elemental shear strain, here designated as γ_{DMT}. Mayne (2001) indicates a range for γ_{DMT} within 0.05–0.1%, while Ishihara (2001) suggests that the range can be much higher, varying from 0.01% to 1%. Marchetti et al. (2006) reconstructed soil stiffness decay curves for the Treporti case history from local vertical strains measured at the centre of the embankment under each load increment. The intersection of the DMT data points with the observed in-situ decay curves indicated that γ_{DMT} was in the range 0.01–0.1% in sand and between 0.1% and 1% in silt. More recently, Amoroso et al. (2014) in a wider study concluded that γ_{DMT} varied from 0.015 % to 0.30 % in sand, 0.23 % to 1.75 % in silt/clay and higher than 2 % in soft clay.

3.2 *Tentative method for deriving in situ G-γ decay curves from SDMT*

The use of the SDMT to assess the in situ decay of stiffness at various test sites is explored using data obtained in granitic residual soils of Guarda and where both SDMT data and "reference" stiffness decay curves, obtained by triaxial tests, were available. The procedure adopted correspond to the proposed by Amoroso et al. (2014):

a) Using SDMT data obtained at the same depth of each available reference stiffness decay curve, a working strain modulus G_{DMT} is derived from M_{DMT} and normalized by its small strain value G_0 derived from V_S.

b) The G_{DMT}/G_0 horizontal ordinate line is superimposed to the same-depth experimental stiffness

c) decay curve, in such a way that the data point ordinate matches the curve;

d) The "intersection" of the G_{DMT}/G_0 (or E_{DMT}/E_0 in terms of Young's moduli) horizontal ordinate line with the stiffness decay curve provides a shear strain value referred to here as γ_{DMT}.

This methodology was applied in the present case, by using two SDMT and triaxial tests executed over samples retrieved at the same depth and subjected to same confinement observed in the DMT depths of determination. The respective results are presented in Figure 5, from where it is possible to draw the following considerations:

a) G_{DMT} results are within the same locus of the 1st yield, suggesting that installation of the equipment does not affect deeply the cementation structure, which was also noted by Cruz (2010);

b) The maximum stiffness obtained at small strain in triaxial tests are in the same order of magnitude that the obtained via shear wave velocities, which demonstrates the high quality achieved in the sampling processes;

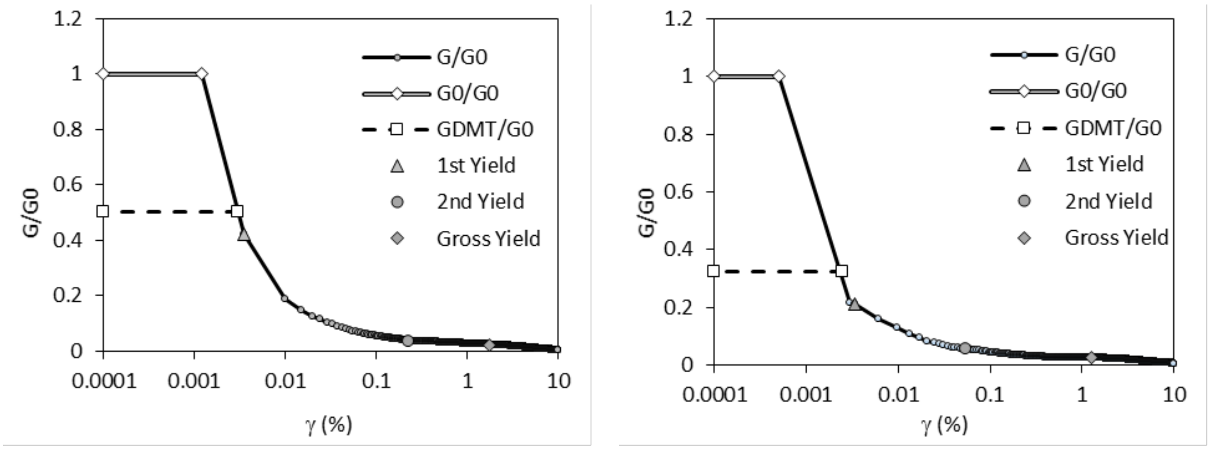
c) Correspondent γ_{DMT} falls within 0.0025 % and 0.003 %, which are one order magnitude lower than those proposed by Amoroso et al. (2014) for sedimentary soils with similar grain size (0.015 % to 0.30 %), illustrating very well the influence of cementation structure on the mechanical behaviour of these soils.

4 PROPOSED NUMERICAL G- γ DECAY CURVES

Several authors (Hardin & Drnevich 1972, Bellotti et al. 1989, Byrne et al. 1990, Fahey and Carter 1993, Fahey 1998) introduced a hyperbolic model to represent the non-linear stress-strain behaviour of soil in pressuremeter tests. In this respect, the SDMT experimental data determined in the two triaxial tests were used to assist the construction of a hyperbolic stress-strain equation (Eq. 1), that confirm the formulation already found by Amoroso et al. (2014):

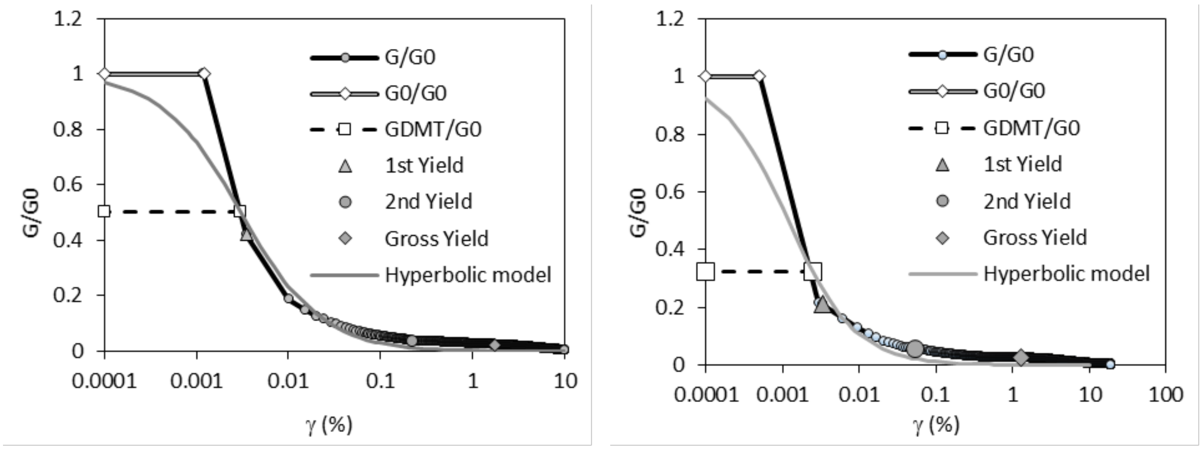
$$\frac{G}{G_0} = \frac{1}{1 + \left(\frac{G_0}{G_{DMT}} - 1\right)\frac{\gamma}{\gamma_{DMT}}} \tag{2}$$

Thus, the ratio G_{DMT}/G_0 obtained from SDMT and the estimated shear strain γ_{DMT} were used to plot the corresponding hyperbolic curve to both test. The results shown in Figure 6 plotted together with the curves obtained from SDMT using Eq. 2 and the coupled values of G_{DMT}/G_0-γ_{DMT}, and they provide a reasonable fit to the "measured" stiffness decay curves in medium to high strains, while at low strain levels the match with hyperbolic model is poor. Amoroso et al. (2014) reported identical behaviour in the Shenton Park sands (Australia).



a) b)

Figure 5 - Laboratory G/G_0-γ curves and superimposed G_{DMT}/G_0 data points at granitic residual soils of Guarda of: a) SDMT1, depth=1 m and b) SDMT6, depth =3.4 m.



a) b)

Figure 6 - Laboratory G/G_0-γ curves and superimposed G_{DMT}/G_0 data points at granitic residual soils of Guarda of: a) SDMT1, depth=1 m and b) SDMT6, depth =3.4 m.

5 CONCLUSIONS

The presented experimental work was based in a high quality characterization program constituted by DMT and triaxial testing performed in a granitic residual environment. Degradation curves (G/G_0-γ) were plotted considering triaxial and DMT results, which were then compared with hyperbolic model resulting curves. The results show that G_{DMT} results are within the same locus of the 1st yield, the maximum stiffness obtained at small strain in triaxial tests are in the same order of magnitude that the obtained via shear wave velocities (reflecting the high quality achieved in the sampling processes) and that correspondent strains (γ_{DMT}) falls within 0.0025% and 0.003%, substantially lower than those proposed by Amoroso et al. (2014) for sedimentary soils with similar grain size (0.015 % to 0.30 %), Hyperbolic model generally fits at medium to high strains, while at low strain levels the match is poor.

6 REFERENCES

Alvarado, G.; Coop, M.R. and Willson, S.M. 2012. On the role of bond breakage due to unloading in the behaviour of weak sandstones. *Géotechnique*, 62(4), 303–316.

Amoroso S., Monaco P., Lehane B. and Marchetti, D. 2014. Examination of the potential of the seismic dilatometer (SDMT) to estimate in situ stiffness decay curves in various soil types. *Soils and Rocks*, Vol. 37, No. 3, 177-194. ISSN: 1980-9743. Brazilian Association for Soil Mechanics and Geotechnical Engineering (ABMS) and Portuguese Geotechnical Society (SPG). São Paulo, Brazil. http://www.soilsandrocks.com.br/soils-androcks/SR37-3_177-194.pdf

Coop, M.R., Willson, S.M. 2003. Behavior of Hydrocarbon Reservoir Sands and Sandstones. *Journal of Geotechnical and Geoenvironmental Engineering*, 129(11), 1010-1019.

Cruz, N. 2010. *Modelling geomechanics of residual soils by DMT tests*. PhD thesis, Porto University, (*www.nbdfcruz.drupalgardens.com*).

Jardine, R.J. 1992. Observations on the kinematic nature of soil stiffness at small strains. *Soils and Foundations*, (32), 111-124.

Lehane, B.M. and Fahey, M. 2004. Using SCPT and DMT data for settlement prediction in sand. *Proc. 2nd Int. Conf. on Site Characterization ISC'2*. Porto: 2, 1673–1679.

Malandraki, V. and Toll, D. (2001). "Triaxial tests on a weakly bonded soil with changes in stress path". Journal of Geotechnical and Geoenvironmental Engineering, 27(3), 282-291.

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

Marchetti, S., Monaco, P., Calabrese, M. and Totani, G. 2006. Comparison of moduli determined by DMT and backfigured from local strain measurements under a 40 m diameter circular test load in the Venice area. Proc. *2nd Int. Conf. on the Flat Dilatometer*. Washington D.C. R.A. Failmezger and J.B. Anderson (eds), 220–230.

Marchetti, S., Monaco, P., Totani, G. and Marchetti, D. 2008. In Situ Tests by Seismic Dilatometer (SDMT). *ASCE Geot. Special Publication* GSP 170 honoring Dr. J.H. Schmertmann. New Orleans March 9–12.

Marchetti, S., Monaco, P., Totani, G., and Calabrese, M. 2001. The flat dilatometer test (DMT) in soil investigations—A report by the ISSMGE Committee TC16. *Proc., 2nd Int. Conf. on the Flat Dilatometer*, R. A. Failmezger and J. B. Anderson, eds., In-Situ Soil Testing, Lancaster, VA, 7–48.TC16 (2001).

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.

Monaco, P., Marchetti, S., Totani, G., Marchetti, D. 2009. Interrelationship between small strain modulus G_0 and operative modulus. Proc. of *International Conference on Performance-Based Design in Earthquake Geotechnical Engineering* (IS-Tokyo 2009), Tsukuba, Japan. 1315-1323.

Monaco, P., Totani, G., Calabrese, M. 2006. DMT-predicted vs observed settlements: a review of the available experience. In R.A. Failmezger and J.B. Anderson (eds), Flat Dilatometer Testing, Proc. *2nd International Conference on the Flat Dilatometer*, Washington D.C. 244–252.