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Small Shear Strain Modulus Degradation by the Seismic Dilatometer Marchetti Tests (SDMTs)

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ABSTRACT: In this paper some Italian sites, prone to high seismic risk, were studied to know the dynamic soil profile. For site characterization of soil deep investigations have been also undertaken. Borings and dynamic in situ tests have been performed. Among these Cross-hole (CH), Down-hole (DH) and Seismic Dilatometer Marchetti Tests (SDMT) have been carried out, with the aim to evaluate the soil profile of shear waves velocity (V_S). Moreover the following laboratory tests were carried out on undisturbed and/or reconstituted samples: Oedometer tests, Direct shear tests, Triaxial tests, Resonant Column and Torsional shear tests. The availability of a large number of different tests for the same site both on site and in the laboratory allows us to correctly define the dynamic characteristics of the soils under study. In particular the purpose of this study is to verify the possibility of obtaining by SDMT the construction of stiffness strain decay curves for different soil type. At various test sites was evaluated the small strain stiffness (G_o from V_S) and then introduced a working strain stiffness (G_{DMT}) based by the values of the constrained modulus M_{DMT}. The working strain moduli G_{DMT} are compared with reference stiffness decay curves obtained by dynamic laboratory tests. The shear strains γ_{DMT} associated with working strain moduli G_{DMT} enable us to define the trend of in situ stiffness decay curves for different soil tested.

Keywords: seismic dilatometer; small strain stiffness; working strain stiffness; constrained modulus; shear strains.

1. Introduction

Soil stiffness at small strain is a key parameter to solve many geotechnical problems, such as the design of the foundation, the seismic behavior of soils and the study of soil amplification and liquefaction. There are many direct methods to perform the shear wave velocity measurements in the soil: Down Hole (DH), Cross Hole (CH), SASW, MAWS, etc. Among these methods, the use of Seismic Dilatometer Marchetti Tests (SDMT), to measure the shear wave velocity profile, was developed and commonly used in Italy. These tests shows good repeatability of the measurements and the possibility to know, at the same time, the mechanical soil characteristics in the static field.

Six Italian cohesive and uncohesive test soils in Catania, Messina and San Giuliano di Puglia (CB) have been studied to evaluate the potential of SDMT in defining the G-γ decay curves. For this reason was used both the stiffness at small strains (the small strain shear modulus G_o) obtained from the shear wave velocity V_S as $G_o = \rho\ V_S$ and the stiffness at operative strains G_{DMT} (as represented by the constrained modulus M_{DMT} obtained by the usual DMT interpretation).

2. The Dilatometer Marchetti Test (DMT)

More than 30 years ago, Prof. Silvano Marchetti designed and constructed the first dilatometer at the L'Aquila University in Italy; this device and principles of soil investigation were presented in 1975 at the conference of the American Society of Civil Engineers (ASCE) in Raleigh [1]. Dilatometer investigations consist of measurements of gas pressure acting on the membrane of the dilatometer blade at selected depths (Figure 1). In soil tests, two pressure measurements (A and B) are usually carried out, which force the membrane center to move by 0.05 mm to the ground (A reading) and the diaphragm center to the ground by approximately 1.05 mm (B reading). In order to extend the dilatometer tests, pressure measurements are sometimes carried out when the membrane returns to the ground contact position (C reading).

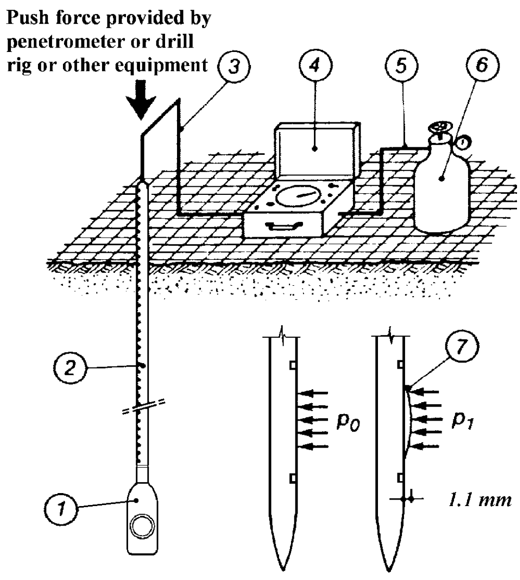


Figure 1. General layout of the dilatometer test. 1) Dilatomer blade; 2) Push rods; 3) Pneumatic electric - cable; 4) Control box; 5) Pneumatic - cable; 6) Gas tank; 7) Expansion of the membrane.

The values of readings A, B, and C are corrected due to the inertia of the diaphragm and marked as p_o, p_1, and p_2, respectively. The value of the vertical component of effective vertical stress σ'_{vo} are used to determine the following dilatometer indexes: material index I_D, lateral stress index K_D, and dilatometer modulus E_D [2, 3, 4, 5, 6, 7, 8, 9, 10, 11].

Material index I_D:

$$I_D = f(A, B, u_o) = \frac{p_1 - p_o}{p_o - u_o} \quad (1)$$

Horizontal stress index K_D:

$$K_D = f(A, u_o, \sigma'_{vo}, B) = \frac{p_o - u_o}{\sigma'_{vo}} \quad (2)$$

Dilatometer modulus E_D:

$$E_D = f(A, B) = 34.7 \cdot (p_1 - p_o) \quad (3)$$

Pore pressure index U_D:

$$U_D = f(A, C, u_o, B) = \frac{p_2 - p_o}{p_o - u_o} \quad (4)$$

3. The Seismic Dilatometer Marchetti Test (SDMT)

Supplementing the equipment used to perform dilatometer tests with two geophones in the SDMT seismic dilatometer extended the possibilities of interpretation of dilatometer tests [12, 13, 14, 15, 16, 17].

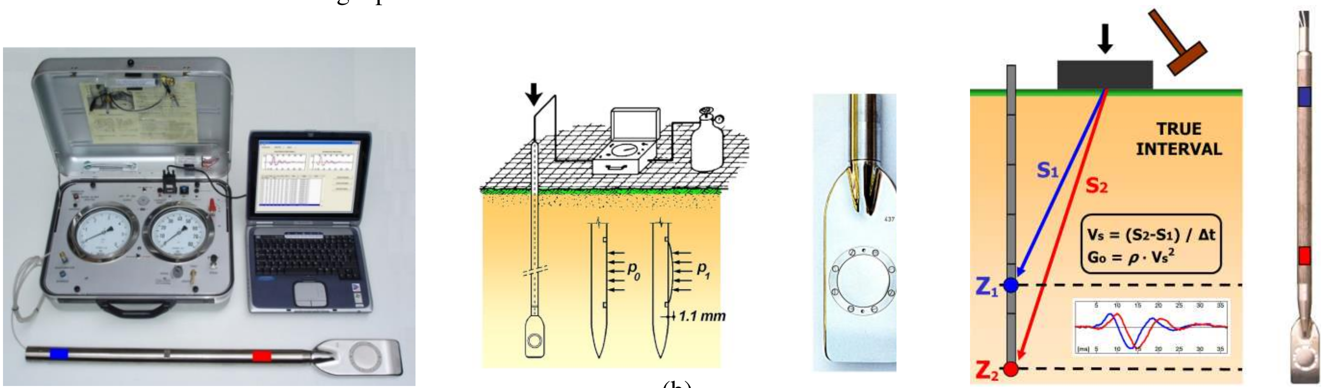
The seismic dilatometer (SDMT) is the combination of a standard dilatometer DMT equipment presented by Marchetti [18] with a seismic module for measuring the shear wave velocity of the seismic propagation V_S. Initially conceived for research, the SDMT is gradually entering into use in current site investigation practice.

The SDMT [15, 17] provides a simple means for determining the initial elastic stiffness at very small strains and in situ shear strength parameters at intermediate level of strains in natural soil deposits [19, 20, 21]. This apparatus was also used in offshore condition by Cavallaro et al. [22, 23].

The test is conceptually similar to the seismic cone (SCPT). First introduced by Hepton [24], the SDMT was subsequently improved at Georgia Institute of Technology in Atlanta, USA [16, 25, 26].

The seismic modulus is a cylindrical instrumented tube, located above the DMT blade [18], housing two receivers at a distance of 0.50 m (see Figure 2). 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).

Moreover 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.



(a) (b) (c)

Figure 2. Seismic dilatometer equipment (a). Schematic layout of the flat dilatometer test (b) and of the seismic dilatometer test (c).

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 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 (while the mechanical DMT readings are taken every 0.20 m).

The shear wave source at the surface 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.

Source waves are generated by striking a horizontal plank at the surface that is oriented parallel to the axis of a geophone connects by a co-axial cable with an oscilloscope [16, 25[. The measured arrival times at successive depths provide pseudo interval V_S profiles for horizontally polarized vertically propagating shear waves.

In Figure 2 it is shown the SDMT scheme for the measure of V_S while Figure 3 shows an example of seismograms obtained by SDMT at various test depths at the site of "DPC" area (it is a good practice to plot side by-side the seismograms as recorded and re-phased according to the calculated delay).

The determination of the delay from SDMT seismograms, normally obtained using a cross-correlation algorithm rather than relying on the first arrival time or specific single points in the seismogram, 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 (Figures 2 and 3). It may be noted the repeatability of the V_S profile is very high, similar to the repeatability of the other DMT parameters, if not better. The coefficient of variation of V_S is in the range 1 - 2 %.

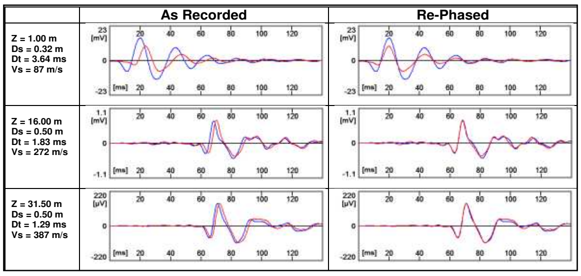


Figure 3. Example of seismograms obtained by SDMT at the site of DPC - Messina.

V_s may be converted into the initial shear modulus G_o by the theory of elasticity by the well-known relationships:

$$G_o = \rho V_S^2 \tag{5}$$

where: ρ = mass density.

The combined knowledge of G_o and of the one-dimensional modulus M (from DMT) may be helpful in the construction of the G-γ modulus degradation curves [27, 28].

A summary of SDMT parameters are shown in Figure 4 where:

- I_D: Material Index; gives information on soil type (sand, silt, clay);
- φ': Angle of Shear Resistance;
- M: Vertical Drained Constrained Modulus;
- C_u: Undrained Shear Strength;
- K_D: Horizontal Stress Index; 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;
- V_S: Shear Waves Velocity (Figure 4).

Comparisons between measured V_S by DH and measured V_S by SDMT is reported as an example in Figure 5 and 6 for the "INGV" and "DPC" test sites.

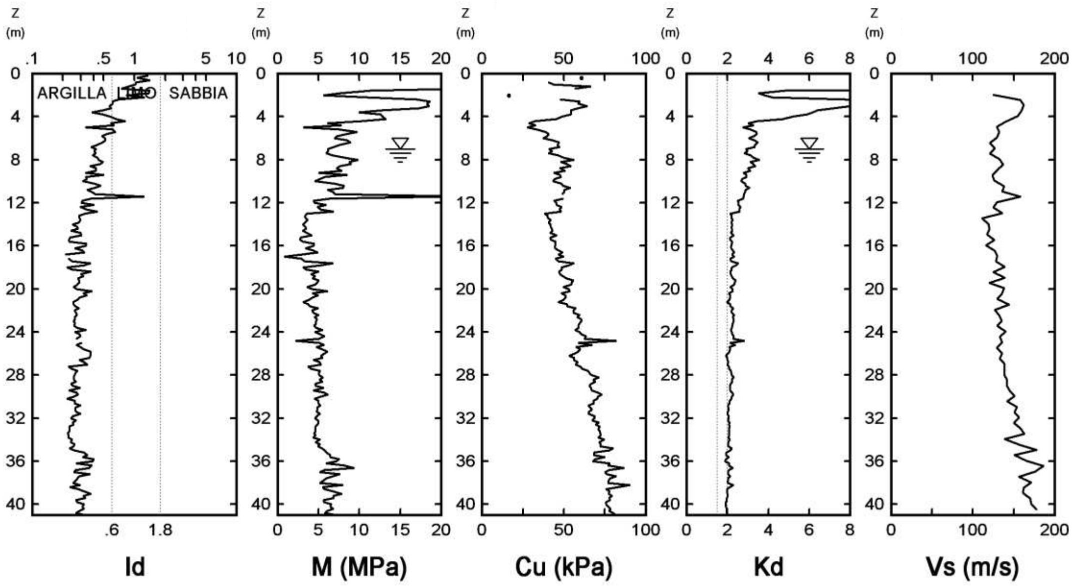


Figure 4. Results of the SDMTs in terms of geotechnical parameters for "Piana di Catania" area.

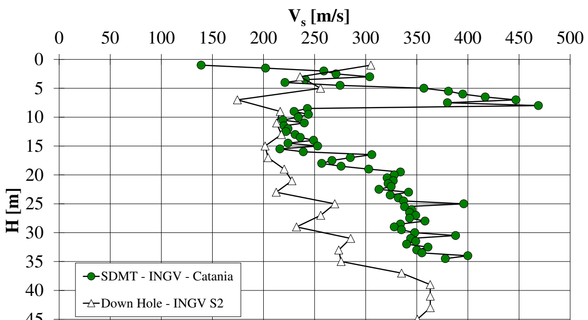


Figure 5. Shear wave velocity V_S measured by DH and SDMT in the INGV - Catania area.

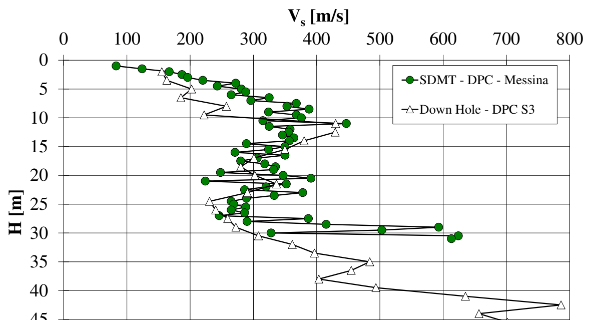


Figure 6. Shear wave velocity V_S measured by DH and SDMT in the DPC - Messina area.

4. In Situ G-γ Decay Curves by SDMT

Marchetti et al. [15], investigate the possible use of the SDMT for deriving "in situ" decay curves of soil stiffness with strain level (G-γ curves or similar). Such curves could be tentatively constructed by fitting "reference typical-shape" laboratory G-γ curves (see e.g. Figure 7, where G is normalized to G_o) through two points, both obtained by SDMT: (1) the initial small strain modulus G_o (obtained as $G_o = \rho V_S^2$), and (2) a working strain modulus G_{DMT}.

In Figure 7, Maugeri [29] proposes a comparison between the results obtained for the clay of Catania [30] and those proposed by other authors Hara [31], Yokota [32], Tatsuoka (in Iwasaki [33]) and Athanasopouls [34].

To locate the second point on the G-γ curve it is necessary to know, at least approximately, the shear strain corresponding to G_{DMT}. Indications by Mayne [35] locate the DMT moduli at an intermediate level of strain ($\gamma \approx 0.05$ - 0.1 %) along the G-γ curve. Similarly Ishihara [36] classified the DMT within the group of methods of measurement of soil deformation characteristics involving an intermediate level of strain (0.01 - 1 %). The above qualitative indications need to be confirmed by further investigations.

Therefore, SDMT allows the evaluation of the dependence of the soil stiffness decay curve (G/G_o) on the shear strain level [37, 38, 39]. A key feature distinguishing SDMT from other seismic tests is that in addition to G_o, a "working strain" shear modulus, G_{DMT} is determined. The availability of two datapoints (G_o and G_{DMT}) may help in selecting the G-γ decay curve, important in soil dynamics [26].

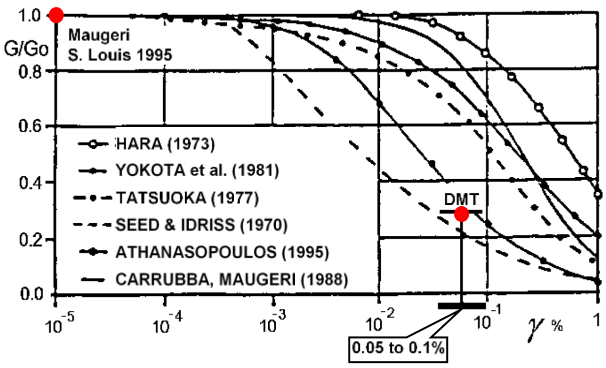


Figure 7. Tentative method for deriving G-γ curves from SDMT (Maugeri [29] adapted by Marchetti [15]).

Following the approach suggested by [39], values of the working strain shear modulus G_{DMT} have been derived by the values of the constrained modulus M reported in Figure 8 provided by the DMT tests, using the following equation:

$$G_{DMT} = \frac{(1-2\cdot\nu)}{2\cdot(1-\nu)} \cdot M_{DMT} \quad (6)$$

where ν (Figure 9) is the Poisson ratio, obtained from Down Hole (DH) or Cross Hole (CH) tests (noting that M_{DMT} is a drained modulus).

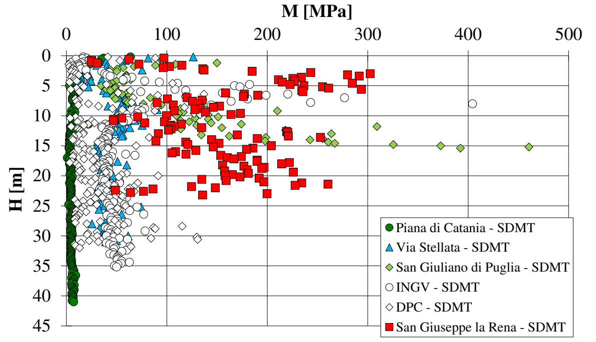


Figure 8. Constrained modulus M obtained by DMT in the test sites.

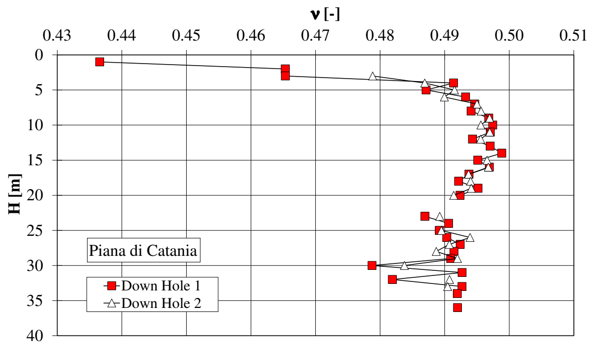


Figure 9. Poisson ratio from Down Hole (DH) test in the "Piana di Catania" area.

It should be noted that correlations between the DMT parameters (E_D and K_D) and M_{DMT} proposed by Marchetti [18] are based on the assumption that M_{DMT} represents a reasonable estimate of the "operative" or drained working strain modulus (i.e. the modulus that, when introduced into the linear elasticity formulae, provides realistic estimates of the settlement of a shallow foundation under working loads).

The assumption that M_{DMT} can provide a reasonable estimate of the operative working strain modulus is supported, for example, by research of Monaco et al. [40], who reviewed a large number of well documented case histories comparisons between measured and DMT-predicted settlements or moduli. Marchetti et al. [15] also show how the use of M_{DMT} predicted reasonable settlements at the predominantly silty deposits test site of Treporti, Venice, Italy.

Therefore, it is necessary to know the elemental shear strain that the value of G_{DMT} corresponds to (referred to here as γ_{DMT}). Mayne [35] indicates a range $\gamma_{DMT} \approx 0.05$ - 0.1 %, while Ishihara [36] suggests that the range can be much higher, varying from 0.01 % to 1 %.

Marchetti et al. [41] re-constructed soil stiffness decay curves for the Treporti case history and indicates a range of γ_{DMT} of 0.01 - 0.1 % in sand and between 0.1 % and 1 % in silt. Moreover, Amoroso [42] examined data from many tests sites and concluded that γ_{DMT} varied from 0.01 % to 0.15 % in sand, 0.1 % to 0.2 % in silt/clay and to in excess of 2 % in soft clay.

The use of the SDMT to assess the in situ decay of stiffness at various test sites is explored in the following sections using data obtained in different soil types and where both SDMT data and "reference" stiffness decay curves were available. Such stiffness decay curves were obtained by laboratory tests on six Italian cohesive and uncohesive test soils in Catania, Messina and San Giuliano di Puglia (CB).

The procedure adopted in all cases is as follows, and is shown schematically on Figure 10:

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

2) The G_{DMT}/G_o (or E_{DMT}/E_o) horizontal ordinate line is superimposed to the same-depth experimental stiffness decay curve, in such a way that the data point ordinate matches the curve;

3) The "intersection" of the G_{DMT}/G_o (or E_{DMT}/E_o) horizontal ordinate line with the stiffness decay curve provides a shear strain value referred to here as γ_{DMT}.

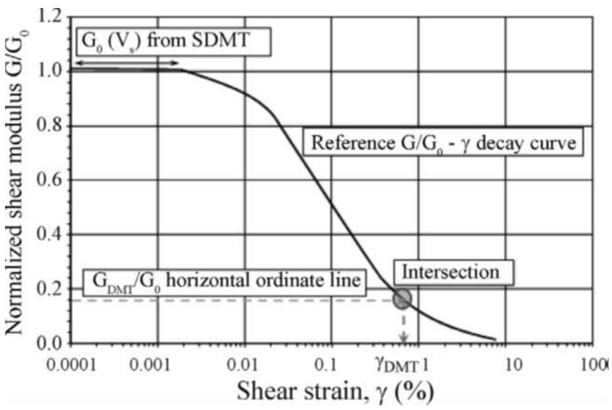


Figure 10. Procedure to derive *in situ* G-γ decay curves from SDMT (Amoroso et al. [39]).

5. Dynamic Laboratory Tests

The dynamic laboratory tests were carried out on sample retrieved in the following test site areas.

The "Piana di Catania" area [43], in the S-E zone of Catania, is mainly constitute by clayey soil with a clay fraction (CF) prevalently in the range of between 40 to 80 %. The values of the natural moisture content w_n prevalently range from between 35 and 45 %. In laboratory Resonant Column Tests (RCTs) were performed, for the "Piana di Catania" area. Moreover, in situ Cross Hole test (CH) is available.

The "Via Stellata" area [43], in the central zone of Catania, mainly consist of silty clay with a natural moisture content from between 20 and 27 %, with a plasticity index of PI = 18 - 32 %. RCTs results are available. Moreover, in situ Down Hole (DH) were performed.

In the "Saint Nicola alla Rena Church" area [44], in the central zone of Catania, the lava and tuff strata are interbedded with soils lenses of variable thickness mainly consisting of sand and gravel. The cohesive condition of sample investigated in RCTs is guaranteed by the presence of silty fraction that reaches a maximum value of 4.6 %. The natural moisture contents ranged from 21 to 30 %. Moreover, in situ Down Hole (DH) is available.

In the central area of Catania, the "Piazza Palestro" deposits [45] consist of fractured lava, sand and silty with a natural moisture content w_n of about 26 - 35 %. In laboratory RCTs were performed on cohesive sample. Moreover, in situ Down Hole test (DH) is available.

In the "Via Dottor Consoli" site [46], in the central zone of Catania, in mainly constitute by silty clay (grey color) The value of the natural moisture content w_n prevalently ranges from between 22 - 24 %. Characteristic, G_s ranged between 2.54 and 2.67. In laboratory RCTs were performed, for the "Via Dottor Consoli" area. In situ Down Hole (DH) is available.

The "San Giuliano di Puglia (CB)", located in Molise region in the Southern Italy, is characterized by clayey silt soil. The natural moisture content w_n prevalently range between 17 and 22 %. Characteristics values for the Atterberg's limits are: w_l = 53 - 63 % and w_p = 23 - 24 %, with a plasticity index of PI = 30 - 40 % [47, 48, 49].

The "ENEL box" [50] site is located in the Catania Plain area in the S-E zone of the city. The values of the natural moisture content w_n in the clayey layers is about 30 % with a plasticity index of PI 17.29 %. The specific gravity values G_s obtained is equal to 2.65.

The "INGV" (National Institute of Geophysics and Volcanology) area in the central zone of Catania, is mainly constitute by silty clay (blue color) with a natural moisture content w_n of about 16 - 26 %. In laboratory RCTs were performed. Moreover, in situ Down Hole (DH) and Cross Hole tests (CH) are available [51].

The "DPC" (Civil Defence Department) area [52] in the central zone of Messina, is mainly constitute by clayey sandy silt. The value of the natural moisture content w_n prevalently ranges from between 12 - 40 %. Characteristic values for G_s (specific gravity) ranged between 2.74 and 2.79. Down Hole (DH) and Cross Hole tests (CH) are available.

The "San Giuseppe la Rena" site [53, 28] along the southern coast line of Catania is characterized by fine sands with thin interbeddings of gravelly sands 0.24, the water table lies around 2 m below the ground surface. The values of γ_{min} = 14.50 % and γ_{max} = 16.85 % were obtained The specific gravity values G_s is equal to 2.68.

Several other laboratory tests have been performed in the static field, including grain size distribution test, oedometer test, direct shear test and triaxial test (UU, CU, and CD).

Based on the laboratory tests typical range of physical characteristics, index properties and strength parameters of the deposits mainly encountered in these areas are reported in Table 1.

In the dynamic field the Resonant Column Tests (RCT) have been performed. Shear modulus G and damping ratio D of deposits were obtained in the laboratory from Resonant Column Tests (RCT).

A Resonant Column/Torsional shear apparatus was used for this purpose. G is the unload-reload shear modulus evaluated from RCT, while G_o is the maximum value or also "plateau" value as observed in the G-log(γ) plot.

The laboratory test conditions for cohesive soils and the obtained small strain shear modulus G_o are listed in Table 2.

Table 1. Mechanical characteristics for investigated areas.

Test site	Soil type	γ [kN/m^3]	W_n [%]	PI	G_s	e	c' [kPa]	ϕ' [°]
Piana di Catania - Catania	Clayey silt	17.7-20.0	13-45	27-46	2.57-2.71	0.472-1.438	0-29	18-24
Via Stellata - Catania	Silty clay	19.2-20.5	20-27	18-32	-	0.551-0.695	43	24
Saint Nicola alla Rena Church - Catania	Silty sand	12.8-18.3	21-31	-	2.88-2.96	0.539-0.565	0	28-39
Piazza Palestro - Catania	Silty sand	18.8-19.3	26-35	11-31	-	0.818-0.916	37	21
Via Dottor Consoli - Catania	Grey Silty clay	19.6-19.8	22-24	16-24	-	0.561-0.648	40	25
Sangiuliano di Puglia (CB)	Clayey silt	19.5-21.5	17-27	29-37	2.72-2.77	0.474-0.724	-	-
ENEL box - Catania	Clayey silt	18.53	29	17	-	0.647	36	13
INGV - Catania	Blue Silty clay	18.2-20.0	16-26	-	2.72-2.79	0.57-0.77	11-51	16-29
DPC - Messina	Clayey sandy silt	17.9-19.9	12-40	-	2.74-2.79	0.54-1.11	9-30	21-41
San Giuseppe la Rena - Catania	Sand	18.6-21.1	-	-	-	0.664-0.778	0	33-46

c′ (Cohesion) and ϕ′ (Angle of shear resistance) were calculated from CD and CU triaxial tests for "Piana di Catania" site and from direct shear tests for "Via Stellata", "San Nicola alla Rena Church", "Piazza Palestro", "Via Dottor Consoli", "Sangiuliano di Puglia", "ENEL box", "INGV", "DPC" and "San Giuseppe la Rena" sites.

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.

The laboratory test conditions for uncohesive soils and the obtained small strain shear modulus G_o are listed in Table 3.

Table 2. Test conditions for cohesive soils specimens.

Site	Borehole No.	H [m]	σ'_{vc} [kPa]	e	PI	RCT	G_o [MPa]
Piana di Catania - Catania	S2-C1	6.95	70	1.160	41	U	32
Piana di Catania - Catania	S2-C2	11.15	106	1.093	35	U	17
Piana di Catania - Catania	S2-C4	22.75	240	1.280	31	U	28
Piana di Catania - Catania	S3-C5	35.50	240	1.282	30	U	17
Piana di Catania - Catania	CPTU-2	56.00	400	1.023	30	U	33
Via Stellata - Catania	DH1-C4	22.00	246	0.582	29	U	64
Via Stellata - Catania	DH1-C9	35.70	375	0.653	20	U	77
Via Stellata - Catania	DH1-C10	39.00	411	0.695	31	U	93
Saint Nicola alla Rena Church - Catania	SP1-CR1	7.80	104	0.539	-	U	65
Saint Nicola alla Rena Church - Catania	SP4-CR1	12.30	175	0.555	-	U	87
Saint Nicola alla Rena Church - Catania	SP4-CR2	21.00	384	0.565	-	U	119
Piazza Palestro - Catania	DH2-2	20.70	211	0.873	-	U	62
Via Dottor Consoli - Catania	S2-I1	5.00	101	-	20	U	49
Via Dottor Consoli - Catania	S2-I2	10.00	201	-	16	U	61
Via Dottor Consoli - Catania	S2-I4	28.00	557	-	24	U	136
ENEL box - Catania	S1-I1	16.00	352	0.696	17	U	88
San Giuliano di Puglia (CB)	S3-C1	1.75	98	0.720	37	U	36
San Giuliano di Puglia (CB)	S5-C2	7.15	155	0.523	30	U	144
San Giuliano di Puglia (CB)	S11-C1	2.25	350	0.579	29	U	133
San Giuliano di Puglia (CB)	S11-C3	11.75	397	0.464	31	U	173
San Giuliano di Puglia (CB)	S11-C4	14.70	397	0.506	32	U	145
INGV - Catania	S1-C1	4.75	75	0.570	-	U	95
INGV - Catania	S3-C1	5.70	90	0.760	-	U	62
INGV - Catania	S2-C3	14.25	170	0.760	-	U	30
INGV - Catania	S2-C5	72.25	475	0.750	-	U	47
DPC - Messina	S1C1	7.20	100	0.67	-	U	91
DPC - Messina	S3C2	14.80	300	0.52	-	U	225
DPC - Messina	S2C3	18.25	450	0.52	-	U	216
DPC - Messina	S1C2	19.75	380	0.67	-	U	176

where: U = Undrained; G_o from RCT.

Table 3. Test conditions for uncohesive soils specimens.

Site	Test No.	σ'_{vc} [kPa]	γ_d [kN/m^3]	D_r [%]	e	RCT	G_o [MPa]
San Giuseppe la Rena - Catania	1	38	15.20	46.25	0.721	U	71
San Giuseppe la Rena - Catania	2	57	15.40	54.80	0.711	U	79
San Giuseppe la Rena - Catania	3	105	15.59	63.13	0.685	U	113
San Giuseppe la Rena - Catania	4	39	14.61	19.25	0.796	U	62
San Giuseppe la Rena - Catania	5	55	14.90	33.02	0.765	U	60
San Giuseppe la Rena - Catania	6	102	14.80	28.49	0.769	U	82

where: U = Undrained; G_o from RCT.

The size of hollow cylindrical specimens are internal Radius = 30 mm, external radius = 50 mm and height = 100 mm. The solid cylindrical specimens were reconstituted by using tapping [54], in order to obtain the required relative and a good uniformity during the deposition.

The mold is assembled and a little depression is applied to let to the membrane to adhere to the inside surfaces.

Non-linearity of site response is also one of the major issues in evaluating site effects as soils exhibit strong strain-dependency of modulus and damping characteristics. Evidence of non-linear behaviour has been detected in observed earthquake ground motion records.

The experimental results of specimens from test sites were used to determine the empirical parameters of the equation proposed by Yokota et al.[32] to describe the shear modulus decay with shear strain level (Figure 11):

$$\frac{G(\gamma)}{G_o} = \frac{1}{1+\alpha\gamma(\%)^{\beta}} \qquad (7)$$

in which: G(γ) = strain dependent shear modulus; γ = shear strain; α, β = soil constants.

The expression (7) allows the complete shear modulus degradation to be considered with strain level. The values of soil constants α and β obtained from RCTs for cohesive and uncohesive soils are listed in Table 4.

Table 4. Soil constants for cohesive and uncohesive soils from RCTs.

Test	α [-]	β [-]	η [-]	λ [-]
Piana di Catania	7.15	1.223	19.87	2.16
Via Stellata	11	1.119	31	1.921
San Nicola alla Rena	7.5	0.897	90	4.5
Piazza Palestro	6.9	1	23	2.21
Via Dottor Consoli	16	1.2	33	2.4
Sangiuliano di Puglia (CB)	24	1.184	46	2.42
ENEL box - Catania	-	-	-	-
INGV - Catania	22	1.05	10	1.05
DPC - Messina	20	0.87	19	2.3
San Giuseppe la Rena	9	0.815	80	4

As suggested by Yokota et al. [32], the inverse variation of damping ratio with respect to the normalised shear modulus has an exponential form as that reported in Figures 12 for cohesive and uncohesive soils:

$$D(\gamma)(\%) = \eta \cdot \exp\left[-\lambda \cdot \frac{G(\gamma)}{G_o}\right] \qquad (8)$$

in which: D(γ) = strain dependent damping ratio; γ = shear strain; η, λ = soil constants.

The values of soil constants η and λ obtained from RCTs for cohesive and uncohesive soils are listed in Table 4. Considering in the equation (8) maximum value assumed by D_{max} for $G(\gamma)/G_o = 0$ and the minimum value by D_{min} for $G(\gamma)/G_o = 1$, the equation (8) can be re-written in the following normalised form:

$$\frac{D(\gamma)}{D(\gamma)_{max}} = \exp\left[-\lambda \cdot \frac{G(\gamma)}{G_o}\right] \qquad (9)$$

These values have been used to describe degradation curves and damping curves used for site response analyses in the studied areas (Figures 11 and 12).

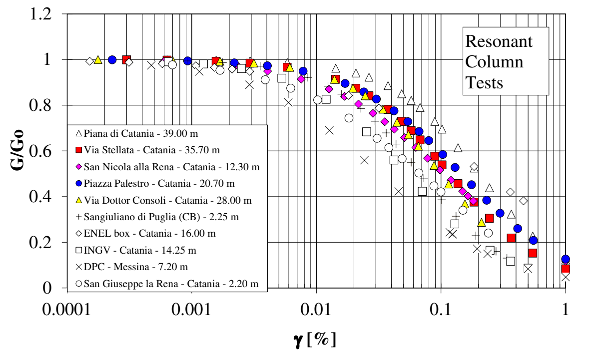


Figure 11. G/G_o - γ curves at different depths from RCT for Catania, Messina and Sangiuliano di Puglia (CB) test sites.

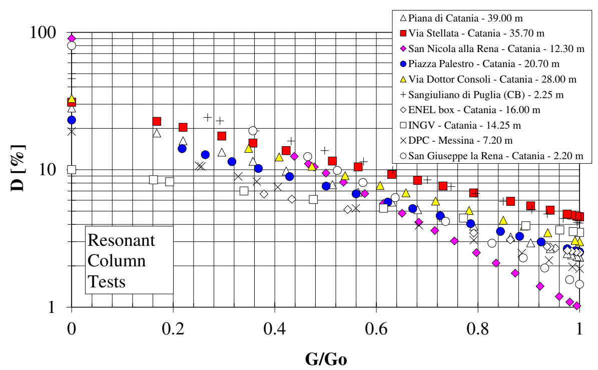


Figure 12. D - G/G_o curves at different depths from RCT for Catania, Messina and "Sangiuliano di Puglia (CB)" test sites.

4. Stiffness Decay by SDMT at Various Test Sites

The G/G_o-γ decay curves, for cohesive and uncohesive soils, are shown from Figure 13 to Figure 18 and were reconstructed by the results of RCTs.

The working strain shear modulus G_{DMT} was calculated from M_{DMT} obtained by SDMT at the same depths of the samples tested in the laboratory by use of Equation (6), assuming $\nu = 0.2$ at both sites. The values of G_{DMT}/G_o, reported in Table 5, ranged from 0.07 to 0.10 for the clayey silt. While for silty clay G_{DMT}/G_o ranged from 0.09 to 0.28. Avalue of 0.39 was obtained for the sand.

The intersection of G_{DMT}/G_o horizontal ordinate line, where the small strain value G_o is derived from V_s by SDMT, with the stiffness decay curve reported in Figures 13 to 18 provides a shear strain value referred as γ_{DMT} which can be compared with the results given by laboratory tests using the hyperbolic stress-strain equation proposed by Amoroso et al. [39] based on SDMT data.

The values of the shear strain γ_{DMT} resulting from the "intersection" of the G_{DMT}/G_o data points with the reconstructed reference G/G_o-γ decay curves (dot symbols in Figures 13 and 18), are reported in Table 5. On the available information shown in Figures 13 - 18, the range of γ_{DMT} for clayey silt soils is typically in the range about 0.45 - 1.5 %, while for silty clay soils γ_{DMT} is in the range of 0.12 - 0.7 %. For clayey sandy silt soil γ_{DMT} assumed the value of 0.5 %, while for sand a value of γ_{DMT} was obtained equal to 0.12 %. It is apparent that γ_{DMT} values in cohesive soils are higher than those in sand.

Several authors [55, 56, 57, 58, 59] introduced a hyperbolic model to represent the non-linear stress-strain behaviour of soil in pressuremeter tests. In this respect, Amoroso et al. [39] proposed the use of the SDMT experimental data determined at all the investigated test sites (Figures 13 to 18) to assist the construction of a hyperbolic stress-strain equation:

$$\frac{G}{G_o} = \frac{1}{1+\left(\frac{G_o}{G_{DMT}}-1\right)\frac{\gamma}{\gamma_{DMT}}} \tag{10}$$

Table 5. Values of G_{DMT}/G_o obtained from SDMT and corresponding shear strain γ_{DMT} determined from the intersection with the G/G_o - γ laboratory curves at six test sites.

Test site	Sample	Depth [m]	Soil type	V_S [m/s]	G_o [MPa]	M_{DMT} [MPa]	ν [-]	G_{DMT} [MPa]	G_{DMT}/G_o [-]	γ_{DMT} [%]
Piana di Catania - Catania	S3-C5	35.50	Clayey silt	161	44.98	7.8	0.2	2.93	0.07	1.5
Via Stellata - Catania	DH1-C9	35.70	Silty clay	289	164.57	39.1	0.2	14.66	0.09	0.7
Sangiuliano di Puglia (CB)	S11-C1	2.25	Clayey silt	164	48.60	13.1	0.2	4.91	0.10	0.45
INGV - Catania	S2-C2	14.25	Silty clay	236	102.48	76.7	0.2	28.76	0.28	0.12
DPC - Messina	S1-C2	19.75	Clayey sandy silt	347	228.70	54.9	0.2	20.59	0.09	0.5
San Giuseppe la Rena - Catania	-	2.20	Sand	221	93.84	96.5	0.2	36.19	0.39	0.12

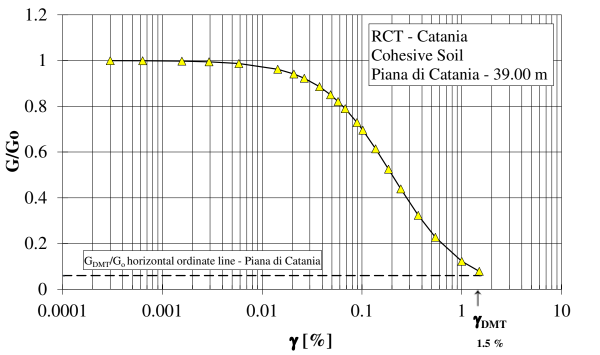


Figure 13. G_{DMT}/G_o horizontal ordinate line for "Piana di Catania" soil.

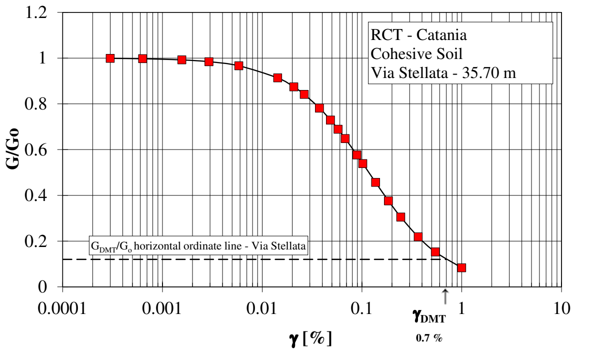


Figure 14. G_{DMT}/G_o horizontal ordinate line for "Via Stellata" soil.

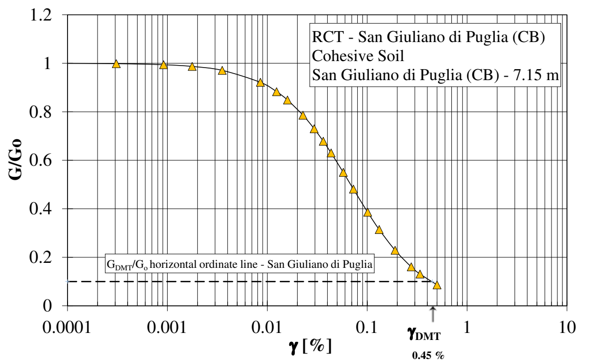


Figure 15. G_{DMT}/G_o horizontal ordinate line for "Sangiuliano di Puglia (CB)" soil.

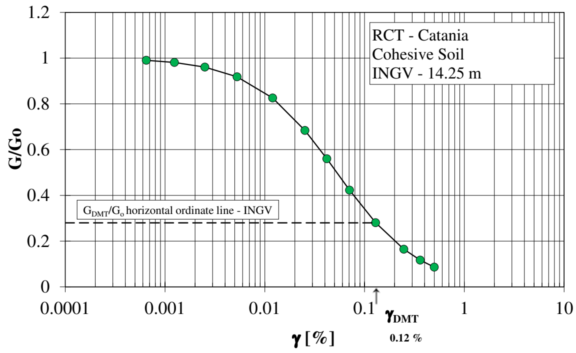


Figure 16. G_{DMT}/G_o horizontal ordinate line for "INGV" soil.

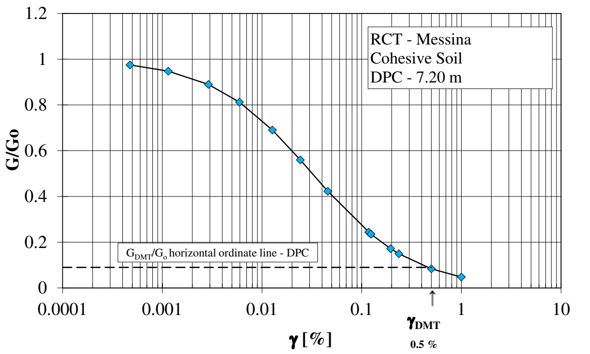


Figure 17. G_{DMT}/G_o horizontal ordinate line for "DPC" soil.

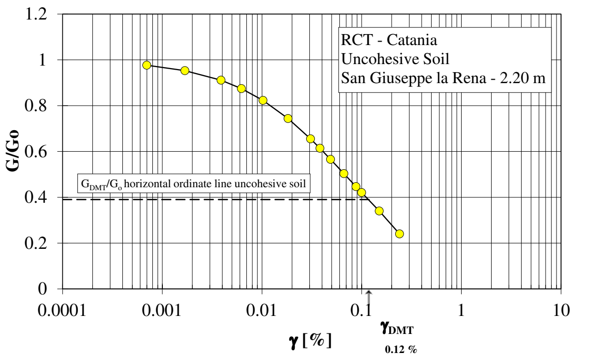


Figure 18. G_{DMT}/G_o horizontal ordinate line for "San Giuseppe la Rena" soil.

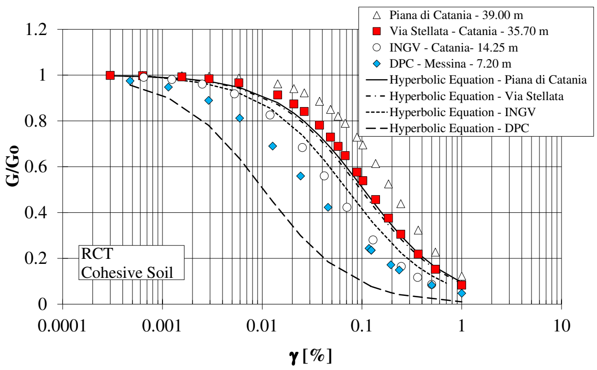


Figure 19. G- γ curves by Yokota et al. [32] equation and by Amoroso et al. [39] hyperbolic equation for cohesive Catania and Messina soils.

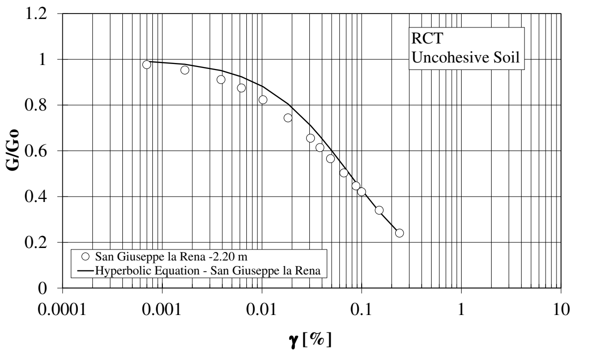


Figure 20. G- γ curves by Yokota et al. [32] equation and by Amoroso et al. [39] hyperbolic equation for uncohesive Catania soil.

Thus, the ratio G_{DMT}/G_o obtained from SDMT and the estimated shear strain γ_{DMT} were used to plot the corresponding hyperbolic curve at cohesive and uncohesive soil tests sites. Figure 19 shows a comparison between the experimental G/G_o decay curve and the hyperbolic equations proposed by Amoroso et al. [39] for cohesive test sites of "Piana di Catania", "Via Stellata", "INGV" and "DPC". Figure 20 shows a comparison between the experimental G/G_o decay curve and the hyperbolic equations proposed by Amoroso et al. [39] for uncohesive test site of "San Giuseppe la Rena".

The hyperbolic equation proposed by Amoroso et al. [39] is in good agreement with the experimetal data for "Via Stellata" (silty clay) and "INGV" (silty clay) sites while a certain detachment was observed in the case of "Piana di Catania" (clayey silt) and "DPC" (calyey sandy silt).

It is also possible to observe a good agreement between the hyperbolic stress strain equation proposed by Amoroso et al. [39] with the G/G_o-γ curves obtained by laboratory tests for sand in "San Giuseppe la Rena" site. It would be appropriate for future studies to consider the influence of the variation of ν as shown in the Figure 9 and of other geotechnical parameters such as IP, CF, OCR etc.

5. Conclusions

The possibility of obtaining the decay curve of the Young/shear modulus directly from in situ tests would represent a result capable of obviating the problems of undisturbed sampling of soil samples to be used in laboratory tests.

This paper studies the possible to use the SDMT results to assess in situ the decay of stiffness with strain level and to know the G-γ curves trend in various soil types. This descends from the possibility of the SDMT to provide, at each test depth, both a small strain stiffness (G_o from V_S) and a working strain stiffness G_{DMT} (derived via elasticity theory from the constrained modulus M_{DMT} provided by the usual DMT interpretation). Laboratory decay curves of soil stiffness with strain level (G-γ curves or similar) may be tentatively fitted through these two stiffness values G_o and G_{DMT}. To locate the second point on the G-γ curve, it is necessary to know (at least approximately) the shear strain γ_{DMT} corresponding to working strain modulus G_{DMT}.

Typical ranges of γ_{DMT} in different (cohesive and uncohesive) soil types have been evaluated from the "intersection" of the stiffness decay curves obtained by dynamic laboratory tests (RCT) with SDMT data points in correspondence of the same-depth reference.

Based on the results obtained, the range of γ_{DMT} for clayey silt soils is typically in the range about 0.45 - 1.5 %, while for silty clay soils γ_{DMT} is in the range of 0.12 - 0.7 %. For clayey sandy silt soil γ_{DMT} assumed the value of 0.5 %, while for sand a value of γ_{DMT} was obtained equal to 0.12 %.

The values obtained are comparable with those determined by Amoroso et al. (2014) which for γ_{DMT} identifies the following approximately ranges: $\gamma_{DMT} \approx$ 0.01-0.45 % in sand, $\gamma_{DMT} \approx$ 0.1 -1 .9 % in silt and clay, γ_{DMT} > 2 % in soft clay.

Finally the use of a hyperbolic equation, which requires to input ratio G_{DMT}/G_o based on knowledge of shear strain γ_{DMT} for a given soil type, can provide a tentatively estimate of G/G_o -γ curves from SDMT data.

Further investigations should be carried out on the influence of the variation of ν by in situ dynamic tests and of other geotechnical parameters such as IP, CF, OCR etc.

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