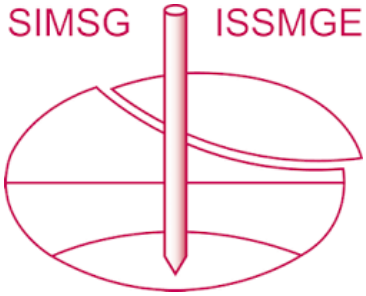
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Dynamic shear modulus and stiffness decay curves of a tropical sandy soil via laboratory and in situ tests

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ABSTRACT: The maximum shear modulus (G_o) is a geotechnical parameter for assessing the soil dynamic behavior, as well as for static deformation analysis of excavations and foundations via the stiffness decay curve. Although a large portion of Brazil is covered by tropical soils, the literature on the dynamic behavior of these soils is limited. Seismic flat dilatometer (SDMT), bender elements and resonant column tests were carried in a research site with residual soils from Sandstone, substantially modified by pedogenetic and morphologic processes. Advantages and limitations regarding the test procedures and interpretation are discussed and the in situ and laboratory G_o values are compared. The G_o/E_D ratio determined from SDMT was used to assess the presence of microstructure and possible soil suction influence. G/G_o *vs.* γ curves determined by the resonant column test and by SDMT are also presented and discussed for the studied soil.

Keywords: Dynamic parameters, SDMT, bender elements, resonant column; tropical soils.

1. Introduction

The maximum shear modulus (G_o) and the stiffness decay curve (G/G_o *vs.* γ) are relevant information in the evaluation of the mechanical behavior of the soils for both dynamic and static loading. Dynamic tests are not currently performed in Brazil, and the geotechnical literature about the dynamic behavior of tropical soils is limited. Nonetheless, a growing search for nuclear power plants, offshore structures and foundations for vibrations sensible equipment demand more information about the dynamic behavior of these soils.

The crosshole seismic test is the most effective technique for the in situ determination of shear wave velocity (V_s) for calculating the maximum shear modulus (G_o) via elastic theory. Currently, hybrid tests, such as seismic cone penetration test (SCPT) and the seismic flat dilatometer test (SDMT) have been used by the geotechnical community as a logging tool for site characterization as well as to determine the G_o profiles. The resonant column and the bender elements can be used to determine the V_s in laboratory under controlled conditions, so it is possible to evaluate the influence of confining pressure, shearing strain amplitude and soil suction on the G_o values.

This paper presents and discusses the results of seismic flat dilatometer (SDMT), bender elements and resonant column tests carried out in a tropical sandy soil, substantially modified by pedogenetic and morphologic processes. The G_o/E_D ratio determined from SDMT was used to assess the presence of microstructure and possible soil suction influence. V_s (and G_o) determined by these three techniques are compared as well as the G/G_o *vs.* γ determined by the resonant column and those ones from the hyperbolic stress-strain formulation proposed by Amoroso et al. [1] via SDMT data.

2. Study site

The study site is located at the São Paulo State University, in the city of Bauru, in the central part of São Paulo State, Brazil, on the vicinities of the scarps of "*cuestas*" at the *Paulista* Central Plateau. The soil profile has a colluvial Neo-Cenozoic deposit up to 13 m depth, followed by a residual soil from Sandstone formed during the Quaternary period [2]. These soils have undergone pedogenic and morphogenetic processes, which typically take place in tropical zones. As a result, they are unsaturated porous soils with high saturated hydraulic conductivity (10^{-5} to 10^{-6} m/s) and with cohesive-frictional behavior. An important geotechnical problem in this area is the soil collapsibility caused by wetting.

A tropical wet-and-dry climate predominates at the site, where the rainy season coincides with summer [3]. This type of seasonal weather can lead to variations on the in situ soil suction since it presents high annual temperatures with wet summers and dry winters.

The typical soil profile was defined based on SPTs and it is presented in Fig. 1.a. The N-values from SPTs increase almost linearly with depth, up to 13 m depth. The interpretation of MCT classification [3] test data separated lateritic (LA') from non-lateritic (NA') soil behavior almost at the same depth (13 m). Fig. 1.c and 1.d present CPT data. It was assumed that measured cone resistance (q_c) was equal to corrected cone resistance (q_t), since the soil is unsaturated and pore pressure was not recorded. The cone tip resistance (q_t) and the sleeve friction (f_s) presented higher value at the top 1 m and tends to increase with depth leading to a friction ratio (R_f) between 1 and 3 %. Grain size distribution for the soil samples retrieved every meter from one of the SPTs were determined using dispersant (Fig. 1e) and without dispersant (Fig. 1f). It can be observed that clay and silt

particles are naturally aggregated by oxides and hydroxides of iron and aluminum, which is typical in tropical soils. Dry unit weight (ρ_d) can be considered approximately constant with the depth and the void ratio at 1 m depth is equal to 0.72 and 0.55 to 16 m depth based on a sample pit excavated in the site.

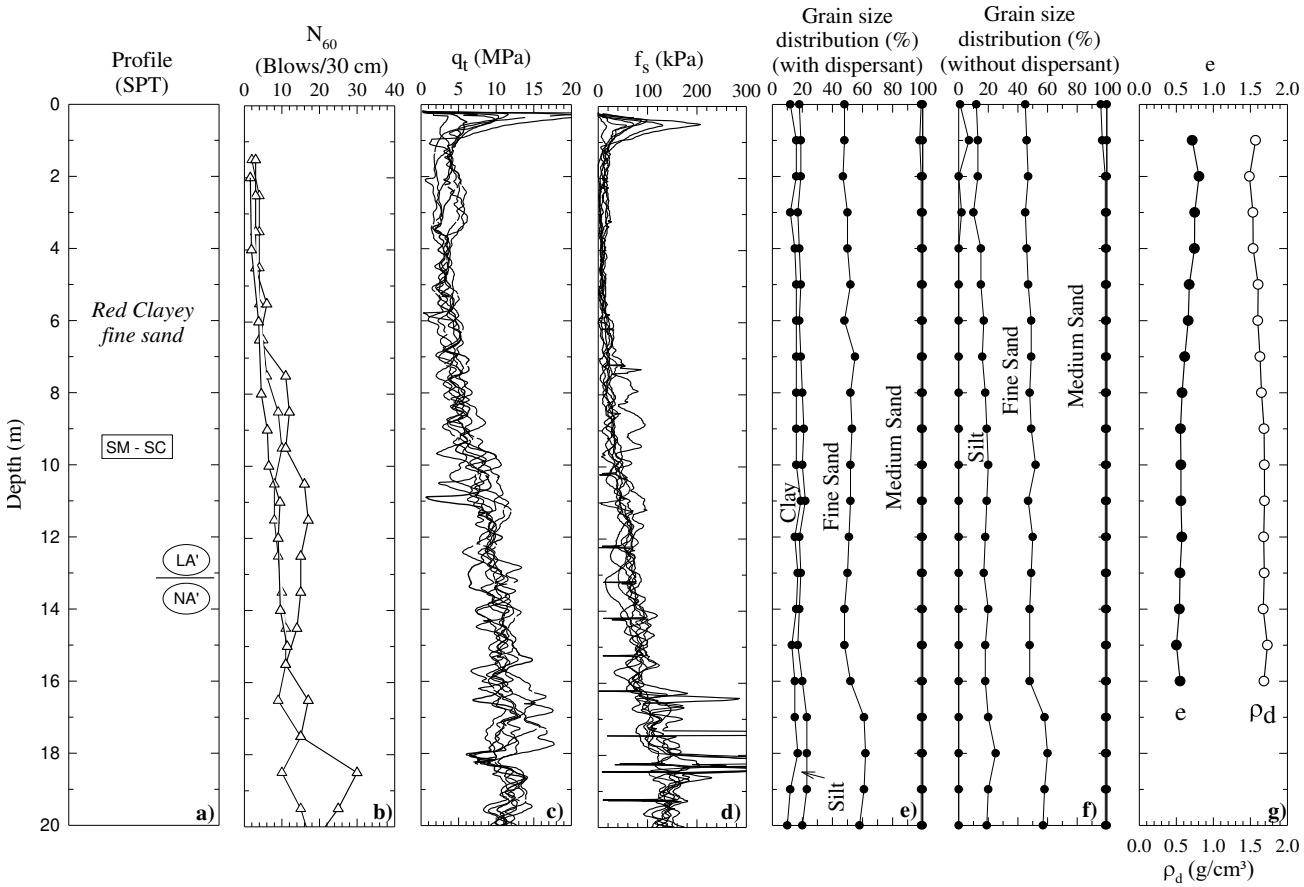


Figure 1. In situ and laboratory tests data (adapted from Rocha et al. [4]).

3. SDMT

The seismic dilatometer (SDMT) is the combination of the standard DMT with a seismic module for measuring the shear wave velocity (V_s) [5]. The seismic module is a cylindrical element placed above the DMT blade, equipped with two receivers, spaced 0.5 m apart. Six SDMTs were carried out at the site up to 19 m depth. Seismic flat dilatometer was conducted by a multi-function penetrometer with a 150 kN thrust capacity and it was pushed into the ground at a constant rate of 20 mm/s, measuring p_0 and p_1 every 20 cm intervals. V_s measurements were obtained every 0.5 or 1.0 m depth. The SDMT testing procedure followed the ASTM D6635-15 [6].

The maximum shear modulus (G_o) was calculated by the equation 1:

$$G_0 = \rho . V_s^2 \quad (1)$$

where V_s is shear wave velocity, and ρ is the soil density, which was determined from undisturbed soil samples collected in a sample pit excavated in the site.

3.1. V_s and G_o from SDMT

Shear wave velocity and maximum shear modulus can be determined from the seismic dilatometer (SDMT and estimated based on correlations suggested Marchetti et al. [5] as show in Fig. 2.

According Robertson [7], most empirical correlations to estimated V_s (and G_o) were developed from soils with little or no microstructure. Thus, such correlations should be used with care since G_o in highly structured soil can be underestimated. So, the measured V_s (G_o) is highly sensitive to the presence of microstructure (e.g. cementation/bonding and ageing) in soil [8-10].

Marchetti [11] has shown that the relative error in the estimated V_s (from I_D, K_D, and M_{DMT}) is on average 20%. Berisavljevic & Berisavljevic [12] shows that the boundary separating soils with and without a significant presence of microstructure can be drawn at a ratio of measured and estimated G_o (G_{mea}/G_{est}) of 1.5, which is consistent with was reported by Marchetti [11]. So, comparing measured and estimated V_s values can be used to detect soils that behave differently from "*ideal*" soils, i.e., soils without significant presence of microstructure.

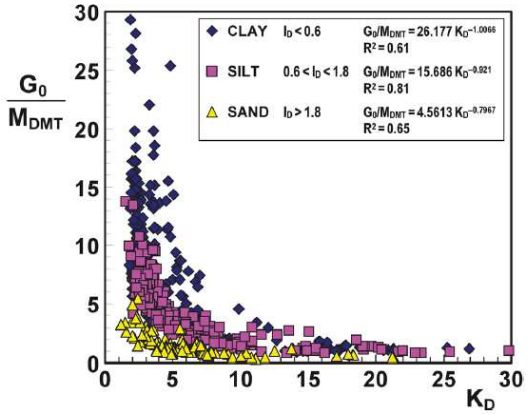


Figure 2. G_o/M_{DMT} *vs.* K_D for various soil types (Monaco et al. [13]).

3.2. G-γ decay curves from SDMT

Marchetti et al. [5] and Amoroso et al. [1] proposed a method based on SDMT for deriving in situ stiffness decay curves (G-γ). It could be tentatively constructed by fitting "reference typical-shape" laboratory G-γ curves through two points, both obtained by SDMT: (1) the maximum shear modulus G_o, and (2) a working strain modulus (G_{DMT}).

According to Marchetti et al. [5], G_{DMT} can be derived from the M_{DMT} provided by the classical DMT interpretation [14]. As a first approximation, by referring to linear elasticity, as shown by Equation (2):

$$G_{DMT} = \frac{1-2\mu}{2(1-\mu)} . M_{DMT} \quad (2)$$

where μ is the Poisson's ratio.

The procedure suggested by Amoroso et al. [1] is shown schematically on Fig. 3 as follows:

a) From SDMT data obtained at the same depth of the available reference stiffness decay curve, a working strain modulus G_{DMT} is derived from M_{DMT} and normalized by its small strain value G_o derived from V_s.
b) The G_{DMT}/G_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;
c) The "*intersection*" of the G_{DMT}/G_o horizontal ordinate line with the stiffness decay curve provides a shear strain value referred as γ_{DMT}.

Amoroso et al. [1] proposed an approach to represent the non-linear stress-strain behavior of soils from SDMT by Equation 3:

$$\frac{G}{G_o} = \frac{1}{1+\left(\frac{G_o}{G_{DMT}}-1\right)\frac{\gamma}{\gamma_{DMT}}} \quad (3)$$

Thus, the G_{DMT}/G_o ratio obtained from SDMT and the estimated shear strain γ_{DMT} were used to plot the corresponding hyperbolic curve at each investigated test site.

Based on the available information, the author observed that γ_{DMT} is typically about 0.1% in sands, about 0.5 to 1.0% in silts and clays and greater than 2.0% in soft clays.

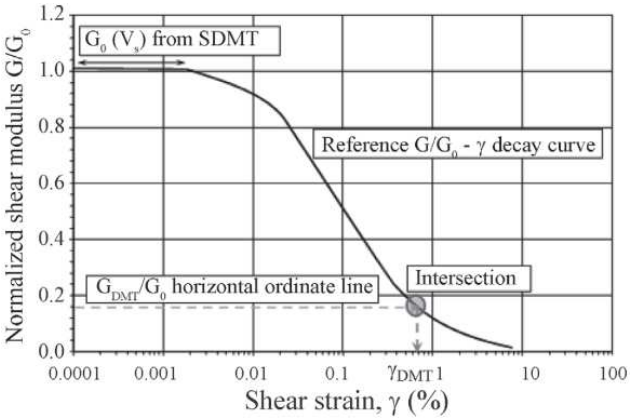


Figure 3. Deriving *in situ* G/G_o *vs.* γ curves from SDMT as proposed by Amoroso et al. [1]).

4. Laboratory tests

4.1. Bender elements

Since the tropical wet and dry climate predominates at the study site, the in situ soil suction varies seasonally, as discussed by Giacheti et al. [15]. Triaxial tests with bender elements on undisturbed soil samples collected at 1.5, 3.0, and 5.0 m depths were carried out to examine the influence of soil suction on soil stiffness parameters. The purpose of the laboratory tests was to assess suction influence on the soil behavior.

The maximum shear modulus (G_o) determination was done in different states of isotropic stress using a triaxial chamber equipped with bender elements. In these tests, specimens with 70 mm in diameter by 140 mm in high were used, molded from the undisturbed samples collected at 1.5, 3.0, and 5.0 m depths. The applied suction values were 0, 50, 200 and 400 kPa and the net normal stresses used for enforcement of the isotropic state were of 25, 50, 100 and 200 kPa. The shear waves velocities were determined after consolidation, by measuring the arrival times for each imposed stress state. Table 1 presents the geotechnical properties and net stress applied to the tested soil samples.

The determination of the time arrival was done by the phase angle and by the first time of arrival methods. The initial height of each specimen less the thickness of each blade of the transducers from bender elements was considered to calculate V_s. The variations of G_o *vs.* soil suction, as well *vs.* the net normal stress were determined for each tested sample.

4.2. Resonant Column

The resonant column tests were carried out by Giacheti [16] in soils samples collected in a sample pit excavated in another site with similar characteristics of the study site. The objective of these tests was also to evaluate the influence of the confining pressure in maximum shear modulus (G_o) as well as to obtain the stiffness decay curves. The tested specimens were in the natural water content but unfortunately the soil suction was not monitored during such tests.

The resonant column device was similar to that one described by Hardin [17]. It uses cylindrical specimens

with 36 mm in diameter and 80 mm in height, fixed at the basis and excited in torsion at the top.

The procedure to perform the test was the multistage technique, as described by Anderson and Stokoe [18]. Different magnitude of confining pressure (20, 50, 100 and 200 kPa) near the in situ effective confining stress were applied to the same specimen.

A torsional excitation of very low amplitude was applied to the top of the specimen and the shear wave velocities were determined at the logarithmic time intervals up to 1,000 minutes or up to 10,000 minutes in some cases for each stage of confining pressure. Subsequently the excitation force was gradually increased and the variation of the shear modulus ratio with the shear strain amplitude were determined.

5. Test data and Analysis

5.1. SDMT

Fig. 4 and Fig. 5 present the DMT (I_D, K_D and E_D) and the seismic data (V_s and G_o) profiles for the study site. I_D, K_D and E_D were calculated by Marchetti's [14] equations. The V_s values were determined via SDMT and the unit weight (ρ) values necessary to calculate G_o were obtained from undisturbed soil samples collected in a sample pit excavated in the site. There is a good agreement between the V_s and G_o profiles determined by all tests. V_s and G_o values increase with depth up to 10 m and this tendency gets almost constant after that depth (Fig. 6).

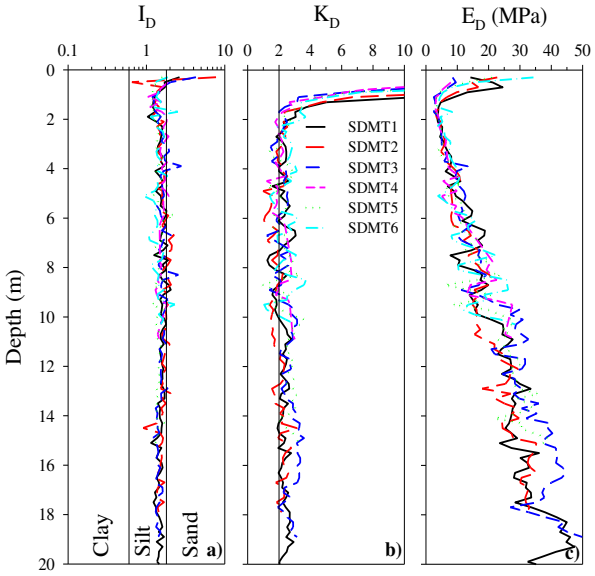


Figure 4. SDMT tests data for the study site.

It is worth to mention that the three SDMT campaigns (two tests per campaign) were carried out in the wet season. Disturbed soil samples were collected by a helical auger to determined water content profiles (Fig. 6.a). So, the soil suction can be estimated based on soil water retention curves (SWRC) determined by Fernandes et al. [19] from undisturbed soil samples collected at 1.5, 3.0, and 5.0 m depths (Fig. 6.b). They were determined using the filter paper and suction plate tests by the drying process. The soil water content varied from 8% to 13% between 0.5 to 8.0 m depths (Fig. 6.a), resulting in soil suction values lower than 20 kPa (Fig. 6.b).

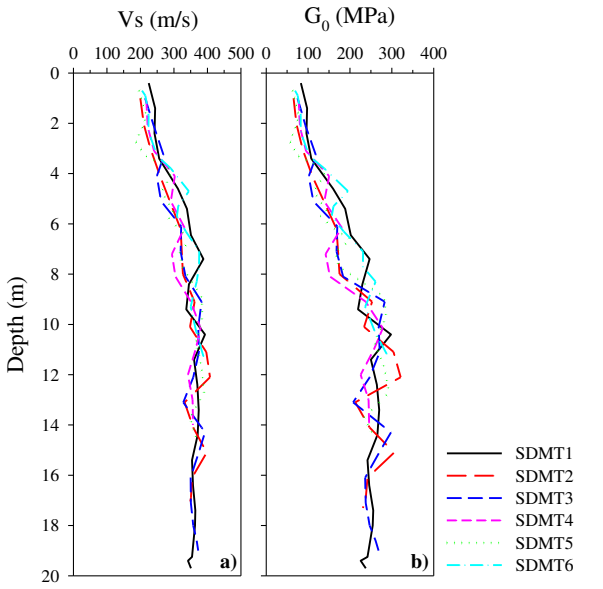


Figure 5. V_s and G_o profiles from SDMTs carried out at the study site.

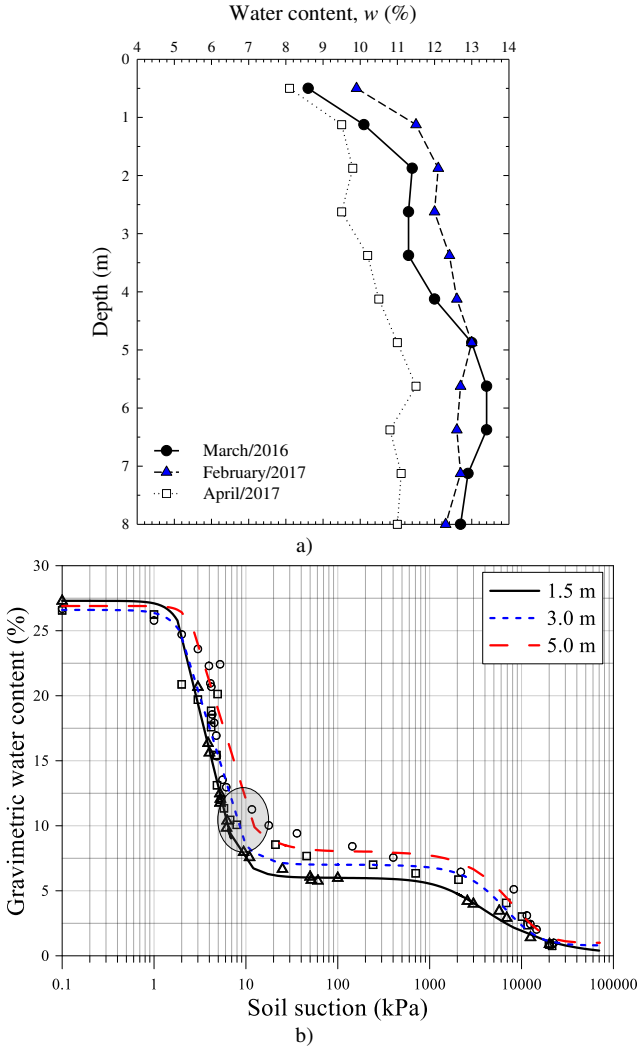


Figure 6: a) Water content profiles from four SDMT campaigns (adapted from Rocha [20]). b) SWRC (drying path) for samples collected at 1.5, 3.0 and 5.0 m depth (Fernandes et al. [19]).

5.2. Bender elements

The shear wave velocity (V_s) in a soil specimen can be determined by the bender elements as previously described. Fernandes et al. [19] determined G_o for different states of isotropic stress using a in a triaxial test cell equipped with bender elements. The G_o tends to increase non-linearly with suction and net stress (σ - u_a) for sandy soils, reaching an asymptotic value [21-23]. So, a hyperbolic function can be used to adjust the experimental data, as presented in Equation 4.

$$G_o = G_{o,sat} + a(\sigma - u_a) + \frac{S}{b+c(S)} \quad (4)$$

where $G_{o,sat}$ is the saturated maximum shear modulus, S is soil suction, a, b and c are empirical fitting parameters, G_o and $G_{o,sat}$ are expressed in MPa, (σ - u_a) and S in kPa.

Fig. 7 shows the typical variation from G_o with soil suction and net stress, as well as the fitting equations for sample collected at 1.5, 3.0 and 5.0 m depths.

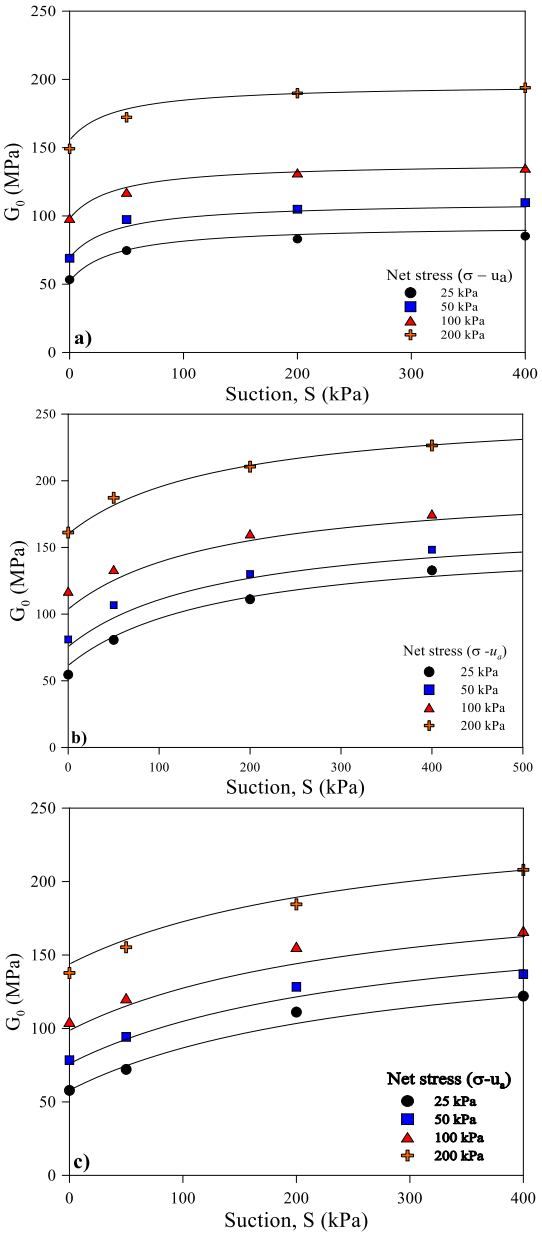


Figure 7. Variation of the G_o with the net stress (σ-u_a) and the suction (S) for (a) 1.5 m, (b) 3.0 m and (c) 5.0 m depths (adapted from [18]).

Table 1 presents the parameters of the Equation 4 for each net stress. As can be seen in the Fig. 8, the experimental data from the study site fitted to a non-linear relationship between G_o and the variables suction and net stress.

Table 1. Hyperbolic parameters for the study site.

	1.5 m depth	3.0 m depth	5.0 m depth
$G_{o,sat}$ (MPa)	40.7	47.4	53.4
a	0.574	0.563	0.452
b	0.969	1.792	2.54
c (kPa^{-1})	0.025	0.011	0.009

5.3. Resonant column test

Giacheti [16] determined G_o *vs.* time of confinement in the resonant column test and observed that the soil samples tested presented a quasi-linear increase of G_o per logarithmic cycle of time since the beginning drained condition. The variations of G_o at 1,000 minutes of confinement *vs.* the confining pressure are show in Fig. 8. Fig. 9 presents the G/G_o-γ decay curves determined by this author for different confining pressure for the soil samples collected at 0.9, 4.8 and 8.8 m depths.

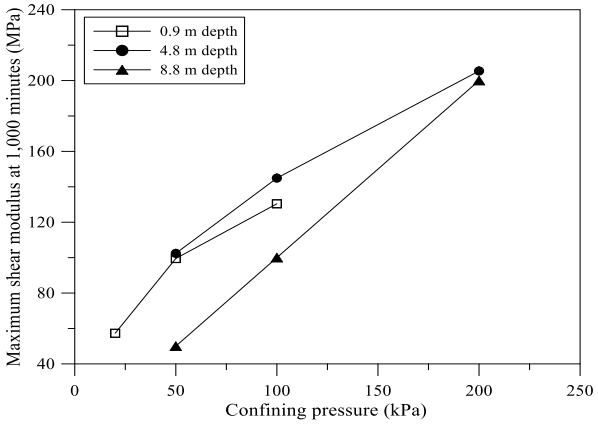


Figure 8. G_o at 1,000 minutes of confinement for the samples from different depths and for different confining pressures [16].

5.4. Comparing in situ and laboratory data

The G_o values from the SDMT, the resonant column and the bender elements techniques are not determined at the same confining stresses. It was necessary to estimate the in situ effective confining stress, based on the coefficient of earth pressure at rest (K_o) which was determined by the Jaky's equation [24]. The G_o from the resonant column tests are that one determined at 1,000 minutes of confinement with the soil samples in the natural water content with no suction control. The G_o from the bender elements are that one determined for the suction equal to 50 kPa. The G_o profiles from the SDMT were determined in situ at the natural water content.

Fig. 10 and Fig. 11 show the differences between the in situ and the laboratory G_o values. It can be observed in these figures that the measured in situ G_o values were 17% to 46% higher than those ones determined by the resonant column tests. These values were 5% and 18% higher than those ones determined by the bender ele-

ments at 1.5 and 5.0 m depths and 20% lower for the sample collected at 3.0 m depth. The observed differences can be attributed to possible sample disturbance, errors in the estimative of the in situ effective confining stress and on the time of confinement [25-27], as well as from soil suction influence on G_o [21-23].

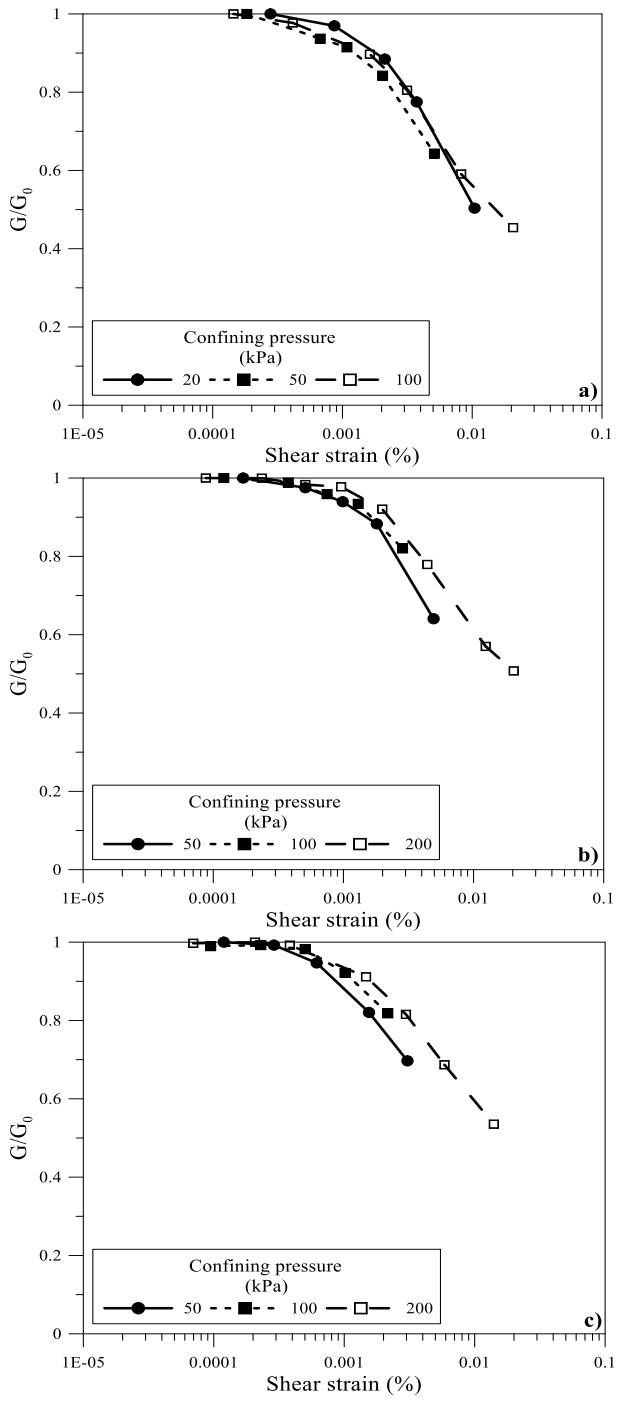


Figure 9. G/G_o-γ decay curves for soil samples collected at 0.9, 4.8 and 8.8 m depths [16].

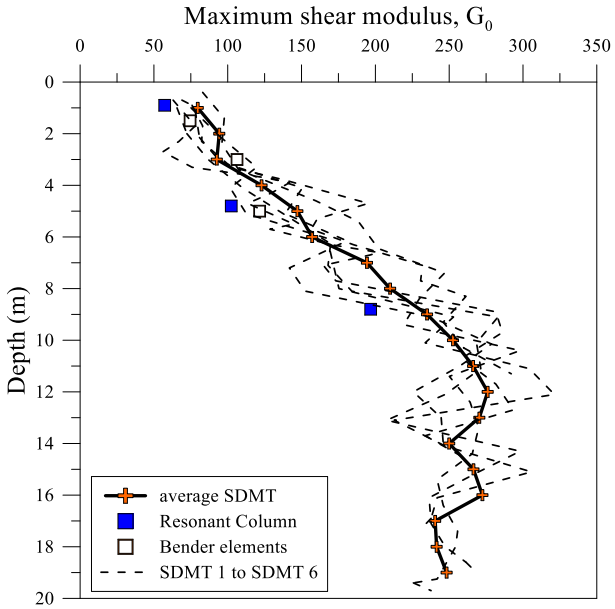


Figure 10. SDMT, bender elements and resonant column values of G_o for the studied site (adapted from [16,19]).

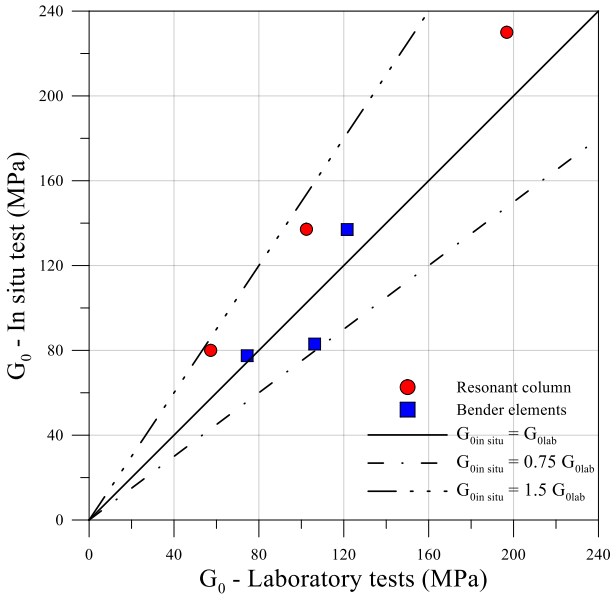


Figure 11. Comparison of in situ and laboratory of G_o values.

5.4.1. V_s and G_o estimative via correlations

The measured and estimated G_o and V_s profiles are presented in Fig. 12 and Fig. 13, respectively. The measured V_s and G_o profiles increase almost linearly with depth, up to around 10 m depth. On the other hand, the estimated velocity and shear modulus profiles tend to gradually increases with depth since the ground surface.

The relative error between the measured and estimated V_s (Figs. 12). and the G_{mea}/G_{est} ratio (Figs. 13) are higher than 20% and 1.5 up to 10 m depth, respectively.

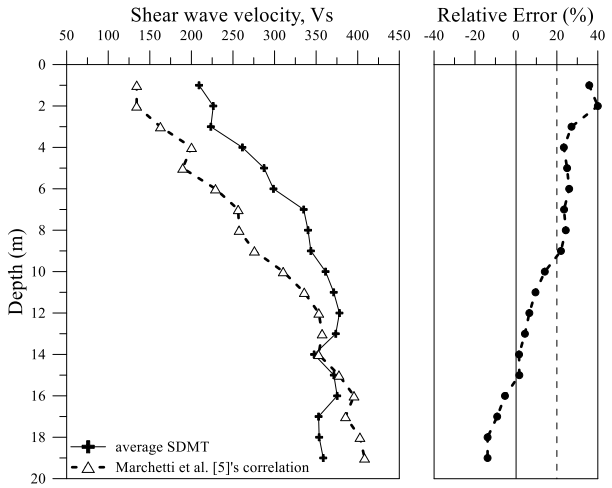


Figure 12. Comparison between the measured and estimated shear wave velocity (V_s) profiles.

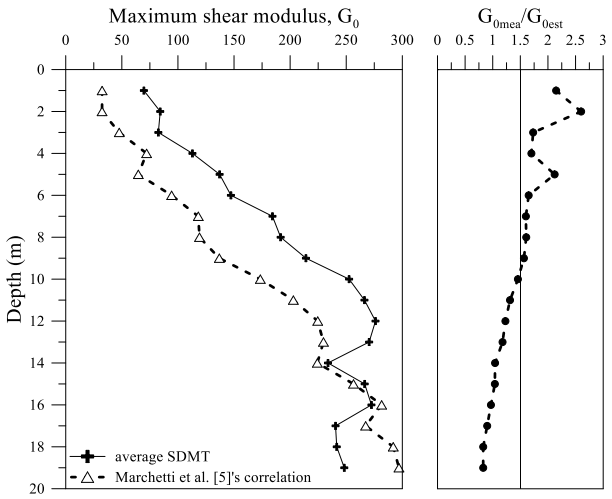


Figure 13. Comparison between the measured and estimated maximum shear modulus (G_o) profiles.

The observed differences are associated to the presence of microstructure in the soil. So, the classical correlations suggested for ideal soils (Fig. 2) should be used with caution when there is an indicative that the soil is structured, as studied tropical soils. It is important to emphasize the investigated soil site has undergone pedogenic and morphogenetic processes by its on nature, which typically take place in tropical zones, resulting in an open unstable structure and low water content. Particles are maintained in their positions in the soil structure by means of bonds capable of providing temporary additional strength. Such bonding may be created by suction (capillary and adhesive forces) or by cementing substances as iron oxides and carbonates, or both [2].

5.5. Stiffness decay curves

Amoroso et al. [1] presented an interesting tentative method for deriving in situ stiffness decay curves (G/G_o *vs.* γ) from SDMT. A graphic with the summary of this study is showed in Fig. 14, which depicts the possible use of the SDMT for calibrating the in situ G/G_o *vs.* γ for various soil types. The shaded areas in this figure, superimposed to "*typical shape*" of the stiffness decay curves, representing the range of values of the G_{DMT}/G_o available in different soil types (soft clay, silt and sand) and its corresponding shear strain.

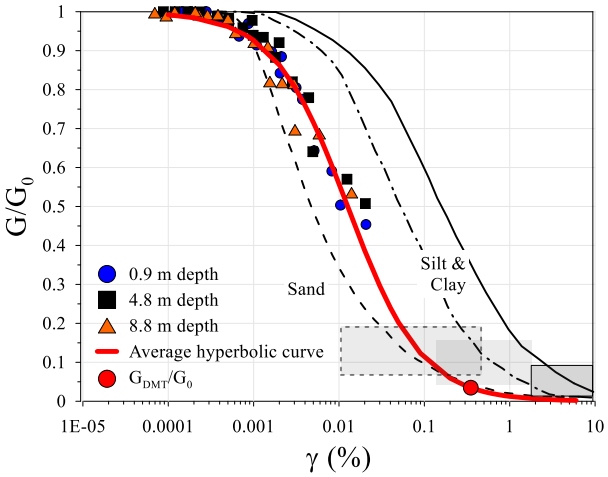


Figure 14. Estimated and measured stiffness decay curves (G/G_o *vs.* γ) by Amoroso et al. [1] approach and by using the resonant column test for the samples from 0.9, 4.8 and 8.8 m depth [16].

Table 2 shows G_o, M_{DMT}, G_{DMT}/G_o values determined from SDMT and the corresponding DMT shear strain (γ_{DMT}) assuming the studied soil is a silty sand based on the grain size distribution determined without dispersant (Fig. 1.f) and from what has been suggested by Amoroso et al [1] for different soil types.

Table 2. Considered fitting parameters for using the Amoroso et al. [1] model for the studied site.

G_o (MPa)	M_{DMT} (MPa)	G_{DMT}/G_o	γ_{DMT} (%)
140	13	0.035	0.35

Fig. 14 shows the G_{DMT}/G_o ratio determined from the SDMT, the estimated shear strain (γ_{DMT} - red symbol) and the average curve derived from SDMT using Equation 3 (red line). They are presented together with resonant column test data for the samples collected at 0.9, 4.8 and 8.8 m depth. The G_{DMT}/G_o value determined from the average degradation curve is equal to 0.035 for the studied site, which are lower than the typical values reported in the literature (shaded areas) in Fig. 14. The reason is that G_o from SDMT is much higher than G_{DMT}. Such big difference might be attributed to the effect of natural cementation of particles and to the unsaturated condition on G_o, which is common in tropical soils. Therefore, just a very little small fraction of cementation remains on G_o at the working strain for the studied soil. On the other hand, the corresponding value of shear strain (γ_{DMT} in Table 2) for the studied soil is in the range of values normally reported in the literature (0.2 to 1.0%).

Considering the range G/G_o *vs.* γ curves presented in Fig. 14 for different soil types, and the average SDMT curve adjusted for the soil from the studied site, there is a reasonable agreement with the resonant column tests data. The Amoroso et al. [1] approach provides a first tentative to the stiffness decay curve even for the soil from studied site.

6. Conclusions

- Differences between the G_o values determined by SDMT, bender elements and resonant column were presented. The in situ G_o values were basically 5% to 46% higher than those ones determined in laboratory. Such differences are more significative closer to the ground surface, where the lateralization processes and soil suction influence is more intense.
- Comparison between measured and estimated V_s and G_o provided a relative error between the measured and estimated V_s and the G_{mea}/G_{est} ratio that are higher than 20% and 1.5 up to 10 m depth, respectively, which can represent that the soil may have microstructure. It is related to the pedogenic and morphogenetic processes which occurs on tropical soils.
- The average G/G_o *vs.* γ curve determined from SDMTs carried out in the studied site based on Amoroso et al. [1] approach shows a reasonable agreement with the curves determined by the resonant column tests. This approach can be a first tentative to estimate the stiffness decay curve for the soil from studied site.

Acknowledgement

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References

[1] Amoroso, S., Monaco, P., Lehane, B. M., Marchetti, D. "Examination of the Potential of the Seismic Dilatometer (SDMT) to Estimate In Situ Stiffness Decay Curves in Various Soil Types", Soils and Rocks, 37(3), pp. 177-194, 2014.

[2] De Mio, G. (2005). "Geological conditioning aspects for piezocone test interpretation for stratigraphical identification in geotechnical and geo-environmental site investigation". Ph.D. thesis. Escola de Engenharia de São Carlos, Universidade de São Paulo, 2018. [online] Available at: https://teses.usp.br/teses/disponiveis/18/18132/tde-27042006-170324/pt-br.php [Accessed: 30/09/2019]. (*in Portuguese*).

[3] Nogami, J. S., Villibor, D. F. "A new soil classification for highway purposes. In: Symposium on Tropical Soils in Engineering", Rio de Janeiro, Brazil, 1981, pp. 30-41 (in Portuguese).

[4] Rocha B. P., Castro B. A. C., Giacheti H. L. "Seismic DMT Test in a non-text book type geomaterial". In: 3rd International Conference on the Flat Dilatometer, Roma, Italy, 2015, pp. 505–512.

[5] Marchetti, S., Monaco, P., Totani, G., and Marchetti, D. "In Situ Tests by Seismic Dilatometer (SDMT)". In: Symposium Honoring Dr. John H. Schmertmann for His Contributions to Civil Engineering at Research to Practice in Geotechnical Engineering Congress, New Orleans, United States, 2008, pp. 292-311. https://doi.org/10.1061/40962(325)7

[6] ASTM International. ASTM D6635-15 - Standard Test Method for Performing the Flat Plate Dilatometer. ASTM International, West Conshohocken, 2015. https://doi.org/10.1520/D6635-15.

[7] Robertson, P. K. "Soil behavior type using the DMT". In: 3rd International Conference on the Flat Dilatometer, Roma, Italy, 2015, pp. 243-250.

[8] Schnaid, F., Lehane, B. M., Fahey, M. "In situ test characterization of unusual geomaterials", In: 2nd Geotechnical and Geophysical Site Characterization, Porto, Portugal, 2004, pp. 49-74.

[9] Cruz, N. "Modelling Geomechanics of residual Soils with DMT Tests". Ph.D. thesis. Porto: Porto University, 2010. [online] Available at: https://repositorio-aberto.up.pt. [Accessed: 25/09/2019].

[10] Robertson, P. K., Viana da Fonseca, A., Ulrich, B., Coffin, J. "Characterization of unsaturated mine waste: a case history". Canadian Geotechnical Journal, 54(12), pp: 1752-1761, 2017. https://doi.org/10.1139/cgj-2017-0129.

[11] Marchetti, S. "The seismic dilatometer for in situ soil investigations". In: Indian Geotechnical Conference, Kakinada, India, 2014, pp. 1-9.

[12] Berisavljević, D., Berisavljević, Z. "Determination of the presence of microstructure in a soil using a seismic dilatometer". Bulletin of Engineering Geology and the Environment, 78(3), pp: 1709-1725, 2018. https://doi.org/10.1007/s10064-018-1234-5.

[13] Monaco, P., Marchetti, S., Totani, G., Marchetti, D. "Interrelationship between small strain modulus Go and operative modulus". In: International Conference on Performance – Based Design in Earthquake Geotechnical Engineering, Tsukuba, Japan, 2009, pp. 1315–1323.

[14] Marchetti, S. "In Situ Tests by Flat Dilatometer", Journal of the Geotechnical Engineering Division, ASCE, V-106, nº GT3, pp. 299-321, 1980.

[15] Giacheti, H. L., Rodrigues, R. A., Bezerra, R. C., Rocha, B. P. "Seasonal influence in CPT: An unsaturated soil site example". Journal of Rock Mechanics and Geotechnical Engineering, 11(2), pp. 361-368, 2019. https://doi.org/10.1016/j.jrmge.2018.10.00

[16] Giacheti, H. L. "Experimental study about Dynamic Soil Parameters of some tropical soils of São Paulo State". Ph.D. thesis. Escola de Engenharia de São Carlos, Universidade de São Paulo, 1991 (*in portuguese*).

[17] Hardin, B. O. "Suggested Method of Test for Shear Modulus and Damping of Soil by Resonant Column". In: Special Procedures for testing Soil and Rock for Engineering Purposes, West Conshohocken, United States, 1970, pp.519-529.

[18] Anderson, D. G., Stokoe, K. H. "Shear Modulus: A time dependent soil property". In: Dynamic Geotechnical Testing, West Conshohocken, United States, 1978, pp. 66-90. https://doi.org/10.1520/STP35672S

[19] Fernandes, J. B., Rocha, B. P., Rodrigues, R. A., Giacheti, H. L. "Strength and Stiffness Parameters of an Unsaturated Tropical Soil". In: Second Pan-American Conference on Unsaturated Soils, Dallas, United States, 2017, pp. 440–450. https://doi.org/10.1061/9780784481707.044.

[20] Rocha, B. P. Geotechnical Characterization of Unsaturated Tropical Soil by In situ tests. Ph.D. thesis, Escola de Engenharia de São Carlos, Universidade de São Paulo, 2018. [online] Available at: https://teses.usp.br/teses/disponiveis/18/18132/tde-03122018-103909/pt-br.php [Accessed: 20/09/2019]. (in Portuguese)

[21] Leong, E. C., Cahyadi, J, Rahardjo, H. "Stiffness of a Compacted Residual Soil". In: 4th International Conference on Unsaturated Soils, ASCE, Carefree, United States, 2006, pp. 1169-1180. https://doi.org/10.1061/40802(189)95

[22] Nyunt, T. T., Leong, E. C., Rahardjo, H. "Strength and small strain stiffness characteristics of unsaturated sand". Geotechnical Testing Journal, 34(5), pp: 551-561, 2011. https://doi.org/10.1520/GTJ103589

[23] Georgetti, G. B., Vilar, O. M., Rodrigues, R. A. "Small-strain shear modulus and shear strength of an unsaturated clayey sand". In: 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris, France, 2013, p. 1113-1116.

[24] Jaky, J. "Earth pressure in soils". In: 2nd International Conference on Soil Mechanics and Foundation Engineering, Rotterdam, Netherlands, 1948, pp. 103-107.

[25] Ferreira, C., Viana da Fonseca, A., Nash, D. F. T. "Shear wave velocities for sample quality assessment on a residual soil", Soil and Foundations, 51(4), pp: 683-692, 2011. https://doi.org/10.3208/sandf.51.683

[26] Baligh, M. M.; Azzouz, A. S.; Chin, C. T. "Disturbances due to ideal tube sampling". Journal of Geotechnical Engineering, ASCE, 113(7), pp: 739-757, 1987.

[27] Sas, W., Gabryś, K., Szymański, A. "Effect of Time on Dynamic Shear Modulus of Selected Cohesive Soil of One Section of Express Way No. S2 in Warsaw". Acta Geophysical, 63(2), pp: 398-413, 2015. https://doi.org/10.2478/s11600-014-0256-z.