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Maximum shear modulus estimative from SPT for some Brazilian tropical soils

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Technical Note

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Correlations

Abstract

Maximum shear modulus (G_0) has been used in various geotechnical jobs (e.g., seismic site assessment, machine vibration and pile driven). Laboratory and in situ determination of G_0 is not a current practice in Brazil. G_0 can be estimated from empirical correlations based on in situ tests like Standard Penetration Test (SPT) and Cone Penetration Test (CPT) in the preliminary design phase. Several empirical correlations to estimate G_0 from SPT *N* value have been developed and are available in the literature. However, most of these correlations were established based on experience with well-behaved soils formed in temperate and glacial zones, which may not always be used for tropical soils. This paper assessed and discussed the applicability of some correlations for G_0 estimative from SPT data in lateritic and saprolitic soils. The classical correlations for sedimentary soils underestimated G_0 of tropical soils. After updating the database, the tropical soils correlations reasonably estimated G_0 for the lateritic ones, which was not the case for the saprolitic soils. It was observed that differentiating the soils only as lateritic or saprolitic was not adequate for a good G_0 estimate for the saprolitic sandy soils. It was found that only the lateritic soils correlation can be used with caution as a preliminary attempt to estimate G_0 from SPT *N* value in soils with similar characteristics to the ones presented in this paper.

1. Introduction

The maximum shear modulus (G_0) is an input parameter in soil dynamic and static analyses (Bang & Kim, 2007; Brandenberg et al., 2010; Décourt, 2018; Poulos, 2021). Another G_0 application is on the estimative of G-γ decay curves (Amoroso et al., 2014; Lehane & Fahey, 2004). Moreover, G_0 can be correlated with the SPT *N* value, cone resistance (q_c) or constrained modulus obtained by Flat Dilatometer (M_{DMT}) in order to assist soil classification, state parameter estimative, identification of microstructure (age and/or bonding structure) and collapsible soils (Robertson, 2016; Rocha et al., 2022; Schnaid et al., 2020, 2004).

The G_0 can be determined by in situ and laboratory tests. The available laboratory tests are the resonant column (ASTM, 1995; Hoyos et al., 2015; Werden et al., 2013) and the bender elements (Leong et al., 2005) tests. The main in situ tests to determine G_0 are the crosshole (ASTM, 2007), the downhole (ASTM, 2008), the seismic cone (SCPT) (Robertson et al., 1986) and seismic dilatometer (SDMT) (Marchetti et al., 2008). However, these tests are not always available or cannot be supported in the preliminary site investigation program.

The SPT has been commonly used for site characterization because of its simplicity, robustness, speed, and cost-effectiveness (Akca, 2003; Anderson et al., 2007; Schnaid, 2008). For this reason, several researchers have studied and proposed correlations between SPT *N* value and G_0 mainly for well-behaved clays and sands (reconstituted and isotropically consolidated clay and the reconstituted sands) (Anbazhagan et al., 2012; Imai & Tonouchi, 1982; Leroueil & Hight, 2002; Seed et al., 1983).

Brazil is a large country where tropical soils occur. A typical tropical soil profile includes the lateritic (upper horizon) and the saprolitic (lower horizon) soils. The lateritic soil undergoes a pedogenetic evolution called laterization, which results in a highly porous horizon with minerals that are more stable (e.g., quartz and kaolinite) and with an enrichment of the soil with iron and aluminum and its associated oxides (Mio, 2005; Vargas, 1985). In addition, foundation engineering practice has shown that lateritic soils are stiffer than non-lateritic soils for the working load (Décourt,

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2018). Saprolitic horizon is residual and retains the macro fabric or the chemical bond of the parent rock (Brand, 1985; Mio & Giacheti, 2007; Lumb, 1965; Rahardjo et al., 2020).

Tropical soils have a unusual behavior compared to sedimentary soils (Gidigasu, 1976; Vargas, 1985). They are characterized by cohesive-frictional nature, unsaturated condition, bonding and structure, and anisotropy. This behavior cannot be accurately represented by means of models and correlations developed by well-behaved soils (Berisavljević & Berisavljević, 2019; Robertson, 2016; Schnaid et al., 2004).

Giacheti (1991) and Barros & Pinto (1997) observed that the estimated G_0 value by using empirical correlations obtained from well-behaved soils (Table 1) significantly underestimates measured G_0 for lateritic soils. The discrepancy can be associated to the cemented structure from the lateritic soils (Figure 1a). Barros & Pinto (1997) also observed that the investigated saprolitic soils presented G_0 values which were higher than calculated values for low SPT N values. The opposite was observed for high SPT N values (Figure 1b). The authors also concluded that lateritic and saprolitic soils present different behavior: the higher the SPT N value, the greater the differences in G_0 for these soils, as shown in Figure 1c. Hence, Barros & Pinto (1997) suggested correlations for estimating G_0 from SPT N value for lateritic and saprolitic soils for foundation engineering projects in Brazilian tropical soils (Décourt, 2018). These authors used the MCT Classification System (Mini, Compacted, Tropical) proposed by Nogami & Villibor (1981) to classify the soils with respect to their lateritic behavior. Table 1 shows the empirical correlations obtained from well-behaved soils and lateritic and saprolitic soils.

It is important to point out that the correlations proposed by Barros & Pinto (1997) were defined from the available G_0 and SPT N values derived from crosshole and SPT tests at that time: 46 data points for lateritic soils and 26 data points for saprolitic soils. A total of 16 pairs of G_0 and SPT N values were determined on sandy soils and 30 pairs of points on clayey soils for the lateritic soil. For the saprolitic soils, 24 pairs of G_0 and SPT N values were determined for clayey soils and only 2 pairs of points for sandy soils. It is important to mention that the use of only two points of saprolitic sandy soils might not represent the behavior of saprolitic sandy soils, a fact observed and discussed later in this paper. Note that some SPT N values higher than 60 blows per 30 cm

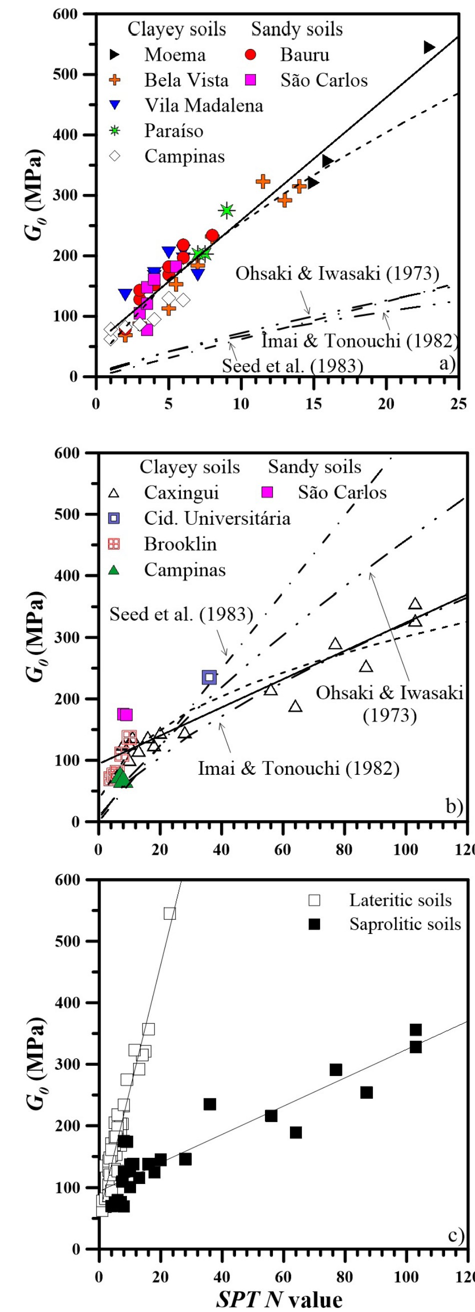

Figure 1. Experimental data for a) lateritic, b) saprolitic, and c) the comparison between lateritic and saprolitic soils [adapted from Barros & Pinto (1997)].

Table 1. Main correlations to estimate G_0 from SPT N value.

Type	Reference	Correlation	Type of soil
Well-behaved soils	Ohsaki & Iwasaki (1973)	$G_0 = 11.5N^{0.8}$	All soil types
	Imai & Tonouchi (1982)	G_0 $14.07N^{0.68}$	All soil types
	Seed et al. (1983)	$G_0 = 6.22N$	Sands
Lateritic soils	Barros & Pinto (1997)	$G_0 = 55.2N^{0.66}$	All types of lateritic soils
		$G_0 = 56 + 20.3N$	
Saprolitic soils	Barros & Pinto (1997)	$G_0 = 43.8N^{0.42}$	All types of saprolitic soils
		$G_0 = 94 + 2.3N$	

were defined by extrapolation in the proposed correlations for saprolitic soils.

This paper re-examines and discusses the correlations for estimating G_0 from SPT N value for some Brazilian tropical soils, considering not only the classification as lateritic or saprolitic soils, and points out the need to identify unusual soil behavior. The updated database incorporates additional G_0 and SPT N values (for clayey and sandy soils) by seismic cone (SCPT), downhole (DH), seismic SPT, and seismic dilatometer (SDMT) tests to those presented by Barros & Pinto (1997). It emphasizes the importance of performing G_0 measurements using appropriate techniques to check for unusual soil behavior and the need to adjust site-specific correlations.

2. Brazilian tropical soils correlations

Most of the correlations available in the literature between G_0 and SPT N value are defined as follows:

$$G_0 = \mathrm{A} \, . \, N^B \tag{1}$$

Where the constants A and B are obtained by statistical regression of a data set, although linear correlation ($G_0 = A + B.N$) is also used. Some authors recommend correcting the SPT N for energy efficiency, rod length, borehole diameter, and fine content (Andrus et al., 2004; Cetin et al., 2004; Hasancebi & Ulusay, 2007). Moreover, the SPT N value and G_0 can be corrected for overburden stress since both SPT N value and G_0 are affected by it, however, it is found that an uncorrected SPT N value and G_0 gives the best fit with a high regression coefficient when compared to G_0 and corrected SPT N values (Anbazhagan & Sitharam, 2010). Some key references cite the importance of associating behavior indices (i.e. I_c or SBT) in the correlations to estimate G_0 from a penetration test such as SPT and CPT (Jefferies & Davies, 1993; Jefferies & Been, 2006; Robertson, 1990, 2009), however, as previously presented, the vast majority of correlations between G_0 and SPT N value does not consider behavior indices (Anbazhagan & Sitharam, 2010; Hara et al., 1974; Ohsaki & Iwasaki, 1973).

2.1 In situ tests and database

A larger number of SPT and seismic tests (crosshole, downhole, seismic cone, seismic SPT and seismic dilatometer) performed in Bauru, São Carlos, and Campinas is now available (Table 2). There are 132 data points (G_0 versus SPT N values) for the lateritic soil and 82 for the saprolitic soil from Bauru. In São Carlos, there are 64 data points for the lateritic soil and 86 for the saprolitic soil. There are 38 data points for the lateritic soil and 62 data points for the saprolitic soil from Campinas. The thickness of the lateritic soil horizon for Bauru, São Carlos and Campinas is respectively 13, 6 and 7 m and it was defined based on the MCT Classification System (Nogami & Villibor, 1981). The average values of G_0 and SPT N along depth were calculated to assess the correlations

Table 2. Main soil characteristics and the references for all data.

Site	Reference	Geological information	Tropical soil classification	Soil type	*USCS*
Bauru	Giacheti & Mio (2008)ℵ Rocha (2018)ℵ Vitali et al. (2012)ℵ	Colluvium and Residual (Sandstone)	Lateritic and Saprolitic	Clayey sand	SM-SC
São Carlos	Giacheti & Mio (2008)ℵ Rocha (2013)ℵ Vitali et al. (2012)ℵ	Cenozoic Sediment and Residual (Sandstone)	Lateritic and Saprolitic	Clayey sand	SC
Campinas	Giacheti & Mio (2008)ℵ Rocha (2013)ℵ Vitali et al. (2012)ℵ	Colluvium and Residual (Sandstone)	Lateritic and Saprolitic	Silty clay	CL-ML
Moema	Barros & Pinto (1997)	Red clays São Paulo Sedimentary Basin	Lateritic	Sandy clay	CL
Bela Vista	Barros & Pinto (1997)	Red clays São Paulo Sedimentary Basin	Lateritic	Sandy clay	CL
Vila Madalena	Barros & Pinto (1997)	Red clays São Paulo Sedimentary Basin	Lateritic	Sandy clay	CL
Paraíso	Barros & Pinto (1997)	Red clays São Paulo Sedimentary Basin	Lateritic	Sandy clay	CL
Caxangui	Barros & Pinto (1997)	Residual (Gneiss)	Saprolitic	Sandy silt	SM
Cidade Universitária	Barros & Pinto (1997)	Residual (Migmatite)	Saprolitic	Silty sand	N.A.*
Brooklin	Barros & Pinto (1997)	Residual (Migmatite)	Saprolitic	N.A.*	N.A.*

*Information not available. ℵNew data.

considering representative data for each site, without having a disproportional increase of data between soils of different sites. It is important to mention that saprolitic soils from Bauru and São Carlos (clayey sand) and from Campinas (silty clay) with different grain sizes were included in the correlations: clayey sand from Bauru e São Carlos and silty clay from Campinas were not used in the correlations proposed by Barros & Pinto (1997).

2.2 Estimating G_0 from SPT *N* values

The data points (G_0 versus SPT *N* value) for the lateritic and the saprolitic soils for all sites as well as the regression lines are respectively shown in Figure 2 and Figure 3. The SPT *N* values were not corrected for energy efficiency. So, correlations were stablished assuming SPT *N* values for a 72% efficiency according to Brazilian SPT practice (Décourt, 2018; Décourt et al., 1989).

It is important to mention that correlations were also tested between SPT *N* and measured G_0 as well as for the values corrected for estimated energy and overburden stress. However, it was found that an uncorrected value of SPT *N* and G_0 gives the best fit with a higher regression coefficient when compared to corrected SPT *N* and G_0 values, as discussed by Anbazhagan & Sitharam (2010).

In addition, SPT *N* values higher than 60 were not considered for the correlations because they have no physical meaning, since they represent a condition beyond rupture (Aoki & Cintra, 2000). The potential and linear regression equations for the lateritic (Equations 2 and 3 – Figure 2) soils are given as follow:

$$G_0 = 57.3 N^{0.66} \quad (R^2 = 0.801) \tag{2}$$

$$G_0 = 64.4 + 19.7 N \quad (R^2 = 0.884) \tag{3}$$

The fitting equations obtained with a larger number of data are in accordance with the findings from Barros & Pinto (1997) for the lateritic soils (Figure 2). It is noteworthy that the well-behaved soils correlations (Table 1) significantly underestimated G_0 for the lateritic soils, as already presented and discussed by Barros & Pinto (1997). On the other hand, it was not possible to define the fitting equations for saprolitic soils since the values for the sandy soils are very different from those found for the clayey soils (Figure 3).

In order to verify the distinct behavior of sandy and clayey saprolitic soils (Figure 3), all lateritic and saprolitic data (previous and the new ones) are plotted in Figure 4, similarly to what was presented in Figure 1c. It can be seen in Figure 4 that lateritic and saprolitic soils present different behavior. It can also be observed in this figure that the data

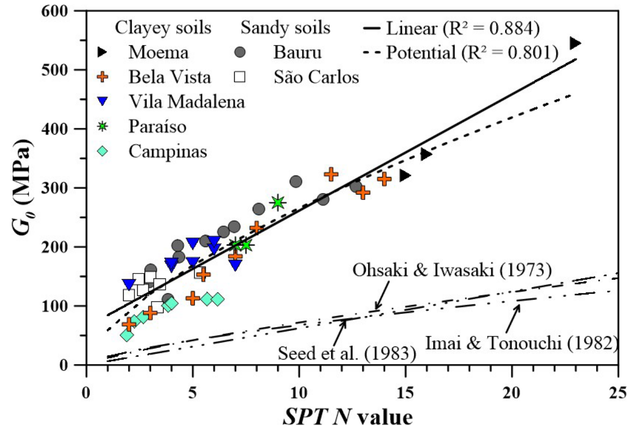

Figure 2. G_0 versus SPT *N* value and updated correlations for the lateritic soils.

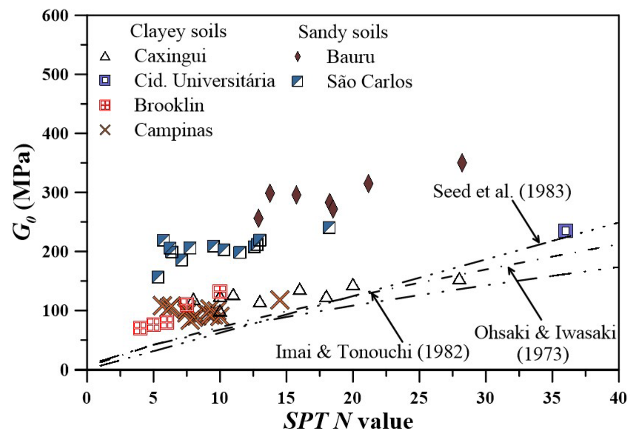

Figure 3. G_0 versus SPT *N* value for the saprolitic soils.

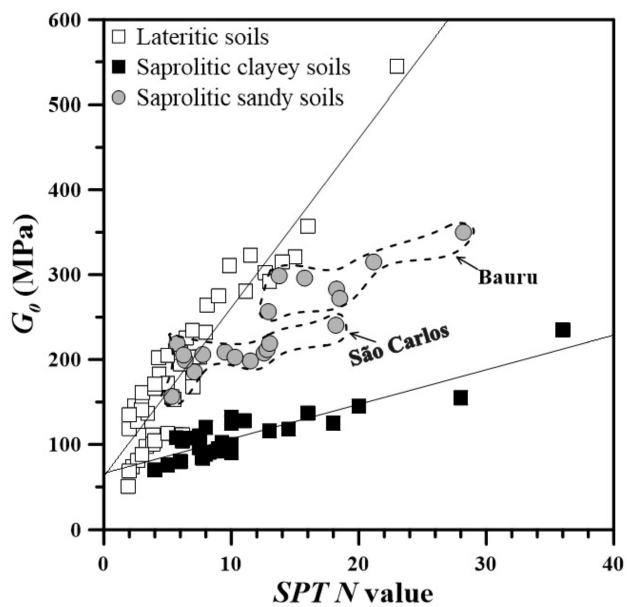

Figure 4. Comparison between G_0 and SPT *N* values from lateritic and saprolitic soils.

for the saprolitic sandy soils from Bauru and São Carlos are closer to that of the lateritic soils. This behavior can be related to another soil characteristic, such as grain size distribution and unusual behavior associated to cementation and/or bonding structure (Robertson, 2016; Schnaid et al., 2004).

The unusual behavior was evaluated using the chart (Figure 5) proposed by Schnaid et al. (2004) for the lateritic and saprolitic soils presented in Table 2. It correlates the G_0/N_{60} ratio versus $(N_1)_{60}$, where $(N_1)_{60}$ is calculated by Equation 4. This chart allows to assess the presence of microstructure (cementation and/or bonding structure).

$$\left(N_1\right)_{60} = N_{60}\left(\frac{p_a}{\sigma'_{vo}}\right)^{0.5} \tag{4}$$

where p_a is the atmospheric pressure, σ'_{vo} is the vertical effective stress and N_{60} is the SPT N value to a reference value of 60% of the potential energy of the SPT hammer calculated from Equation 5:

$$N_{60} = SPT\ N\ value\ \frac{72\%}{60\%} \tag{5}$$

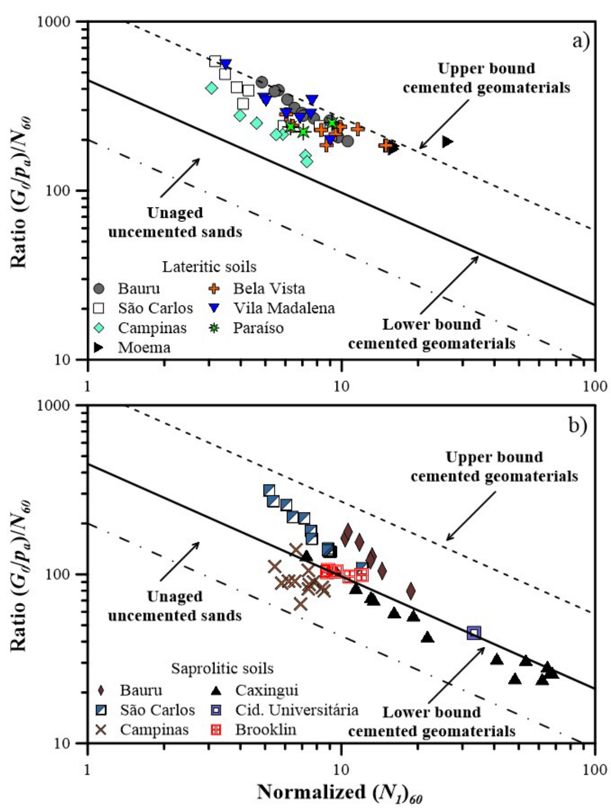

Figure 5. G_0/N_{60} versus $(N_1)_{60}$ chart and the boundaries for cemented and uncemented soils and the data for a) lateritic soils and b) saprolitic soils [adapted from Schnaid et al. (2004)].

It can be seen in Figure 5a that all lateritic soils data points are above the lower limit for cemented sands, indicating the presence of typical cementation from lateritic soils. It is the reason for the limitations of classical sedimentary soils correlations for estimating G_0 in soils with microstructure, such as the lateritic ones (Figure 2). For the saprolitic soils (Figure 5b), all clayey soils are below the lower limit for cemented soils while the sandy saprolitic soils (São Carlos and Bauru sites) are above the lower limit for cemented sands indicating they also have microstructure. This can be the reason for distinct behavior between sandy and clayey saprolitic soils, so it is not possible to define just one correlation for the saprolitic soils.

The correlations for G_0 estimation via SPT N value proposed by Barros & Pinto (1997) agree with the equations presented in this paper after expanding the database of lateritic soils from São Paulo state. It is important to emphasize that these correlations should be used with caution in a preliminary phase of the project and verified before their use. On the other hand, the equations proposed for saprolitic soils presented by Barros & Pinto (1997) did not adequately represent the behavior of the sandy saprolitic soils from Bauru and São Carlos and should not be applied. At the moment it is not possible to suggest correlations to estimate G_0 from SPT N values for saprolitic sandy soils due to the limited number of data and sites.

It is highly recommended to check whether the soil has microstructure before selecting a correlation, i.e., whether the soil has microstructure (cementation and aging), by using charts equivalent to that one proposed by Schnaid et al. (2004) with seismic CPT data and that one proposed by Cruz et al. (2012) with the seismic DMT data. The correlations developed for temperate and glacial zones cannot be used after the unusual soil behavior has been identified. In such cases correlations must be site specific.

3. Conclusion

The applicability of classical correlations for G_0 estimative from SPT data in lateritic and saprolitic soils was assessed. It was observed that lateritic soils behave differently from saprolitic soils and G_0 cannot be predicted by classical temperate and glacial zones soils correlations.

The equations proposed by Barros & Pinto (1997) for lateritic soils are consistent with those presented in this paper from a larger database. The equations for saprolitic soils proposed by these authors, however, should not be used for estimate G_0 for investigated saprolitic sandy soils. It can be related to the presence of microstructure (cementation and aging) in the saprolitic sandy soils. It is not possible to propose a correlation for estimating G_0 for saprolitic sandy soils due to the limited amount of data for this soil type. Furthermore, just identifying the soil as saprolitic does not guarantee an adequate estimate of G_0, since the soil type (sandy or clayey) and the presence of microstructure (cementing and aging) must be considered. A laboratory or in situ test is recommended to identify possible unusual soil behavior before using correlations.

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Declaration of interest

The authors declare that they have no conflict of interest.

Authors' contributions

Breno Padovezi Rocha: conceptualization, data curation, methodology, validation, writing – original draft, writing – review & editing. Bruno Canoza da Silva: conceptualization, methodology, validation. Heraldo Luiz Giacheti: formal analysis, supervision, writing – review, funding acquisition, project administration, resources.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

List of symbols

p_a	atmospheric pressure (equal to 100 kPa)
q_c	cone tip resistance
A	constant determined by statistical regression
B	constant determined by statistical regression
CL	clays of low plasticity
CPT	cone penetration tests
DH	downhole
G	shear modulus
G_0	maximum shear modulus
I_c	normalized SBTn index
I_{SBT}	non-normalized SBT index
MCT	mini, compacted, tropical classification system
M_{DMT}	constrained modulus obtained by Flat Dilatometer
ML	silts of low plasticity
N_{60}	corrected N value for 60% energy delivery
$(N_1)_{60}$	normalized N_{60}
SC	clayey sands
SCPT	seismic cone penetration tests
SDMT	seismic dilatometer tests
SM	silty sands
SPT	standard penetration tests
USCS	unified soils classification system
V_s	shear wave velocity
γ	shear strain
ρ	total mass densities
σ'_{v0}	effective vertical stress

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