The seismic SPT test in a tropical soil and the G_0/N ratio

L'essai SPT sismique pour le sol tropicaux et la relation G_0/N

Giacheti H.L., Pedrini R.A.A.
Universidade Estadual Paulista, Departamento de Engenharia Civil e Ambiental, Bauru – SP – Brazil
Rocha B.P.
Universidade de São Paulo, Departamento de Geotecnia, São Carlos – SP – Brazil

ABSTRACT: The seismic SPT, a test which associates the up-hole technique to the SPT, is briefly described. The maximum shear modulus (G_0) can be determined together with the N value with this hybrid test. Seismic (Cross-hole, Down-hole and SCPT) and SPT test data for a Brazilian tropical sandy soil are presented and discussed emphasizing the advantage of using the interrelationship between the small strain stiffness (G_0) and an ultimate strength (N value) to identify different soil behavior. A seismic SPT test was carried out in this research site and the G_0/N ratio is discussed as an interesting index to help characterize tropical soils, similar to what has been suggested for the Go/q_c ratio determined in a single test.

RÉSUMÉ : Le SPT sismique, qui associe le up-hole au SPT est brièvement décrit. Le module de cisaillement maximale (G_0) peut être déterminé avec la valeur N de ce test hybride. Des données sismiques (Cross-hole, Down-hole and SCPT) et SPT pour un sol sableux tropical du Brésil sont présentées et discutées soulignant l'avantage d'utiliser la corrélation entre (G_0) et une résistance à la rupture (valeur N) afin d'identifier le comportement de différents sols. Un essai SPT sismique a été réalisé dans le site expérimental et la relation G_0/N est discutée comme un indice intéressant pour aider à caractériser les sols tropicaux, de la même façon que ce qui a été proposé pour le rapport G_0/q_c mesuré dans un essai unique.

KEYWORDS: In situ testing, SPT, seismic, up-hole, tropical soil, G_0/N ratio.

1 INTRODUCTION

Site characterization can be defined as the process of identifying the geometry of relatively homogeneous zones and developing index, strength and stiffness properties for the soils within these zones. Some in situ testing can be used as an alternative to the traditional approach of drilling, sampling and laboratory tests. Combining stratigraphic logging with a specific measurement in a in situ test is a modern approach for site characterization.

Some authors have shown that it is possible to incorporate the measurement of shear wave velocities using the SPT blow by the up-hole technique. This hybrid test is known as the seismic SPT (S-SPT), which combines stratigraphic logging, estimative of geotechnical parameters and determining small strain stiffness (Go) in one single test similarly to the SCPT.

This paper briefly describes a system to carry out the S-SPT test and the approach to interpret the seismic data. It also discusses the applicability of the interrelationship between (Go) and N value to identify unusual soil behavior based on the tests carried out in a research sites located in the city of Bauru, inland of São Paulo State, Brazil emphasizing the advantage of using the S-SPT test for this approach.

2 BACKGROUND

2.1 *Tropical Soils*

Tropical soils are formed predominantly by chemical alteration of the rock, and they are considered a non-textbook type geomaterial because their peculiar behaviors that cannot be explained by the principles of classical soil mechanics.

The term *tropical soil* includes both lateritic and saprolitic soils. Saprolitic soils are necessarily residual and retain the macro fabric of the parent rock. Lateritic soils can be either residual or transported and are distinguished by the occurrence of the laterization process, which is an enriching of a soil with iron and aluminum and their associated oxides, bonding a highly porous structure. Saprolitic soil has structural or chemical bonding retained from the parent rock. The contribution of this cementation to the soil stiffness depends on the strain level the soil will experience. Differences between the mechanical behaviors of the mature (lateritic) and young (saprolitic) soils have been reported for both natural and compacted conditions.

2.2 *Go/q_c Ratio*

The pore pressure measurements cannot always be considered useful to allow an adequate classification of tropical soil based on CPTU data. The small strain stiffness (Go) and cone tip resistance (qc) ratio has been suggested as an additional information for classifying different soil types, especially to identify soils with unusual compressibility. Schnaid et al (2004) suggested that the ratio Go/qc provides a measure of the ratio of the elastic stiffness to ultimate strength and may therefore be expected to increase with sand age and cementation, primarily because the effect of these on Go are stronger than on qc. They proposed a chart and boundaries by correlating Go/qc *versus* normalized type resistance (qc_1). This chart can be used to evaluate the possible effects of stress history, degree of cementation and ageing for a given profile. Three lines divide upper and lower bounds for cemented and uncemented sands.

Giacheti & De Mio (2008) presented SCPT test results from three tropical research sites in the State of São Paulo, Brazil and plotted all the data in the Schnaid et al (2004) chart as shown in Figure 1. The authors pointed out that the SCPT test allows calculating Go/qc ratio simplifying interpretation and reducing site variability. The SCPT data interpretation indicated that the bonded structure of tropical soils gives Go/qc ratios that are systematically higher than those measured in cohesionless soils.

The results are in agreement with the propositions of Schnaid et al. (2004). They also observed that lateritic soils tends achieve a higher Go/qc ratio than the saprolitic soils.

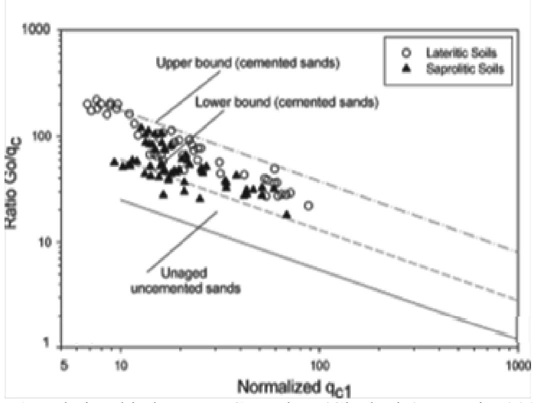

Figure 1. Relationship between Go and qc (Giacheti & De Mio, 2008).

2.3 *Go/N Ratio*

Schnaid et al. (2004) suggested that the N values from SPT test can also be combined with Go, using the Go/N ratio, to help assessing the presence of bonding structure. This approach is presented in Figure 2. Viana da Fonseca & Coutinho (2008) included data from experimental sites from Portugal in this figure. These authors pointed out that the bonded structure have a marked effect on the behavior of residual soils, with a Go/N values considerably higher than those observed in cohesionless materials. Lines are also shown in Figure 3 to define the upper and lower bounds for cemented and uncemented sands.

Similarly to what has been presented by Giacheti & De Mio (2008) for tropical soils based on SCPT data, the interrelationship between small strain stiffness (Go) and N value could be used to identify different soil behavior using the seismic SPT similarly to the SCPT.

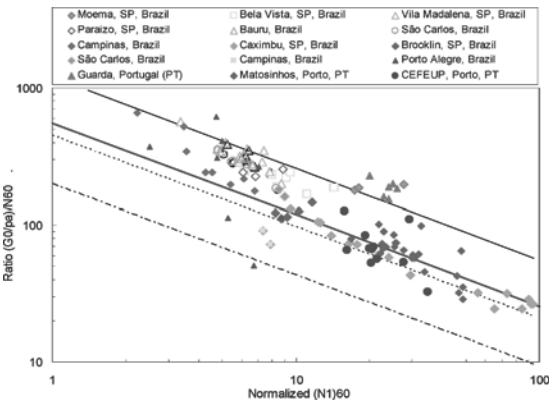

Figure 2. Relationship between Go and N_{60} (Schnaid et al 2004, completed by Viana da Fonseca & Coutinho, 2008).

3 STUDIED SITE

3.1 *The site*

The Unesp experimental research site is located inland of the State of São Paulo, Brazil, in the city of Bauru (Figure 3). Several site characterization campaigns including SPT, DMT, PMT, CPT, SCPT, cross-hole and down-hole tests were previously carried out at the site. A sample pit was excavated to retrieve disturbed and undisturbed soil blocks to be tested in the laboratory to characterize the soils and to determine geotechnical properties.

The subsoil is a sandy soil where the top 13 m has lateritic soil behavior (LA') overlaying a soil of non-lateritic behavior (NG') derived from weathering of Sandstone rock. The MCT Classification System proposed by Nogami & Villibor (1981) for tropical soils was used to define and classify the soils with regards to its lateritic behavior.

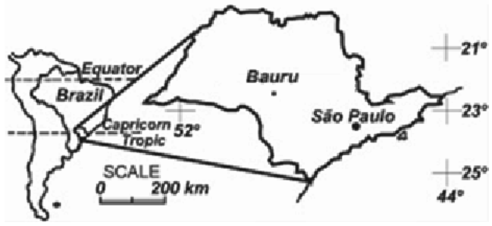

Figure 3. Bauru city, where the studied site is located.

3.2 *SPT and seismic testing data*

The typical soil profile for the studied site was defined based on the SPT tests and it is presented in Figure 4.a, together with N values correct by 60% efficiency (N_{60}) for all SPT tests (Figure 4.b). The shear wave velocities (Vs) were determined with cross-hole, down-hole and SCPT tests (Figure 4.c). Total mass densities were obtained from undisturbed soil samples collected in a sample pit excavated at the site. They were used to calculate Go values based on Elastic Theory and the data are presented in Figure 4.d.

An average Go/N_{60} ratio for every one meter depth was calculated, so the Go_{avr}/N_{60avr} values *versus* depth are presented in Figure 4.e. The criteria to calculate this ratio was averaging Go and N_{60} from all the tests and after that calculating the average ratio with the closest depth from Go and N_{60}.

Site variability can be assessed based on N_{60} and Vs values and these data indicate that the site is quite variable. Giacheti at al (2003) discussed variability for this site based on several CPT tests. They also concluded that the site is variable and test data can be affected by suction and cementation. The authors pointed out that the SCPT1 shows the presence of a region with low qc and high R_f between around 10 and 16 m depth. These data are quite different from those recorded with the SCPT2 test, so Vs values were not considered to calculate Go for this portion of the soil profile for the SCPT1 test. This variation is probably related to the morphogenetic and pedogenetic processes and probably reflects different degrees of cementation in the profile.

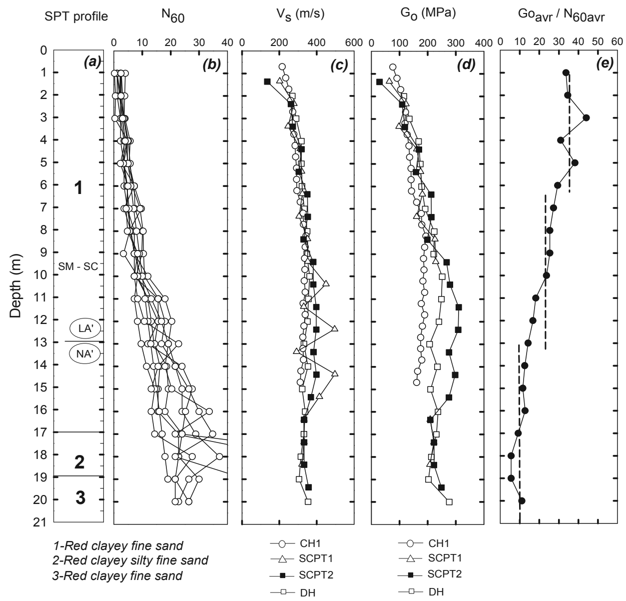

Figure 4. SPT and seismic testing data and Go/N_{60} for the studied site.

3.3 *The Go/N ratio*

It can be observed in Figure 4.e that the average Go/N_{60} tends do decrease with depth, with an average value equal to 35 between 1 and 6 m depth, 23 between 6 to 13 m depth and 10 below 13 m depth. These results indicate that Go/N_{60} ratio is higher in the lateritic soil layer (1 to 13 m depth) and tends to decrease as the residual soil is less developed.

The average Go and N_{60} values for the study site were plotted in the Go/N_{60} *versus* $(N_1)_{60}$ chart (Figure 5). Almost all the data points are in the upper bound for cemented sands which indicates that the bonded structure of tropical sandy soils produces Go/N_{60} that are systematically higher than those measured in cohesionless soils. It is also interesting to note in Figures 4.e that the lateritic soils (G_0/N_{60}=35 to the upper portion and 23 to the lower portion) present a higher cementation than the saprolitic soils (average G_0/N_{60}=10). These results are similar to what had been presented by Giacheti & De Mio (2008) based on Go/qc from SCPT test (Figure 1) and indicate the use of the ratio between the small strain stiffness (Go) and an ultimate strength (N or qc) to identify unusual soil behavior and degree of evolution of residual soils.

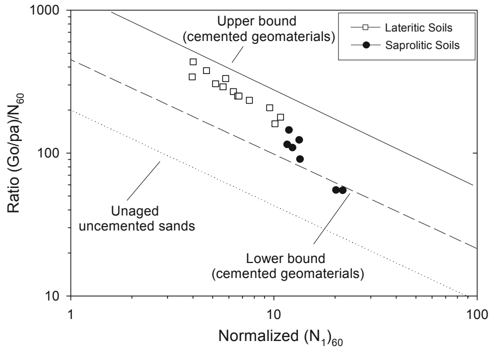

Figure 5. Relationship between Go and N_{60} for the studied site.

4 THE SEISMIC SPT TEST

4.1 *Principle*

It is possible to incorporate the shear wave velocity (Vs) measurements during the SPT test applying the up-hole technique. This approach has been used in the past and it is recently presented in detail by Bang & Kim (2007). This hybrid test allows measuring the SPT N value together with Vs (so Go) at the same time and in the same borehole. For each sampler depth (usually at every meter) a seismic wave is generated and it can be recorded on the ground surface. A schematic representation of the S-SPT test is show in Figure 6.

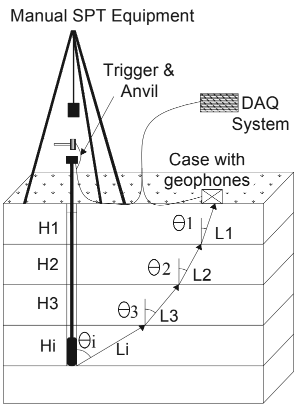

Figure 6. Schematic representation of an S-SPT test and a seismic refracted path (adapted from Bang & Kim, 2007 by Pedrini et al, 2012).

The test equipment is the same currently used for the SPT test. An arrangement of transducers (usually geophones) placed in appropriate boxes on the ground surface, a triggering system and the seismic source, which is the SPT sampler itself, are added for the seismic SPT test.

4.2 *Vs from the S-SPT test*

Determining Vs from the S-SPT test data is not straightforward. Bang & Kim (2007) described two methods: DTR (delay time between serial receivers) and DTS (delay time between serial sources). Pedrini (2012) suggested using the DTS method. In this method, the time interval of the S waves arrival for each sample depth in which the test was carried out is determined identifying the exact moment of the first arrival time plotting the wave receptions generated at different depths. Figure 7 shows a typical wave recordings profile as well as the point of the first S wave arrival. Another important aspect is the geometry. Bang & Kim (2007) recommend that Snell's Law (the refraction and reflection during the propagation of waves in stratified layers of different densities) should be taken into account when determining the refracted wave path.

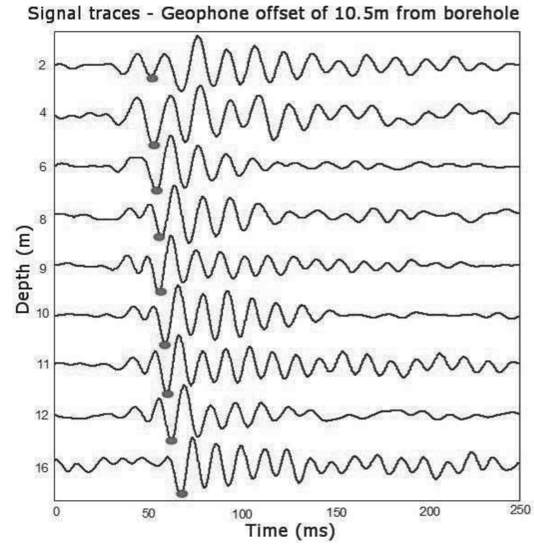

Figure 7. Profile of seismic wave and the identification of the common arrival point of the S waves (Pedrini et al, 2012).

The refracted ray pathway calculated based on Snell's Law depends on various wave velocities and it can be determined by considering two conditions: the Snell's law and a geometrical criteria. The following assumptions must be done: 1) each sample layer is equal to the depth where the SPT test was carried; 2) each layer is homogeneous and the propagated wave velocity is assumed constant in each layer as show in Figure 6. An iterative method must be used to solve the equation system and determine the length (L) that the wave propagates in each soil layer. Details can be found in Bang & Kim (2007).

4.3 *The S-SPT equipment*

The system for carrying out S-SPT tests and the method of analysis were implemented and described by Pedrini (2012). The main characteristics of this system are presented by Pedrini et al (2012) and will be summarized herein.

Bang & Kim (2007) used the drop of the SPT weight as the source to generate waves while Pedrini (2012) used a 2 kg sledgehammer. The triggering device was digital, with one terminal (positive or negative) fitted into the anvil head and the other attached to the sledgehammer.

Two geophones were installed inside of six boxes placed on the ground, one vertical and other horizontal oriented in a radial pattern. A National Instruments, model NI-USB-6353, data acquisition system was used. It has 16 bits resolution, 32 single ended channels and 16 differential channels, a digital and analogue trigger and a receiving rate of 1.25 ms/s. Software in the Labview and Matlab platforms were developed by Pedrini (2012) to trigger, capture the waves, signal processing, represent the traces, analyzing the recorded data and calculating the velocities.

4.4 *The S-SPT test procedure*

An S-SPT test was carried out using this system in the studied site. Seismic data were recorded from waves generated every one meter depth up to 21 m, right after the N SPT measurement using the equipment described in the previous sub-item. A six box arrangement was placed on the ground surface after removing the top soil to enable better coupling. The distance between each box (which contains a pair of geophone) was 1.5 m and they were all placed between 4.5 m to 12.0 m away from the test borehole.

4.5 *The S-SPT testing data*

The N_{60} values measured during the S-SPT test carried out at the studied site are presented in Figures 9.b. This hybrid test allowed determined Vs simultaneously to N every 1 m interval (Figure 8.c) for calculating Go (Figure 8.d). The Go/N_{60} values *versus* depth are also presented in Figure 8.e for the studied site with no averaging.

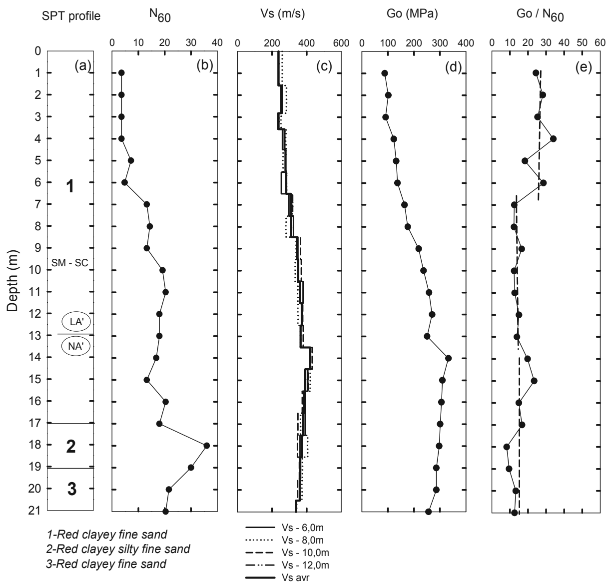

Figure 8. S-SPT testing data and Go/N_{60} for the studied site.

4.6 *The Go/N ratio*

The Go/N_{60} profile (Figure 8.e) obtained from the S-SPT test data are similar to what was found when averaging all SPT and seismic test data (Figure 4.e) for the top lateritic layer (1 to 6 m depth) with a lower average Go/N_{60} equal to 27, a bit lower than what was previously found, 35. In the lower part of the lateritic layer (6 to 13 m depth) it was found an average Go/N_{60} equal to 14, also lower than what was previously found (23) and the same average value for the saprolitic layer.

These data were also plotted in the Go/N_{60} *versus* $(N_1)_{60}$ chart as shown in Figure 9. All the data points are in the upper bound for cemented sands. In this case the difference between lateritic and saprolitic soils is not so clear, just the upper portion of the lateritic layer reflects a higher degree of cementation. Soil variability in this particular site probably related to the morphogenetic and pedogenetic processes, already pointed out by Giacheti et al (2003) and Giacheti & De Mio (2008) could explain the observed differences.

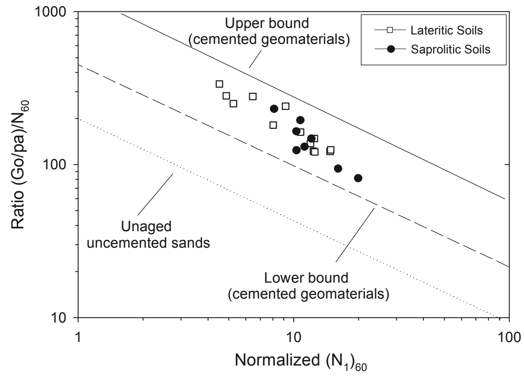

Figure 9. Relationship between Go and N_{60} for the seismic SPT test.

5 CONCLUSIONS

It was observed that the average ratio Go/N from several SPT and seismic tests carried out in the studied site was higher in the lateritic soil than in the saprolitic soil, particularly in the top layer. The seismic SPT test was used to derive Go/N values in the same site. Similar results were achieved with this single test, which allows determining both parameters simultaneous, reducing the effects of site variability. Relating an elastic stiffness (Go) to an ultimate strength (N value) is an interesting approach to help identify tropicals soils since the low strain modulus from seismic tests reflects the weakly cemented structure of lateritic soils while the SPT sampler penetration brakes down all cementation. The preliminary results from the seismic SPT test indicate that this hybrid test opens up new possibilities for geotechnical site characterization of tropical soils, based on the relationship Go/N, which is similar to the Go/qc ratio in the SCPT test.

6 ACKNOWLEDGEMENTS

The authors gratefully acknowledge FAPESP (*State of São Paulo Research Foundation*) and CNPq (*National Council for Scientific and Technological Development*).

7 REFERENCES

Bang, E. S. & Kim, D.S. 2007. Evaluation of shear wave velocity profile using SPT based up-hole method, Soil Dynamics and Earthquake Engineering 27, p. 741-758.

Giacheti, H. L. & De Mio, G. 2008. Seismic cone penetration tests on tropical soils and the ratio Go/qc. 3rd Geotechnical and Geophysical Site Characterization Conference, ISC´3, Taiwain, v.1. p. 1289-1295.

Giacheti, H. L.; Peixoto, A. S. P. & Marques, M. E. M. 2003. Cone Penetration Testing on Brazilian Tropical Soils. XII Panamerican Conference on Soil Mechanics and Geotechnical Engineering, Cambridge/USA, v.1. p. 397-402.

Nogami, J. S. & Villibor, D. F. 1981. Uma nova classificação de solos para finalidades rodoviárias, Simpósio Brasileiro de Solos Tropicais em Engenharia, Brasil, V. 1, p. 30-41.

Pedrini, R. A. A. 2012. Desenvolvimento de sistema para realização de sísmica up-hole em conjunto com sondagem SPT. M.Sc. thesis, FEB/Unesp. Bauru/SP, Brazil.

Pedrini, R. A. A. & Giacheti, H. L. 2012. The seismic SPT to determine the maximum shear modulus, 4th Geotechnical and Geophysical Site Characterization Conference, ISC´4, Brazil, CD-Rom.

Schnaid, F.; Lehane, B. & Fahey, M. 2004. In situ test characterization of unusual geomaterials. 2nd Geotechnical and Geophysical Site Characterization Conference, ISC´2, Portugal, v. 1. p. 49-74.

Viana da Fonseca. A. & Coutinho, R. Q. 2008. Characterization of residual soils, 3rd Geotech. and Geoph. Site Characterization Conf., ISC´3, Taiwain, v. 1. p. 195-249.