

Geotechnical characterization of igneous saprolite using the Seismic Cone Penetration Test (SCPTu) from a jungle site in South America

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ABSTRACT

This paper summarizes and discusses the results from Seismic Cone Penetration Tests (SCPTu) on a 40 m thick, igneous, saprolite horizon at a jungle site in South America. These results are compared against the results from conventional geotechnical drilling with in-situ tests (e.g., Standard Penetration Tests (SPT) and down-hole Vane Shear Tests (VST), and laboratory testing results. Saprolite is formed in situ by chemical weathering of the parent rock, resulting in soils with significant microstructure. This is evaluated under the framework of the Soil Behaviour Type (SBT) and the Modified Normalized Small-strain Rigidity Index, K^*_G . A discussion of the main limitations of conventional SCPTu classification and empirical correlation methods, when applied to saprolite, is presented in this paper along with a framework for interpretation and classification of this material, using information from the drilling and laboratory testing programs.

RÉSUMÉ

Cet article résume et discute les résultats des tests de pénétration de cône sismique (SCPTu) sur un horizon de saprolite ignée de 40 m d'épaisseur sur un site de jungle en Amérique du Sud. Ces résultats sont comparés aux résultats de forage géotechnique conventionnel avec des tests in situ (par exemple, des tests de pénétration standard (SPT) et des tests de cisaillement en auge de fond (VST), et des résultats de tests de laboratoire. La saprolite est formée in situ par altération chimique la roche mère, qui donne des sols de microstructure importante, évaluée dans le cadre du type de comportement du sol (SBT) et de l'indice de rigidité normalisé modifié des petites déformations, K^*_G . Une discussion des principales limites de la classification SCPTu conventionnelle. Les méthodes de corrélation empiriques, lorsqu'elles sont appliquées à la saprolite, sont présentées dans cet article, ainsi qu'un cadre d'interprétation et de classification de ce matériau, utilisant les informations provenant des programmes de forage et d'essais en laboratoire.

1 INTRODUCTION

Characterization of residual soils for geotechnical design is challenging due to its inherent complex composition and origin, topographic setting and accessibility, and climatic conditions. A series of geotechnical investigation methods are typically required to assess the best-suited interpretation upon design objectives.

This paper summarizes the approach taken on a field investigation at a jungle site in South America and provides lessons learned and recommendations for future programs in similar conditions. Results from Seismic Piezocone Penetration tests (SCPTu), Standard Penetration Tests (SPT), and down-hole Vane Shear Tests (VST) are reviewed to establish site-specific correlations, soil type characterization, behaviour-type characterization, and interpretation in liaison with laboratory testing data. Discussion on influence of microstructure in the interpretation of results is given using the framework proposed by Robertson (2016).

Details on terminology for describing or classifying residual soils are outside the scope of this paper. Pertinent information on this subject can be found in the following references: Burton (1998), Blight (1997), Deere and Patton (1971), Fookes (1997), ICOLD (2009), and Wesley (2010).

2 SITE CHARACTERISTICS

Characteristics of the site are summarized in Table 1. The site is located within the fersiallitic soil zone (high rainfall

promoting high leaching) described in Figure 1 by Burton (1998). The site presents average annual precipitation greater than 3000 mm distributed at regular intervals throughout the year (no dry season).

Most of the local terrain is shrouded in dense tropical cloud forest that, at lower elevations or in river valleys, often meets pastoral lands, clearings or swaths of secondary growth along river valleys.

The weathered soil profile at this site reaches depths of about 45 m, comprising a near-surface mottled soil horizon or laterite (no evidence of the rock structure) to saprolite (the fabric of the rock is apparent in the soil), then a transition zone (rock and soil present) to bedrock. The parent rock is igneous, intrusive, granodiorite/monzonite. Other surface materials in the area include alluvium and colluvium deposits. The groundwater level at this site follows the topography and it is shallower at the lower elevations and deeper on higher ground.

The site investigation program encountered numerous challenges, such as: permits, accessibility to the areas, transportation of resources into site and samples out of site, size of investigation equipment, and climatic effects. These challenges limited the number and type of investigations and the size of samples collected for testing.

Table 1. Characteristics of the Site

Characteristics	Site
Average Elevation	1500 m.a.s.l.
Average Precipitation	3400 mm
Annual Evaporation	1100 mm
Main Rock Type	Igneous Intrusive Granodiorite/ Monzonite
Residual Profile Depth	45 m

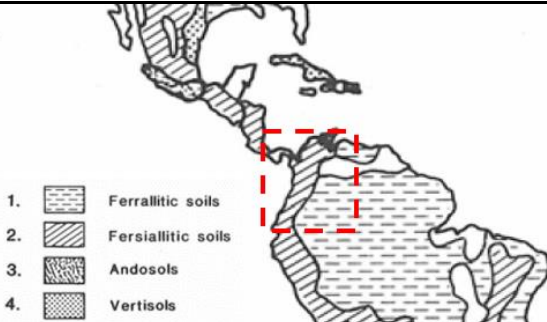


Figure 1. General site location shown on simplified world distribution of tropical soils (from Fookes, 1997; based on F.A.O. World Soil Map, extracted from Burton, 1998)

3 EVALUATION FRAMEWORK

Saprolite (soil-like material with fabric of the parent rock present as relic structure) is the dominant foundation soil in this site and is also the main source for construction material when relatively impervious fills are required for seepage control and/or containment.

As noted later in this paper, the characterization of these soils are challenging and require a variable set of testing procedures in order to establish a site-specific characterization of material behavior and performance to obtain best-judgement design parameters and/or approach. Spatial variability is complex and has large variability in test results itself.

Residual soils are known for having a complex geological background compared to transported soils; thus, the presence of microstructure is anticipated and is logical that investigation methods will focus on assessing the influence of this factor into the soil behaviour and response, rather than investigating its presence.

The following framework was considered prior to the site investigation planning:

- Assess soil properties, such as: gradation, moisture content, index properties (plasticity) and variability in terms of coarse-grained or fine-grained, spatially and with depth.
- Assess response to in-situ testing and to advance laboratory testing and influence of macrostructure (layering, fissuring, etc.) or microstructure (particle scale, aging, weathering, bonding (cementation)).
- Assess the behaviour/response in terms of dilative or contractive response and observe if there is evidence of sensitive or non-sensitive soils, or if strain softening is observed during undrained shear.

The presence of microstructure and inferred soil behaviour type is evaluated based on recommendations given in Robertson (2016), and it is inferred with the modified normalized small-strain rigidity index (K^*_G), which represents the relation between the rigidity and the resistance of the soil. A value of $K^*_G > 330$ indicates significant microstructure in the soil.

Site-specific correlations are presented, using empirical correlations available for SCPTu (e.g., Robertson 2009) and the SPT, and VST. Advanced laboratory testing was used to assess material response to shearing.

4 FIELD INVESTIGATIONS

4.1 Investigation Methods

The investigation methods included shallow and deep investigations in an area of 200 m by 200 m for foundation characterization for mine infrastructure. Investigation locations were spaced about 50 m and aimed to characterize the foundation profile from the surface down to bedrock and to collect undisturbed samples for laboratory testing.

Deep investigations consisted in triple-tube diamond drilling with HTW (double tube thin wall) (diameter core (70.9 mm) to fresh rock with final depths ranging between 41 m and 70 m. The shallow investigations included test pits (dug manually and with excavator) and portable Light Percussion Drilling (LPD) achieving a maximum depth of 6 m. This device proved to be of great use for investigation of shallow residual soils where access for an excavator was not available.

The Standard Penetration Tests (SPT) was conducted at intervals up to 3 m to an average depth of 30 m. The SPT used an automatic trip hammer. A Geonor H-70 Vane Shear Tests (VST) with maximum capacity to 160 kPa was used at variable depths in drill holes to average depths of 15 m. Shallow and deep stand-pipe piezometers were installed to measure groundwater levels in side-by-side holes.

SCPTu used a 10 cm² tip pushed with a thrust force of 15 tonnes generated with a 1-tonne lightweight rig anchored to the ground with augers to sounding depths ranging from 20 m to 36 m. Pore pressure dissipation tests were conducted at 2 m to 6 m intervals. Shear wave velocity testing was conducted at 1 m intervals by hitting a steel beam with a hammer from ground surface.

Table 2 summarizes the field investigation conducted at the site.

Table 2. Summary of Investigations

Investigation	Quantity
Shallow Test Holes Investigations	
Test Pits	2
LPD	6
Deep Investigations	
Drill Holes	6
SCPTu Locations	6
SPT Locations	6
VST Locations	6
Standpipe Piezometers	
Nested Piezometers Locations	6

4.2 Soil logging and sampling

Soils were logged per the Modified Unified Soil Classification system and Kohn Crippen Berger's (KCB) "Field Practices Manual" while the weathering profile was described following recommendations in Deere and Patton (1971) and Fookes (1997).

Grab, disturbed, samples were collected from test pits and drill holes for laboratory index testing. Block samples (approximately 0.3 cm to 0.7 cm cubes) were carved in test pits for index testing and advance laboratory testing. Shelby tube samples were obtained from the drill holes at selected depths.

5 MATERIAL CHARACTERIZATION

Figure 2 shows a typical photograph of the saprolite found at site. Saprolite was determined to be a low plasticity silt to sandy silt (ML) becoming coarser-grained with depth, to a silty sand (SM). As shown in Figures 3 to 5, saprolite shows large variability of gradations and fines contents (passing 0.075 mm) ranging between 25% and 90%. The residual profile grades from a finer particle size distribution near surface to a higher percentage of sand-sized particles and no gravel content below 10 m to 15 m depth. Table 3 summarizes the residual soil horizons observed at site.



Figure 2. Typical photograph of saprolite soil

Most of the samples plot below the A-line (Figure 4) confirming its USCS classification as silts (ML or MH) and within the range expected for "tropical red clays" (Wesley, 2010). Moisture content (Figure 5) decreased with depth, ranging from 20% to 60% in the upper 5 m (excluding upper residual layer) to about 20% to 40% below 15 m depth.

Laboratory testing of samples oven-dried at 50°C (Blight, 1997) and air-dried showed a difference of less than $\pm 4\%$ compared to oven-dried at 110°C (ASTM D2216), indicating low influence of structural water in test results.

As observed in Figure 5, plastic index is typically below 7 for depths greater than 12 m to 20 m, except for one location, which presented highly variable plasticity throughout the entire depth (typically between 7 and 10, with values over 20 between 5 m and 10 m depth). Liquidity index is between 0 and 1 up to 15 m depth through the finer-grained portion of the residual profile. Activity typically ranges between the Kaolinite-type to Illite-type range. For reference on material characteristics, the natural water content is between 10% and up to 30% over

the optimum moisture content (OMC) from a Standard proctor (ASTM D698) compaction tests.

Water table was observed at ground or below 2 m depth measured from the ground surface.

Table 3. Residual soil description summary

Horizon	Description
Residual	Clayey SILT (ML); low plasticity; firm to stiff; reddish brown or light brown; dry to moist; does not show evidence of parent rock structure.
Saprolite	SANDY SILT or SILT (ML); low plasticity; varies from soft to very stiff with depth; colour varies from reddish brown, pink, and white to yellowish brown or light brown, with depth. Parent rock structure is evident. Below 15 m and close to the transition zone, is generally described as SILTY SAND (SM)

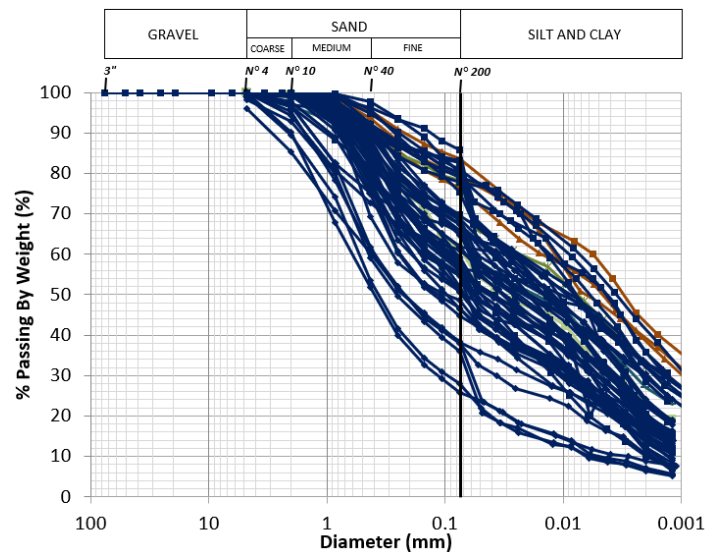


Figure 3. Typical particle size distribution

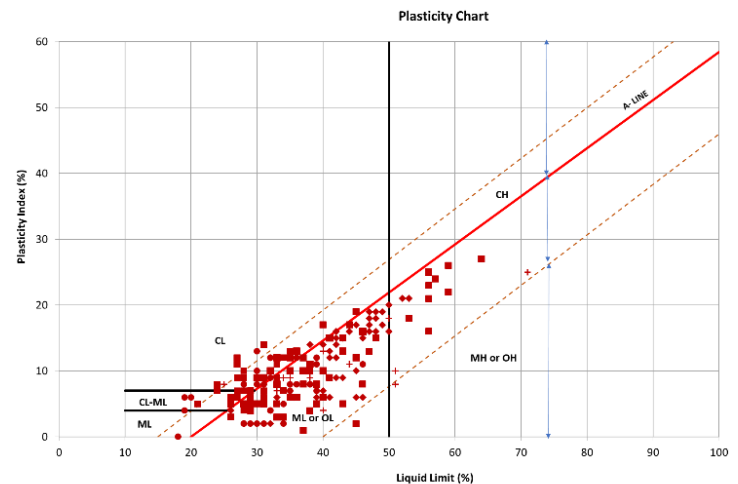


Figure 4. Typical plasticity data

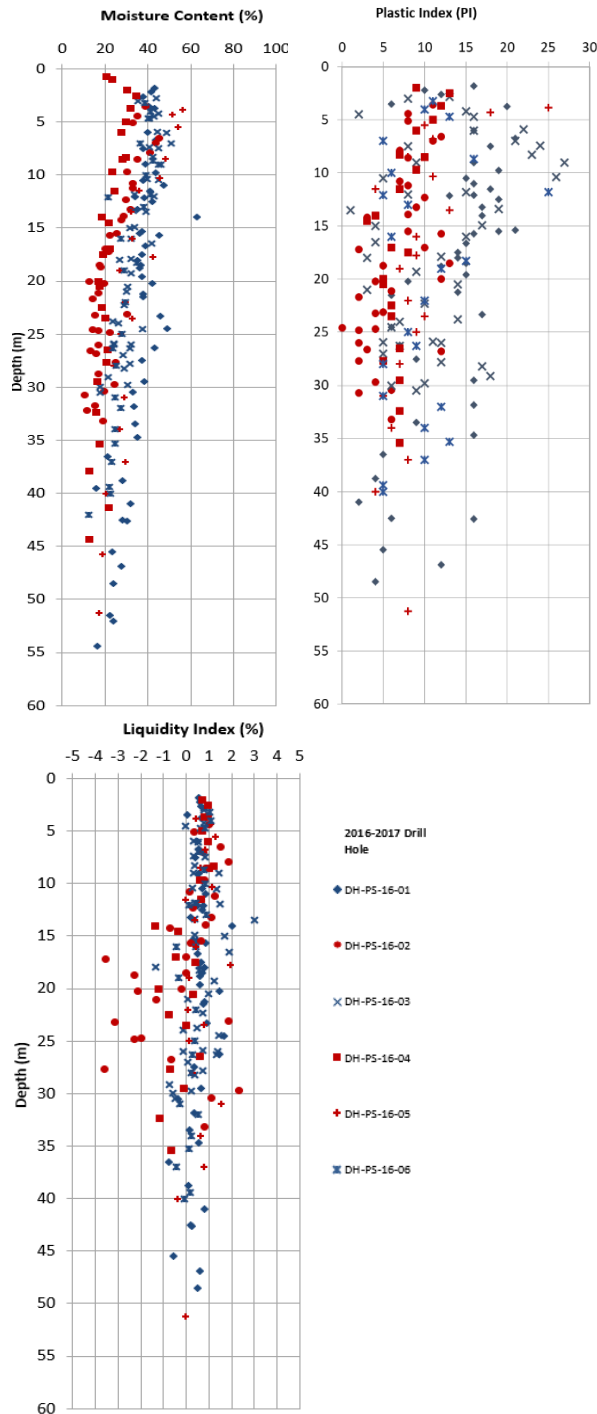


Figure 5. Natural Water Content, Plasticity and Liquidity Index Profiles

6 IN-SITU TEST RESULTS

6.1 Standard Penetration Tests (SPT) and Vane Shear Tests (VST)

SPT and VST data is shown in Figure 6. These plots show highly variable results, but with increasing trends of density and stiffness with depth.

Blow counts were recorded every 2.54 cm (1 inch), with the N-value represented by the sum of the blows from 15.2 cm to 45.7 cm. Refusal was assumed if more than 25 blows were required to penetrate 1 inch. SPT showed consistency varying from very soft to stiff, with average N-value of 5 to 15 in the upper 10 m, increasing to an average of about 40 blow count at 30 m before transition zone (defined as the transition from saprolite to weathered rock, being highly variable in texture from soil-like to rock-like materials).

Undrained shear strength from VST testing ranges from 50 kPa to over 100 kPa with depth. Below 7 m depth, some VST values exceeded the maximum capacity of the testing device (160 kPa, see Figure 6), but values exceeding the device capacity coincided with increasing sand-sized particle contents observed in laboratory testing. Remoulded values ranged from 25 kPa to 50 kPa and showed slightly to medium sensitivity (ratio between peak and remoulded was typically 2, with some values about 4 to 5), which shows influence of structure in tests conducted.

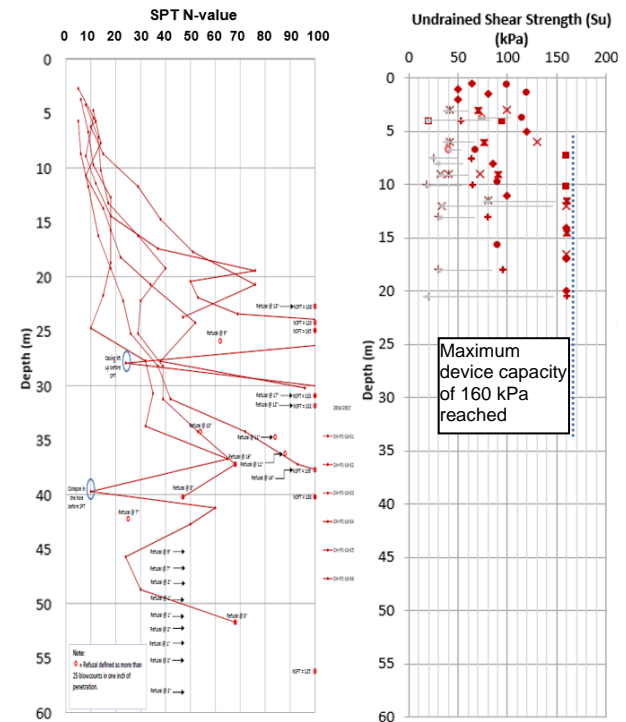


Figure 6. Typical SPT Blow-Count Results

6.2 Seismic Piezocone Penetration Test (SCPTu)

The SCPTu data showed similar trends as per other investigations; however, it provided additional information on pore pressure conditions and allowed for continuous data collection with depth. Refusal was encountered when approaching the transition zone, which proved to be a mean for residual profile characterization with sounding rigs as deep as 36 m even using a light-weight rig (1 tonne).

The tip resistance and shear wave velocity (V_s) increased with depth. V_s ranged from 100 m/s to 250 m/s up to 20 m.

As discussed previously, the SCPTu does not provide insight on material characteristics rather provides insight on its respond to undrained shearing. As stated by Robertson (2016), the current methodology used to interpret this response (SBT-modified) is affected by the presence of microstructure in the soil. When microstructure is present, a different chart is proposed by Robertson (2016) which was modified from Schneider et al. (2008).

The data obtained from the local contractor was evaluated and filtered to prepare different plots for the Normalized Rigidity Index (K^*_G) chart (see Figure 7). Estimations of the small-strain stiffness (G_o) were obtained from average V_s records at given intervals. Other correlations for G_o from SPT and tip resistance (q_c) were attempted. The most reasonable data was from the V_s estimates and representative or small strains; thus these were used to advance the assessment of microstructure as shown in Figure 7.

Figure 7 shows variable results falling within and outside the microstructure threshold. Higher K^*_G values were observed on the upper 15 m; however, these higher values were also observed at some intervals with depth. As sounding gets deeper, the K^*_G appears to decrease (without an obvious trend) which could relate to the increasing coarseness of the soil profile, but this could not be correlated accurately.

Even though the upper horizon (residual soils) have completely lost the texture of the parent rock and do not show obvious microstructure (relic structure) or cementation, high K^*_G values were estimated. This could be attributed longer aging and higher weathering.

As shown in Figure 8 for one sounding, the typical SBT-modified chart used for transported soils would frame the upper, finer grained saprolite to have a Transitional Dilative (TD) response and Clay-like Dilative (CD) response for the deeper saprolite (coarser-grained). This differs significantly from the response predicted when using the plot recommended for soils with microstructure (Figure 9), where Transitional Contractive (TC) and Clay-like Contractive (CC) response is predicted. TC response typically agrees with $K^*_G > 330$. Figure 10 shows data for all soundings and result in similar inferred response to undrained shearing.

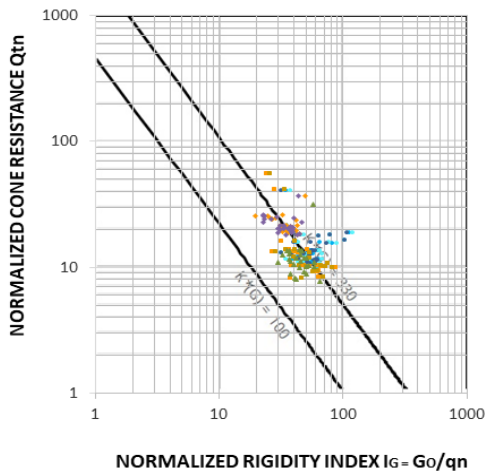


Figure 7. Normalized Rigidity Index chart to assess microstructure (Robertson 2016)

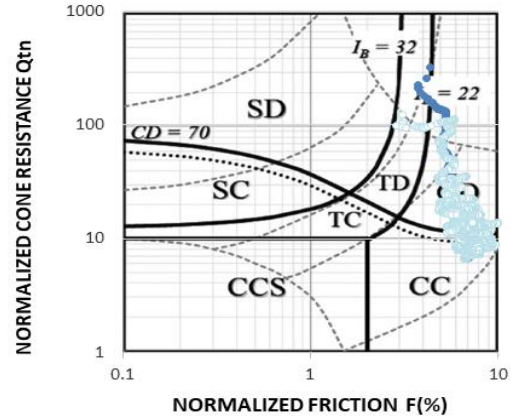


Figure 8. SBT-Modified Chart for one SCPTu sounding

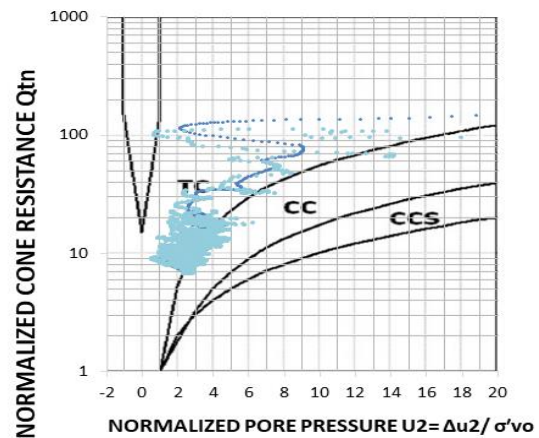


Figure 9. Modified chart from Schneider (2008) for one SCPTu sounding

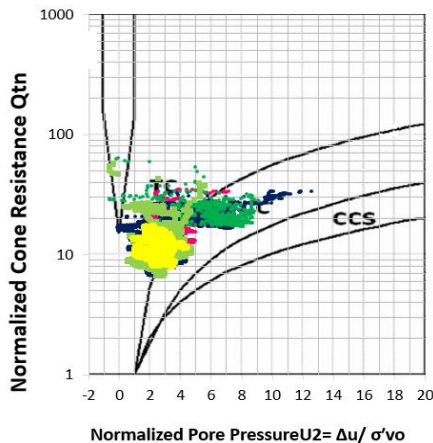
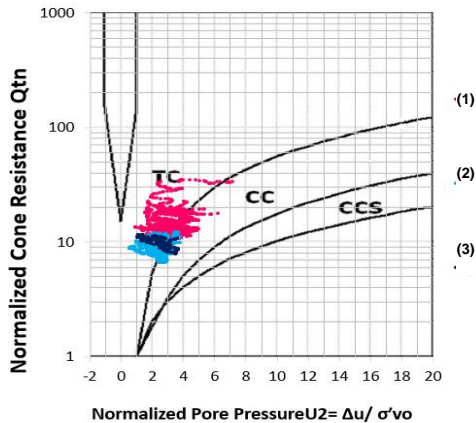


Figure 10. Modified chart from Schneider (2008) for all SCPTu soundings

Based on index testing alone ($PI < 12$, $w\%/LL > 0.85$), the saprolite profile will fall within the sand-like or transitional response, with susceptibility to liquefaction. This is somehow misleading as observed in SCPTu behavioral assessment and will be also confirmed from laboratory testing (discussed in section 7).

An attempt was made to group intervals of SCPTu data based on soil classification from index testing. As shown in Figure 11 (for one sounding), there was no obvious trend other than the silt unit plotted between the CC and TC zone and typically showed K^*_G over 330. The response to shearing, as observed in advance tests, provides a comparative qualitative for comparison with the SCPTu evaluation.



Legend: Silt trace sand (1), Silt some Sand (2), Sandy silt (3), Silty sand (4).
Figure 11. Modified chart from Schneider (2008) for one SCPTu sounding, with soil classification screening

6.3 Site-Specific Correlations

SCPTu, SPT, and VST data was found to be highly variable through the saprolite profile, but some trends were observed for site-specific correlations.

Figure 12 shows VST S_{u-peak} versus SPT N-value (or N_{60} assuming 60% energy ratio) plots. Based on this, estimated correlation factors of 6 or higher can be used to correlate S_u with blow-counts. These are higher than the correlation factor proposed by Stroud and Butler (1975) for transported over-consolidated clays.

Figures 13 and 14 show VST S_{u-peak} versus CPT data for estimation of N_{kt} (factor that correlates normalized tip resistance and S_u) and $N_{\Delta u}$ (factor that correlates change in pore pressure and S_u). Typical estimated N_{kt} and $N_{\Delta u}$ ranges for this site are given in Table 4.

Approximate undrained shear strength ratios (S_u/σ'_v) are shown in Figure 15 with VST, and correlated data from SPT and SCPTu testing. Assuming that the water table is at ground surface, the S_u/σ'_v lower bound ranged from 0.3 to 0.4; when assuming water table at 2 m depth, the lower bound ratios are about 0.7 to 0.8, which is more consistent with laboratory testing results from laboratory testing (see Section 7). For the given range of stresses at the time of the in-situ testing, there appears to be an effect of the structure on the observed strength with depth. This was confirmed with oedometer testing on saprolite samples that showed "strain-hardening" behavior with no clear evidence of yield stresses at low vertical effective stresses, with yield stress being defined as the stress to which the chemical bond or relic structure, created or left in place during weathering, is broken.

However, if a large structure were to be built over this site, these S_u/σ'_v ratios would decrease with confining

stress. As reference, the "remoulded" VST values fall within a S_u/σ'_v value of about 0.4.

Table 4. Site Specific Correlations

Host Rock Type	S_u/σ'_v Lower Bound	S_u/N_{60}	N_{kt}	$N_{\Delta u}$
Igneous	Water table at ground: 0.3 to 0.4; Water table at 2 m depth: 0.7 to 0.8	6 to 8 (7)	10 to 17 (14)	3 to 4 (3)

As shown in Figure 15, different type of in-situ tests, such as the SPT and VST, can be used for estimation of site-specific correlated S_u/σ'_v ratios; however, the range of factors used to define the undrained shear strength parameters would be not understood if multiple tests are not conducted in parallel with laboratory testing at a similar range of stresses expected for the design objective.

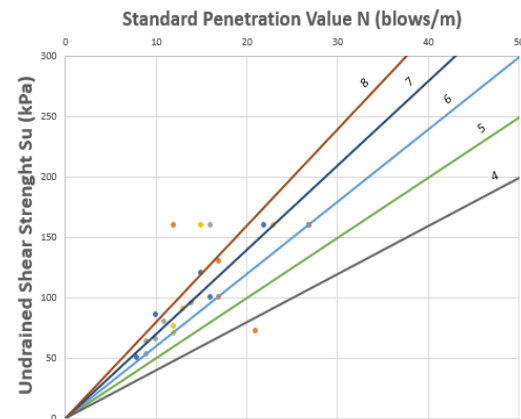


Figure 12. SPT N-value versus Undrained Shear Strength from VST

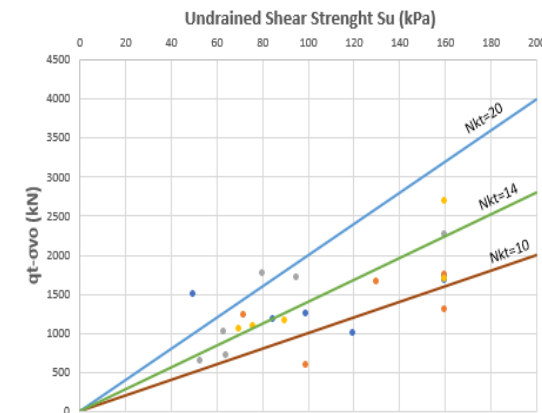


Figure 13. Normalized Tip Resistance versus Undrained Shear Strength from VST (N_{kt})

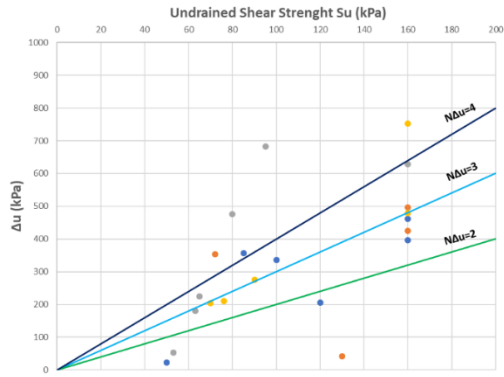


Figure 14. Change in pore pressure versus undrained shear strength from VST ($N_{\Delta u}$)

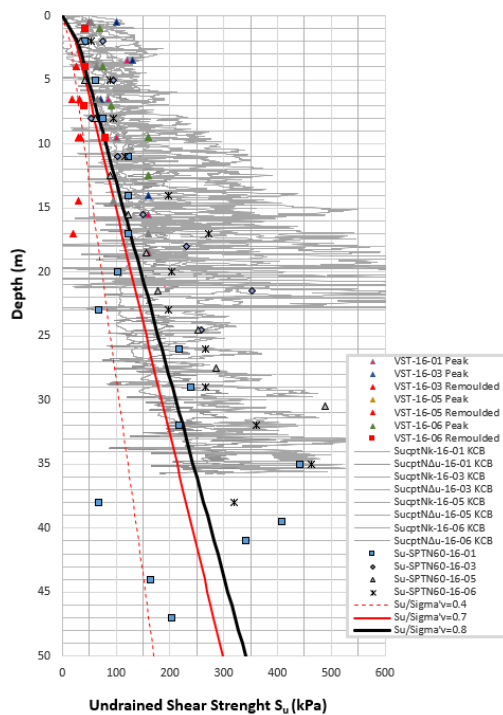


Figure 15. Undrained shear strength profile for VST and correlations from SPT and SCPTu (Water depth assumed at 2 m for S_u/σ'_v ratios)

7 LABORATORY TESTING

7.1 Compressibility

Oedometer tests were completed on specimens trimmed from block and Shelby samples. The specimens were trimmed directly into the oedometer ring with interior dimensions of approximately 25 mm in height and 63.5 mm in diameter.

Figure 16 plots vertical strain against vertical effective stress at natural scale. The oedometer results are shown in this fashion following Wesley (2010), because a standard e - $\log \sigma'$ plot does not represent the compressibility of saprolite soils properly, as it does for transported soils.

7.2 Shear Strength

No shear strength testing was conducted on samples collected at this location; however, advance testing from nearby areas were used to assess observed site investigation results on samples with similar characteristics. The results are summarized in Table 5.

Shear strength tests included: (i) Consolidated Drained Direct Shear Tests (DS), (ii) Consolidated Isotropic Undrained (TXCU) Triaxial Tests and (iii) Direct Simple Shear Tests (DSS).

In general, the shear test results showed that saprolite contracts under shearing for stresses above 100 kPa, which is below the expected stress levels of the future infrastructure at site; therefore, the controlling behaviour under shearing will be undrained. Figure 17 shows S_u/σ'_v versus confining stress.

For reference, effective strength parameters are provided in Table 5 and plotted in correlation with Atterberg limits, as proposed by Wesley (2010) as show in Figure 18.

Table 5. Summary of Laboratory Testing Values

Test Type	c' (kPa)	ϕ' (°)	S_u/σ'_v (kPa) (100-1000kPa)	m_v (kPa ⁻¹) (200-400kPa)
DS	32-36	31-34	-	1.3×10^{-4}
TXCU	0-10	28-35	0.84 to 0.34	to
DSS	-	-	0.30 to 0.28	1.5×10^{-4}

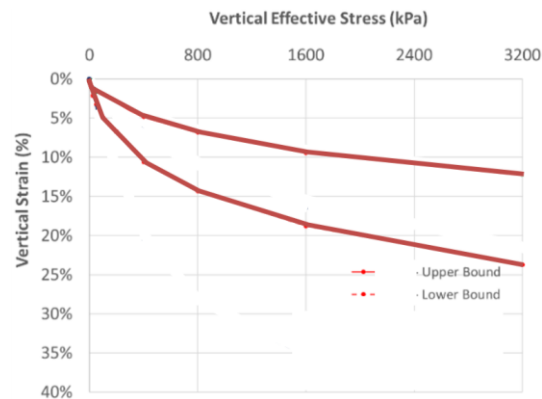


Figure 16. Consolidation Results

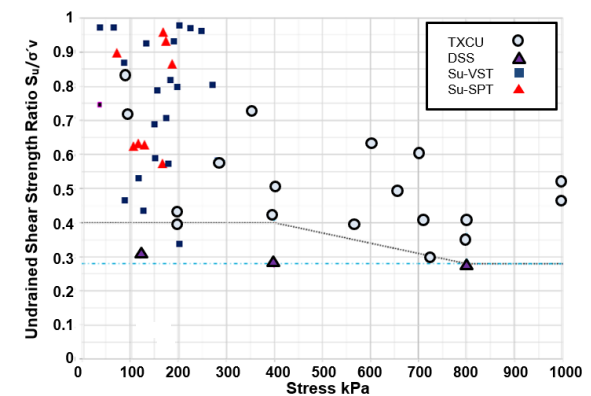


Figure 17. TXCU and DSS S_u/σ'_v ratio versus Stress

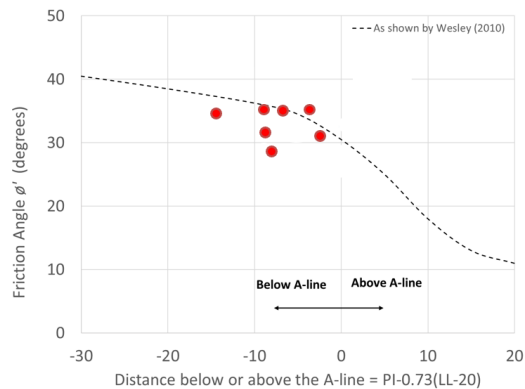


Figure 18. Friction angle versus position on plasticity chart

The undrained shear strength results showed S_u/σ'_v ratios between 0.84 and 0.34 from the TXCU and between 0.30 and 0.28 from DSS, with values decreasing with stress. Typically, the DSS is assumed as the average undrained shear strength along a failure mode in stability analyses. The effect of the increasing confining stress is evident, and some yielding is observed passing 100 kPa to 200 kPa. As discussed previously, care should be taken if only in-situ tests are used for design, as the detrimental effect of the increasing loading/confinement in the foundation has to be considered.

8 DISCUSSION

Saprolite soils are unique and require different tools for a complete interpretation of its classification and behaviour under shearing and compression. The SCPTu test showed to be a very useful tool to evaluate soil response/behaviour when proper interpretation is conducted (Robertson 2016; Schneider 2008); however, we note that the interpretation of K^*_G was highly sensitive to the method and quality of data used for its estimation.

Most importantly, the geological understanding of the site and formation processes associated with this type of soils is required to acknowledge that microstructure or aging effects will be present and will have an influence on the results to be obtained with the SCPTu.

Portable light-weight equipment can be used to push the SCPTu throughout the entire saprolite profile. This is relevant in dense tropical forests since disturbance for and platform preparation and transport can be reduced.

The SCPTu testing showed good agreement with results obtained from drilling or test pit samples. The latter are preferred for review of texture and index classification, while the former proved to be a real-time/non-invasive (relatively deep) investigation tool to assess performance and to provide continuous data and (if properly spaced intervals used) pore pressure conditions and response, as well as shear wave velocity profiling to confirm trends or to provide insights for a more detailed investigation program drilling with in-situ testing.

The observed transitional-contractive to clay-like contractive at large strains behaviour agreed with the observed response from advanced testing and somehow showed trends with varying material characteristics, with

K^*_G over 330 typically for silts near surface on the laterite horizon and decreasing when coarseness increases (likely less chemical weathering). The interpretation of this data within the correct design objective will require an assessment of disturbance, yielding, and predicted confining stresses.

Although no obvious trends were observed, site-specific correlations, for sensitivity assessments, could be made using the SCPTu and the other tools used. The correlated results showed that the saprolite investigated at this site, showed higher values or correlation factors are typically obtained for transported soils as published in the literature.

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