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In-situ regolith depth measurements by DPL tests

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SUMMARY: The dynamic cone penetrometer light (DPL) test has been used extensively for geotechnical investigation due to its speed, economy and mobility. In this work, we measure the depth to bedrock using DPL in a natural forested basin of Rio de Janeiro, Brazil. We compare our definition criteria of soil-bedrock interface with other approaches used internationally. In addition, we show where, in a river basin or slope, this test is more reliable, as well as places where there might be bias in the interpretation of the test. We also present a statistical method to delineate possible heterogeneities between the ground surface and the rock mass surface. This stratigraphic information is then confronted with laboratory tests, which indicated a low correlation between the DPL penetration rate and soil texture.

KEYWORDS: depth to bedrock, DPL tests, field investigation, stratigraphy, soil texture.

1 INTRODUCTION

Regolith depth controls a myriad of processes by influencing subsurface flow paths, erosion rates and soil moisture. As hillslope interiors are very difficult and costly to illuminate and access, the topography of the bedrock surface is largely unknown. Moreover, at field scale, limited tests, topographic constraints, high gradients and dense vegetation make estimating depth to bedrock difficult, time consuming and cost prohibitive.

Several direct and indirect measurement methods have been used to estimate depth to bedrock. Examples of direct measurement methods include rod penetrometers, excavated pits, hand and gasoline or electric-powered augers, road cuts and erosion gullies, and dynamic cone penetrometers. This last measurement device is particularly promising as it can help delineate soil stratigraphy and layers with contrasting hydraulic properties. Example of this device is the dynamic cone penetrometer light (DPL). Indirect bedrock depth measurement methods include the use of gravity survey, geophysical, seismic refraction, electrical resistivity tomography, and airborne electromagnetic. These latter five measurement methods make it possible to determine noninvasively the physical properties of the subsurface, yet inversion methods are required to interpret these indirect observations of the bedrock depth. Much effort is required to use these measurement methods to characterize bedrock depth variations at the spatial scale of a hillslope or watershed.

For many geological and geotechnical conditions found in southeastern Brazil, it is necessary to determine thick and heterogeneous soils. DPL is an alternative and cost-effective approach to

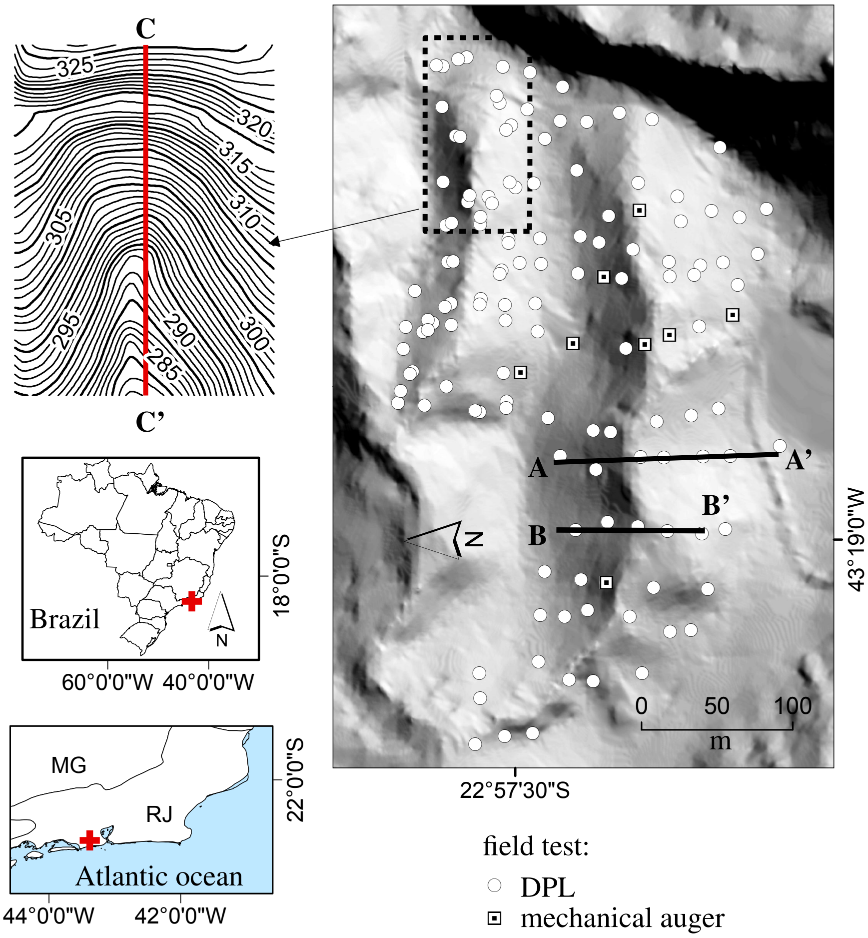

Figure 1: Geographic overview (left) and shaded relief image (right) of the Papagaio river basin experimental field site (red cross) in Rio de Janeiro, Brazil. The white circles (right) denote the DPL measurement locations and the white squares with black dots represent additional mechanical auger tests. The transect **AA**' is used to demonstrate the results of DPL tests. The transects **BB**' and **CC**' are also of particular interest.

achieve these requirements. Basically, DPL consists of guide rod, a set of rods, a hammer and a cone. In general, its operation involves the fall of a hammer from a determined height, generating thus energy that guide rods into the ground at a penetration rate. Hence the penetration rate is an empirical measure of the soil mechanical strength.

In this article, we present a detailed field investigation of a natural region of the Tijuca Massif, Rio de Janeiro, Brazil (Figure 1). We describe a method to estimate the soil-bedrock interface of residual soils as well as possible resistant layers between the ground surface and the underlying bedrock using DPL tests. Additional surveys with mechanical auger are also conducted to obtain information on the sand, silt and clay content. Correlations between results of DPL tests and textural information are explored.

2 FIELD INVESTIGATIONS

Field investigations were carried out in two adjacent watersheds in the Papagaio river basin in Rio de Janeiro, Brazil. These two watersheds have been studied extensively by many different authors in the literature after mass movements occurred in 1996 (see for instance Vieira and Fernandes (2004)). The geographic location of the field sites is depicted with a red cross in Figure 1 which also presents (right hand side) the topography of the two experimental basins. The white dots signify $n = 137$ DPL measurement locations, and the withe squares with a black dot represent 8 positions where mechanical auger probing were also executed. The hillslope transects are used herein to summarize, respectively, results of DPL tests (**AA**'), confidence intervals of a depth to bedrock model (**BB**', Gomes et al. (2016a)) and a slope stability investigation (**CC**', Gomes et al. (2016b)). The elevation in the surveyed region ranges between 190 and 360 meters above sea level with slopes that vary between 0 to 57°. The local bedrock consists of high-grade metamorphic rocks (Archer gneiss is most frequent) with granite intrusions of coarse-medium granular texture (Vieira and Fernandes, 2004).

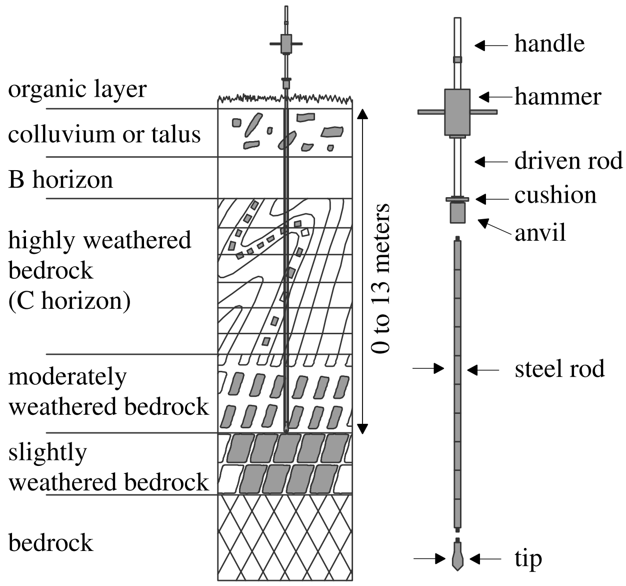

Figure 2: Representative weathering profile of the Archer gneiss in Tijuca Massif, Rio de Janeiro (Brazil). DPL measures the depth to slightly weathered bedrock. The main parts of the DPL apparatus are depicted in the right.

2.1 DPL tests

Figure 2 shows a typical weathering profile found in many gneissic regions of Brazil (Pastore, 1995). The main components of the DPL Nilsson (Nilsson, 2008), used in this study, are also represented in Figure 2. The test consists of a steel cone that is driven into the soil by the falling energy of a 10 kg hammer. The hammer slides over the driven rod and transmits an exact amount of energy (of a fixed height of 50 cm) to an anvil (static part of DPL). The driven rod is coupled to a set of 1 m length steel rods. The set of rods can be propagated up to 13 m into the soil. A wood cushion between the hammer and the anvil serves as a shock absorber. With the hammer impact, the set of rods penetrates vertically and number of blows to advance 10 cm (N_{10}) is computed. The higher the N_{10}-value, the more resistant is the soil. DPL tests can be easily conducted from the top soil (organic layer) to the B horizon. After this stage a notable increase in the N_{10}-value is observed in the penetrograms (soundings).

By dismantling the DPL ensemble in small parts we have safely transported the equipment to forested, high gradient regions of Figure 1. Only two people are needed to perform the test, although three persons is desirable for efficiency. The rod's verticality was guaranteed with a bubble level placed every 10 cm of penetration for the first rod and every 20 cm for the second rod. However, in some cases, even with this control, heterogeneities related to roots and small rocks have caused difficulties to maintain verticality of the test. To illustrate this issue, Figure 2 shows small rocks next the soil surface (colluvium layer), where the rods needed to keep vertical.

2.2 Mechanical auger tests

Eight mechanical auger tests have been executed near specific DPL tests for reproducibility (see Figure 1). We have collected disturbed samples for various soil layers. Laboratory tests have been conducted in 52 soil samples to characterize the soil textural classes of the study site.

3 DEFINITION OF THE SOIL-BEDROCK INTERFACE

In this work, we implement the following criteria to measure the bedrock-depth surface:

1. 100 blows to advance 10 cm;

2. 80 or more blows to advance 3 consecutive segments of 10 cm;

3. 60 or more blows to advance 5 consecutive segments of 10 cm;

4. depth greater than 12∼13 meters.

DPL has a limitation to achieve depths greater than 13 m, since the extraction of the rods may be compromised. Therefore, not always the depth at which the test was stopped corresponded to bedrock. However, our field experiments demonstrated that measured regolith depth was predominantly in the range between 0 and 13 meters. What is more, our criteria used to define the soil-bedrock boundary is consistent with approaches adopted in the literature. This stopping criteria was proposed by Nilsson and Cunha (2004) as DPL field limit (capacity).

N_{10}-value or penetration rate is an empirical measure of the soil mechanical resistance. To gain insights on the results of the DPL tests, Figure 3 illustrates the behavior of N_{10} with depth considering the four situations in which soil-bedrock interface was assumed. The criterion #1 line shows that N_{10} reaches the maximum value of 100 blows to advance 10 cm. The criterion #2 line indicates that the estimated regolith depth is slightly lower than 6m-depth. The criterion #3 line demonstrates a hard layer about 10 m-depth, whereas the criterion #4 line represents that test stopped at 12 m-depth.

N_{10} record is a good example of information about soil stratification. An increase in N_{10} is observed in a soft layer as the cone tip reaches an underlying stratum of higher resistance; in the other hand, the penetration resistance decreases in a dense soil as the cone tip approaches a lower softer layer. Although the results presented in Figure 3 indicate different stratigraphic conditions, a common feature of these plots is that after an intermediate value of $N_{10} \geq 30$, the penetration resistance variability increases substantially, which suggests the presence of a highly weathered saprolitic zone (Figure 2). This might be related with anisotropy in the vertical direction. We will revisit this issue further in this work.

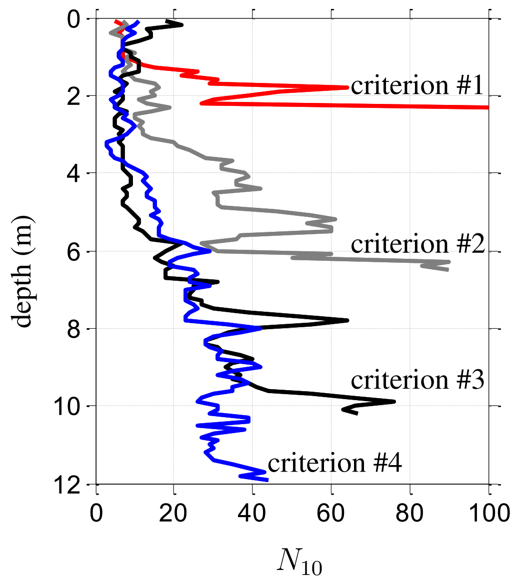

Figure 3: Penetration resistance versus depth for typical penetrograms (soundings) registered in the study site. The four different criteria used to identify the soil-bedrock interface are depicted.

Regolith depth ranged from 0 to 14 m (Figure 4). The distribution of the collected bedrock depth data is quite uniform until 6 m depth. After this depth, the histogram of Figure 4 shows a decrease in the measurement density. Note that a peak occurs at 12 m depth. As explained before, our field survey has been limited to this depth. However, some low frequency points have been collected beyond this point.

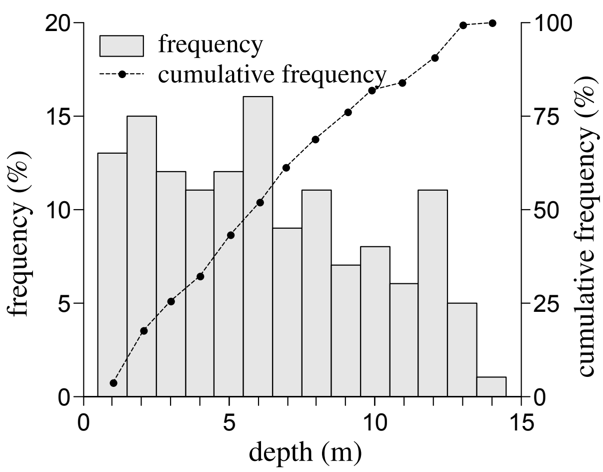

Figure 4: Histogram of depth to bedrock data collected by DPL tests.

We now investigate a common stratigraphic structure observed in the study area. Figure 5 illustrates cross section **AA'** where DPL tests have been executed. The penetrograms are exhibited next to each investigated borehole. The colors representing N_{10} values are coded to match the colors for each corresponding criterion, as shown in Figure 3. In summary, the results indicate a thick regolith in the hilltop and thin layer in the drainage channel. The later condition has been frequently identified near drainage channels (boreholes #108, #107 and #111). Boreholes executed near drainage regions reached $N_{10} = 100$ blows and due to the high hammer rebound, we suggest that fresh bedrock was hit. Moreover, in this region, the decrease in penetration resistance above bedrock surface is an indicative of aquifer zone (borehole #107), where high water content is expected to appear. Similar finding was observed by Kosugi et al. (2009). The criterion 2 has been mainly noted in sideslopes (boreholes #133 and #110). Borehole #100 depicts a test that has been stopped because no refusal (termination condition) has been found. This condition has been mostly identified at hillslope crests and divides. Test #110 shows high N_{10} peak near 4 m-depth, probably associated with quartz gravel or a small colluvium rock.

3.1 Comparison between light penetrometers used to estimate the soil-bedrock interface

To compare the performance between different penetrometers, it is usual (Matos Fernandes, 2014) to adopt the specific energy per blow (E). This is a measure of the hammer kinetic energy per unit of cone section area, expressed as:

$$E = MgH_{\mathrm{d}}/A, \tag{1}$$

where M is the hammer mass [M]; g represents gravity [LT^{-1}]; H_{d} indicates the drop height [L]; and A depicts the cone area [L^2]. Let N_I and N_{II} be N_{10}-values corresponding to the light penetrometers I and II. The combination between the energies (Equation 1) of both penetrometers is (Matos Fernandes, 2014):

$$E_I N_I / L_I = E_{II} N_{II} / L_{II}, \tag{2}$$

where L is the penetration length unit, generally 10 cm. Eq. 1 and 2 are adopted here to facilitate the comparison between different penetrometers, although it should be mentioned that the energy transmitted to the soil depends on other variables not included, such as the weight of the anvil and the weight of the rods.

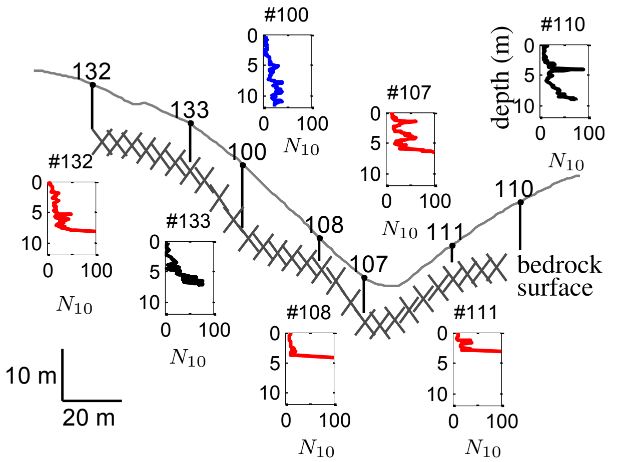

Figure 5: DPL tests executed in the transect **AA'** of the study site. The colors representing N_{10} are coded to match the colors for each corresponding criteria, as shown in Figure 3. Vertical axis in the small plots represent depth in meters.

Table 1 presents a review of different dynamic cone penetrometers used in the literature to delineate the soil-bedrock interface. Cone area (A), hammer mass (M), drop height (H_{d}) and penetration length (L) have been reported by different authors. The symbol N_{10}^{sb} represent the value adopted by past investigators to describe the soil-bedrock interface. The N_{10}^{sb} value varies from 30 to 100, but this value must be compared with the DPL used in this work. By using equations (1) and (2) we calculate, respectively, the kinetic energy per unit of cone section area (E) and the corresponding N_{10} value equivalent to the DPL Nilsson, N_{10}^{DPL}. Table 1 indicates that the energy is very different for each penetrometer due to differences in A, M and L. As a consequence of variations in E, N_{10}^{DPL} also have significant difference. The results show that the soil-bedrock interface correspond to N_{10} ranging from 30 to 162. This large difference reflects heterogeneities found in the saprolitic zone, as well as different site specific conditions. However, the mean value of N_{10}^{DPL} is 68, which is substantially lower than the criteria used in this work to delineate the soil-bedrock interface. This finding indicates that DPL Nilsson is a robust option to describe bedrock surface and heterogeneities (hard layers).

4 DEFINITION OF HARD LAYERS

In geotechnical site characterization, definitions are needed for demarcation of vertical boundaries of soil layers. In this paper, we follow Hegazy and Mayne (2002) to delineate soil stratigraphy from DPL tests based on cluster analysis. Cluster analysis is a statistical method for grouping data with similar mathematical information, i.e., it is a numerical method of classification.

One of 137 DPL tests conducted by the authors is shown in Figure 6. The penetrogram depicted in (a) shows a 10 m depth regolith. Dark grey regions in (a) represent hard-soil layers obtained by cluster analysis. These layers have at least 0.5 m thickness and mean N_{10} greater than 30. The minimum layer thickness of 0.5 m has been adopted based in the work of Hegazy and Mayne (2002), whereas the N_{10} threshold has been chosen according to the results present in Table 1. The dashed blue line represents the top of layers (0.5 m thickness or higher) in which N_{10}-value is greater than 30. This line agrees well with the first hard layer defined by cluster analysis in Figure 6 (a). In Figure 6 (b), we show a common output of the developed code for cluster analysis. We have chosen N_c = 6 number of clusters to divide our borehole results. The light grey regions denotes four layers with similar behavior due to penetration resistance. The corresponding mean N_{10}-value for each layer is indicated in the plot. In summary, two main groups can be separated between ground surface and the soil-bedrock interface: a top "weak" layer and a bottom "hard" layer. The remaining groups can be classified as outliers. In the interface between these two layers, it is expected that mechanical and hydrological properties might change (Kosugi et al., 2009). We use now textural results to investigate possible differences in sand, silt and clay content. Figure 6 (c) illustrates that sand and silt content increases with depth. This finding might suggest some correlation between penetration resistance and soil textural classes.

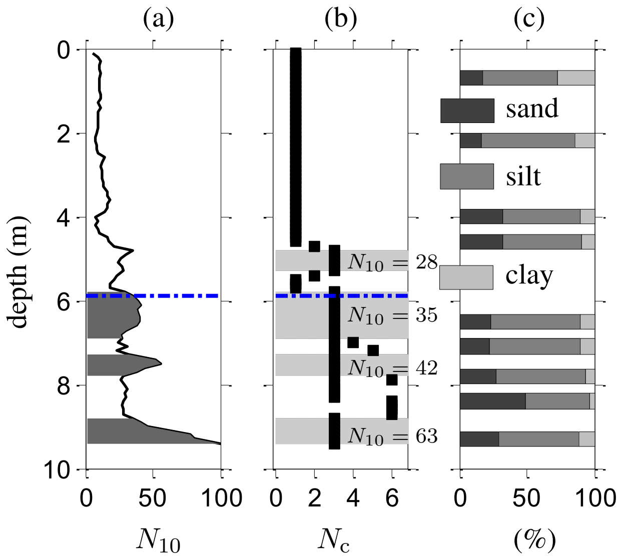

Figure 6: Interpretation of cluster analysis of DPL data. In (a), three hard-soil layers are depicted with a dark grey color. The dashed blue line represents the top of the layer in which N_{10}-value is greater than 30. In (b), a typical outcome of the statistical analysis indicates two main groups of soils (thick black vertical lines). The light grey layers represent clusters. In (c) we show the corresponding textural information for this borehole: sand (dark gray), silt (medium grey) and clay (light gray).

5 CORRELATION WITH TEXTURAL INFORMATION

Table 2 presents correlations coefficients of the measured N_{10}-values and percentages of sand, silt and clay. A weak correlation exists between penetration rate and textural classes: sand (0.31), silt (-0.22) and clay (-0.29). As noted in section 4, sand contend increases with depth. This result has also been reported by Vieira and Fernandes (2004) for the present study site. The strong negative correlations between sand and silt contents (-0.82) and sand and clay contents (-0.89) indicates that the greater the percentage of sand,

Table 1: Characteristics of dynamic cone penetrometers used to limit the soil-bedrock interface.

Reference	A (cm^2)	M (kg)	H_d (cm)	L (cm)	N_{10}^{sb} blows/L	E (kJ/m^2)	N_{10}^{DPL} blows/10 cm
Ohnuki et al. (1997)	3.00	5.00	50	10	40	81.75	65
Shanley et al. (2003)	2.40	5.00	63	5	15	128.76	77
Uchida et al. (2003)	0.95	1.17	20	4	100	24.16	121
Katsuyama et al. (2005)	1.95	1.17	20	4	100	11.77	59
Kosugi et al. (2006)	7.07	5.00	50	10	50 to 100	34.69	35 to 69
Fujimoto et al. (2008)	0.71	1.17	20	4	100	32.33	162
Ohnuki et al. (2008)	4.91	5.00	50	10	50	49.95	50
Kosugi et al. (2009)	3.14	2.00	50	10	50 to 100	31.24	31 to 63
Springman et al. (2009)	10.00	10.00	50	10	30	49.05	30
Tsuchida et al. (2011)	4.91	5.00	50	10	55	49.05	55
Askarinejad et al. (2012)	10.00	10.00	50	10	30	49.05	30
Wiegand et al. (2013)	1.25	10.00	30	10	30	235.44	141
Masaoka et al. (2016)	2.00	2.00	50	10	100	49.05	98
This work	10.00	10.00	50	10	30	49.05	100

the lower the content of the remaining textural classes. The correlation between silt and clay contents is less evident (0.45). In summary, correlation coefficients showed in Table 2 indicate that it is difficult to predict penetration resistance values from measured textural information. This was our main intended goal. We conclude that, due to the lack of information on soil heterogeneity, the measured soil textural information could be used as mean values for all regolith depth (homogeneous soil).

Table 2: Correlation coefficients of the measured N_{10}-values (from DPL tests) and textural classes (from mechanical auger tests).

variable	unit	correlation coefficients N_{10}	sand	silt	clay
N_{10}	†	1.00			
sand	%	0.31	1.00		
silt	%	-0.22	-0.82	1.00	
clay	%	-0.29	-0.89	0.45	1.00

† blows/10 cm

6 CONCLUSIONS

In this paper we have detailed a field investigation to delineate the soil-bedrock interface by DPL tests. Our criteria used define this boundary is consistent with approaches adopted internationally, and has the advantage of being more robust, which can lead to less biased estimates of regolith depth. Two-dimensional plots demonstrated that DPL measurements are efficient for shallow depths (up to 12 m-depth). In thick slope crests, DPL data might underestimated bedrock depth.

DPL measurements are particularly promising as it can help delineate soil stratigraphy and layers with contrasting hydraulic properties. We have proposed a method to identify hard-soil layers using DPL data by cluster analysis. The method can be useful to characterize adequately heterogeneity within Brazilian residual soils. Due to the lack of correlation between textural classes and DPL data, we suggest that the soil in the study site can be modeled as homogeneous.

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REFERENCES

Askarinejad, A.; Casini, F.; Bischof, P.; Beck, A. and Springman, S. (2012). Rainfall Induced Instabilities: A Field Experiment on a Silty Sand Slope in Northern Switzerland, *Rivista Italiana di Geotecnica*, Vol. 3, p. 50–71.

Fujimoto, M.; Ohte, N. and Tani, M. (2008). Effects of Hillslope Topography on Hydrological Responses in a Weathered Granite Mountain, Japan: Comparison of the Runoff Response between the Valley-head and the Side Slope, *Hydrological Processes*, Vol. 22, p. 2581–2594.

Gomes, G.J.C.; Vrugt, J.A. and Vargas Jr., E.A. (2016a). Toward Improved Prediction of the Bedrock Depth Underneath Hillslopes: Bayesian Inference of the Bottom-up Control Hypothesis using High-Resolution Topographic Data, *Water Resources Research*, Vol. 52.

Gomes, G.J.C.; Vrugt, J.A.; Camargo, J.T.; Vargas Jr., E.A.; Velloso, R.Q. and Carbono, A.J.J. (2016b). A Computer Program for Integrating Probabilistic 3D Unsaturated Flow Simulations and Numerical Limit Analysis, *XVIII Braz. Conf. on Soil Mech. and Geotech. Eng.*, COBRAMSEG, Belo Horizonte, Vol. 1.

Hegazy, Y.A. and Mayne, P.W. (2002). Objective Site Characterization Using Clustering of Piezocone Data, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 128, p. 986–996.

Katsuyama, M.; Ohte, N. and Kabeya, N. (2005). Effects of Bedrock Permeability on Hillslope and Riparian Groundwater Dynamics in a Weathered Granite Catchment, *Water Resources Research*, Vol. 41.

Kosugi, K.; Katsura, S.; Katsuyama, M. and Mizuyama, T. (2006). Water Flow Processes in Weathered Granitic Bedrock and their Effects on Runoff Generation in a Small Headwater Catchment, *Water Resources Research*, Vol. 42.

Kosugi, K.; Yamakawa, Y.; Masaoka, N. and Mizuyama, T. (2009). A Combined Penetrometer-moisture Probe for Surveying Soil Properties of Natural Hillslopes, *Vadose Zone Journal*, Vol. 8, p. 52–63.

Masaoka, N.; Kosugi, K.; Yamakawa, Y. and Tsutsumi, D. (2016). Processes of Bedrock Groundwater Seepage and their Effects on Soil Water Fluxes in a Foot Slope Area, *Journal of Hydrology*, Vol. 535, p. 160–172.

Matos Fernandes, M. (2014). *Mecânica dos Solos: Introdução à Engenharia Geotécnica*, 1st ed., Oficina de textos, São Paulo, Vol. 2, 576 p.

Nilsson, T. (2008). Parameter Approach from DPL Nilsson Test, *3rd Int. Conf. on Site Characterization*, ISC-3, Taipei, Vol. 2, p. 1415–1418.

Nilsson, T. and Cunha, R. (2004). Advances and Equations for Pile Design in Brazil via DPL Tests, *2nd Int. Conf. on Site Characterization*, ISC-2, Porto, Vol. 2, p. 1519–1523.

Ohnuki, Y.; Terazono, R.; Ikuzawa, H.; Hirata, I.; Kanna, K. and Utagawa, H. (1997). Distribution of Colluvia and Saprolites and their Physical Properties in a Zero Order Basin in Okinawa, Southwestern Japan, *Geoderma*, Vol. 80, p. 75–93.

Ohnuki, Y.; Kimhean, C.; Shinomiya, Y. and Toriyama, J. (2008). Distribution and Characteristics of Soil Thickness and Effects upon Water Storage in Forested Areas of Cambodia, *Hydrological Processes*, Vol. 22, p. 1272––1280.

Pastore, E.L. (1995). Weathering Profiles, *10th Pan. Conf. on Soil Mech. and Found. Engn.*, ISSMFE, Guadalajara, Vol. 1, p. 353–364.

Shanley, J.B.; Hjerdt, K.N.; McDonnell, J.J. and Kendall, C. (2003). Shallow Water Table Fluctuations in Relation to Soil Penetration Resistance, *Ground Water*, Vol. 41, p. 964–972.

Springman, S.; Kienzler, P.; Casini, F. and Askarinejad, A. (2009). Landslide Triggering Experiment in a Steep Forested Slope in Switzerland, *17th Int. Conf. on Soil Mech. and Geotech. Engn.*, ISSMGE, Alexandria, Vol. 1, p. 1698–1701.

Tsuchida, T.; Athapaththu, A.; Kano, S. and Suga, K. (2011). Estimation of In-situ Shear Strength Parameters of Weathered Granitic (Masado) Slopes Using Lightweight Dynamic Cone Penetrometer, *Soils and Foundations*, Vol. 51, p. 497–512.

Uchida, T.; Asano, Y.; Othe, N. and Mizuyama, T. (2003). Analysis of Flowpath Dynamics in a Steep Unchanneled Hollow in the Tamakami Montains of Japan, *Hydrological Processes*, Vol. 17, p. 417–430.

Vieira, B.C. and Fernandes, N.F. (2004). Landslides in Rio de Janeiro: The Role Played by Variations in Soil Hydraulic Conductivity, *Hydrological Processes*, Vol. 18, p. 791–805.

Wiegand, C.; Kringer, K.; Geitner, C. and Rutzinger, M. (2013). Regolith Structure Analysis - A Contribution to Understanding the Local Occurrence of Shallow Landslides (Austrian Tyrol), *Geomorphology*, Vol. 183, p. 5–13.