Geological origin as an input variable in reliability-based designs: for an accurate exploration in geotechnical engineering

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ABSTRACT: Soil is one of the most difficult materials to characterize realistically, which partly explains the uncertainty between the designs and the geostructures real behavior. Different recommendations have arisen with respect to carrying out field investigations in order to reduce the uncertainties inherent to the soil. However, the field exploration and the implementation of sophisticated geotechnical models have proven to be insufficient to mitigate the geotechnical uncertainty. Therefore, Reliability-Based Designs (RBD) emerge as a decision-making tool through the definition of the probability of failure in conjunction with the typical Factors of Safety. RBD requires a previous understanding of the most appropriate soil probabilistic models, such as the Shear Strength Varying with Depth (SSVD) analysis, traditional Monte Carlo simulations or random fields. Soil shear strength uncertainty is related to soil geological characteristics, however, geology has been commonly used in geotechnical engineering as a definition of the layers' distribution on the soil mass, where the definition of the accurate RBD models according to the geological origin has been missing. Therefore, two geological formations were analyzed: residual soils (stationary origin) and mudflows (dynamic origin). The results show that random fields are more related to the mudflows due to the random nature of these soils, thus the exploration resources should be focused on the determination of the Probability Density Functions (PDF) and the spatial variability of the shear strength (SS) properties (laboratory tests have priority over the in situ tests). Residual soils present a higher SS space uniformity because these soils have not been previously mobilized, thus the exploration resources should be focused on the determination of the SSVD (field tests have priority over the laboratory tests). Therefore, defining the geological origin as an "input variable" will allow recognizing the most important variables and the definition of the best soil exploration for an accurate and cost-effective RBD in geotechnical engineering.

Keywords: Reliability-based designs; Undrained strength varying with depth; RFEM; Geological influence; soil exploration.

1. Introduction

Geotechnical engineering is the area of civil engineering that studies the mechanical properties and behavior of soils for the design and construction of foundations, retaining walls and slopes. From its conception, geotechnical engineering has based its formulations and analysis on the influence of grain size distribution on the geostructures behavior. However, the uncertainty observed in real soils highlights the complexity of defining accurate models and mechanical properties due to the inherent variability of soils. Soil inherent variability was noted since the beginning of modern geotechnical engineering. According to Terzaghi (1948), *"... in earthwork engineering the designer has to deal with bodies of earth with a complex structure and the properties of the material may vary from point to point."* Therefore, different recommendations arise to carry out field research methods in order to reduce the inherent uncertainty due to the soil distribution [1].

Although the above allows recognizing how the soil mass distribution impacts the geotechnical analysis, this is not enough to understand how the soil inherent variability of the shear strength properties influences the performance of the geotechnical structures. Therefore, Reliability-based designs (RBD) emerge as a decision-making tool to evaluate the uncertainties that enter in the formulation of a geotechnical problem through the definition of the probability of failure in conjunction with the traditional factors of safety or reduction factors [2].

RBDs in geotechnical engineering may be considered incomplete until having the soil statistical characterization in terms of the shear properties Probability Density Function (PDF), Spatial variability (θ) and the shear strength varying with depth (SSVD). However, the definition of the most appropriate statistical characterization for each site is a highly complex activity, where doing everything is unpractical and expensive. Therefore, it is common to define statistical soil variability as reported in the literature. However, an erroneous statistical characterization can generate RBDs with inaccurate probabilities of failure.

Considering the above, an analysis of the influence of the geological origin in the definition of the statistical properties was performed, in order to evaluate how this feature influences the soil exploration and the probabilistic analyses. As highlighted by Prof. Richard Jardine in the 56th Rankine Lecture "*Integrating geology and rigorous analysis with advanced laboratory and field experiments is the key to resolving the complex geotechnical problems raised*" [3]. Therefore, the integration of geology with reliability-based designs in geotechnical engineering will allow performing a more accurate and economical exploration and statistical modeling in order to reduce, to some extent, the gap between the uncertainty of the designs and the real soil behavior.

2. Reliability based-designs in geotechnical engineering

Reliability-Based Designs (RBD) emerge as a decision-making tool that allows taking into account the inherent variability of soils through the different shear strength statistical properties. Soil variability is evident due to the high coefficients of variation (Cv) presented in the shear strength properties. According to Lee et al. [4] and Uzielli et al. [5], the Cv varies from 6% to 80% for the undrained shear strength (c_u) and from 4% to 15% for the friction angle. Therefore, the use of prediction models that consider the soil variability is desirable in geotechnical designs.

The increased interest in RBDs has been noticeable in recent years as is shown in the latest 2014 edition of the Canadian Highway Bridge Design Code (CAN/CSAS614:2014) which is based on reliability calibrated resistance factors [6]. The above is related to the computational advances, as it is now possible to perform different statistical models with the traditional limit equilibrium design methods through the Monte Carlo, FOSM and FORM simulations. The Monte Carlo method is the most used in RBD due to the versatility of evaluating any type of PDF [7].

Lately, more computationally demanding methods have been developed to model spatial variability of soils, such as the Random Finite Elements (RFEM). RFEM reported originally by Griffiths & Fenton [8], arises as a method used to realistically represent the spatial variation of the soil properties as they do in nature [9]. The implementation of statistical models that are able to estimate the uncertainties of the classic methodologies can overcome the lack of accuracy in the deterministic methods.

2.1. Summary of the probabilistic process

Fig. 1 illustrates the statistical properties required for different probabilistic designs. Firstly, Fig. 1 (a) shows a process that uses all data expressed in the form of a Probability Density Function (PDF), characterized by the mean and the standard deviation. RFEM combines the finite-element analysis with the random fields using the Local Average Subdivision (LAS) and the shear strength PDFs in order to obtain a soil property random field [10], as is shown in Fig- 1 (b). In contrast, Fig. 1 (c) shows c_u varying with depth in the same layer, also known as Shear Strength Varying with Depth (SSVD) property. These analyses are commnly used to describe the increase with depth following a linear function [11–14], however, it has been shown that other types of c_u function can be used [15].

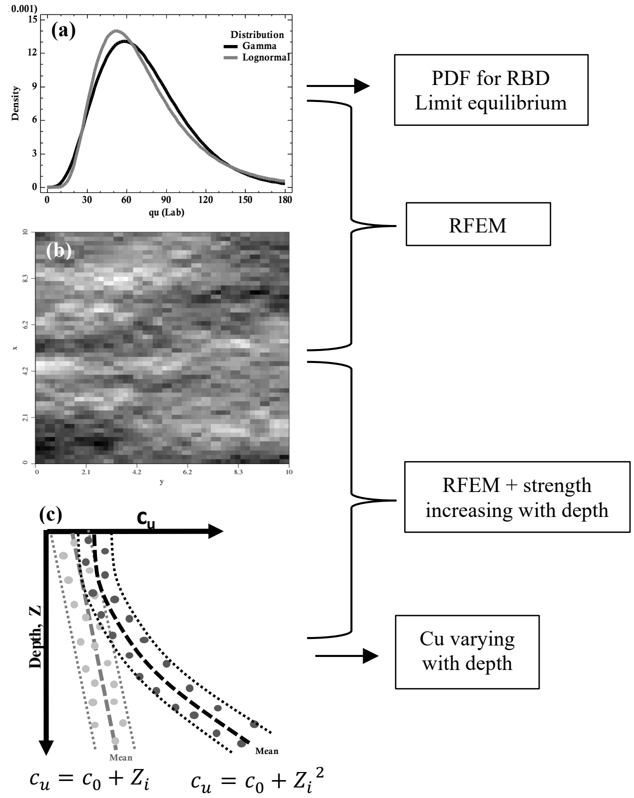

Figure 1. Statistical properties required for the different probabilistic designs. (a) Probability Density Function (PDF), (b) Random field, (c) c_u varying with depth.

The properties listed above, although can be related to each other, require different research procedures to obtain the necessary data for the statistical property definition. The procedures required for each of the parameters are listed below.

1. **Probability Density Function (PDF)**: PDFs used in the reliability-based design identifies the probabilities of occurrence of the soil properties. The determination of the PDFs for the drained and undrained shear strength parameter requires enough number of laboratory and field tests, which are rarely available to prescribe a full joint distribution [16]. In order to define the most appropriate PDF, enough data has to be obtained in order to fit the PDF to the histogram according to the goodness of fit test method (Chi-Square,

Kolmogorov–Smirnov or Anderson–Darling). However, the random processes in soil are usually represented by a normal or lognormal PDF [1, 16–22].

2. **Random fields**: In addition to the PDF, soil parameters present a spatial variability commonly obtained by the correlation length (θ) as described by Vanmarcke [23]. θ is defined as the distance where the values will present a significant correlation (similar properties), where those values separated at greater distances will not have any type of correlation [16]. The definition of spatial variability requires the performance of sufficient field exploration in order to perform the autocorrelation exponential fit.
3. **Shear Strength Varying with Depth:** This method consists of the definition of a function that describes the soil properties' increase with depth, where the undrained shear strength (c_u) has been the most commonly studied. Geotechnical engineering developed an interest in the evaluation of how the c_u tendency with depth influence the slope stability analysis [11, 13, 14]. The evaluation of the c_u tendency can be of great importance to evaluate a more real soil condition.

3. Geological role in geotechnical engineering

Geological origin consists of a categorical classification of the processes of formation that explain the most relevant aspects of the soil structure. The geological environment in geotechnical practice is commonly used to define the best type of field exploration (e. g. SPT, DMT, rotary drill). However, geology can also explain the discrepancies usually observed in the mechanical behavior of different types of soils in order to understand soil inherent uncertainty (presence of outliers, soft zones, and presence of different layers) [15]. The most important uncertainties related to geological origin are presented below.

1. **Layer distribution uncertainty**: Many studies have dealt with the geological uncertainty associated with the layered geological distribution of soils [24, 25]. Although the uncertainty associated with the distribution of the layers is of great importance for all geotechnical designs, this type of analysis has a greater relevance on geologies formed by sedimentary soils. ***Sedimentary soils*** are characterized by relative medium to low tract variations in depth.

2. **Inherent soil shear strength uncertainty**: Relatively large tracts of soil are prevalent in many parts of the world, especially in ***tropical soils***. These analyzes do not consider the variability of the distribution of the layers, instead, they focus on the characterization of the variability of the intrinsic properties of the shear strength. Hence, several papers (e. g. [11–14, 26]) have emerged to understand the statistical processes that allow understanding the soil properties in order to obtain more realistic soil conditions

According to the above, a geological analysis was performed in order to recommend the most appropriate soil exploration to obtained the statistical properties. The evaluation was performed mainly in two types of soils: *Mudflows* and *Residual Soils*. Mudflows are soils that were formed by previous landslides subjected to transportation and particle sorting that can lead to tremendous uncertainties in the geotechnical shear strength properties [27, 28]. Residual soils are materials that form directly from the weathering of the in situ rocks and exhibit an advanced weathering process favored by the climatic and topographical conditions but have never been transported [29]. Fig. 2 shows the physical formation processes of mudflows and residual soils according to the geological context of the city of Medellin.

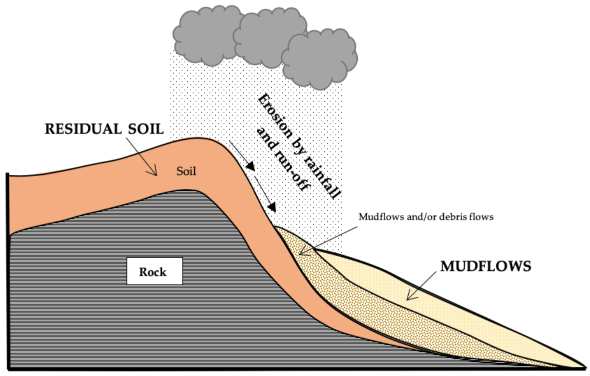

Figure 2. Diagram of soil formation processes according to the geological conditions in the city of Medellin (adapted from Wesley, [30])

4. Results

The PDFs and results given below come from the data set presented by Viviescas et al. [15], Viviescas [31] and Viviescas [32].

4.1. Undrained Probability Density Function (PDF).

The undrained shear strength (c_u) laboratory tests conducted on the undisturbed soil samples recovered at the two distinct geological formations included CD and CU direct shear test, unconfined compression and Triaxial tests, as it was shown by Viviescas [31]. From these results, a Bayesian PDF goodness of fit of the laboratory histogram was performed in order to obtain the c_u PDF. The obtained results of the geologies PDFs are shown in Fig. 3.

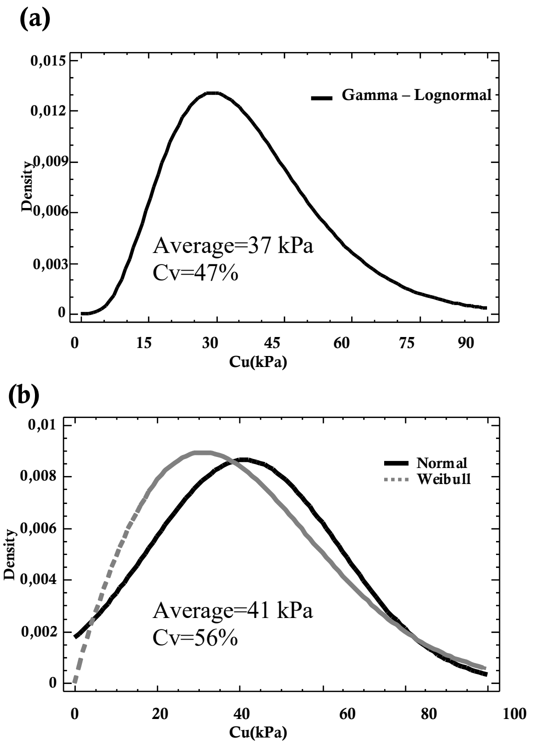

Figure 3. c_u Probability density functions obtained from laboratory tests for (a) Mudflows and (b) IC Residual Soils. (taken from Viviescas [31])

4.2. Random field

Random fields require the definition of the soil property correlation length (θ). Of the overall correlation functions on literature to obtain θ, the Markovian (exponential) is widely used in geotechnical engineering (e. g. [10, 33–39]). Therefore, the Markovian correlation function was employed in order to determine the horizontal and vertical θ according to Eq. (1).

$$\text{Markovian} \qquad \rho(\tau) = \exp\left\{-\frac{2|\tau|}{\theta}\right\} \tag{1}$$

Where $|\tau|$ is the absolute distance between points.

The determination of the correlation length was obtained through exponential goodness of fit in the lag distance vs the correlation length graph obtained from the in situ data on each geology. The above was performed in order to evaluate the horizontal and vertical correlation. The borehole distribution is presented by Viviescas [32].

4.2.1. Horizontal correlation length.

An example of the horizontal spatial correlation for both geologies is shown in Fig. 4. The overall results show that the average θ_H for mudflows is $\theta_H \approx 6.0m$ and residual soils are $\theta_H \approx 20m$. Based on these results, the residual soils θ_H is approximately three times the mudflows' horizontal length, as is shown in Eq. (2).

$$\theta_{H-\text{Residual Soils}} \approx 3x\theta_{H-\text{Mudflows}} \tag{2}$$

According to Eq. (2), the geological influence in the θ_H magnitude is related to the geological processes that formed the soils. Materials with abrupt changes (mudflows) will present lower θ_H compared with stationary soils (residual soils).

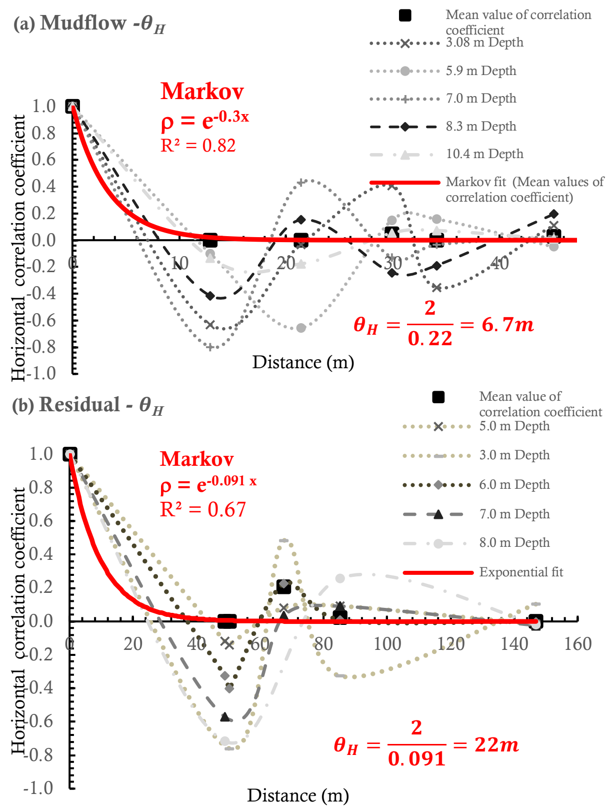

Figure 4. Example of the horizontal correlation length estimation for (a) Mudflows and (b) IC Residual Soils.

4.2.2. Vertical correlation length.

An example of the vertical spatial correlations for both geologies is shown in Fig. 5. The overall results show that the average vertical correlation length for mudflows' is $\theta_V = 1.45m$ and the residual soils' is $\theta_V = 1.31m$. These results show that the θ_V has similar values for both geologies, indicating that it may be mainly influenced by the vertical effective stress regardless of the soil's origin.

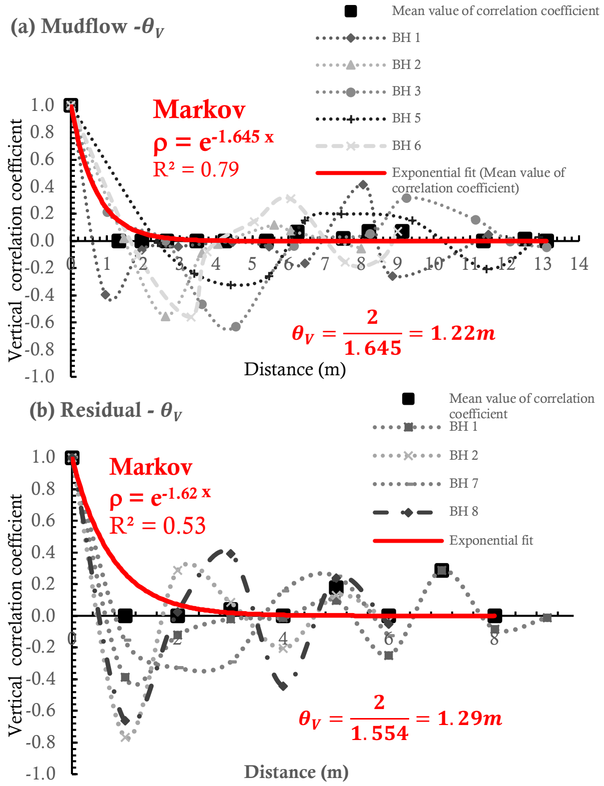

Figure 5. Example of the vertical correlation length estimation length for (a) Mudflows and (b) IC Residual Soils.

4.3. Shear Strength Varying with Depth (SSVD)

According to the results obtained from a previous cluster analysis by Viviescas et al. [15], a regression analysis on a project on each geology was performed in order to identify the shear strength functions that best describe the soil behavior according to the geological context. In a complementary way, Viviescas [32] obtained a $(N_1)_{60}$ - c_u correlation for each analyzed geology which allowed to obtain the function of c_u with depth as it was shown in Fig. 6. From these results, it was shown that both geologies have a *square Z* function (where Z is depth in meters), as it was shown in Eq. (3).

$$c_u = c_0 + \Delta Z^2 \tag{3}$$

Where the c_0 is the compressive strength at the surface (Z=0) and Δ is the gradient of the c_u, which increases with depth Z.

According to the results presented on each project, it is noted that the residual soils have a Δ value of about twice the value for mudflows as is shown in Eq. (4). The above can be partly explained by the overburden pressure; however, the degree of weathering decreases with depth in residual soils, and hence the deeper the exploration goes, the more resistant soil is found, increasing the function gradient.

$$\Delta_{Residual} = 2x\Delta_{Mudflow} \tag{4}$$

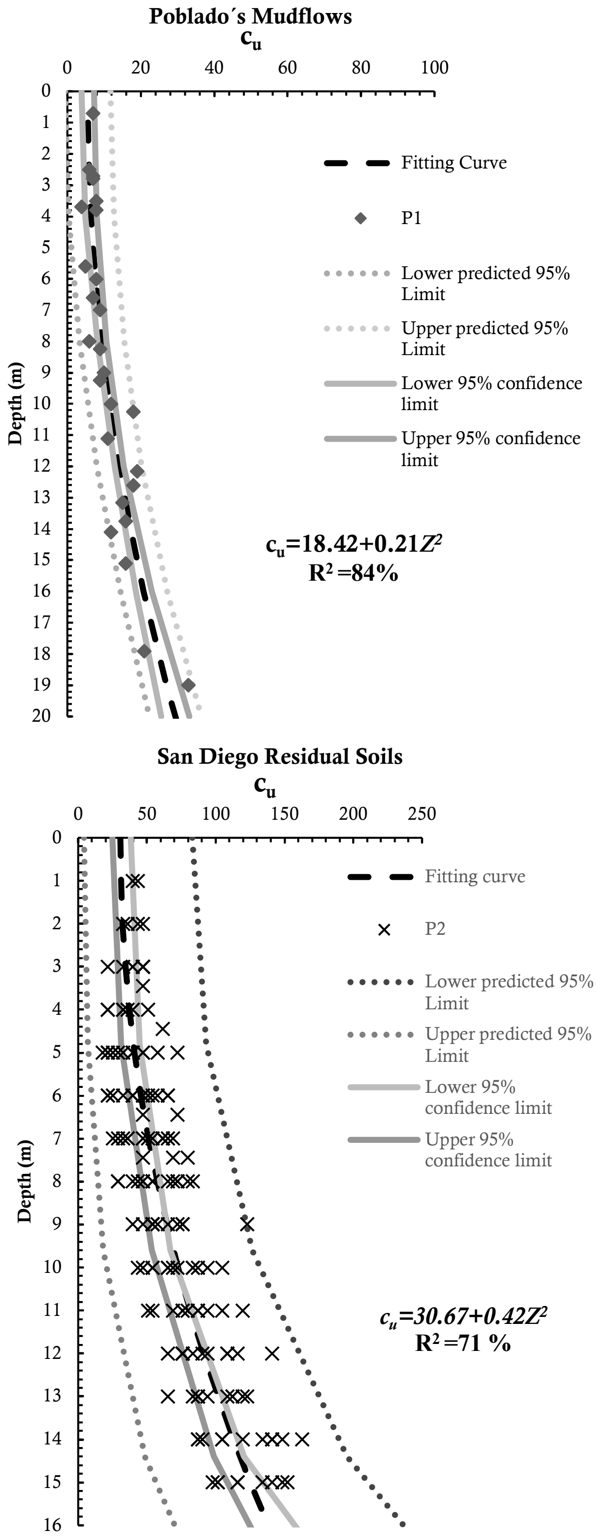

Figure 6. Scatter plot of the c_u variation with depth for Mudflows and Residual Soils of the analyzed projects (P). (adapted from Viviescas et al. [15])

5. Summary of results and discussions

5.1. Undrained Probability density function.

The c_u PDF between the two geologies does not present substantial changes from the average and Cv point of view. However, the shape of the PDF presents significant differences that can be explained according to the geological context. Mudflows present a Gamma - Lognormal PDF due to the presence of rock fragments that increase the shear strength resistance in some values (evidence of the PDF long-tail) and the void ratio variation according to the location of the deposit as is shown in Fig 7(a). On the other hand, residual soils (stationary soils) presents a Logistic- Weibull PDF soils due to the low shear strength variation throughout the same state of weathering as is shown in Fig 7(b).

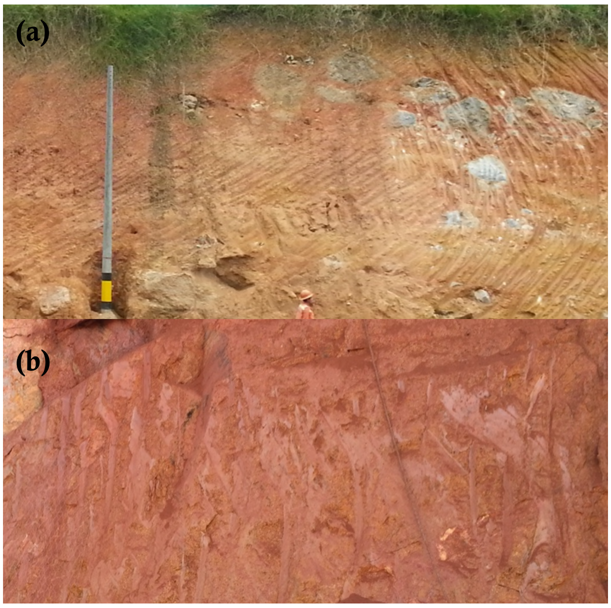

Figure 7. a) Mudflow and b) residual soils characteristics

5.2. Random fields.

According to the Markovian exponential fit results, the θ_V and θ_H values for both geologies fell within the range of the reported values [33, 41, 42]. However, θ_H in residual soils is approximately three times the mudflows' horizontal length. The geological influence in the θ_H magnitude is related to the geological processes that formed the soils. Therefore, soils formed by previous landslides (mudflows) will result in a more heterogeneous material compared with soils that were never transported (residual soils).

The values obtained of the vertical correlation length ranges around $\theta_V \approx 0.5$ to 1.5m, similar to those reported in the literature [40, 41]. The above may indicate that θ_V is mainly influenced by the vertical effective stress regardless of the soil's origin. Therefore, the estimation of the horizontal correlation length is the most important parameter for the generation of the random field.

According to Fenton et al. [42], the θ magnitude and the sampling location influence the resistance factors (RF) for the undrained designs of shallow foundations according to the load and resistance factor designs (LRFD) methods in geotechnical engineering as is shown in Eq. (5).

$$\varphi_g \hat{R} \geq \sum_i I_i \eta_i \alpha_i \hat{F}_i \tag{5}$$

Where the φ_g is a geotechnical resistance factor, $\hat{R}$ is the characteristic geotechnical resistance (e. g. bearing capacity), for the ith characteristic load effect ($\hat{F}_i$), I_i is a structure importance factor, η_i is a load combination factor, and $\alpha_i$is the load factor.

As an example, and considering the similarity of the c_u Cv in the analyzed geologies, the θ values previously obtained were used in order to evaluate the bearing capacity RF (φ_g) for each geology to obtain a probability of failure (p_f) of 0.001. The above was performed on a shallow foundation supported by a Random soil through the RFEM software developed by Fenton & Griffiths [43].

According to the analyzes in Fig. 8, the importance of the spatial variability in the analyzes is evidenced. Although the two geologies have similar average and Cv of c_u, θ extremely differs for each geology. Therefore, the bearing capacity of foundations located on mudflows must be highly reduced $(\varphi_g = 0.46)$ in comparison with residual soils $(\varphi_g = 0.69)$ in order to obtain the same p_f.

Therefore, obtaining θ on mudflows is one of the most important tasks in RBDs in order to define a low-risk RF. However, residual soils present higher values of those recommended for a high degree of understanding of the site according to the Canadian Highway Bridge Design Code (CAN/CSAS614:2014). Therefore, in residual soils, traditional RFs meet with the security conditions, where the most important evaluation is the shear strength tendency with depth.

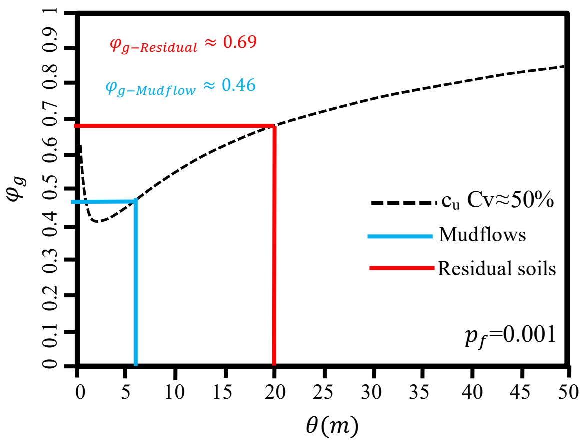

Figure 8. Resistance factor (φ_g) required to achieve an acceptable probability of failure (p_f=0.001) when soil sample is under footing (adapted from Fenton et al. [42] and Fenton et al. [44])

Finally, geology-based analyzes will allow defining the more appropriate RF according to the area of analysis, which are directly related to the soil's origin characteristics.

5.3. Shear strength varying with depth

The geological influence in the definition of the shear strength functions is evident from Fig. 6. The above was evidenced by Viviescas et al. [15], who reported that defining an SSVD on Mudflows is difficult due to the significant soil randomness in space, where residual soils present a better estimation of the c_u function regardless of the analyzed area.

At least one project for each geology has a *square Z* function, where the function gradient in residual soils is approximately 2 times that of the mudflows. This is related to the increase of the overburden pressure in addition to the decrease in the state of weathering with depth, which increases the shear strength in residual soil. Therefore, the SSVD analyses in residuals soils can be feasible for the analysis of different geotechnical designs (especially in the slope stability analyses), regardless of the analyzed area, in order to evaluate a more realistic soil behavior.

6. Conclusions.

Geological origin is an important aspect that allows understanding the most important characteristics of the soil shear strength variability (e. g. transportation, weathering, sedimentation). Therefore, geology not only helps to define the best geotechnical field exploration, but also the definition of the most appropriate resistance factors in the light of the probabilistic geotechnical design, as it was shown for the analyzed geologies:

Mudflows are highly random soils, difficult to characterize in their shear strength with depth due to the inherent geomorphological variability of the landslides that originate them. Therefore, RFEM analysis is the most appropriate probabilistic method. It is concluded that in mudflows the exploration resources should be focused on the determination of the probability density functions and the spatial variability, prioritizing laboratory tests over in situ tests.

Residual soils, on the other hand, present higher spatial uniformity (i.e. low spatial variability) of the shear strength properties. Therefore, residual soils mainly depend on the state of weathering which influences the shear strength properties with depth. Therefore, these soils can be analyzed according to the Shear Strength Tendency with depth. It is concluded that in residual soils the exploration resources should be focused on field tests such as SPT, DMT, and PMT over the laboratory tests.

Finally, it is concluded that geological origin can be denominated as a "*probabilistic input variable*" in reliability-based designs in geotechnical engineering. This denomination allows recognizing the most important variables to determine the best and cost-effective exploration for the achievement of an accurate and realistic probabilistic evaluation.

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