Mechanical and Hydraulic Behaviour of Unsaturated Residual Soils

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Abstract. The negative effect of rains on the stability of the slopes is a problem that, added to anthropic factors and population settlements, currently generate not only material but also human losses. Therefore, the evaluation of threat by mass movements has become a first order problem. However, one of the aspects that presents the greatest uncertainty in these evaluations is the effect of soil saturation. This paper presents a methodology for evaluating the effect of rainfall by estimating the probability of soil saturation using the Richards equation and the first order and second moment method-FOSM. The methodology was applied considering two residual soils from the area of north-western Colombia named Aburra valley. For this purpose, a characterization of each material was made, evaluating the variability of shear strength parameters and hydraulic parameters. Subsequently, infiltration models were made using the Richards equation with a historical rain event that occurred between October 27 and November 13, 2010, which exceeded the failure thresholds established for the Aburra Valley and generated several landslides. The advance of the wetting front was evaluated, and the probability of saturation was determined. It was found that, in all the evaluated soils, full saturation reaches depths between 600 and 6000 mm and the probability of saturation is greater in soils from Stock de Altavista that report a lesser values of air entry suction. The mean values of $\phi^b$ varies between 1.3° and 6.5° for soils from Stock de Altavista.

1. Introduction

The negative effect of rains on the stability of the slopes is a problem that, added to anthropic factors and population settlements, currently generate not only material but also human losses. In highly populated and mountainous countries, quantifying landslide hazard and other risks associated with heavy rainfall is important, because landslides cause damage to property and loss of human lives. Due to high levels of impact on mass movements, this has generated a great interest in the study of related phenomena in an attempt to understand physical aspects [1], [2], [3], and economy-related issues [4], [5]. Quantitative methods for landslide risk assessment allow a more objective form of analysis and in recent years several evaluation techniques have been presented in the literature [3] [6] [5] [7]. Generally, for quantitative determination, the risk (R) can be defined in terms the hazard $P[T]$, understood as the total probability of a threatening event happens, the vulnerability $P[C|T]$, understood as the conditional probability of damage considering that a failure has already occurred and the cost of the consequences $C$, by the equation:

$$ R = P[T] \times P[C/T] \times C $$

(1)
In early years, a methodology for the landslide hazard assessment developed by [5] through a calculation model based on FOSM. This methodology allows calculating the total probability of failure (TPF) according to the theorem of total probability of failure of a slope by the equation:

$$TPF = P[T] = P_{fs} \times P_{s} + P_{fns} \times (1 - P_{s})$$ (2)

Where $P_{fs}$ is the probability of slope failure due to the action of the rainfall in saturated condition, $P_{fns}$ is the probability of failure where condition is not saturated, $P_{s}$ is the marginal probability that the soil is saturated and $(1-P_{s})$ is the marginal probability that the soil is not saturated. The probability of failure of the slopes in saturated and unsaturated condition can be calculated independently but determine the probability that the soil is saturated is difficult due to the complexity of the phenomenon of variation of the conditions of soil water content.

The saturation of the soil is a random phenomenon that must be taken into consideration in the evaluation of the probability of landslides. In this case it was considering the probability that the soil is saturated or not. In tropical regions covered by residual soils and subjected to tropical rainfall regimes, a high percentage of these landslides are triggered by heavy, frequent or prolonged rainfall [8], [9], [3]. The role of rainfall infiltration on triggering landslides in tropical regions is being a challenge for geotechnical and geologists engineering [10].

In order to improve the knowledge about the effect of soil saturation on the risk of landslides, a research was developed in which the probability of saturation of residual soils was estimated. In this work, the uncertainty of hydraulic properties is considered and the effect of saturation on the shear strength of residual soils is explored.

2. Probability of Soil Saturation (PSS)

Several attempts have been made to develop coupled models to simulate the effects of the rainfall on the slope stability ([11], [12], [13], [14], [15]), these authors have used models that consider the gradual wetting front progress, the suction reduction, and shear strength of the soils. These methods are still based on major simplifications and the input parameters are difficult and expensive to obtain for common cases. In recent years, slope stability analyses have been expanded to include coupled hydromechanical processes under variably saturated conditions. These analyses incorporate the variation of saturation, leading to more accurate assessments of slopes stability (under infiltration conditions), and demonstrate that a better physical representation of water flow and stress can be attained in unsaturated soils [16]. Hence, the analysis of seepage and coupled stress-deformation should be linked simultaneously [17]. Some recent studies are specifically focused on infiltration-induced landslides. However, most of these studies only consider slope failure below the groundwater table, overlooking the contribution of effective stress (suction stress) to the strength of the soil under transient unsaturated flow conditions [16]. Generally, these works use the Richards equation for water flux:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ K(h) \left( \frac{\partial h}{\partial z} - \alpha \eta \right) \right]$$ (3)

Where: $\alpha$ is the angle between flux direction and horizontal plane, $h$ is the pressure head, $z$ is the coordinate of the parallel position to the flow direction, $K(h)$ is the hydraulic conductivity for a given pressure head, which in turn is a function of soil moisture content $\Theta$, and $t$ is the time. The relationship between the suction and the degree of saturation, or moisture content, is established by means of the soil water characteristic curve (SWCC).

There are several empirical models to describe the characteristic curves [18]. However, in this work it is proposed to use the equation of Fredlund and Xing [19]. This is a model of three continuous parameters for the entire suction domain. The parameters of the model are related to the air inlet pressure ($a$), the distribution of pore sizes ($n$), and the symmetry of the curve ($m$). The model is based
on the possibility of describing the distribution of soil pore sizes from statistical functions [20]. The proposed equation, obtained from integrating a law of frequency distribution in the suction domain, corresponds to:

\[
\theta = \frac{1}{[n(e+\left(\frac{\psi}{\alpha}\right)^n)]}
\]

Volumetric moisture represents the relationship between the volume of water and the total volume of the soil. To determine the parameters of this equation, locate the inflection point in the soil-water characteristic curve, and then draw a tangent line through those points. The slope of the tangent line is denoted as “S”. Most of the time, the infiltration evaluations are done in a deterministic way, which ignores the uncertainty that is present in this flow process. As it was presented above, it is necessary to estimate the probability of saturation in order to calculate the total probability of failure. There is a probabilistic analysis which ignores the spatial variability of the unsaturated deposits of soil and underestimates the probability of slope failure. Due this, the effects of soil spatial variability on unsaturated slope have been scarcely studied.

2.1. Shear strength

The shear strength of partially saturated soils incorporates the variation of moisture content or the degree of saturation, which are considered by means of suction, influencing the behaviour of water in the soil layer. Now, the suction is a negative internal pressure that is generated in the structure of the soil, produced by a capillary phenomenon and by the concentration of salts in the voids.

The shear strength grows directly with the suction and it is observed particularly that this ratio of increments is saved up to a maximum value, from which resistance begins to decrease until reaching the dry state and losing the effect of suction. In 1978, Fredlund et al [21], presented an expression to determine the shear strength which is an extension to the Mohr Coulomb criterion, in which the effect of suction is involved through the third term \((U_a - U_w)Tan\Phi^b\).

\[
\tau = c' + (\sigma - U_a)Tan\Phi' + (U_a - U_w)Tan\Phi^b,
\]

where:
- \(c'\): soil cohesion in saturated condition
- \(\Phi'\): internal friction angle of soil
- \(U_i\): Interstitial air pressure
- \(U_w\): Interstitial water pressure
- \(\Phi^b\): internal friction angle in relation to matric suction

They also determine the correlation between \(\Phi^b\) and \(\Phi'\), the latter being generally higher, indicating that the increase of \((U_a - U_w)\) has a greater contribution in strength than the increase in \((\sigma - U_a)\).

3. Materials and methods

3.1. Laboratory tests

For this work, it was collected residual soils from geological formations named “Stock de Altavista” (RAS) and “Dunita de Medellín” (RSD), located at different zones of Medellín city, at northwest of Colombia. These geological formations were selected because in these areas there are a fast urbanistic expansion of the city and exist several records of landslides occurrences in early years.

For RAS, it was taken 10 undisturbed samples in cubic wood boxes (0.3 m in side). With the objective to determine the saturation effect on the shear strength, direct shear strength tests were made, submerged an unsubmerged. In submerged condition, the CD method was used (ASTM D3080-11) and for the unsubmerged condition, the same times determined for the submerged condition were adopted for both the normal load application and the shear stage. For RSD, it was conformed a data
base with results of 56 direct shear strength tests modality CD performed over undisturbed samples. These results of laboratory tests were supply by DEACIVIL S.A.S consultant engineers.

For hydraulic characterization of the soils, the SWCC were determined using the filter paper technique. Wartman 42 paper was used in this case and the standard ASTM D5298-16 was followed. For the samples obtained from the RAS, the permeability in saturated condition was determined from the theory of consolidation using the data from the CD direct shear test. For RSD, the permeability was determined with field infiltration tests with a double ring infiltrometer, where the maximum value of speed of water penetration through the soil surface, matches the hydraulic conductivity of the saturated soil. The SWCC were adjusted following Van Genutchen's model [22] using the Solver tool of the Excel program.

Additional, each sample was subjected to characterization tests by granulometric distribution (ASTM D422-63), Atterberg limits (ASTM D4318-17), moisture content (ASTM D2216-10) and specific gravity (ASTM D854-14). All the tests were carried out several times in order to estimate their variability.

3.2. Probability of saturation

In this work, it is proposed a probabilistic methodology that use the FOSM method and the Richards’ equation to obtain the probability of saturation. Similarly, in the $\beta_1$ index for FOS, for the saturation probability in terms of $Z$, a reliability index $\beta_2$ as a function of the hydraulic properties of the soil in addition to the wetting front progress modeled is defined as:

$$\beta_2 = \frac{E(Z_c) - Z_c}{\sigma_Z},$$

where $Z_c$ is the deep (m) of the wet front, $E(Z_c)$ is the $Z_c$ mean and $\sigma_Z$ is the standard deviation of $Z_c$ obtained using the FOSM method described in Equation 3 and 4 taking as a function the Richards’ equation.

To solve the Richards’ equation, this methodology uses the CHEMFLO-2000 software [21], which is based on the finite difference method. Soil parameters (characteristic curve and saturated permeability) are required as input data. In this case, the Fredlund and Xing model is used and some borders conditions are defined as a flow rate, infiltration rate or hydraulic load. Any of these boundary conditions requires that the rainfall characteristics of the zone be determined. To do this, it can use the following procedure:

- Getting rainfall information from meteorological stations near the study area. These rainfalls can be accumulated daily or with a higher resolution, and must have records for at least 20 years.
- To calculate the infiltration, process by which water penetrates from the surface into the soil, using the Horton, Green-Ampt and the curve number (CN) models [22]. In the study of infiltration processes, a particular problem is to determine the variation of the soil infiltration capacity, the variation of the wetting front and the suction of the soil, that occurred during a rainfall event, since they influence the magnitude of the torrential avenues associated with this event.

The probability distribution of the wetting front progress was determined, in function of the random variables that condition this function ($\alpha, n, \theta_s, \theta_r$). A modelling was done in the software, using the infiltration model of the curve method as the most conservative, the random variables were slightly modified by a parameter of variation $\alpha$, which according to the literature can be assumed 10 (ten).
4. Results and Discussion

4.1. Shear Strength
The RAS soils belong to the IB horizon of the Deere & Patton classification [25]. With the 30 direct shear strength test, a statistical analysis was carried out and the statistical moments of the different groups of results were determined. The results obtained are presented in Table 1.

For the RSD, 56 direct shear strength test CD-type were analyzed, and the statistical analysis was performed, and the results for both formations are presented in Table 1.

| Soil | Property                      | Mean   | Standard deviation | Coefficient of variation (%) |
|------|-------------------------------|--------|--------------------|------------------------------|
| RAS  | Dry unit weight (kN/m3)       | 11.3   | 1.2                | 11                           |
|      | Wet unit weight (kN/m3)       | 15.9   | 1.4                | 9                            |
|      | Unsaturated cohesion (kPa)    | 27.4   | 9.8                | 36                           |
|      | Effective cohesion (kPa)      | 6.5    | 6.3                | 98                           |
|      | Unsaturated internal friction angle (°) | 34.5   | 10.2               | 30                           |
|      | Effective internal friction angle (°) | 37.1   | 14.6               | 39                           |
| RSD  | Dry unit weight (kN/m3)       | 12.0   | 1.6                | 13                           |
|      | Wet unit weight (kN/m3)       | 17.8   | 1.2                | 7                            |
|      | Effective cohesion (kPa)      | 20.8   | 14.7               | 71                           |
|      | Effective internal friction angle (°) | 23.9   | 7.3                | 31                           |

It can be seen (Table 1) that the values of the effective internal friction angle differ from the unsaturated internal friction angle, which in theory are equal [26]. These differences can be attributed to the lack of control of saturation conditions during the test in unsaturated conditions, which indicate high values of uncertainty when using unsaturated direct shear strength tests, a practice that has become common in Colombia. It is observed that the results obtained for the coefficient of variation of the effective and unsaturated internal friction angle, wet unit weight, and unsaturated cohesion, are consistent with the ranges of variation reported in the literature and those of effective cohesion are considerably different of these ranges.

There are not many data and results in the literature that show the variability and uncertainty of shear strength parameters of soils as studied, however, there are some results obtained for RAS that show that the order of magnitude of the parameters obtained is consistent. From CU triaxial tests, variable internal friction angles between 27º and 37º and variable cohesion between 10 and 18 kPa have been reported. On the other hand, there are results of granite-derived soils that show values of effective internal friction angle between 27º and 38º and effective cohesion between 12 and 26 kPa and φ values with mean 37.8º and standard deviation 4.5º.

This highlights that the data reported in the literature can serve as a guide to evaluate the uncertainty of some of the parameters mentioned, but that it is necessary to experimentally evaluate the variability of many of them in the case of residual soils. In Figure 1, one of the Mohr Coulomb failure envelope is presented for the RAS in unsaturated condition, where the shear strength (τ) in kPa, the normal strength (σ) in kPa and the matrix suction Ψ (kPa) are related. From the failure envelopes made for the RAS, it was found that the variation range of Φb is between 1.3 ° and 6.5°.

4.2. Hydraulic properties
The soil water characteristic curve was determined using the filter paper technique described in the ASTM D 5298-16 standard. The Wartman 42 paper was used for this case. The curve was adjusted
following Van Genuchten's model [22] using the Solver tool of the Excel program. Figure 2 shows the soil-water characteristic curve obtained for the residual soils.

\[ \psi (kPa) \]
\[ \sigma (kPa) \]
\[ \tau (kPa) \]

**Figure 1.** Failure envelope RAS

### 4.3. Rainfall characterization

For assess the probability of saturation, it was used hydrological information from the “Villa Hermosa” meteorological station, which has 67 years of records that begin in July 1948 and end in July 2015. Different procedures were performed, which have as a fundamental principle, the processing of the rainfall data of the station. Through the average annual cycle of monthly rainfall, two annual peaks were identified in the analysis period, corresponding to the months of May and October, months with average rainfall greater than 180 mm [24]. The daily rainfall was determined for the analysis period and the calculation of the rainfall of the previous 3 and 15 days was carried out for the subsequent classification of the events, according to the thresholds defined by [25]. Subsequently, a day of analysis was selected that coincided with some report within the historical records of landslides in the Aburra Valley [24]. The disaster that occurred on November 13th, 2010 in “Villa Tina” neighbourhood, urban area of the city of Medellin, was selected for the analysis, because it is located in the same area where “Villa Hermosa” station is located. In the area, there was a mass movement which was detonated by high accumulated rainfall in the previous days [26], and that resulted in the death of one person, one person injured, one house destroyed, and two more houses were affected. Figure 1 shows daily rainfall data for the 18-days preceding the event, which according to the documented information is the cause of the mass movement, also this accumulative rainfall is 296.4 mm, it has a return period of approximately 20 years, therefore, the probability of the event being exceeded is 5%. In order to evaluate the probability of exceedance of the rainfall threshold, a frequency analysis of the data was performed, where the rainfall series of 18-days that exceed the threshold were selected, the annual maximum records were selected, and with these results the probability of recurrence was determined for different return periods and confidence intervals according to the distribution functions proposed by Gumbel, Log-Normal and Frechet. Once defining the mechanical and hydraulic properties of the soil, the boundary conditions and hydrogeological properties of the soil were determined. Rainfall data were collected, allowing to validate the failure thresholds and the amount of water infiltrated in this punctual zone. For this purpose, rainfall data were collected with daily resolution in the analysis period. This information was processed in order to characterize the rainfall regimes of the area. Subsequently, a rainfall event was established which exceeded the failure thresholds and that had been documented. For this event the intensity of the
rainfall was determined [24]. The Figure 1 shows the results for rainfall used in the models. Table 2 presents the Van Genuchten’s model parameters determined mean fitting for each soil.

![Figure 2. Soil water characteristic curve for tested soils](image)

**Table 2. Results of the soil characteristic curve**

| Soil | \( \alpha \) (kPa\(^{-1}\)) | \( n \) | \( m \) | \( K_s (m.s^{-1}) \) |
|------|------------------|------|-----|------------------|
| R.A.S | 0.005 | 1.45 | 0.31 | 4.3\times10^{-6} |
| R.S.D | 0.018 | 1.30 | 0.23 | 1.3\times10^{-5} |

4.4. *Probability of saturation*

In order to determine the standard deviation of the selected parameters, a statistical base of 44 data was collected from the literature and laboratory tests executed in the development of this work [24]. It reports the expected value and the reliability index for each formation of the hydraulic properties that allow to finally determine the probability of saturation. (Figure).

![Figure 3. Daily rainfall of the 18-days antecedent to the mass movement of the day 13th of November 2010](image)
5. Conclusions
This methodology can be an element for decision making because it allows to calculate the probability of saturation as a function of the advance of the wet front in the superficial layers to be incorporated in risk analysis for landslides.

The statistical analyzes performed on the laboratory results show that except for the cohesion [c], the variability of the mechanical parameters of residual soils derived from RAS and RSD are within ranges similar to those of other tropical soils reported in the literature. In the case of cohesion, a coefficient of variation greater than 50% was determined, and also a standard deviation is significant. The above reaffirms the need to consider infiltration models based on suction curves, so that this variable is adequately characterized.

The SWCC from RAS present lesser values of air entry pressure and residual volumetric water content than RSD. The shear strength for RAS presents variability with the saturation degree. The mean values of $\phi^b$ vary between 1.3 ° and 6.5 °. In soils RSD was not determined the variability with saturation.

The advance of the wetting was evaluated and the probability of saturation was determined. It was found that, in all the evaluated soils, full saturation reaches depths between 600 and 6000 mm and the probability of saturation is greater in RAS that RSD.

Acknowledgment(s)
Authors wishing to acknowledge to the University of Medellin for the financial support for this research.

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