# Slope geometry and its impact on the porepressure gradients inside the soil mass

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## Abstract

*Tropical soils present peculiarities of properties and behavior due to the action of geological and pedological processes. These soils, typically found on humid regions, have as subtypes, for example, the saprolitic and lateritic soils. The latter subtype shall be considered in the present paper. Lateritic soils are characterized by a deeply weathered profile which, when in the unsaturated state, heavily affects the suction distribution. This parameter is crucial to analyze the soil's behavior and its water retention capacity. The soil's water retention curve, together with different altitudes, slope geometry, infiltration path and sun exposure, among others, govern the water movement inside the porous matrix. Thus, the morphology of the terrain can control the surface and subsurface flows in both the saturated and unsaturated soil phases. In special, slope concavity is an important aspect which may have a direct impact on suction distribution and, therefore, on the mechanical behavior of the soil. In the present paper, the influence of the slope's geomorphology, in special geometrical concavity, has been studied. Following equal boundary conditions, a finite element simulation has been performed to analyze the porepressure distribution in slopes with different shapes. The moisture distribution, suction distribution profile and groundwater level in the soil mass were some of the variables studied. These results indicate a direct influence of the geometrical features on the suction profile, which impacts the hydromechanical behavior of the soil. Thus, geometrical features may possibly corroborate to the triggering and evolution of erosive processes, commonly present in the tropical regions.*

## 1 INTRODUCTION

The study of saturated and unsaturated tropical soils is an important field of soil mechanics. We classically deal with the saturated mode for soil behavior, but in many situations, especially in countries with tropical climate, there is a need to place greater emphasis on studies and analyzes of unsaturated soils, in order to provide greater safety, durability and economy to the construction. In many cases, the soil's composition, which will be addressed later, may present elements which interact with each other, adding complexity to the behavior of such soils.

According to Coelho Netto (2007), water is a very important physical element for the terrestrial landscape due to its modeling function of the landscape. In turn, Silva (2011) highlights the importance of rainfall water on the soil moisture content, increasing or decreasing the volume of water present in the soil mass. According to that author, the influence on the soil-water regime occurs at the local scale, possibly in slope, for example. Therefore, the following landscape elements must to be studied: altitude, slope angle, length, slope shape, sun exposure, etc.

In other words, morphology becomes essential to understand the surface and subsurface flows, both in the saturated and unsaturated masses. Thus, the geometry of the slopes, specially their concavity, represent direct intervening factors in the suction, in the mechanical behavior and in the water content of the soil.

Following the ideas presented by Camapum de Carvalho et al. (2007), regarding the influence of the slope shape on the way the flow occurs in unsaturated media, the present study is built. For this purpose, a case of a hypothetical slope was simulated using the Abaqus software. The simulation was carried out in two ways, being both represented as three-dimensional domains.

In short, an embankment domain was modeled in order to study the impact of the slope concavity. The details of the analyzes will be seen in the subsequent topics, as well as the bibliographic collection related to the theme and the results obtained with the relevant discussions.

## 2 SATURATED AND UNSATURATED SOIL

Soil mechanics can be subdivided into saturated and unsaturated analyzes.

Saturated soils can be analyzed as two-phase systems, where a compressible fluid fills in the pores of the matrix, i.e. a solid phase (mineral particles) and a liquid phase (water). Unsaturated soil is considered a mixture of several phases. According to Lambe and Whitman (1969), an unsaturated soil is considered as a three-phase system, that is, it consists of three phases: solid, liquid and gaseous (air).

In tropical soils, especially in deeply weathered lateritic soils, the solid part is generally composed of organic matter and iron oxyhydroxides (hematite, goethite), aluminum (gibbsite) and forming agglomerates. The liquid part of the system is composed of water, which, being a solvent, promotes the solubilization of ions adhered to the surface of the minerals that make up the soil, in addition to dissolving occluded gases in the pores. Finally, the gaseous part of the system may have its origin related to the contact of the porous matrix with the atmosphere or may come from reactions and transformations inside the porous matrix.

From a behavioral point of view, the importance of the forces transmitted through the soil skeleton from one particle to another was discovered in 1923 when Terzaghi presented the principle of effective tension, an intuitive relationship based on experimental data. The principle, in its strict form, applies to saturated soils and relates the following aspects:

- Total normal stress ($\sigma$): force per unit area transmitted in the normal direction through the plane within the porous mass;
- Water pressure in the pores ($u$), also called poropressure or neutral pressure: pressure of the water that fills the empty spaces between the solid particles;
- Effective normal stress ($\sigma'$): stress transmitted only through the skeleton of the ground in the plane.

Regarding unsaturated soils, besides the stresses previously presented, one of the main factors which alter the properties and mechanical behavior of such soils is the existence of negative water pressure in the pores, called suction.

It is observed in Figure 1 some graphs illustrating the situations where saturated and unsaturated soils are found, as well as changes in their state. In general, both saturated and unsaturated states exist in a given soil mass. The position of the water table will dictate how important each stratum is to the total mechanical behavior of a given geotechnical design.

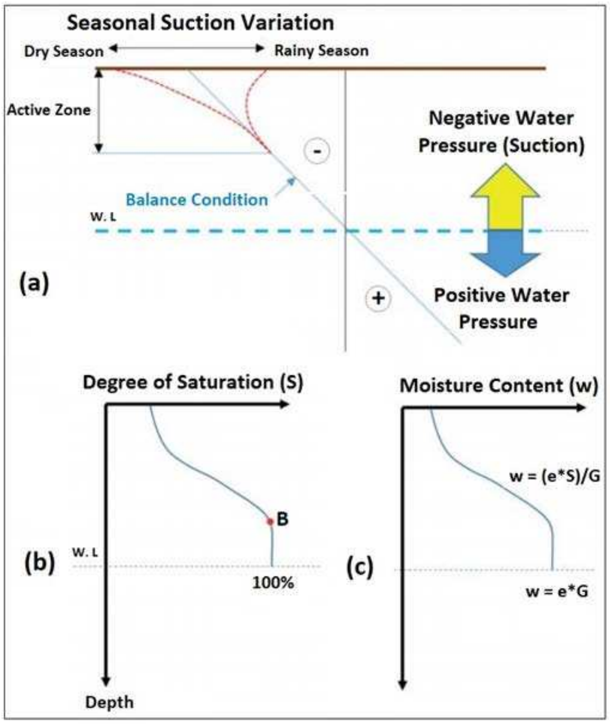


Figure 1. Variation in soil condition and soil water retention (Marinho, 2016).

In Figure 1 (a), below the water level (W.L), the soil is considered saturated and the water pressure is positive. Above such level, the water rises by capillarity and keeps the soil saturated up to a certain height, mainly due to suction and non-saturation of the soil. The pressure diagram is indicated as an equilibrium condition, in which the profile pressure is represented by a straight line, whose coefficient is the specific weight of the water. It is observed that the suction can vary according to the time of the year. This seasonal variation is induced by evaporation or infiltration, which alters the equilibrium profile, increasing or reducing the suction. The depth to which this influence of the atmosphere penetrates the soil is called the active zone. In Figure 1 (b and c), until point B the soil is saturated. The information in the graphs when obtained at equilibrium represents the water retention curve.

Besides the degree of saturation of the soils *in loco*, when one is studying the stability of slopes, another relevant aspect mentioned by Camapum de Carvalho et al. (2007) is the geometry of the slope itself. Geometry can control the surface and subsurface flows in both the saturated and unsaturated strata.

Normally, a complete profile evaluation (considering both saturated and unsaturated strata) is the ideal solution to assess the stability of a given slope. On the other hand, this may need additional information on the characteristic curve of the soil within the unsaturated zone.

The present paper presents a discussion on the geometrical building aspects of a hypothetical slope. Therefore, for simplicity, a fully saturated medium shall be considered. This enables to reader to solely analyze the geometrical aspects involved. Further studies may be carried out to account for the coupled effect of unsaturated state and geometrical features, but these are currently out of the scope of the present paper.

In the field of saturated soils, the undermining of the base of slopes stands out as relevant in the analysis of erosive processes, favoring their rupture and internal erosion. Ross (1994) points out that the increase in the slope inclination increases its fragility to erosions. Therefore, this indicates an important influence of the slope shape into the water content of the soil within it. Also, Silva (2011) points out that the slope has a fundamental role in the infiltration and runoff of rains, as the greater the slope inclination, the greater the tendency to increase the superficial flow and, on the contrary, the lower the slope, the higher the infiltration rates. Therefore, geomorphology plays an important role on the study and on the behavior of the soils.

## 3 COMPUTATIONAL TOOLS FOR FINITE ELEMENTS

The problems involving slope stability and saturation within the massif can be studied analytically, numerically or experimentally. Unfortunately, analytical solutions cannot be always used, as many problems, in practice, are too complex to be mathematically modeled by using differential equations, generating the need to use approximations. This already justifies the use of numerical methods, as with the increasing technological advances, complex problems can already be studied by using of computers with a low cost and speed. Finally, the use of an experimental method is used to verify in practice the results obtained by numerical approximations, but they are almost always associated with high costs.

Among the numerical methods most used for the analysis of mechanical problems, the Finite Element Method (FEM) stands out, which is one of several numerical methods used to obtain the solution of boundary value problems. The method, based on a variational principle and a methodology of convenient and automated choice of approximation functions, can be applied to practically all sectors of engineering. The method is the theoretical basis for several commercial applications, including Abaqus, ANSYS and Nastran, for example. The increasing technological advancement has significantly reduced the time to analyze complex problems, allowing for the use of personal computers. In the present study, Abaqus is used as a computational tool for the analysis of the slope geometry.

Abaqus contains two parts

- Graphics: ABAQUS/CAE and ABAQUS/ Viewer modules
- Solution: ABAQUS/Standard and ABAQUS/Explicit modules

ABAQUS/CAE is the one that develops the geometric model and can act as both pre and post processor. The preprocessor generates the input file that contains the parts, sections, material properties, boundary conditions, applied loading and the finite element mesh, with its properties. The post-processor allows the results to be graphically displayed. ABAQUS/Viewer works exclusively as a post-processor.

ABAQUS/Standard and ABAQUS/Explicit are in charge of the simulations. ABAQUS/Standard is the most accurate method, the most stable solution, as it solves the system of equations in each increment of the solution process, but it requires more computational time to solve problems. It is recommended for static and linear dynamic analysis. ABAQUS/Explicit is the module for faster resolution of dynamic problems with large deformations and displacements, since it determines the solution without iterations, with an explicit integration of the next kinematic state from the state obtained from the previous increment, thus requiring less computational time.

The ABAQUS/CAE, ABAQUS/Viewer and ABAQUS/Standard modules were used to analyze and obtain the results of this research.

## 4 METHODOLOGY

For the present research, the influence of the slope geometry on poropressure gradients within the soil mass was studied. For this purpose, sections of a concave slope and sections of a convex slope were analyzed. As discussed, in order to foment the discussion about this topic, a completely saturated problem has been studied.

This is justifiable in cases where the whole slope is saturated. During and excavation of a high phreatic level terrain, this is easily verified. On the other hand, for places with shallow phreatic levels, after a tropical rain this may be also verified. The results can also be interpreted under unsaturated premises, as shall be further discussed.

The simulations were performed to assess porewater pressure at different places in the slopes, to verify the hypothesis of concavity influence.

### 4.1 Steps of numerical simulations

The numerical analysis in the Abaqus program was carried out in two distinct stages, a first simulation for the slope condition with concave geometry (Fig. 2) and another for the convex condition (Fig. 3). For simplicity and to save space, geometrical aspects of the results are presented in Figs. 2 and 3, but the color scale and the results are to be discussed.

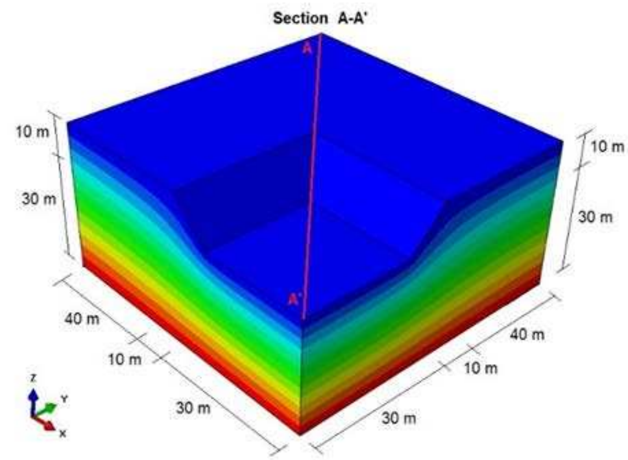


Figure 2. Slope with concave geometry.

In order to compare the analysis, the same materials, boundary conditions, mesh and saturation were used. As highlighted in Figures 2 and 3, the section chosen for comparison was a longitudinal section that cuts the model's diagonal. The justification for this choice is that this section is the one that best represents the behavior of poropressure on the slope.

In both models, a soil of Brasilia, DF, Brazil with typical local characteristics was used. According to Camapum de Carvalho et al (1993), the subterranean soil of the region is composed of a red porous clay, in which the movement of water within this porous matrix determines the conditions of the state of these soils. Table 1 shows the characteristics of the soil assigned in the program.

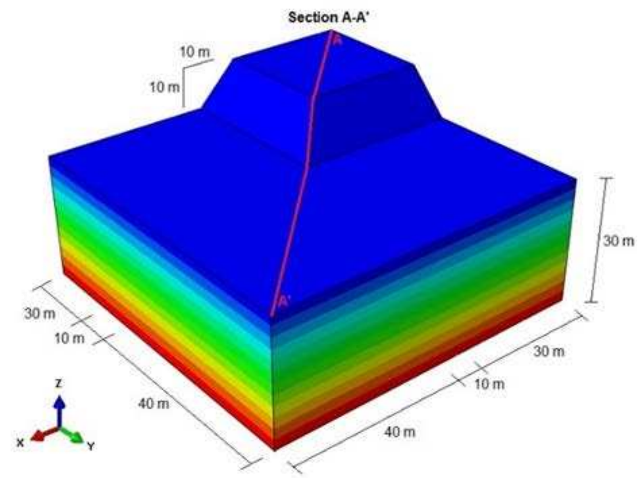


Figure 3. Slope with convex geometry.

Table 1. Soil characteristics attributed in the program

| Soil Parameters | Soil 1 | |
|---|---|---|
| Mass Density | 1950 kg/m$^3$ | |
| Young's Modulus | 10000000 Pa | |
| Poisson's Ratio | 0.35 | |
| k | 1E-007 m/s | |
| Void Ratio | 1.3 | |
| Specific weight of wetting liquid | 10000 N/m$^3$ | |
| Sorption | Pore pressure | Saturation |
| | -2000 Pa | 0.04 |
| | -200 Pa | 0.05 |
| | 0 Pa | 1 |

Regarding the boundary conditions, the whole model was considered fixed, that is, displacements and rotations in all directions were prevented. In addition, it was considered that the pore pressure was equal to zero on the entire surface of the model and equal to 4.0e + 05 Pa at the base. This maximum value was attributed by multiplying the specific weight of the water (10000 N/m$^3$) and the maximum height of the model (40 meters).

The mesh used was tetrahedral with an overall size of approximately 4 meters. Finally, saturation was assigned to equal 1 throughout the model.

## 5 RESULT ANALYSIS AND DISCUSSIONS

Before starting the analysis of the results, it is worth mentioning that, in a case study carried out by Santos (2007), one week after the front of the excavation passed, a slope rupture occurred in a concave excavation section. Out of curiosity, the straight and convex sections of the slope remained intact. When checking the safety factors after the numerical analyzes, it was found that the concave slope had lower values when compared to the convex section.

In the present case, in order to study the variation of poropressure along the soil mass and the variation of the water table in the excavated faces of the slope in the concave and convex sections, three-dimensional flow analyzes were carried out in the locations indicated by the sections present in Figures 2 and 3.

Figure 4 shows the longitudinal section, highlighted in Figure 2, for the slope with concave geometry. Similarly, in Figure 5 the longitudinal section of the slope of convex geometry is highlighted.

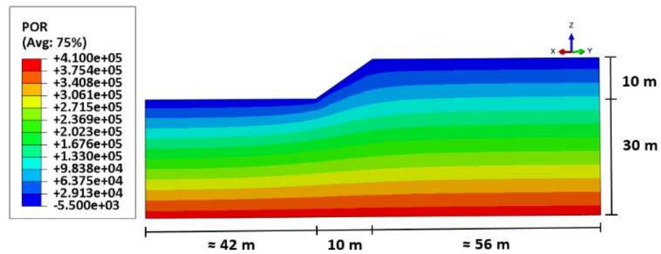


Figure 4. Longitudinal section of the slope with concave geometry. Porewater pressure in Pa is presented.

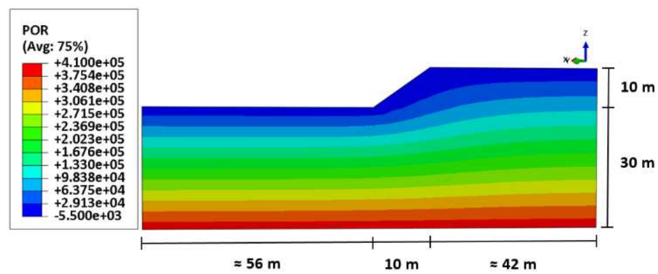


Figure 5. Longitudinal section of the slope with convex geometry. Porewater pressure in Pa is presented.

It is noted in the comparison between the results that there is an intense increase in the value of pore pressure, especially at the foot of the concave geometry slope. Thus, it is possible to confirm the concentration of the flow lines in the model, generating an increase in the water table in the concave face of the excavated slope and a decrease in the convex face.

Regarding the unsaturated behavior of these slopes, the convexity/concavity interferes directly in the suction and in the behavior of the soil. Together with the highest concentration of flow lines, revealed by the saturated analysis, there is a greater active zone where suction may be determinant. Therefore, the greater is the risk of, in the process of infiltration of rainwater, reaching pressures in the air phase that exceed the soil cohesion, favoring the erosion process. On the other hand, when suction is not that high, the water level around the base of the concave slope increases while compared to the convex case, which diminishes the resistance of the soil mass and may cause ruptures. Such results, when compared to the case study by Santos (2007), converge in terms of flow lines in the longitudinal section and the understanding of safety factors.

In the surface mechanisms, the concave shape acts by concentrating the flow and expanding the erosive potential of the precipitated water. This increase in concentration of superficial flow, according to Jesus (2013), usually occurs for two reasons: the lateral slope favorable to concentration and the tendency to narrow the flow area. In the convex form in plan, the trends are opposite.

Such analyzes reinforce the conclusions made by Camapum de Carvalho et al. (2007), paying attention to the analyzes of the influence of the propagation of stresses on the hydromechanical behavior of the soil mass, as they represent the opposite while compared to the flow analyzes. Thus, in terms of stresses, in phenomena such as the erosive process, both in its start and in its evolution, the concave shape presents a concentration of stresses close the slope, which increases the resistance of the soil. In the convex form, these tensions are relaxed, contributing to the loss of soil resistance. Consequently, the imbalance, generating ruptures and erosive processes, will occur at the critical point arising from the relation between the two opposing components of influence: the flow and the state of tension.

## 6 CONCLUSIONS

This research focused on understanding the geometry of the slope and its impact, in terms of flow, on the pore pressure gradient present in the soil mass. Additionally, results were used for discussion and comparison with conclusions from other studies by different authors. The cross-validation, interesting in terms of reflection, corroborated for a better analysis of the theme.

The results were satisfactory, showing that for the sections in front of the excavation, the geometry of the slope impacts on the distribution of poropressures. The concave shape concentrates the flow lines and generates an increase in the water table level, intensifying the rise in the pore pressure values. In the convex form, a decrease was noted.

According to the analyzes carried out in the literature, in soils with similar characteristics, attention should be paid, in addition to the geometry of the slope, as to the type of analysis and the condition of soil saturation.

Finally, the tool used proved to be suitable for this study due to its ability to simulate the process.

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