Artificial modelling of unsaturated tests considering the suction control on porous collapsible clay

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Abstract. Soils with a tendency to show phenomena of collapsibility generally have a susceptibility to be controlled by partial saturation, due to its structural configuration which reveal in some cases bonds of cementing minerals, that can be broken in process of wetting. This cementation is governed by the lateritic genesis, as well as for a microporl predominance. Laboratory tests that intend to reproduce the unsaturated condition, need a suction control to simulate properly the levels of stress required in the sample, according with the in-situ stresses presents in the soil mass. However, these tests are difficult to have access to given that they have a complicated assembly and can last several days (even months), due to the benefit in the resistance imposed by the suction on the soil. For this reason, it is extremely important to validate numerically by means of an appropriate constitutive law, at least at the laboratory level, the unsaturated response of a material. In this case a collapsible porous clay of lateritic origin, cause the high dependency of specialized laboratory tests can lead to non-necessaries delayed researches, that can impact in the economy of any project. In this research, an emphasis is placed on the numerical simulation of partially saturated tests through a hypoplastic constitutive model that involves suction in its mathematical formulation. The results are oriented to show the dependence of the suction with the shear strength of the material.

1. Introduction

The unsaturated response of a material not only depends on external factors such as the geotechnical complexity of the site under study, but also of intrinsic conditions that control the mechanical-hydraulic behavior of the soil, such as mineralogy, porosimetry, microstructure, among other aspects [1-3].

Transferring this condition that occurs naturally in the soil, to the laboratory requires expensive and highly complex equipment that allows to control the suction levels that are applied to the material. This is because the increase of suction increases the shear strength reciprocally on the soil. Likewise, the triaxial tests that cause the failure of the material can last several days [4].

From the above, there is an opportunity to try to simulate artificially the unsaturated behavior using numerical techniques by using an appropriate constitutive model designed for this purpose, at least at the laboratory level, as it is proposed by current research [5].

So far, the prediction of geotechnical problems where the unsaturated response of the soil is involved is limited, either for geotechnical design activities or even for the modeling of future scenarios. This is because nowadays, designers are accustomed to using classic constitutive models that do not accurately reproduce the behavior of the soil and end up overestimating the stresses and deformations that the geotechnical structure can support, which is beneficial for builders since they may earn economic
resources with the concrete and steel used in the works. Generating more efficient geotechnical designs from research articulated with practical engineering is not a priority for construction companies [6].

This research tries to numerically simulate the laboratory-level behavior of collapsible porous clay soil samples subjected to triaxial tests with suction control using a hypoplastic theory that considers suction within its mathematical formulation.

The main contribution of this research in the field of materials science and engineering, is related with the possibility in the near future to be able to replace an adequate number of expensive and delayed laboratory tests with numerical simulations.

2. Background
As mentioned above, the tasks of numerical prediction in geotechnical structures are not part of the daily routine of practical engineering, much less when suction is involved as an essential parameter within a multitemporal analysis, where the environment-soil interaction is considered in geotechnical design.

| Constitutive model | Theory / Contribution |
|--------------------|-----------------------|
| EP^a / Surface representing the variations in the ratio of voids as a function of the net stress state and suction |
| EP / BBM - extension of the elastoplastic model of Modified Cam-Clay for unsaturated soils, which integrates the volume changes with the shear strength |
| EP / proposes an alteration in the calculation of hydraulic parameters of [9] using a bilog scale to be used in the calculation of soil compressibility for various suction parameters |
| EP / Extension of the BBM, modification is based on the existence of two levels in the soil structure; micro and macro, Barcelona Expansive Model (BExM). |
| EP / Concept of the surface of intrinsic plastification |
| HP^b / The soil is modeled using four constants of the material, the combination of HP and capillarity explains the response of wet soil under triaxial compression and simple shear |
| EP / The concept of effective stress is extended for the case of unsat. materials through the inclusion of a capillary pressure. An EP model is used, valid in the case sat. or dry and it is expanded for unsat. soils with the concept of capillary hardening |
| EP / Main emphasis on the behavior of the solid skeleton, a simple EP model is described using few parameters to define the effect of desaturation |
| EP / Incorporation of the effects of the variation of the degree of sat. in the stress-strain behavior. It represents the change of the position of the WRC during the load, that is, the hydraulic behavior is coupled to the stress-strain relation. |
| EP / It explicitly considers the mechanisms that affect the mechanical behavior due to suction, as well as the dependence on the degree of sat. |
| EP / Consider hydraulic hysteresis and def. irreversible due to wetting and drying cycles capable of reproducing the comp. of expansive soils. |
| EP / Reproduces the effect of anisotropy, the effect of cementation between particles, and the destructuring effect for saturated soils. |
| EP / They propose a new EP model for unsaturated soils using two independent stress state variables |
| EP / Emphasizes the effect of stiffness due to suction on the mechanical response and collapse by wetting. It is possible to add an extension for structured soils |
| EP / They extend the EP S-CLAY1S model to capture the behavior of the unsat soil. (structured soils) |
| EP / It proposes an EP model based on the MCC that reproduces the influence of state variables such as the ratio of voids, degree of sat., temp., in addition to considering effects of hysteresis due to wetting and drying cycles |

^a Elastoplasticity
^b Hypoplasticity
Consequently, the constitutive models that reproduce the mechanical-hydraulic behavior of the soil considering the unsaturated response are limited and not as abundant as in the case of traditional models, such as conventional elasticity and plasticity.

It is necessary to add that most of these models are not formulated numerically to be inserted in a software based on the finite element method or another numerical method. This is another reason why the prediction of geotechnical problems is not widely developed in the world. In Table 1, some of the most used constitutive models about unsaturated soils can be found in the state-of-the-art.

It is worth noting the constitutive models shown, most of them have been evolving to date simulating responses to phenomena associated with partial saturation, e.g. drying, wetting, cementation, structuring, etc. This research takes advantage of the evolution, using a modern constitutive model (a hypoplastic model for mechanical response of unsaturated soils), to reproduce adequately effect of stiffness due to suction on the mechanical response and collapse by wetting. The above is the essential characteristic of the study of unsaturated soils.

3. Methodology

3.1. Material and testing program

The material used is from the region of Brasilia in the center-west of Brazil. This region is characterized by high temperatures and abundant rainfall, which are preponderant aspects for the formation of tropical soils of lateritic character. Regarding the distribution of particle sizes and pores, this type of soil must be characterized in a special way due to the microstructural and mineralogical configuration that is part of the lateritic material. The particle size distribution (PaSD) of the sample was carried out according to the peculiarity showed by this soil, due to the composition formed by means of clay micro-concretions or silt-sandy grains that may show unreliable results. The test was executed using deflocculant, not only for the fine fraction of the sample, but also the coarse fraction (more information in [5-24]). Figure 1 shows the PaSD of the sample. The PSD was obtained through the mercury intrusion porosimetry technique, which allows to identify the predominance of the pore size in the material (Figure 2).

![Figure 1. Particle Size Distribution (PaSD)](image1)

![Figure 2. Pore Size Distribution (PSD)](image2)

Regarding the pore size distribution (PSD), an essential aspect of the characterization of an unsaturated soil given that the mesopores and micropores in the sample will control the levels of suction that the soil can reach. In this specific case, the sample exhibits a predominance of micropores, which suggests that the soil under analysis may have a high susceptibility to be governed by partial saturation, in terms of its mechanical behaviour (Figure 2). Table 2 summarizes the physical properties of the soil.

The experimental phase of the research involved 18 triaxial compression tests and 6 oedometric compression tests. The triaxial tests were carried out with suction control at different stress levels. As can be seen in [21], these tests are ideal for obtaining the necessary parameters as to hypoplastic reference model of this research.
Table 2. Geotechnical properties of the material.

| Depth (m) | w (%) | γ_s (kN/m²) | γ_d (kN/m²) | γ (kN/m³) | Gs | e | LL (%) | LP (%) | IC |
|----------|-------|-------------|-------------|-----------|----|---|--------|-------|----|
| 6.00     | 26.8  | 28.01       | 11.39       | 14.70     | 2.81| 1.45| 48     | 29    | 1.13|
| 9.00     | 19.6  | 28.02       | 12.88       | 15.51     | 2.82| 1.08| 50     | 30    | 1.55|

3.1.1. Test results. The mechanical response in terms of stress-strain within the framework of the shear strength of a material, is typical of a slightly overconsolidated clay of the region under study. In Figure 3, the results of triaxial compression tests can be analysed for different suction levels, between 0 kPa and 200 kPa following a constant drained path. Regarding the volume change, the samples are deformed in the same way up to approximately 4% and the dilatant tendency continues, explained by the clay fabric that presents itself as an open (porous) configuration and with a secondary predominance of macropores that can be meaningful. At the time of shearing, there is a change in volume due to the expulsion of air from the pores and reconfiguration of the clusters in the soil.

Figure 3. Results of triaxial tests in the space q-ε\text{ax} (a) and ε\text{pv}-ε\text{ax} (b)

3.2. Reference constitutive model

3.2.1. Literature overview. In the last decades, since 1980, hypoplastic models have had a breakthrough, going from being a promising constitutive model to a reality nowadays in terms of adequate reproduction of the mechanical behaviour of the soil, even with practical applications for design [25]. Through these years, this model has undergone several variations and/or extensions to simulate different aspects in the soil, among them the unsaturated response of the soil. The first attempts at hypoplastic constitutive models to simulate the performance of partially saturated soils were established by [13,26]. More recently, [21] implemented a hypoplastic model for fine soils. This model considers the essential behaviour of the influence on the effective forces and antiparticle forces caused by the suction, which consequently improves the rigidity of the material, expanding the state boundary surface (SBS) [21], in the same way as cementing material in saturated soils. The size of the SBS is governed by the normal compression line (NCL), which is based on [27], according to Equation (1) (Figure 4).

\[
\ln(1+e) = N(s) - \lambda^*(s) \ln\left(\frac{p}{p_e}\right)
\]  

(1)

Where, e – void ratio (state variable), N(s) and \(\lambda^*(s)\) – predict the locus of the compression virgin line. The values of barotropy \(f_b\) and picnotropy \(f_d\) were reevaluated by [28], since the influence of \(N(s)\) on the values originally proposed by [26] was considered. This model simulates the behavior for any state of
overconsolidation, which is important for the current study because the material used is a slightly overconsolidated clay. To define the hypoplastic constitutive equation, it must be taken into account that the stability of the interparticle contacts is controlled by the level of suction and in open fabric soils, the coordination number tends to be lower (see Equation (2)).

\[
\dot{T} = f_u (L: D + f_d N \|D\|) + f_u H
\]  

(2)

Where T: Zaremba-Jaumann tensor, \( f_u \): picnotropy factor, D: strain tensor, and H: collapse control.

4. Results
The numerical simulation stage of the tests with suction control requires a previous phase of parameters calibration of the constitutive model of reference [21]. The calibration is carried out following a parametric study of each one of the variables involved in the mechanical behavior according to its physical meaning. The reference model contains some basic saturated parameters \( (N, \lambda^*, \kappa^*, \phi_c, r) \). The first three are calibrated from oedometric compression tests, according to the slopes of the virgin branch of loading and unloading (Figure 4).

![Figure 4. Calibration of parameters N, \( \lambda^* \), \( \kappa^* \) (a) and shape of the SBS (b)](image)

The critical state angle \( \phi_c \) is found using a linear regression, by means of the critical state points of the triaxial tests performed on the material. The regression is plotted in the s-t space of the MIT stress invariants. Similarly, the parameter \( r \) is found by a parametric study that is considered adequate, since there is no correlation with other parameters of the reference model The extension for unsaturated response includes the influence of the suction on \( N \) and \( \lambda^* \), defined as \( N_{(s)} \) and \( \lambda^*_{(s)} \), where the parameters \( n \) and \( l \) are included. Likewise, \( m \) controls the collapse of the material in the humidification path and \( S_e \) the air entry value (AEV); more information in [21].

The simulation of triaxial tests with suction control were carried out by the software Triax element test driver [29] (Figure 5). A constitutive model for unsaturated soils based on hypoplasticity was used, using the command: hypoplastic_clay_unsat. The instruction to model the triaxial test with suction control and isotropic consolidation is: triax_drained epax -0.3. The calibrated parameters of the constitutive model used can be seen in Table 3.

| \( \phi_c \) | \( \lambda^* \) | \( \kappa^* \) | N | r | m | l | n | \( S_e \) |
|---|---|---|---|---|---|---|---|---|
| 31.3° | 0.072 | 0.004 | 1.087 | 0.1 | 2.0 | 0.0 | 0.032 | 39 kPa |
As shown in Figure 5, the simulations adequately follow the tendency of increase in shear strength as the suction in the test increases. Therefore, this actually validates the reproduction of the suction in the mathematical formulation of the model. For lower suctions, the critical state of the soil is modelled better than in the higher suctions corresponding to 100 kPa and 200 kPa. It is important to keep in mind that the parameter calibration phase is not done directly on the results of the triaxial test, which could be a post-calibration task. However, it would be a class C or C1 prediction as established [30]. For this reason, through a numerical prediction class A it is extremely difficult to accurately anticipate the exact behaviour of the soil.

5. Conclusions
It was possible to validate the effectiveness of the hypoplastic constitutive model when simulating geotechnical problems where the suction is involved in a partially saturated soil. That is, as the suction is imposed in the test, the simulation shows the beneficial effect on the shear strength.

The calibration of parameters is an essential phase within a numerical prediction class A, as this is when it is most useful, both in basic geotechnical problems like this, or in complex geotechnical structures, since future critic scenarios within the performance of the structure can be anticipated.

It is important to keep in mind that the numerical predictions were class A. This means that they were carried out without knowing the real result of the simulated triaxial test, but with only a calibration based mainly on parametric studies of the variables involved. This explains the dispersion that occurs in the results of the triaxials with suction control at high levels (100 kPa and 200 kPa). A class C prediction would allow a more adequate simulation, but based on prior knowledge of the results of the actual tests. These a posteriori prediction end up fitting the real behaviour of the soil with the reference model by trial and error, which is not very appropriate for the real understanding of both the numerical model and the mechanical behaviour of the material.

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