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SLOPE STABILITY IN UNSATURATED LOW PLASTICITY SOILS USING THE BARCELONA BASIC MODEL (BBM) AND CALIBRATION OF TRIAXIAL TEST DATA

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SUMMARY

The stability of slope in unsaturated low plasticity soils is also a major issue particularly in areas where the level of water changes. This paper looks into how the Barcelona Basic Model (BBM) applies to the evaluation of the stability of a real slope that consists of low plasticity silt in the Chilca region, Peru. There was a complete characterization of soil in lab tests of index properties, water retention curves (WRC) and permeability characteristic curves (PCC) and triaxial tests at the unsaturated conditions. The parameters of BBM model were determined using an inverse methodology relying on the triaxial tests. CODE BIGHT software was used to perform numerical simulations aimed at measuring slope stability at different conditions of moisture and suction. The findings demonstrated that the BBM model forecasted the behavior of the slope with a good level of precision, the deviation of the deviatoric stress and the mean effective stress was only 0.68 % and 2.19 % in comparison to the field data. The sensitivity analysis showed that the cohesion parameter (κ) produced the most significant impact on the calibration accuracy, then the basic friction angle (φb) and suction adjustment parameter (r). The results validate the fact that the BBM model is an efficient method of predicting the stability of unsaturated low plasticity soils as it provides a useful alternative to more complicated, resource-consuming models. This study indicates that the BBM model has potentials in the geotechnical engineering applications especially in arid and semi-arid soils where soil suction is a critical factor in stability.

Key words: *slope stability, unsaturated soils, barcelona basic model (BBM), laboratory tests, numerical simulation.*

INTRODUCTION

The stability of slopes in unsaturated soils is a complicated issue that attracted growing interest in the geotechnical engineering research. Due to the surface tension of water in the pores, which causes suction in these soils, their mechanical behaviour is greatly altered affecting both shear strength and stiffness [15]. Such complicated nature has resulted in constitutive models that explicitly include suction, including the Barcelona Basic Model (BBM) [17]. It has been demonstrated that the BBM model is a promising predictive tool of the behaviour of unsaturated soils in numerous applications [19], including slope stability assessment but also the foundation bearing capacity analysis [10]. Nevertheless, its use is sensitive to its parameters, which can only be done with the help of complex and expensive laboratory tests. The research is necessitated by the concerns over solving the issue of slope stability in low plasticity soils in arid and semi-arid regions where water in the soil is oscillating and suction is a vital component of the soil strength [14]. Here, the present study is concerned with a representative slope in the Chilca region, Cañete, where low plasticity silts (LP) are the common soils and landslides have been documented to occur in the past. The core aim is to consider the relevance of the BBM model to the forecast of the behavior of this slope, by testing the model parameters on the basis of triaxial experiments with unsaturated conditions. Also, this research aims at showing whether the calibration on the basis of triaxial testing which are more affordable and cost-effective compared to controlled suction testing can be an alternative to recover the true predictions of the slope stability. To meet these goals, it will carry out a thorough soil characterization, that is, index properties, water retention curves (HRC) [5] and permeability (PCC) [13] and triaxial tests under unsaturated conditions. Triaxial tests will yield the results that will be employed in calibration of the BBM model parameters in an inverse manner. Lastly, numerical modeling will be conducted to assess the slope stability during varying moisture, suction conditions, and the outcome will be compared with field monitoring outcomes to determine whether the model used is accurate or not.

Key Contribution

- Initial use of the BBM model in slope stability assessment when using low plasticity soils (arid and semi-arid areas).
- The BBM parameters are calibrated by use of triaxial tests under unsaturated conditions, which is a practical and cost-effective point of view compared to suction-controlled tests.
- Comparison of the BBM model predictions with field monitoring data that proves the reliability of the model in real world application.
- Clues to the effect of changes in moisture and suction on the slope stability of low plasticity soils.

The paper is structured in the following way; Section 2 describes the literature review and Section 3 gives the description of the methodology, namely, soil characterization, water retention and permeability testing, and triaxial testing. The results are given in section 4 where the field data is compared with the predictions of the model. Lastly, Section 5 sums up the study by providing crucial findings and possible recommendations on future research.

LITERATURE REVIEW

The behavior of soils that are not saturated has attracted much attention in the field of geotechnical engineering because of its unpredictable behavior in relation to changes in the moisture conditions. The effect of suction in influencing shear strength and stiffness of unsaturated soils has been studied by various researchers. As Nuth and Laloui (2008b) [15] emphasized, suction due to the existence of surface tension in the pores of the soil is important in altering the mechanical properties, especially the shear strength, and stiffness. These are the essential factors in the evaluation of slope stability.

Barcelo Basic Model (BBM) has become an attractive constitutive model of unsaturated soils which has been extensively used in the prediction of the mechanical behavior of soils in different moisture conditions. The BBM, proposed by Sheng et al. (2004) [17], combines the impact of the suction on the soil strength and stiffness and was found to be applicable to various tasks, such as slope stability [19] and foundation bearing capacity [10]. But it cannot be practically implemented without proper calibration of parameters, which is usually determined by the means of costly and time-consuming suction-controlled tests [9].

More recent research, including that of Fredlund and Rahardjo (1993) [8], has proposed that alternative methods of testing, such as triaxial tests, might provide a cheaper substitute when it comes to calibration of such models as BBM in unsaturated conditions. Moreover, slope stability has been also assessed more often by means of numerical simulations with the help of programs such as CODE BIGHT and in different conditions of moisture and suction [9][19]. Such models, when properly calibrated, can be used to predict the behavior of the slopes in unsaturated soils with reasonable accuracy [11].

According to the literature, BBM at its complexity is a good framework that predicts the behaviour of unsaturated soils in slope stability tests. But there is the problem of calculating its parameters, which is usually associated with suction-controlled experiments. This paper aims to fill this gap by calibrating the BBM model against a more cost-effective substitute triaxial tests under unsaturated conditions and prove its predictive power against field data, in a bid to provide a workable solution to the slope stability analysis problem in low plasticity soils.

METHODS

The workflow will start off with soil characterization where laboratory tests like moisture content, liquid limitation, plastic limitation and specific gravity are carried out to identify the rudimentary physical characteristics of the soil. Also tests on water retention curve (WRC) and permeability characteristic curve (PCC) are conducted to describe the hydraulic behavior of the soil. Triaxial testing under unsaturated conditions is the second step in which the triaxial tests (UU, CU, CD) are performed with different levels of suction (0, 10, 20 kPa) to get shear strength values. The calibration of the BBM model is then done with these results, and an inverse method of fitting the BBM parameters (cohesion, friction angle, suction parameters) is used by minimizing the differences between experimental and predicted values. Lastly, the CODE BRIGHT makes use of the calibrated BBM parameters in the numericals with various suction and moisture parameters to evaluate the slope stability. The simulations are able to forecast the behavior and safety factor of the slope and the slope stability can be analyzed in full.

Soil Characterization

The samples of the soil representants were chosen at various levels on a slope in the Chilca region, Cañete, Peru. The slope inclination is 25 o and the height is 12 meters, which are the normal features of slopes constructed in this area to carry out different infrastructural projects. The laboratory tests were conducted according to the ASTM standards to describe the soil [4]. The oven drying method was used to find the moisture content (w) [2], the Atterberg limits - liquid limit (LL) and plastic limit (LP) [1] and the specific gravity of solids (Gs) using the pycnometer method [3]. Precision in the soil characterisation is very important in the proper application of geotechnical models in engineering. These tests performed are shown in Table 1.

Table 1. Results of soil characterization

Depth (m)	w (%)	LL (%)	LP (%)	Gs
1.5	18.5	32	20	2.68
2.5	22.3	36	23	2.70
3.5	25.8	39	26	2.72

The objective of Table 1 is to present the index properties of the soil obtained at different depths of the slope.

These data are essential to understand the mechanical behavior of the soil, its geotechnical classification and its susceptibility to moisture changes, factors that directly influence the stability of the slope [8].

In addition, the water retention curve (CRH) and the permeability characteristic curve (CCP) were determined through specific laboratory tests (Table 2).

Table 2. Data obtained in laboratory

θ	ψ (cm)	K (cm/s)	Se
0.45	0	1.20E-04	1
0.40	-10	8.50E-05	0.625
0.35	-30	4.00E-05	0.375
0.30	-100	1.50E-05	0.25
0.25	-500	5.00E-06	0.125
0.20	-1500	1.00E-06	0

θ: Water Content (%); ψ: Matric Potential (cm); K: Hydraulic Conductivity (cm/s); Se: Effective Saturation.

To model the HRC, the Van Genuchten model [20] was fitted to the experimental data. This model describes the relationship between water content (θ) and matric potential (ψ) by an equation incorporating soil-specific parameters [9]. Similarly, the Mualem-Van Genuchten model [18] was used to represent the PCC, relating hydraulic conductivity (K) to effective saturation (Se) [7], derived from the HRC data.

Water Retention Curve (WRC)

The WRC was obtained using the filter paper method, a widely used technique to determine the relationship between water content (θ) and matric potential (ψ) in soils [12]. In addition, two mathematical models were used to describe this relationship quantitatively in equation 1 and 2:

$$\theta(\psi) = \theta_r + \frac{(\theta_s - \theta_r)}{[1+(\alpha|\psi|)^n]^m} \quad (1)$$

Brooks-Corey [19]

$$\theta(\psi) = \theta_s \left[\frac{\psi_b}{\psi}\right]^l (\text{para } \psi < \psi_b) \theta(\psi) = \theta_s (\text{para } \psi \geq \psi_b) \quad (2)$$

The choice of these models is based on their ability to adequately represent the water behaviour of unsaturated soils, especially in the range of matric potentials relevant to slope stability shown in figure 1.

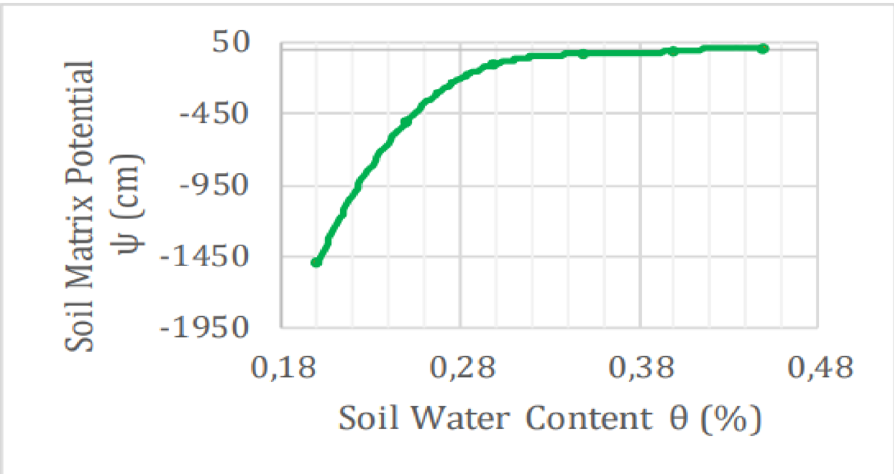

Figure 1. Water retention curve (WRC)

Permeability Characteristic Curve (PCC)

The CCP was determined by using a constant head permeameter, which allows measuring the hydraulic conductivity (K) of the soil at different hydraulic gradients [6].

The data obtained were analyzed to establish the relationship between hydraulic conductivity and effective saturation (Se), using two mathematical models in equation 3 and 4:

Mualem-Van Genuchten

$$K(\theta) = K_s \left(S_e^{1/2}\right)\left[1-(1-S_e^{1/m})^m\right]^2 \quad (3)$$

Burdine-Brooks-Corey

$$K(\theta) = K_s(S_e^{2+3m}) \quad (4)$$

The selection of these models is based on their ability to describe the variation in hydraulic conductivity as a function of effective saturation, a key parameter for understanding water flow in unsaturated soils [16] in figure 2.

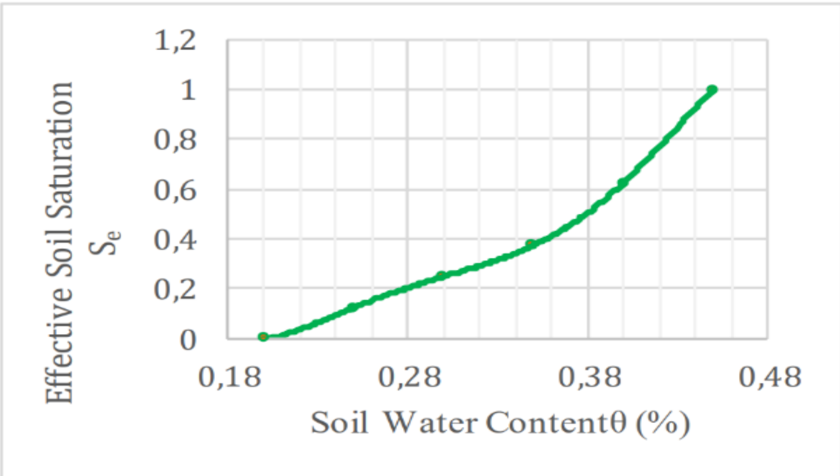

Figure 2. Permeability characteristic curve (CCP)

Triaxial Testing in Unsaturated Conditions

Triaxial tests were performed under unsaturated conditions (UU, CU and CD) to obtain the soil strength envelope as a function of suction. The results of the triaxial tests are shown in Table 3.

Table 3. Triaxial test results

Sample Depth (m)	Rehearsal	Suction (kPa)	Effort Diverter (kPa)	Average Effective Effort (kPa)	Cohesion (kPa)	Angle of Internal Friction (°)
1.5	UU	0	17.7	15	5	28.0
1.5	CU	10	30.1	25	8	30.0
1.5	CD	20	39.9	35	10	32.7
2.5	UU	0	23.8	20	6	29.0
2.5	CU	10	36.2	31	9	31.5
2.5	CD	20	46.1	40	11	33.0
3.5	UU	0	29.5	25	7	29.9
3.5	CU	10	40.7	35	10	32.1
3.5	CD	20	51.0	45	12	33.1

The experimental results helped to demonstrate that the hydrostatic conductivity reduces exponentially with the reduction in the effective saturation, which is in accordance with the anticipated performance of low plasticity soils. This reduction is even greater in the low eutectic zone, which is an indication that soil becomes less pervious as it becomes drier. Mualem-Van Genuchten and the Burdine-Brooks-Corey models succeeded in capturing this trend fairly well, which became a valuable predictor of the soil hydraulic conductivity as a function of its condition of moisture.

RESULTS

BBM Model Calibration

The parameters of the Barcelona Basic Model (BBM) constitutive model were determined by an inverse fitting process, using the results of the triaxial tests as a reference.

For this purpose, the CODE BRIGHT software was used, which made it possible to minimize the discrepancy between the shear strength values obtained experimentally and those predicted by the model.

The parameter adjustment was carried out considering both the soil strength parameters, such as effective cohesion (c') and effective internal friction angle (φ'), as well as the parameters that govern the relationship between suction and the mechanical behavior of the soil, represented by the water retention curves (α, n) and the characteristic permeability curve (ks, kr).

The values of the calibrated parameters are presented in Table 4.

Table 4. Calibrated model parameters BBM

Parameter	Symbol	Worth	Description
Effective cohesion	c'	8.5 kPa	Cohesion of soil under saturated conditions
Effective internal friction angle	φ'	30°	Internal friction angle of soil under saturated conditions
Cohesion adjustment parameter	α	0.7	Controls reduction of cohesion with suction
Friction angle adjustment parameter	n	1.2	Controls increase of friction angle with suction
Saturated hydraulic conductivity	ks	1.2×10^{-5} m/s	Soil's capacity to conduct water when saturated

The values of these parameters are specific to the soil studied and the conditions of the triaxial tests in table 5.

Numerical Simulation with CODE BRIGHT

Table 5. Results by means of CODE BRIGHT

Sample	Suction (kPa)	Shear Stress (kPa)	Average Effective Stress (kPa)	Cohesion (kPa)	Friction Angle (°)
1	0	17.9	14.6	5.2	27.7
1	10	29.7	25.3	7.8	30.1
1	20	40.2	34.8	10.1	32.8
2	0	23.5	19.8	6.3	29.2
2	10	35.9	30.9	9.2	31.7
2	20	46.3	40.3	11.4	33.2
3	0	29.2	25.2	7.4	29.5
3	10	40.4	34.7	10.4	31.9
3	20	50.8	44.6	12.2	32.8

Sensitivity Analysis

To assess the effectiveness of the model calibration, a sensitivity study of the parameters was carried out. The results revealed that the parameter κ, which modulates the decrease in cohesion as a function of suction, is the most influential on the calibration results. It is followed in importance by the basic friction angle, φb, and the parameter r, which controls the increase in the friction angle with suction. Sensitivity analysis of κ: Cohesion tuning parameter are in table 6.

Table 6. Sensitivity analysis of κ

Value of κ	Cohesion (kPa) (s = 10 kPa)	Friction Angle (°) (s = 10 kPa)	Shear Stress (kPa) (s = 10 kPa)
0.01	7.6	31.7	23.6
0.012	7.5	31.7	24.6
0.014	7.4	31.7	25.6

It is observed that with increasing value of κ, cohesion decreases slightly, which in turn affects the deviatoric force. This indicates that parameter κ has a moderate influence on the shear strength of the soil.

Sensitivity analysis of φb: Basic friction angle is shown in table 7

Table 7. Sensitivity analysis of φb

Value of φ (°)	Cohesion (kPa) (s = 10 kPa)	Friction Angle (°) (s = 10 kPa)	Shear Stress (kPa) (s = 10 kPa)
29	7.5	31.2	24.1
29.5	7.5	31.7	24.6
30	7.5	32.2	25.1

Varying the value of φb directly affects the friction angle and, to a lesser extent, the deviatoric force. This suggests that φb has a moderate influence on the shear strength of the soil. Sensitivity analysis of r: Friction angle adjustment parameter is in table 8.

Table 8. Sensitivity analysis of r

Value of r	Cohesion (kPa) (s = 10 kPa)	Friction Angle (°) (s = 10 kPa)	Shear Stress (kPa) (s = 10 kPa)
0.7	7.5	31.4	24.3
0.75	7.5	31.7	24.6
0.8	7.5	32.0	24.9

Table 9. Comparison of shear and effective stress at different suction levels

Sample	Suction (kPa)	Shear Stress (kPa)	Average Effective Stress (kPa) CODE BRIGHT	Difference (%)	Deviatoric Effort (kPa)	Average Effective Effort (kPa) CODE BRIGHT	Difference (%)
1.5	0	17.7	17.9	1.13	15	14.6	-2.67
1.5	10	30.1	29.7	-1.33	25	25.3	1.2
1.5	20	39.9	40.2	0.75	25	34.8	-0.57
2.5	0	23.8	23.5	-1.26	20	19.8	-1
2.5	10	36.2	35.9	-0.83	31	30.9	-0.32
2.5	20	46.3	46.3	0.43	35	35.4	0.75
3.5	0	29.5	29.2	-0.94	25	25.2	0.8
3.5	10	40.7	40.4	-0.66	35	35.1	-0.86
3.5	20	51.0	50.8	-0.32	45	44.6	-0.89

As the value of r increases, the friction angle increases slightly, which in turn affects the deviatoric force. This indicates that the parameter r has a minor influence on the shear strength of the soil compared to κ and φb are shown in table 9.

CONCLUSIONS

It is observed that the obtained results indicate a fantastic correlation between the experimentally measured shear strength values and BBM model as calculated in CODE_BRIGHT, particularly the deviatoric stress. The mean difference in this parameter was only 0.68 and this indicated that the model had a high predictive value in this kind of soil.

However, the greater differences were found in the mean effective stress values, in which the average difference is 2.19%. This difference might be explained by the fact that the BBM model is simplified in nature and it does not explicitly account those factors that might affect the behaviour of an unsaturated soil including anisotropy, microstructure or stress history.

Regardless of these discrepancies, the general strength of the BBM model in terms of describing the behavior of low-plasticity silts in the unsaturated state is impressive. This implies that the model, notwithstanding its shortcomings, can be an efficient tool of determining the shear strength of such soil type in real geotechnical engineering conditions.

It should be mentioned that the BBM model calibration is an iterative process, which presupposes a thorough review of the experiment data and a proper choice of the model parameters. The application of the CODE_BRIGHT software was used in this instance in that the calibration was made possible and a model capable of producing a behavior that is satisfactory in terms of reproducing the triaxial tests was obtained.

It would be interesting to study in future research whether more complex constitutive models can be used, which take into account other variables that affect the shear strength of unsaturated soils, including anisotropy and microstructure. It would also be worthwhile to carry out more triaxial tests in a broader spectrum of suction conditions so that the applicability of the BBM model in other situations can be further proved.

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