Evaluation of Suction and Water Content Fluctuations of a Tropical Soil

Silva Júnior, A. C. & Gitirana Jr., G. F. N.
Federal University of Goiás, Goiânia, Goiás, Brazil

2011 Pan-Am CGS Geotechnical Conference

ABSTRACT
The evaluation of soil-atmosphere interaction is required in several types of geotechnical applications, such as collapse and swelling analysis, construction and operation of embankments, and slope stability analysis. In most cases, the soil is in an unsaturated state and its conditions fluctuate as a result of varying weather conditions. The main objective of this study is to employ and evaluate a mechanistic approach to predict the fluctuations of suction and water content of a tropical soil profile. The profile studied is located in the city of Aparecida de Goiania, Goias, Brazil. Water content, suction, water table and atmospheric conditions at the site were monitored for a period of six months. Numerical analyses of water content and suction were made based on soil-water characteristic curves determined using standard laboratory tests and based on predictions from the grain-size distribution. The results indicate that relatively small differences are obtained using approximate, predicted soil properties. The results also indicate that the analysis of suction and water content for the shallowest depths is significantly more challenging.

RÉSUMÉ
L'évaluation de l'interaction sol-atmosphère est nécessaire dans plusieurs types d'applications géotechniques, tels que l'analyse d'effondrement et d'gonflement, de la construction et fonctionnement des barrages, et l'analyse de stabilité des talus. Dans la plupart des cas, le sol est dans un etat non saturés et de ses conditions fluctuent en raison des conditions météorologiques variées. L'objectif principal de cette étude est d'utiliser et d'évaluer une approche mécaniste de prédire les fluctuations du teneur en eau et de la succion d'un profil de sol tropical. L'profil étudié est situé dans la ville d'Aparecida de Goiânia, Goias, Brésil. Teneur en eau, succion, le niveau de la nappe phréatique et les conditions atmosphériques sur le site ont été surveillés pour une période de six mois. Analyses numériques de teneur en eau et succion ont été faites basée sur les courbes caractéristiques sol-eau déterminée à l'aide des tests de laboratoire standard et basées sur des prédictions de la distribution granulométrique. Les résultats indiquent que relativement peu de différences sont obtenues en utilisant approximative, prédit propriétés du sol. Les résultats indiquent également que l'analyse du teneur en ea et succion pour la moins profond des profondeurs est nettement plus difficile.

1 INTRODUCTION

The soil-atmosphere interaction plays a key role in several examples of geotechnical works. Analysis, implementation and performance of various stages of construction and operation of earth dams depend on the conditions and properties of soils near the surface. In compaction operations, the natural water content of the natural soil interferes in the efficiency and cost of compaction.

In these examples, the soils are usually unsaturated and in direct contact with the atmosphere. The weather, on the other hand, is responsible for constant changes in water content and suction, which is the main factor controlling the behavior of unsaturated soils. Thus, the conditions and hydro-mechanical behavior of unsaturated soils can be considered depending on the conditions at the soil-atmosphere boundary (Fredlund & Rahardjo, 1993).

The soil water content and suction changes can be obtained using mechanistic models. However, the efficiency of the method depends on the accuracy of meteorological data and soil properties.

The main objective of this study is to employ and evaluate a mechanistic approach to predict the changing conditions of suction and water content profile of an unsaturated soil profile located in Aparecida de Goiânia, Goiás, Brazil, using measured and estimated soil-water characteristic curves.

2 BACKGROUND

The development of mechanistic models suitable for the prediction of water content and suction requires the understanding unsaturated soils behavior. The classical theory of soil mechanics focuses mostly in the description of the behavior of clays, silts and sands in saturated conditions, when the water fills all the voids of the soil. This condition usually corresponds to the region with positive pore pressure located below the water level. However, unsaturated soil conditions occur frequently in nature. Having the soil pores filled with both water and air affect significantly the behavior of the soil. This condition usually corresponds to the region with negative pore pressure.

The study of unsaturated soils has extensive applications in engineering such as paving, stability of natural slopes and embankments, foundations and waste disposal.

The soil-water characteristic curve (SWCC) is the most fundamental property used to predict the behavior of unsaturated soil (Fredlund and Rahardjo, 1993). The SWCC defines the relationship between the suction and the corresponding water content of the unsaturated soil. Soil suction is the value of free energy in the soil water per unit volume, also interpreted as a measure of the energy required to remove water from the soil (Fredlund and Rahardjo, 1993). The amount of water is usually calculated in terms of gravimetric water content content (w), degree of saturation (S) or volumetric water content (θ).

Different aspects of the behavior of unsaturated soils, such as shear strength, volume change, diffuse, and absorption as well as many soil properties such as specific heat, thermal conductivity and permeability can be related to SWCC (Fredlund and Rahardjo, 1993).

In addition to understanding the behavior of unsaturated soils there are several other experimental and theoretical components that need to be analyzed for the prediction of water content and suction in a soil profile.

Within the experimental components, the first need is to determine the atmospheric conditions. Historical averages are often used for the forecasting of future conditions. Theoretical models must also be designed to represent the atmospheric conditions in terms of boundary conditions. An important example is the application of special boundary conditions to determine the actual evaporation on the soil surface (Wilson, 1990). Another important example is the application of special boundary conditions to calculate the runoff (Gitirana Jr., 2005).

There is also a need to evaluate the constitutive properties of unsaturated soil and measuring the state of the soil (water content and suction). The constituent properties are necessary for the application of mechanistic model of behavior.

Special attention should be given to indirect approaches, based on prediction from simple data for soil characterization. This approach allows an easier application of the mechanistic approach, since it avoids the use of complex and lengthy testing. Unfortunately, the indirect models for predicting properties of unsaturated soils still need further evaluation, especially related to the unsaturated soil.

Due to difficulties in laboratory and field testing, obtaining the SWCC by a method of prediction is quite interesting. The availability of a forecast method based on simple data soil enables the application of unsaturated soil mechanics in practice. In this research it were used the prediction method of Arya and Dierolf (1989).

Measuring the state of the soil is also needed in various stages of monitoring, back analysis, and performance verification of the behavior models. There are several techniques for monitoring water content and suction, but those are still scarcely used in the geotechnical practice. It is also important to develop simple techniques that are easy to use, to disseminate the use of unsaturated soil mechanics concepts.

Finally, it is necessary as the theoretical component, the development of mechanistic models and mathematical solutions for such models. Mechanistic models should include the main mechanisms of behavior that are applicable in practice.

3 METHODOLOGY

The methodology for this study includes field testing, laboratory testing, and numerical modeling. The experimental site studied is located at the Department of Technical Support and Control of Eletrobras Furnas (Aparecida de Goiânia, Goias, Brazil). This area was chosen for its small distance to the laboratories of Furnas and because it presents a typical tropical soil profile.

3.1 Instruments using for filed monitoring

The main methods used for filed monitoring of soil conditions were: a) filter paper; b) tensiometers; and c) soil sampling. The filter paper method is an indirect measurement of suction. According to Leong, He and Raharjo (2002), the main advantages of this technique are simplicity, low cost and ability to measure a large range of suction. This method can be used in laboratory and field.

The method is based on the principle that a filter paper placed in the same environment as a soil, may reach after a certain period of time a state of equilibrium with the soil suction. The flow of water content between the paper and the soil may occur through capillary flow or vapor flow. The capillary flow occurs through the direct contact of soil pores with the fibers of paper, without water loses its continuity. The suction measured in this case is the matric suction. The vapor flow occurs when water molecules need to overcome the osmotic and capillary forces to leave the pores. For the occurrence of this flow, it is necessary that there is no direct contact between the filter paper and soil, which prevents the flow of salts present in water. In another case the total suction is measured.

Tests on the filter paper in the laboratory are more common than field testing. This apparently is due to greater difficulty in controlling the conditions of handling the filter paper in the field and an equilibrium time of suction between the filter paper and soil, relatively high considering the changing climate. The difficulty of getting accurate field test results is associated to uncontrolled environmental changes.

The tensiometer is an instrument for direct measurement of negative pore-water pressure, and can be used both in laboratory and field. The high air entry ceramic cup promotes the interface between the water inside and the water present in the soil, functioning as porous stone. The permeability of the ceramic cup size depends on the size of your pores. A more permeable ceramic cup has a lower value of the air entry. This indicates the greater the ability of the ceramic cup to keep the air out of the system will result in more time to equilibrate the suction. The body tube is usually made of plastic due to its low heat conduction and durability.

3.2 Commissioning of field monitoring systems

The monitoring activities in the experimental field were taken from March 2010 to January 2011. These activities were preceded by a set of field tests for evaluation of monitoring procedures. The preliminary stage of testing began in March 2010 and completed in July 2010.

The soil profile was instrumented through a monitoring well (Figure 1). The well was equipped with access platforms with trapdoors arranged next to the stairs.

These elements were protected against corrosion using a special coating. The platforms are mobile, being supported on pillars of stairs and a metal rod, located on the opposite side of the stairs. The metal rod was also protected against corrosion and attached to the bottom. Holes made in the precast concrete tubes allow access to soil (Figure 2).

The data of the soil profile monitored in this study were: water content, suction, and groundwater level. The water content was obtained by removal of soil samples followed by drying in oven. The suction was obtained by two measuring methods: filter paper and tensiometer. The water table was monitored using two piezometers installed near the monitoring well.

Table 1 shows the depths used in monitoring. The holes are approximately 5 cm in diameter. Was selected frequency of 14 days for the measurement water content and suction. The water level was also measured every 14 days.

Figure 1. Monitoring well

Figure 2. Detail of the holes

Table 1. Arrangement of equipment along the depth.

Depth (m)	Water content	Tensiometer	Filter Paper
0.48	x	x	x
0.82	x		
1.14	x		x
1.45	x	x	x
1.82	x		x
2.13	x	x	
2.42	x		x
3.10	x	x	x
3.77	x	x	x

3.3 Analysis model

Darcy's law is one of the first models proposed to describe the water flow in saturated soil. But it was Buckingham (1907) who extended Darcy equation for unsaturated soil condition. Then Richards (1928) rewrote the equation proposed by Buckingham, using total head as a potential driving. Richards (1931) combined the equation of mass conservation of water and the flow law, obtaining an equation that governs the one-dimensional transient of water flow in saturated or unsaturated. The equation, known as Richard equation, was used in the analysis model and is written as follows:

$$\frac{\partial}{\partial \mathrm{y}}\left[k(\theta)\frac{\partial h}{\partial y}\right] = \frac{\partial \theta}{\partial t} \qquad [1]$$

where: $\partial/\partial y$ is the derivative with respect to the y -direction; k is the coefficient of permeability; $h = u_w/\gamma_w + y$ is the total load; y is the elevation in relation to a particular reference; u_w is the pore water pressure; γ_w is the specific weight of liquid; θ is the volumetric water content; $\partial/\partial t$ is the derivative with respect to time.

4 NUMERICAL ANALYSIS OF SUCTION AND WATER CONTENT FLUCTUATIONS

The conditions at the experimental field of Furnas in Aparecida de Goiânia were analysed based on soil properties measured in the laboratory and soil properties predicted based on the grain-size distribution curve. Historical weather averages of precipitation and evapotranspiration were adopted for this stage of the research.

4.1 Geometry, Initial conditions and boundary conditions

Based on the laboratory testing results, the soil profile was considered as being divided in two layers. The bottom layer has a unimodal SWCC. The top layer has a bimodal SWCC. This type of profile is typical in tropical regions where the weathering process produces bimodal pore-size distributions.

The initial conditions adopted in the modeling exercise coincide with the conditions at the date when the first measurement of water content in the field was done (March 26, 2010). The corresponding water table is 4 meter deep (Figure 3).

For the region of soil above the water table, the initial negative pore-water pressure corresponds to the water content measured in the field, which is based on the soil-water characteristic curve. An exponential trend line was adopted to fit the data points an represent the initial conditions (Figure 4).

Were considered the historical averages of precipitation and evapotranspiration from the region of Goiânia, capital of Goiás (Figure 5 and Figure 6). The average monthly rainfall and evapotranspiration were considered distributed over time, in others words, punctual intensities of precipitation and evapotranspiration were not considered.

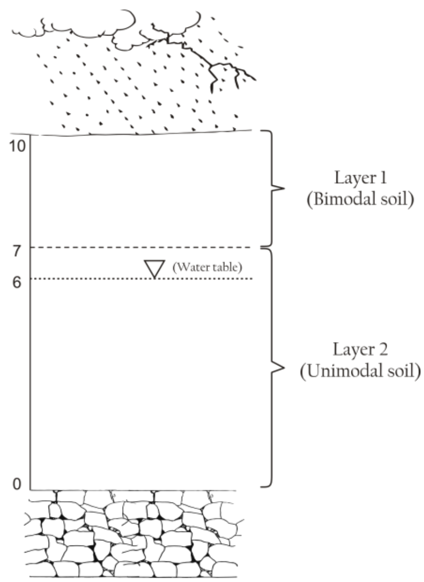

Figure 3. Geometry considered for numerical analysis

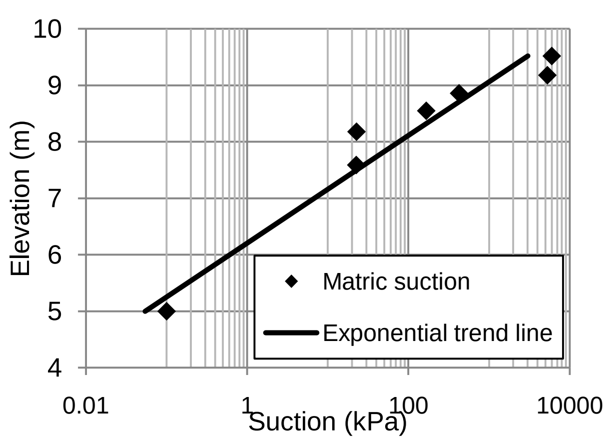

Figure 4. Initial condition of negative pore-water pressure

Figures 5 and 6 present the historical averages for monthly rainfall and evapotranspiration at the site. This data was provided by the Brazilian institute of meteorology and the Brazilian Agricultural Research Agency.

4.2 Soil properties

Some index properties of the two soil types are presented in Table 2. Two sets of soil-water characteristic curves were considered. The first were obtained experimentally by Borges (2010), and the second was obtained by the prediction method proposed by Arya and Dierolf (1989). The resulting SWCC parameters for the two curves mentioned above, are shown in Table 3. The experimental SWCC considered here are the mean values between the wetting and drying curves, which are based on matric suction data.

Three values of saturated permeability were adopted, based on test results presented by Borges (2010). For elevations lower than 5.05 meters, the saturated permeability was considered as 1.3×10^{-7} m/s. Between 5.05 and 7.30 meters a value of 2.8×10^{-8} m/s was adopted. Finally, for elevations greater than 7.30 meters, a value of 1.1×10^{-6} m/s was considered. The unsaturated permeability function was calculated using the method proposed by Brooks & Corey (1964).

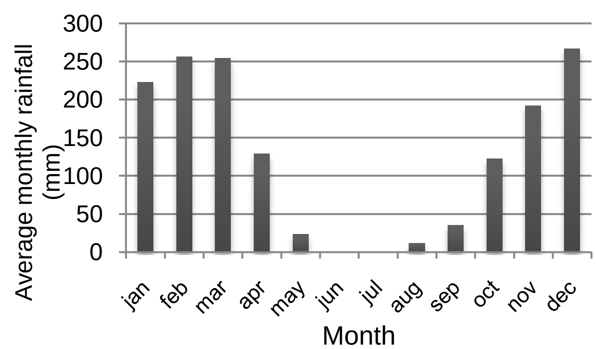

Figure 5. Historical average monthly rainfall for the period 2001 to 2009 (INMET - Brazilian Institute of Meteorology)

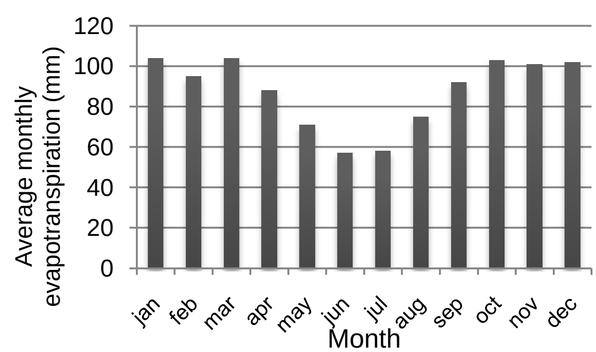

Figure 6. Historical average monthly evapotranspiration for the period 1961 to 1990 (EMBRAPA - Brazilian Agricultural Research Agency)

Table 2. Index properties of soil analysis.

Property	Bimodal soil	Unimodal soil

ρ_s (1)	2.742	2.736
ρ_d (2)	1.338	1.292
e_0 (3)	1.083	0.913

(1) Specific gravity of solids (g/cm³); (2) Specific weight of dry natural (g/cm³); (3) Initial voids

Table 3. Soil-water characteristic curve parameters.

	SWCC - Experimental		SWCC - Arya & Dierolf	
	Bimodal soil	Unimodal soil	Bimodal soil	Unimodal soil
ψ_{b1} (1)	3.50	3.00	3.00	5.00
ψ_{res1} (2)	13.00	490.00	60.00	50.00
S_{res1} (3)	0.445	0.250	0.480	0.370
ψ_{b2} (4)	3500.00	-	4000.00	-
S_b (5)	0.355	-	0.300	-
ψ_{res2} (6)	25950.00	-	20000.00	-
S_{res2} (7)	0.018	-	0.030	-
a (8)	0.06	0.09	0.03	0.09

(1) First air-entry value; (2) First residual suction value; (3) Degree of saturation corresponding to the first residual suction value; (4) Second air-entry value; (5) Degree of saturation value corresponding to the first air-entry value; (6) Second residual suction value; (7) Degree of saturation corresponding to the second air-entry value; (8) Setting parameter.

5 RESULTS AND DISCUSSION

Two numerical analysis for prediction gravimetric water content and suction were performed. The first numerical analysis (AN1) considered the average between the soil-water characteristic curves of wetting and drying related to matric suction, obtained experimentally by Borges (2010). The second numerical analysis (AN2) considered the SWCC provided by the method of Arya and Dierolf (1989). The starting date was considered March 26, 2010. The following time steps were considered in the graphical output: 24 June 2010, 17 September 2010, October 15, 2010 and December 22, 2010. These dates coincide with dates of field monitoring.

The results of prediction of water content are shown in Figure 7 to Figure 14. The experimental data of gravimetric water content (DE) are plotted as points for comparison. The two analyzes give reasonable results for the profile coordination with less than nine feet, where the experimental variations were lower over time. For the region between nine and ten coordinated the results were discrepant.

The results provided suction are shown in Figure 15 to Figure 22. Considering only suctions from water content data, related in the experimental SWCC, the prediction of suction were similar to prediction of water content, considered reasonable to coordinate to 9 meters and disparate to depth shallower. Note also that the suctions at the top of the profile (elevation equal to 10 meters) were always positive, indicating pore-water pressure negative and therefore no standing water. By analysis of the trend curve suction approaches zero, note that the water level changed little over time, keeping close to 6 feet. The results indicate that relatively small differences are obtained using approximate, predicted soil properties.

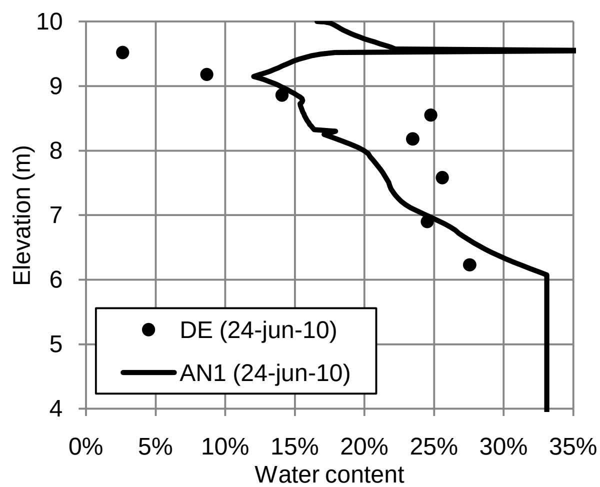

Figure 7: Prediction of water content throughout the profile (Numerical analysis 1, June)

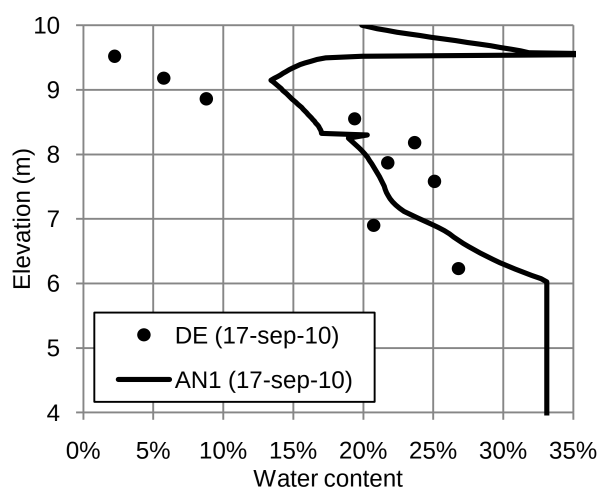

Figure 8: Prediction of water content throughout the profile (Numerical analysis 1, September)

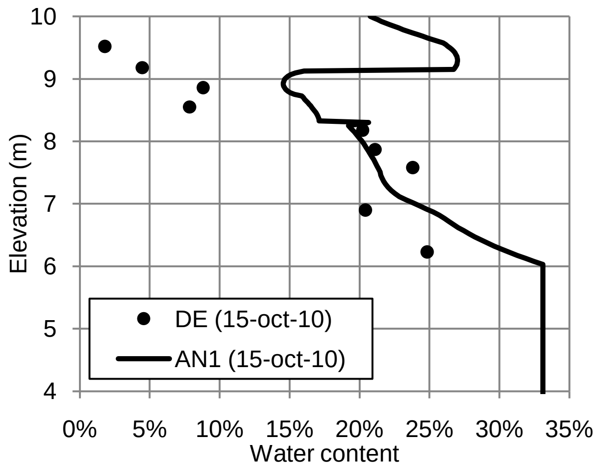

Figure 9: Prediction of water content throughout the profile (Numerical analysis 1, October)

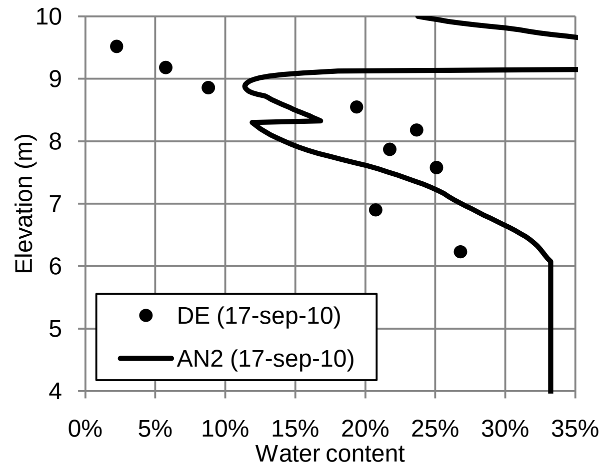

Figure 12: Prediction of water content throughout the profile (Numerical analysis 2, September)

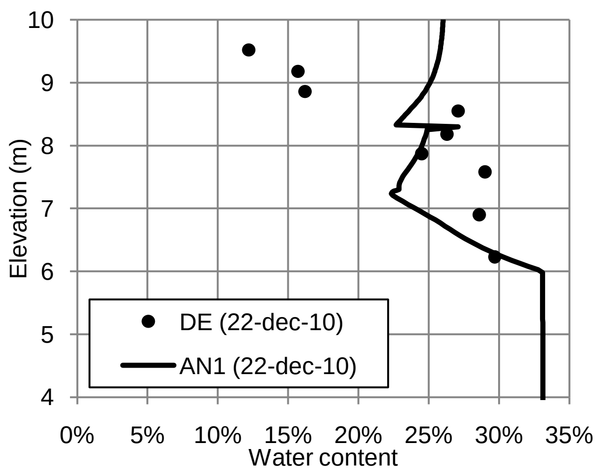

Figure 10: Prediction of water content throughout the profile (Numerical analysis 1, December)

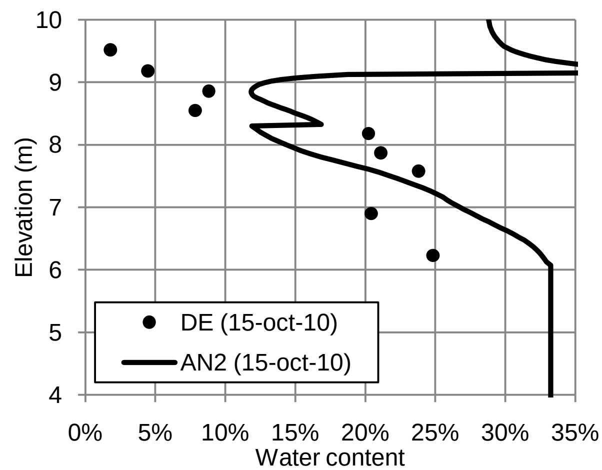

Figure 13: Prediction of water content throughout the profile (Numerical analysis 2, October)

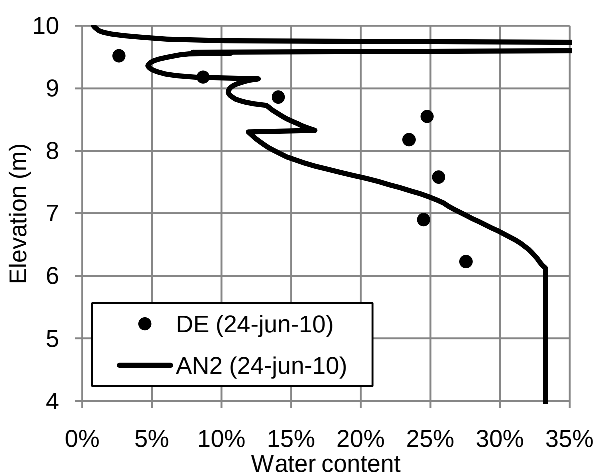

Figure 11: Prediction of water content throughout the profile (Numerical analysis 2, June)

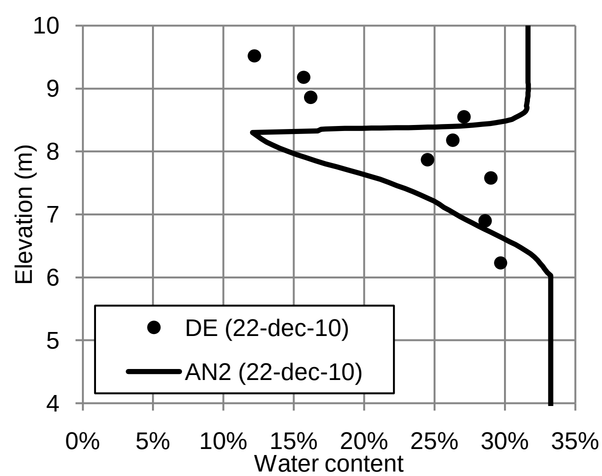

Figure 14: Prediction of water content throughout the profile (Numerical analysis 2, December)

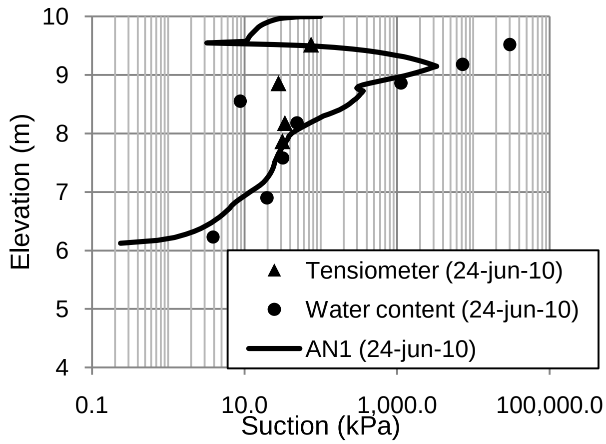

Figure 15: Prediction of suction throughout the profile (Numerical analysis 1, June)

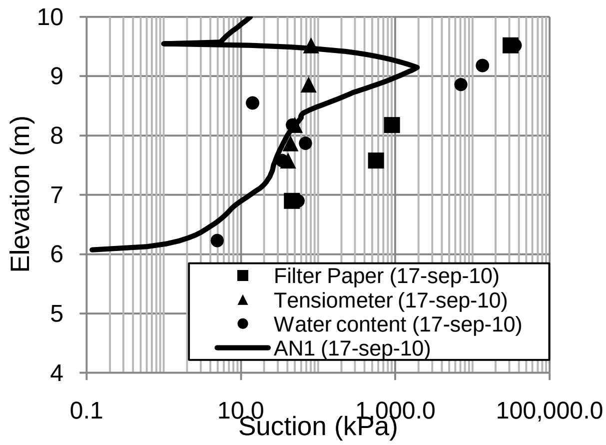

Figure 16: Prediction of suction throughout the profile (Numerical analysis 1, September)

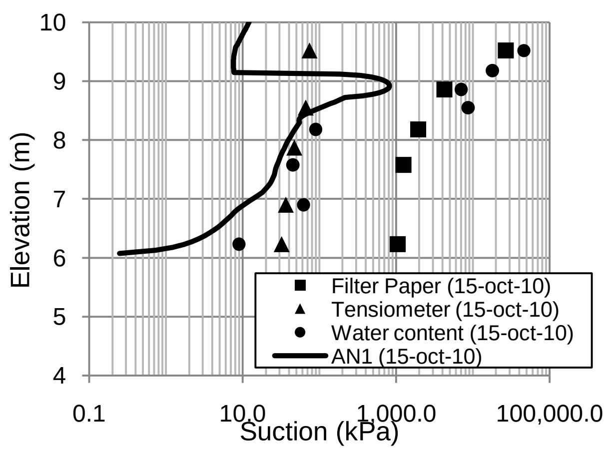

Figure 17: Prediction of suction throughout the profile (Numerical analysis 1, October)

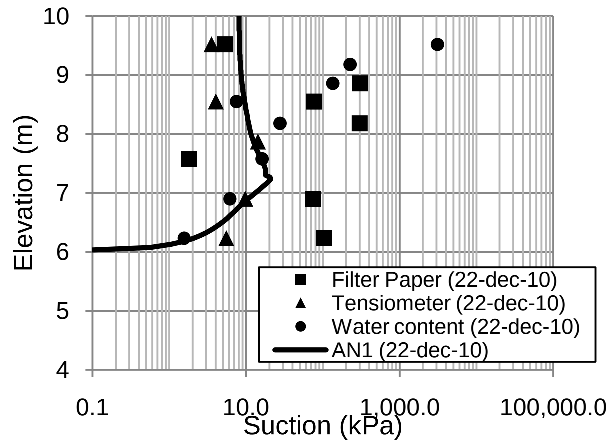

Figure 18: Prediction of suction throughout the profile (Numerical analysis 1, December)

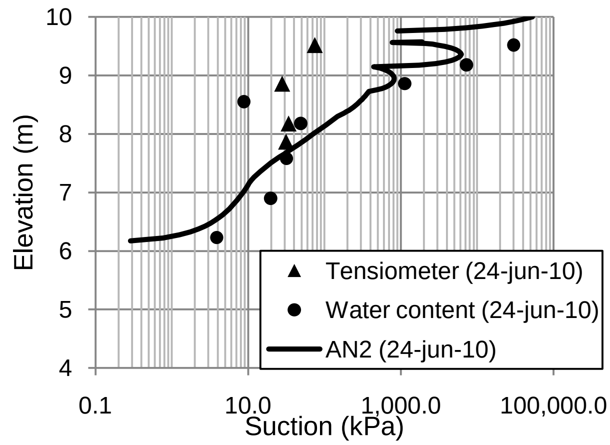

Figure 19: Prediction of suction throughout the profile (Numerical analysis 2, June)

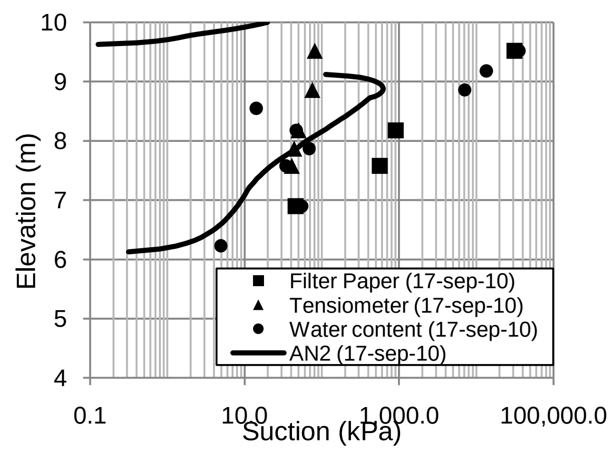

Figure 20: Prediction of suction throughout the profile (Numerical analysis 2, September)

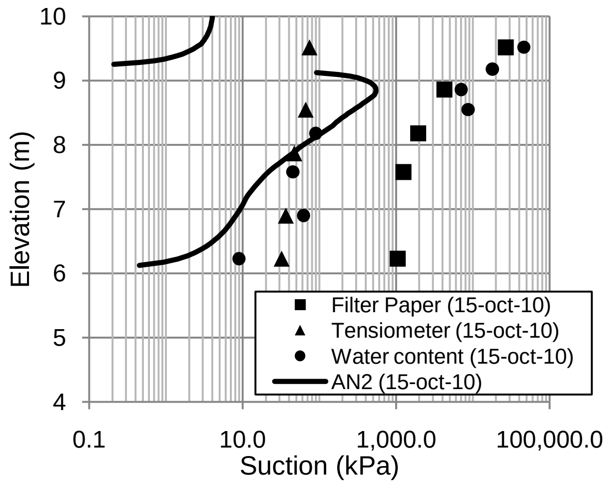

Figure 21: Prediction of suction throughout the profile (Numerical analysis 2, October)

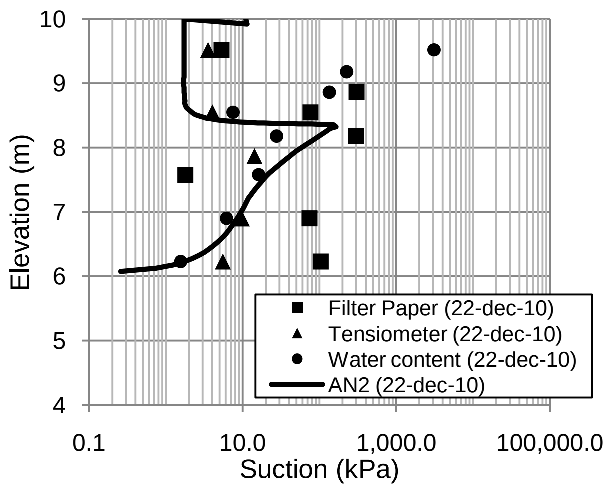

Figure 22: Prediction of suction throughout the profile (Numerical analysis 2, December)

6 CONCLUSIONS

The two analysis carried out to predict the suction and water content generated reasonable results considering the profile deeper. For meters shallower, results indicate that the analysis of suction and water content for the shallowest depths is significantly more challenging. Best results can be obtained by improving the boundary conditions. Using atmospheric data closer to the actual data, rather than historical averages, can improve the results. But the level of complexity and time to solve the problem will be greater.

7 REFERENCES

Arya, L. M.; Dierolf, T. S. 1989. Predicting soil moisture characteristics by particle-size distributions: an improved method to calculate pore radii from particle radii**.** *In: Proceedings of the Int. Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils*, p. 115-124.

Arya, L. M.; Paris, J. F. 1981. A physicoempirical model to predict the soil moisture characteristic from particle-size distribution and bulk density data. *Soil Science Soc. Am. Journal*, v.45, p. 1023-1030.

Borges, C. R. 2010. *Comportamento hidro-mecânico de um perfil de solo não saturado de Aparecidade de Goiânia-GO*. 2010. 2 vol. M.Sc. Thesis, Federal University of Goiás, Goiânia, Goiás, Brazil.

Brooks, R.H. & Corey, A.T. 1964. *Hydraulic properties of porous media***.** Hydrol. Fort Collins, Colo. State University.

Buckingham, E. 1907. Studies of the movement of soil moisture*. U.S.D.A. Bur. Soils Bull*, nº 38.

Fredlund, D.G.; Raharjo, H. 1991. *Soil Mechanics for Unsatured Soil.* John Wiley & Sons, New York, United States of America.

Gitirana Jr., G. F. N. 2005. *Weather-Related Geo-Hazard Assessment Model for Railway Embankment Stability*. Ph.D. Thesis, University of Saskatchewan, Saskatoon, Canada.

Leong, E. C.; He., L.; Rahardjo, H. 2002. Factors Affecting the Filters Paper Method for Total Suction Measurements. *Geotechnical Testing Journal*, v. 25, nº 3, p. 322-333.

Richards, L. A. 1928. The usefulness of capillary potencial to soil moisture and plant investigators. *J. Agriculture*, nº 37, p. 719-742.

Richards, L. A. 1931. Capillary conduction of liquids through porous mediums. *Physics*, nº1.

Wilson, G. W. 1990. *Soil Evaporative Fluxes for Geotechnical Engineering Problems.* Ph.D. Thesis, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.