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Hysteresis Cycles Prediction and Their Behavior on Expansive Soil-Water Retention Curve

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Abstract. Unsaturated expansive soils undergo a volume change due to the physical-chemical reaction produced by variations in their water content. The stress-strain behavior of these soils is very sensitive to this variation, for which reason, buildings constructed on expansive soils present structural problems due to the repetitive stresses produced by shrink-swell cycles caused, in turn, by drying-wetting cycles that generate suction, water content variations and hysteresis cycles. This last phenomenon is generated by water flow through the soil, causing drying-wetting paths, thus requiring knowledge of the real cycles to which the soil has been exposed. While the hydraulic behavior of soil can now be estimated via indirect theoretical models developed to fit the Soil-Water Retention Curve (SWRC) for a soil, the adjustments obtained have a low correlation with experimental SWRC results. The present study compares the most common methods for determining secondary hysteresis cycles based on the fitting of SWRC, two of which are based on predetermined expressions. The other method applied a polynomial fit based on an arrangement table using both methods of interpolation with variable increments and Lagrange's interpolation, resulting in a polynomial fit that generates the numerical SWRC. The results obtained were compared with the experimental results and data reported by other authors. The results show that the main and secondary cycles were consistent with those reported by other authors for sandy and silty soils; however, for clayey soils, only the polynomial method was capable of identifying hysteresis, while the process of fitting the SWRC is unnecessary with the polynomial method, resulting in a quick and easy tool that obtains consistent results.

Keywords. Unsaturated soils. hysteresis cycle. indirect method. soil-moisture model. soil-water retention curve.

1. Introduction

It is known that the behavior of an unsaturated soil depends heavily on suction changes generated, in turn, by changes in the water content [1] produced by wetting-drying cycles. This has led to the use of numerical and computational models to predict these cycles using the Soil-Water Retention Curve. This is of great interest, as the SWRC is used as

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a basis for predicting the parameters of unsaturated soils, with these models reducing the time and cost required to obtain said parameters.

These models have been developed to predict numerical procedures for hysteresis cycles via the SWRC. Among the most commonly used models is that presented by van Genuchten [2] for obtaining the main wetting-drying curves. The methods developed by both Huang et al. [3] and Zhou et al. [4] are based on van Genuchten's method of fitting the main curves of the SWRC, from which the secondary cycles can be predicted. Although these methods have been proven to be feasible and practical in sandy and silty soils, in some cases, the SWRC fitted with these equations has a low level of correlation with the experimental SWRC (clay), leading to inaccurate predictions for the secondary cycles. Therefore, obtaining parameters from the SWRC not be accurate, as it yields inaccurate results for the hydromechanical behavior of unsaturated soil.

The present paper presents the prediction, via the SWRC, of the hysteresis cycles of an unsaturated expansive soil, using the procedures set out in Huang et al. [3], Zhou et al. [4], and Galaviz-González et al. [5] to demonstrate the effectiveness of these methods, and the behavior and effect of predicting hysteresis cycles in expansive soils.

2. Background

Traditional geotechnical engineering design is primarily based on the principles of saturated soil mechanics, while unsaturated soil mechanics are increasingly necessary for studying subgrade soil. During wet seasons, water infiltration into soils leads to a decrease in both levels of matric suction and the shearing strength of the soil [6].

Expansive soils are unsaturated soils that often contain minerals, such as montmorillonite [7], and are recognized as problematic as they severely compromise the civil structures built on them [8], where even lightly loaded structures built on these soils may present structural damage as a result of changes in soil water content [9]. The main problems caused by these soils can be attributed to a poor understanding of the volume changes caused by variations in water content [8]. Expansive soils are capable of adsorbing water in their internal structure, with soil volume increasing in line with water content. This change in volume can exert sufficient pressure on the structure to cause damage. When dry expansive soils shrink, they cause contraction, which can lead to adverse subsidence. The wetting-drying process produces shrink-swell cycles that subject structures to repetitive stress [7].

Given that the behavior of unsaturated soils is more complex than that of saturated soils, modelling this behavior is also a complex task. This is not only because of the role played by suction but also due to the fact that the soil-water retention curve (SWRC) depends on several factors [10], namely the relationship between the amount of water stored (given by the gravimetric water content "w", the volumetric water content "H", and the degree of saturation "Sr") in the pores of unsaturated soils and suction (s) [6] [10-13].

Soil structure is known to control many processes that occur within soils, regulating water retention and infiltration, while pore size distribution may be derived from the SWRC [12]. Among such processes are those relating to soil structure and porosity, which depend on the history of the soil and the direction of the hydraulic path (either wetting or drying) [10]. Due to the fact that the SWRC depends on soil conditions, the drying and wetting paths exhibit hysteretic behavior during wetting and drying cycles; however, the effect of hysteresis [6] is usually ignored in studies conducted on water flow and transport problems [14]. The hysteresis of the water retention curve has a profound influence on coupled hydro-mechanical behaviors in unsaturated soils [15]. The hysteresis associated with the drying and wetting of the soil indicates that there is no unique SWRC. There are a number of transitional (secondary) drying and wetting scanning curves bounded between the main drying and main wetting curves [10]. The main wetting curves can be inferred from theoretical equations using the initial drying curve, which can be easily obtained via laboratory tests [6, 14].

Over the last 40 years, numerous empirical and theoretical models have been published describing hysteresis in the local SWRC. Empirical approaches assume that scanning curves in the SWRC can be scaled from the main wetting and drying curves, while the theoretical models are based on the domain theory of capillary hysteresis. Conceptual models are the most accurate in predicting the scanning curves, but are not easily coupled to numerical water flow models. An empirical model has been developed using the relationship between SWRC and particle-size distribution function [14].

Pham et al. [16] reviewed 28 empirical and physical hysteresis models available in the literature for 34 different soils, finding that the simple empirical model proposed by Feng and Fredlund (1999) provided the closest predictions for the boundary wetting curve and that the Mualem (1974) model provided better predictions for scanning curves.

3. Materials and methods

Fundamental to the design and construction of any building or civil engineering project is the realization of a basic geotechnical site characterization which includes a determination of the index and mechanical properties of the soil. The present study obtained unaltered samples from the town of Jurica, Santiago de Queretaro, Mexico, at a depth of between 0.60 m and 0.80 m. The properties corresponding to the index assays, the Atterberg limits and the soil classification, were then obtained from the granulometric composition and plasticity chart. The results of the soil characterization are summarized in Table 1.

Table 1. Geotechnical properties of Jurica's soil.

Property	Symbol	Magnitude	Property	Symbol	Magnitude
Gravimetric water content	ω	33.46%	Plastic Index	PI	45.79%
Specific gravity	γ_m	16.60 kN/m^3	Contraction limit	CL	16.38%
Relative density of solids	Ss	2.35	Lineal contraction	LC	18.24%
Void ratio	e	1.31	Gravel content	G	0.00%
Porosity	n	0.57	Sand content	S	6.22%
Degree of saturation	Gω	60.01 %	Fines content	F	93.78%
Volumetric water content	θ	34.04%	Classification	UCSS	CH
Liquid limit	LL	74.36%	Clay activity	A	0.95
Plastic limit	PL	28.57%			

For the determination of the effect of the hysteresis cycles on shrink-swell soils, suction tests were performed in the laboratory with unaltered material specimens using the filter paper method [17]. Figure 1 shows the relationship between soil suction (ψ) and the degree of saturation (Sr) in wetting-drying paths. Samples were taken from the same location at which the soil characterization samples were taken.

Soil suction was measured in unaltered specimens with an initial water content rising, in increments of 5.5%, from 0% to 38%, representing a degree of saturation that rises, in increments of 10%, from 0% to 100%.

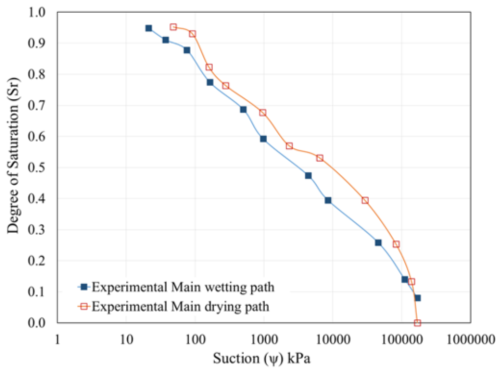

Figure 1. Soil-Water Retention Curve of Jurica's expansive soil.

Currently, there are various SWRC models, with the most popular being the van Genuchten model [3], which proposes an equation (Eq. (1)) for either fitting or predicting the SWRC. This equation is derived from the procedure developed by Mualem [18], where: θ_s = saturated volumetric water content; θ_r = residual volumetric water content; θ = volumetric water content; α, n, and m are not determinate parameters; and, $\Theta(\psi)$ is the degree of saturation, which is a function of soil suction. Eq. (2) provides a new effective degree of saturation (Θ), by means of which the SWRC or the experimental suction values are fitted. This procedure is usually referred to as modeling or SWRC adjustment.

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{1}$$

$$\Theta = \left[1 + |\alpha\psi|^n\right]^{-m} \tag{2}$$

$$m = 1 - \frac{1}{n} \tag{3}$$

Huang et al. [3] presented a procedure to model or predict the secondary cycles of hysteresis, based on the model proposed by van Genuchten [2], where parameters θ_s, θ_r, α, and n are unknowns to be determined, such that the main wetting curve $\theta^w(\psi,1)$ is described by parameters $[\theta_s^w(1), \theta_r^w(1), \alpha^w, n^w]$. In order to eliminate the pumping effect, the $\theta_r^d(1)= \theta_r^w(1)= \theta_r$ y $\theta_s^d(1)= \theta_s^w(1)= \theta_s$ relationships are imposed to close the main hysteresis cycle. Thus, the description of the main wetting and drying curves is $\theta^w(\psi,1)$ and $\theta^d(\psi,1)$ and is used for revising $[\theta_s, \theta_r, \alpha^w, n^w]$ and $[\theta_s, \theta_r, \alpha^d, n^d]$, respectively. Additionally, α^w, n^w and α^d, n^d are equal to the description of several wetting and drying curves. Then, the starting point is the primary path (ψ_i, θ_i) and requires $\theta(\psi,2)$ to meet:

$$\frac{\theta(\psi,2) - \theta_r(2)}{\theta_s(2) - \theta_r(2)} = \left[1 + |\alpha\psi|^n\right]^{-m} \tag{4}$$

The primary curve $\theta(\psi,2)$ also passes through the points investment (ψ_i, θ_i) and (ψ_f, θ_f). Substituting (ψ_i, θ_i) and (ψ_f, θ_f) in (4), gives:

$$\frac{\theta_i - \theta_r(2)}{\theta_s(2) - \theta_r(2)} = \left[1 + \left|\alpha\psi_i\right|^n\right]^{-m} \tag{5}$$

$$\frac{\theta_f - \theta_r(2)}{\theta_s(2) - \theta_r(2)} = \left[1 + \left|\alpha\psi_f\right|^n\right]^{-m} \tag{6}$$

Solving the equations system with two unknowns, formed by (5) and (6), we find $\theta_s(2)$ and $\theta_r(2)$, with their respective shape parameters α, n, and m (wetting and drying). The above process can be applied analogously to the i-th path [3]. Zhou et al. [4] proposed another model based on that proposed by van Genuchten [2], considering a simple nonlinear boundary scanning rule to describe the scan cycles (wetting-drying) occurring between the main wetting-drying cycles, meaning that the main paths are considered borders.

The disadvantage of using these models is that the adjustment of the SWRC achieved generally has a low correlation with the experimental SWRC. Due to the foregoing, the procedure proposed by Galaviz-Gonzalez et al. [5] was used. This method determines the hysteresis cycles of an unsaturated expansive soil using a polynomial approximation of an experimental SWRC, based on an arrangement table, which the authors concluded was an easy and quick tool for obtaining very consistent results.

4. Numerical and experimental comparisons

To assess the ability of the procedures used to show the behavior of the expansive soil-water retention curve, the hysteresis main and secondary cycles were predicted from experimental SWRC shown in Figure 1. The results obtained with the Galaviz-Gonzalez et al. [5] were compared with the Huang et al. [3] and Zhou et al. [4]. The mean absolute deviation (E_m) was used to check the quality of the three procedures, it is defined as:

$$E_m = \frac{1}{n}\sum_{i}^{n}\left|\Delta Sr_i\right| \tag{7}$$

While it is known that the van Genuchten model [2] is suitable for adjusting the SWRC of sandy and loamy soils, it is not as effective when used in clays (expansive soil). Therefore, this paper presents a comparison of the methods found in the literature that enable the prediction of hysteresis loops in order to assess the effectiveness of available procedures for use with an expansive SWRC.

In light of the foregoing, the methods based on the model proposed by van Genuchten [2] require pre-defined equations for establishing the SWRC; however, the method proposed by Galaviz-Gonzalez et al. [5] avoids the need for a predetermined equation for the adjustment process. Therefore, it is an excellent tool for determining secondary hysteresis cycles for unsaturated soils. The main features we observed for the polynomial procedure are: a) the process of adjusting experimental points for the SWRC with a predetermined equation is unnecessary; b) the procedure ensures a 100% correlation between experimental and numerical data; and, c) this correlation increases the accuracy of the curves leading to unsaturated soils.

Based on the foregoing, the present research sought to study the unsaturated expansive soil of the town of Jurica, in the Queretaro valley, soil which has been the subject of a large number of studies due to the number of structural problems occurring in buildings in the area. These problems are due to volumetric changes resulting from variations in water content caused by weather conditions, in both the rainy and dry seasons. Figure 2a shows the water content changes in the soil found in Jurica over a 12-month period (1992-1993), pertaining to data obtained from moisture profiles reported by Perez-Rea [19] and López-Lara [20]. Figure 2a presents the behavior of changes in the water content of the soil over time, demonstrating that the dry period for the city of Querétaro occurs between the months of October and May, while the rainy season occurs from June to September. It is also observed that the greater fluctuations in water content (between 17% and 41%) are found very close to the surface (0.30 m), while, at increasing depth, water content changes tend to be constant (between 20% and 30%). This led us to use these water content values to exemplify and demonstrate the behavior of the hysteresis cycles of the expansive soil in Jurica, via the SWRC, with Figure 2b showing the variation of the water content over the 12-month study period, a variation corresponding to a depth of 0.30 m.

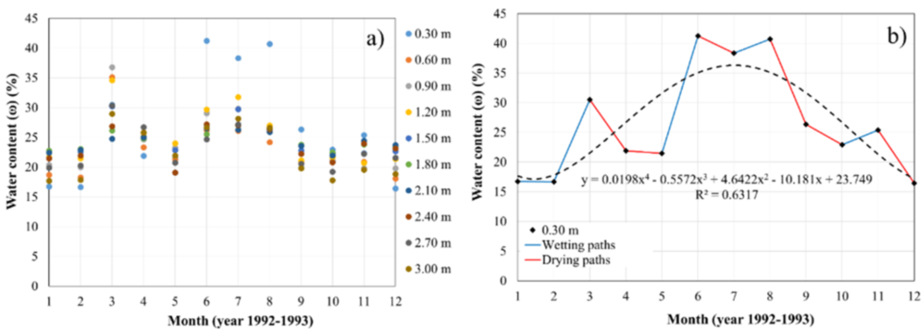

Figure 2. a) Jurica's soil water content variations with respect to time and the depth, b) water content variations at the depth of 0.30 m.

Figure 2b presents the wetting cycles from January to March, May to June, July to August, and October to November and, therefore, the drying cycles from March to May, June and July, August to October, and November to December. Because of this, and to simply and easily present the hysteresis cycles using the SWRC, only the primary wetting cycle (January to July) and secondary drying cycle (July to December) are displayed, showing how the polynomial curve fits the experimental data shown in Figure 2b.

To determine the secondary wetting-drying cycles of the Jurica soil, it was necessary to use the SWRC shown in Figure 1, taking into account the minimum and maximum water content values shown in Figure 2. Furthermore, in order to demonstrate the effect of adjustment and the correlation of the main curves in predicting secondary wetting-drying cycles, the main curves were adjusted using the methods proposed by Huang et al. [3] and Galaviz-Gonzalez et al. [5] (see Figure 4). Subsequently, the mean absolute deviations were calculated for comparison adjustments (see Table 2).

Table 2. Mean absolute deviations (Em) between experimental results and those obtained witt methods using the Jurica's SWRC.

Jurica's	**Method**		
SWRC	**Huang et al.** [3]	**Zhou et al.** [5]	**Galaviz-Gonzalez et al.** [5]
Cycle	E_m	E_m	E_m
Main wetting path	0.0185	0.0185	0.0000
Main drying path	0.0297	0.0297	0.0000
Primary wetting path	----	----	----
Secondary drying path	----	----	----

Analysis of both Figure 3 and Table 2 confirms that the van Genuchten adjustment is not well suited for clayey soils, where, while the lowest mean absolute deviation possible was found, it was clear that SWRC adjustment was not very accurate (see Figure 3a). This meant that the prediction of secondary hysteresis cycles was not successful. Moreover, the methods based on the van Genuchten model [2] are not able to reproduce the phenomenon of hysteresis in the secondary paths of an expansive soil, indicating that the suction values in both secondary cycles are the same for any water content (or degrees of saturation) of the same value. The use of the Galaviz-Gonzalez [5] procedure enabled the mean absolute deviations equal to zero to be obtained, whereby a 100% fit with the experimental data was obtained (see Figure 3b). The prediction of secondary cycles was able to show the hysteresis phenomenon, thus obtaining the suction values for the various water content levels (or degrees of saturation) in various trajectories and showing the ease with which any hysteresis cycle can be obtained. The methods based on predetermined SWRC equations were found not to be able to identify the phenomenon of hysteresis in the prediction of secondary cycles, causing uncertainty in the determination of suction values and subsequent hysteresis cycles.

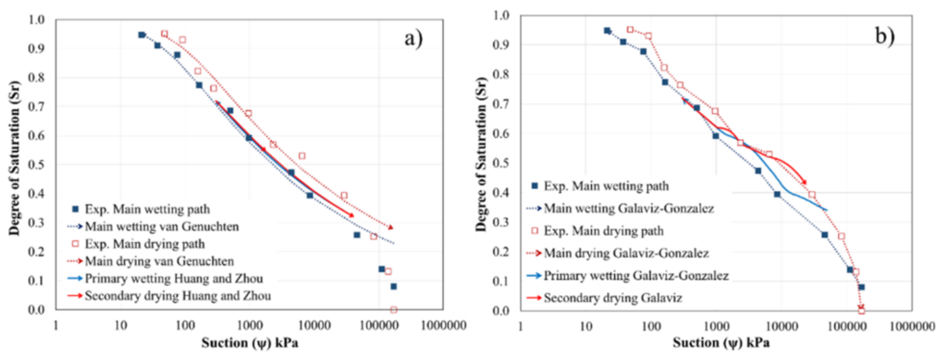

Figure 3. a) cycles prediction using van Genuchten [2], Huang et al. [3], and Zhou et al. [4] methods, b) cycles prediction using Galaviz-Gonzlez et al. [5] procedure.

5. Conclusions

The aim of this research is to presents the prediction of the hysteresis cycles of an unsaturated expansive soil, through the SWRC, using the procedures shown in Huang et al. [3], Zhou et al. [4], and Galaviz-González et al. [5]. The above in order to demonstrate the effectiveness of these methods, the behavior and effect that occurs in predicting the hysteresis cycles in expansive soils. The procedures used in this paper, in order to predict the main and secondary cycles through the SWRCs proved viable and capable for sandy and silty soils. However, when used a clayey soil, the methods based on the model of van Genuchten [2] (Huang et al. [3] and Zhou et al. [4]) were not able to show or reproduce the hysteresis phenomenon in the secondary cycles. On the other hand, polynomial method (Galaviz-Gonzalez et al. [5]) shows the hysteresis phenomenon in both primary and secondary cycles, presenting turn advantages over other existing methods: ensures a 100% correlation with the main numerical and experimental curves. Does not require a predetermined equation for the SWRC. Finally, comparisons of the hysteresis cycles obtained with the different methods and experimental results, show that the polynomial method is a quick and easy tool to get very consistent results.

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