The water retention curve for materials with deformable particles: Experimental study and predicting

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ABSTRACT: *One of the fundamental hydraulic characteristics in unsaturated materials is the water retention curve (WRC). It relates the suction evolution on the water content or on the degree of saturation. Its experimental determination is often difficult and requires specific techniques. In literature the subject was recently investigated. However, the materials which have been studied are, in general, constituted by undeformable particles material, such as sandy or silty soils. Moreover, a large number of materials are constituted by deformable particles. The purpose of this study is to present the experimental water retention curve for deformable materials as swelling clay and perlite. Then, a model based on the particle-size distribution curve is proposed. The fundamental idea is deduced from the Paris Model. The simulations of the experimental results have been done and particularly the material deformability degree effect on the corresponding WRC is quantified. Finally, the good agreement between the predicted WRC and the experimental one shows the practical useful of the proposal model.*

RÉSUMÉ *Une des propriétés fondamentales des matériaux non saturés est la courbe de rétention d'eau (WRC). Elle relie la teneur en eau ou le degré de saturation à la succion. Sa détermination expérimentale est souvent difficile et demande des moyens spécifiques. Plusieurs travaux de recherches traitant la détermination de la WRC sont déjà publiés dans la littérature. Cependant rares qui se sont intéressés aux matériaux à microstructure déformable. Dans cette étude on présente l'étude expérimentale de WRC pour des argiles gonflante et pour la perlite. Le modèle de Paris pour la prédiction de WRC est testé. L'accent est mis sur l'effet de la déformabilité de la microstructure sur la courbe de rétention d'eau.*

KEYWORDS: *water retention curve, deformable particles, experimental determination, modeling.*

MOTS CLES : *courbe de rétention d'eau, particules déformables, détermination expérimentale, modélisation*

1. Introduction

The measurement of macroscopic soil or many unsaturated materials parameters, such us the permeability, the shear strength, and tensile strength, used to describe unsaturated material behaviour is often very expensive, difficult and with long time consuming. Hence, several models were proposed to predict the hydro-mechanical behaviour of unsaturated soils using water retention curve (WRC). Romero and Simms (2008), showed that the macroscopic properties are often explained in terms of microstructural behaviour: particle size, shape and distribution.Other the direct measurement by a specific techniques, for the undeformable soils (without deformable of particles), WRC can be easily estimated using grain size distribution. Several methods have previously been proposed for the estimation of the SWCC (Arya and Paris 1981; Haverkamp and Parlange 1986; Fredlund et al. 1997). The other common method to obtain WRC is the mercury intrusion porosimetry (MIP), which is based on the pore size-distribution. Naturally, basing on this technique, the variation of the size, the form, and the distribution of pores have an important influence on the WRC. For clayey soils, the first way of dependency of the WRC have been assigned to the compaction (Croney and Coleman,1954; Tinjuim et al; 1997; Romero et al., 1999; Romero and Vaunat, 2000; Miller et al., 2002). The difference between the laboratory compaction and the field compaction influence has been investigated by other authors (Prapaharan et al., 1991; Jomni and Sciotti, 2003). All these investigations concluded that the compaction reduces and changes the size and distribution of the pores and conduct to the modification of the WRC. Although the grains are considered undeformable, the quantitative representation of the microstructure via the pore size distribution allows to the variations of the WRC and leads to a quantitative effect on the capacity of water retention. At the same time, this technique can measure the mechanical hysteretic behaviour of the WRC.

For instance, although the performance of the investigation using the microstructure's data, the MIP technique requires a specific material and it is not easily and commonly method. However, for materials with deformable particles, a few of experimental methods and theoretical approaches have been proposed. In the other hand, the swelling soils have a particular relevance to geotechnical applications. In fact, such kind of soils can be considered as soils with deformable particles. In this case, the particles are constituted at mesoscopic level by layers formed by cation/lamell interactions which lead to volumetric deformation and then to the variation of the volumetric particles at the microtextural scale of aggregates. Understanding the swelling effect on WRC does not yet treated. In this study, as an example, a material with deformable grains which is called perlite is considered. To measure and predict the WRC and eventually the permeability function of these materials through microstructural models is a potential route and the aim goal of this paper.

2. Experimental study

This section presents the experimental results of the WRC obtained for different kind of soils, in which we give a comparison between the results for the silty soils and clayey soils. A specific attention is given to the form and after the prediction of bentonite as swelling clay. Numerous common experimental methods already used to obtain the WRC of unsaturated soils covering a large range of suctions. Each of these techniques is characterized by the corresponded response time, its applicability depending on the kind of the soil, capacity of capturing suction value, the range of suction variation. These techniques have been described in detail in various papers. These selected techniques used in this study are listed in Table 1 and the suction measured for soils used in this study is considered as only matrix suction.

Technique	Suction and it's range variation (kPa)	Selected references
Dew-point PotentiaMeter (WP4)	Total suction, : 100 - 8000	Campbell et al. (1973), Leong et al. (2003)
filtre paper	Matrix suction :100 - 10000	Agus et al. (2005)
Salt solutions	Total suction >1500	Guiras (1996), Agus et al. (2005)
Axis translation	Matrix suction : 0-1500	Delage et al. (2007)
Osmotic	Total suction : 0-1500	Delage et al. (1997)

Table 1. *Experimental techniques used in this study to determine the WRC*

Basing on these techniques mentioned below, WRC curves have been determined. Figures 1, 2 and 3 present these data respectively for silty, clayey soils and bentonite. These figures show that the capacity of water retention increases from silty soil to bentonite.

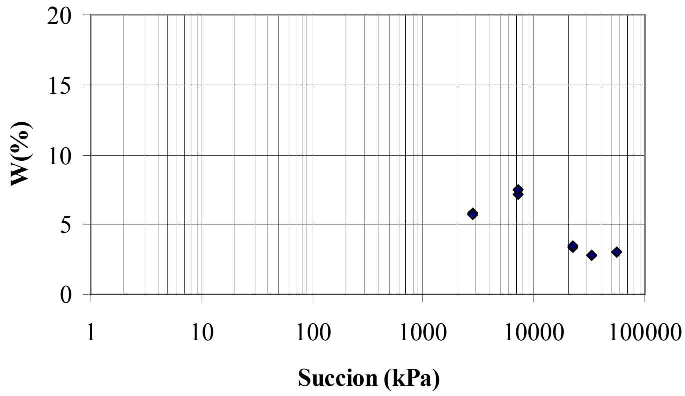


Figure 1. Experimental water retention curve of **silty soil**

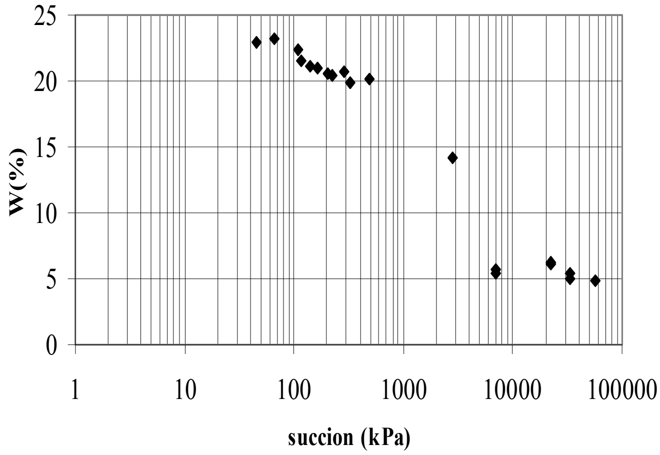


Figure 2. Experimental water retention curve of **clayey soil**

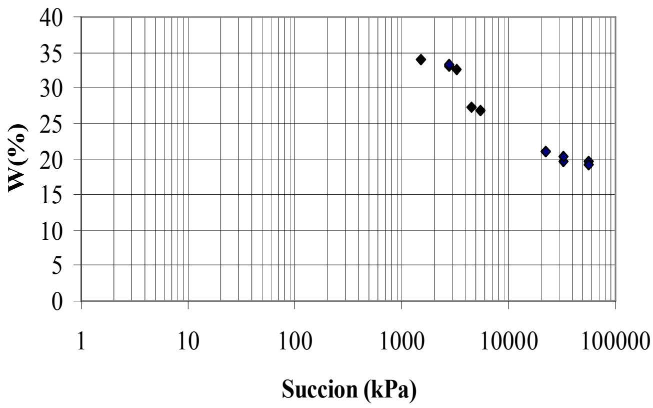


Figure 3. Experimental water retention curve of **bentonite**

3. Theoretical prediction

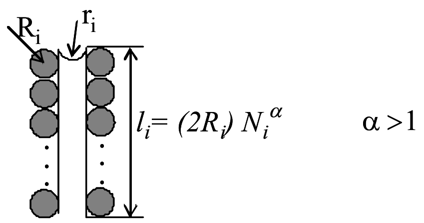
The aim of this study is to test the validity of the Arya and Paris's model for the estimation of the SWCC on swelling soil. The shape of the estimated curve is controlled by the grain size distribution and influenced by the density of the soil. The influence of initial water content, soil structure and stress history, on the SWCC curve was also studied by Vanapalli and al. (1999). As it was shown elsewhere the SWCC curve is influenced by initial water content and stress history for the specimens compacted at dry and optimum conditions (Jamei et al. 2007).

Across the grain-size distribution data, analytical equation is fitted. Then the curve is subdivided in series of intervals which represent the set of homogenous fractions of soil (Fredlund et al. 2000).

3.1. *Description of the model*

Arya and Paris (1981) presented the first physico- empirical methods to estimate the SWCC. The basic information of the model is the grain size distribution curve. Volumetric water content was calculated basing on an estimation of the pore sizes of the soil. **P**ore radius estimation was based on the assumption of spherical particles and cylindrical pores using the capillary theory. An empirical factor is used to take into account uncertainties in the estimation.

The finer particles are the more their stacking spares narrow voids, with each N_i classes of size of particles (N_i fractions), a pore is associated (N_i pores on the whole). The fraction of size R_i is supposed to contain spherical particles. The associated cylindrical pore is supposed to follow the edge of the juxtaposed particles and its length is $l_i = (2R_i)N_i^{\alpha}$ (α is equal to 1 for a rectilinear pore and it is a parameter to be estimated for a natural geometry).



The capillary model used is composed by N_i independent capillary tubes, from which N_i couples of values of suction (s), and water content (W) are calculated. The parameter α is determined by calibration with the experimental data. It may be related to the physical soil parameter like plasticity index (I_p).

The grain size distribution was divided into $\boldsymbol{N_i}$ fractions. Individual weight fractions can then be calculated as follows

$$P_i = (g_{i+1} - g_i)\gamma_t \qquad [1]$$

Where:

- P_i = weight of individual fraction (g);
- g_i = function representing percent passing versus particle diameter;(i = counter from 1, 2,…, N);
- N_i = number of fractions into which grain-size distribution is divided;
- γ_t = total density of the soil sample (g/cm^3).

Calculation of void ratio is possible once void volume is known

$$V_{v\,i} = \frac{P_i}{G_s \rho_w} e_w \qquad [2]$$

Where

- e_w= void ratio corresponding to saturation step defined by a water content;
- ρ_w = density of water;
- G_s= specific gravity of the soil.

$Vv = \sum_{i=1}^{n} V_{vi}$ The sum of all void ratios can be calculated as follows [3]

Hence volumetric water content is

$$\theta_{vi} = \frac{\sum_{j=1}^{i} V_{vj}}{V_T} \qquad [4]$$

The pore radius is calculated according to the following equation:

$$r_i = R_i \left[\frac{4N_i^{(1-\alpha)}}{6} \right]^{\frac{1}{2}} \qquad [5]$$

Where:

- r_i = mean pore radius;
- Ri = mean particle radius;
- N_i = the number of spherical particles in the its particle-range;
- α= an empirical factor and greater than 1.

Pore radius and soil water pressure:

$$s_i = \frac{2T_S \cos\theta}{\rho_w \times g \times r_i} \qquad [6]$$

Where:

- S_i = soil water pressure;
- T_s= surface tension of water;
- θ =contact angle;
- ρ_w = density of water;
- g = acceleration due to gravity,
- r_i = pore radius

In Paris classic model, the unique empirical parameter is parameter which is related to the material.

3.2. *Prediction of the WRC*

Figures 4, 5 and 6 give the WRC predicted with Arya and Paris (1981) model and as it's shown with the modification of this model, in which the variation of dry density the model adjusted presented the first physico-empirical methods to estimate the SWCC. Table 2 resume initial conditions and empirical parameter **α. for** eatch soil The basic information of the model is the grain size distribution curve. Volumetric water content was calculated basing on an estimation of the pore sizes of the soil. Pore radius estimation was based on the assumption of spherical particles and cylindrical pores using the capillary theory. An empirical factor is used to take into account non spherical particles in the estimation. Although, the Arya and Paris model requires a calibration of empirical parameter **α**. For the swelling soils the use of the incremental void ratio which is calculated across the response of soil during the wetting path is the principal idea in this study. In other hand, the empirical parameter is more important for clayey soils (greater than 1.5) than sandy soils as it was mentioned in the original paper of Arya and Paris (around 1.1).

The void ratio function is found using the free swelling tests on the œdometric or triaxial apparatus. Some experimental swelling results obtained for the bentonite are given in Jamei et al. (2007). The analytical formulation of this function is proposed and given with an initial dry density and initial water content. Hence, the determination of the couple of parameters is important in the model.

Figure 7 shows the WRC for a perlite as a high deformable and crushable material. The adaptation of Arya and Paris model is described in other paper. In fact, it has been shown that, the use of Paris model requires the introduction of void ratio variation, in this case, with deformable and crushable behaviour of perlite grain.

Soil Type	W (%)	γ_d (g/cm^3)	γ_s (g/cm^3)	α -
silty soil	14.5	1.79	2.68	1.60
clayey soil	21,0	1.64	2.72	1.38
bentonite	30.2	1.22	2.74	1.57
perlite	55.0	0.25	2.10	2.05

W : Initial water content, γ_d : dry density and γ_s : Specific gravity.

Table 2. *Initial conditions and adjustment parameter α*

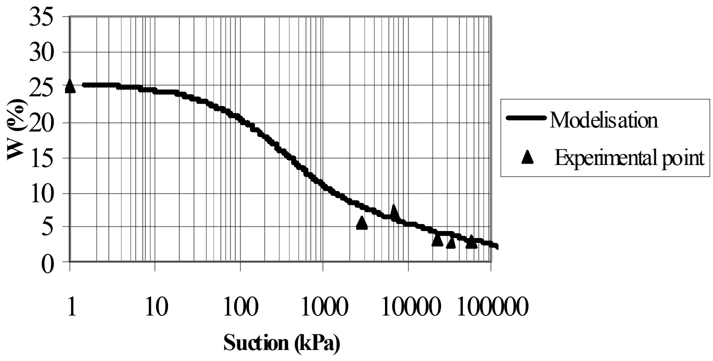


Figure.4. Comparison of experimental and predicted of WRC of **silty soil**

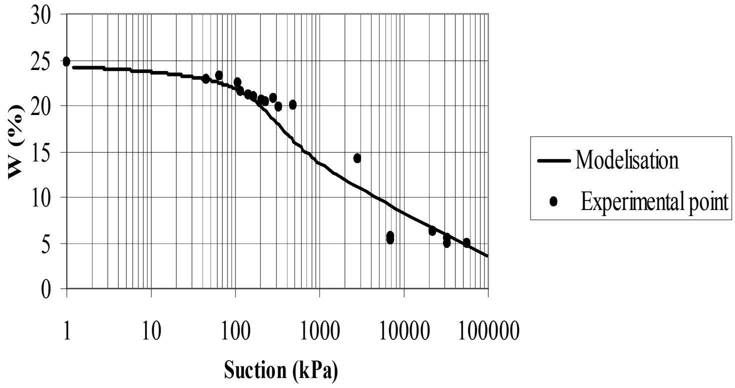


Figure 5. Comparison of experimental and predicted of WRC for **clayey soil**.

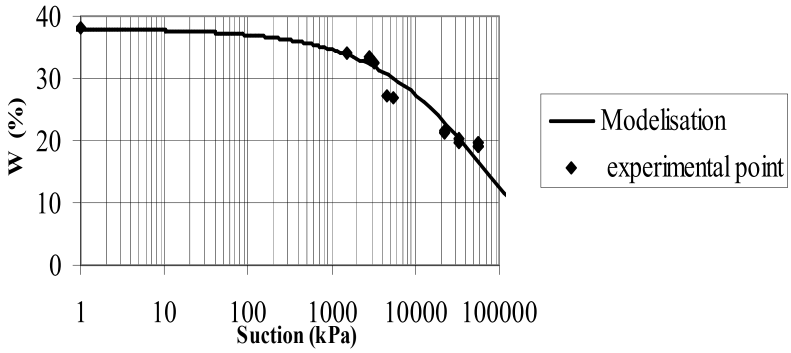


Figure 6. Comparison of experimental and predicted of WRC for **bentonite**.

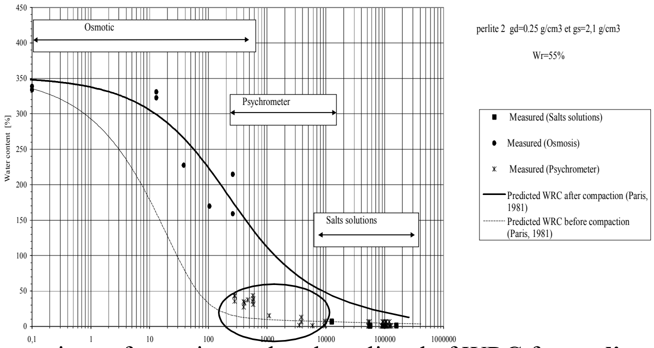


Figure 7. Comparison of experimental and predicted of WRC for **perlite**

4. Conclusion

Often it was found that the estimation of the soil- water characteristic curve from grain size distribution is a reasonably way for a sandy soil and silty soils. Such soils can be characterized by undeformable grains. However for the material with deformable particles, the Paris model remains convenient only when the void ratio is modifies as well as volumetric deformation of microstructure. For the swelling clayey soils, it is easy to include this volumetric deformation when we measure the free swelling and hence the variation of the void ratio during wetting. For other material as perlite, the same process is not suitable and a complementary data including the effect of hydraulic and mechanical loading is necessary.

At the same time and for both material (swelling clay and perlite), the effect of compaction or another loading path effect can be included across the void ratio function variation.

The unique empirical parameter **α** introduced in the Paris model is retained with a convenient adjustment for a material. From the predicted WRC for deformable materials, it seems that the **α** parameter is greater than 1.5.

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