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Numerical Simulations of Water Transfer in Clayey Soil Column Considering Cracks Development

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ABSTRACT: The objective of this paper is to model the experiences of water transfer by the prediction of the unsaturated permeability of soils including the cracks development. The proposal modelling is to perform numerically tests principally in soil columns, for which the laboratory experiences is too long time consuming and complex to success in the case of clay. Because the cracks are often developed by constrained shrinkage, the study presented in this paper try to demonstrate the efficiency of the model by including the variation of the porosity with or without shrinkage. Some experimental results were used to validate the proposal model. The challenge in this paper is to quantify the role of the porosity evolution on unsaturated permeability with suction and on the transfer mass across the columns of soils. The numerical results should give some guidelines to perform the tests of infiltration and evaporation of water across clayey soils in columns tests and quantify the time consuming. The consideration of cracks in the model across the porosity is a main additional originality of this paper.

Keywords: modelling, water transfer, unsaturated permeability, relative humidity, shrinkage, porosity, cracks.

Abbreviations: *WRC*: water retention curve, K_{unsat}: unsaturated permeability, m: matric, c: crack's zone, $K_{unsat(m)}$ unsaturated permeability of matric, $K_{unsat(c)}$ unsaturated permeability of cracked zone, *HR*: relative humidity.

I. INTRODUCTION

Since some tens of years, important and complex of experiences and theoretical models concerning the unsaturated soils, has been developed [2, 9]. The soil cracking due to wetting-drying hydraulic cyclesis one of the concerned topics. In fact, some of active soils such clays and silts are concerned by two opposite phenomena: the swelling under humidification and the shrinkage under drying. More recently, many researches were concerned with the cracks induced by constrained shrinkage and particularly with the characterization of cracks network (see for example, [19, 24]. However, few of studies which concerned with the water transfer by evaporation or infiltration, taking into account a realistic morphology of carks as the opening, length and orientations.

Krisnanto *et al.,* [16, 17] have studied the water flow across idealized cracks in a soil matric and proposed a model to study the lateral flow of cracked soil.

Due to the influences of environmental conditions, the in-situ investigations of the water content distribution und the suction profile in the soil under evaporation and drying are still useful. For this reason, several works have been developed in this direction [5, 23, 28].

For intact soils, one of the main experimental methods is the instantaneous profile which was often used in laboratory to interpret evaporation or infiltration of water in samples with reduced dimensions, which has not been considered as not convenient to use as a test in the field. In fact, more the high of the sample is important comparing to its diameter, the flow is not only happening in one direction but also it takes a long time and consequently the hydraulic equilibrium is not easily reached during a moderate duration of experiences. The same conclusions have been given from the field observations.

Despite the many existing experimental and numerical methods to measure and to predict the unsaturated soils properties and determination of suction and moisture content distributions for intact unsaturated soils, the cracks effect is still a challenging research topic, with many remaining questions about the measurement of unsaturated hydraulic properties in relation with the a size of the studied samples in laboratory and with the scale and the boundary conditions in the field.

Thus, the need for efficient model to predict these properties, having at the same time the capability to predict the moisture and the suction profiles under humidification and drying paths for cracked soils, has increased during the last few years [29].

Habitually some analytical models to link the water content to the suction (Water retention curve: WRC) and the unsaturated permeability (K_{unsat}) to the suction have been used in the fitting of experimental results and implemented in efficient algorithms [21], One of a largely model used was the van Genuchten, 1980 [27] which proposed an analytical equation of WRC using two independent parameters. This model was extended in order to assure the passage from WRC's equation to the unsaturated permeability function [13]. In the literature some other models to assure the passage from WRC to the unsaturated permeability have been proposed [11, 18].

From point of view of damage material, several works were interested in the modeling of unsaturated porous media, particularly for the porous rocks under high stresses for a brittle and under low stress for ductile ones [14]. The important conclusions can be draw up as following:

The permeability is related to the porosity and architectural structures of porous fabrics [26, 30, 31].

The current research in cracked rocks and soils demonstrated the link between the microstructure and the quantitative macroscopic parameters and engineering properties of such materials [3, 15]. It was well mentioned that the absolute porosity value and its distribution inside the rocks and soils affect strongly the mechanical and the hydraulic properties, as respectively strengths (compression, tensile and shear) and permeability. These cited researchers were more interested in the saturated permeability.

The micro-pore distribution was considered as another parameters which exerts a strong influence on mechanical and hydraulic parameters [3, 8, 12].

The fractal aspect of porous media help to describe the dependency of unsaturated permeability on the fractal pores [4, 10, 11, 32, 33] and also the water retention property [1, 22].

For some authors (see for instance [1,6,7], the SWCC of a cracked soil can be represented by a bimodal function due to the Air Entry Value (AEV) of the cracks being much lower than the AEV of the soil matrix.

It was also found that differences between the SWCC for cracked and intact soil appears only in the very low suction range, generally before 1500 kPa [20].

The first crack appears in general for suction more a lessthe air-entry value. The growth and propagation of cracks was happened in general for moderate suction range and stopped largely before reaching the residual suction [25].

Besides all the interesting and various results, few of researches which investigated clearly the role of the thickness of tested samples in the propagation of cracks. More than this, the diffusion of water content during evaporation or infiltration in cracked fine soils was not sufficiently studied. Also, the use of tests in column of fissured soil is yet complex to perform. Thus, using a numerical model, this paper investigates a one direction evaporation tests across different samples with different dimensions. The proposal model uses bimodal unsaturated permeability and water retention functions. It permits the prediction of water and suction profiles during evaporation time and permits to quantify the influence of the crack's characteristics -mainly the intensity factor and the depth of cracks- on these profiles' evolutions.

II. TESTED SAMPLES AND PERMEAMETER DEVICE

According to Unified Soil Classification System (USCS), the tested soil in the permeameter is a clay with high plasticity (liquid limit = 62%, Plasticity index = 32%). The grain size distribution is given in Fig. 1.

The permeameter device contained some confined cell where the sample was placed without confining, permitting a one direction flow (Fig. 2). In the tested sample, some hydrometers were placed laterally to measure the Relative humidity was measured and then the corresponding suction was computed using the Kelvin's law (Eq. 1).

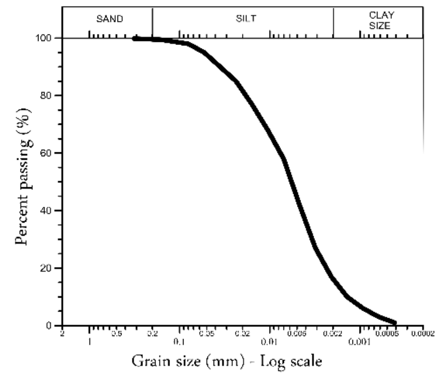

Fig. 1. Gain-Distribution curve.

$$\psi = -\rho_w \frac{RT}{M} \ln(RH) \qquad (1)$$

Where, ψ and RH are respectively the suction and the relative humidity; R is the universal gas constant = 8.3143J/(mol K); T is the absolute temperature (K); M is the molecular weight of water=18.016gr/mol; ρ_w is the density of water (gr/cm^3).

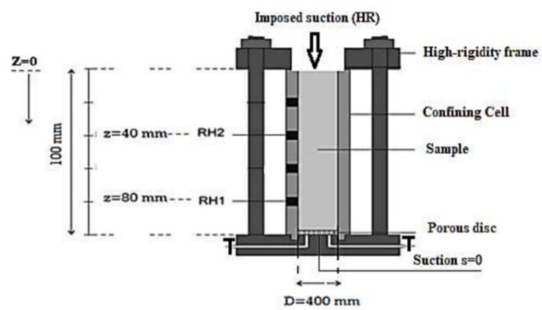

Fig. 2. Permeameter test to determine the unsaturated permeability of intact soil sample

III. MODELLING

A. Constitutive equations

Conventionally for unsaturated soils, Richard's Equation has been used to obtain the field of water content and/or the field of suction in nondeformable soils with time evolution (Eq. 2). However, under shrinkage or swelling the deformations of soil affect strongly these fields evolution. So, we propose here a simple but efficient extension of the Richard's equation by the implementation of two mainly ideas:

— The permeability is considered bimodal by introducing separately the fitting equation of intact soil and the fitting equation of permeability in a zone where the cracks are intensive.

— Under cracking, the soil is considered with double porosity. So, the macro-porosity depends on both volumetric shrinkage deformation and intensity factor (*CIF*).

$$C\frac{\partial(H)}{\partial t} + \nabla.(-K_{unsat}\ \nabla(H+z)) = 0 \qquad (2)$$

Where:

C : specific water capacity (m^{-1}), given by the relation $C = \frac{\partial(\theta)}{\partial t}$; θ is the gravimetric water content;

H : total head(m);

K_{unsat} : unsaturated permeability (m/s),
Z : vertical level (position) (m).
∇ is the gradient operator.
The water retention curve was given by the van-Genuchten as follow:

$$\theta = \theta_r + (\theta_s - \theta_r)(1+|\alpha s|^n)^{-m} \quad (3)$$

Where $\theta_s = 62\%$ and $\theta_r = 5\%$
The bimodal equation of *WRC*was shown as:

$$\begin{cases} \theta_{m,c} = (1-n_c)\theta_m(s) + n_c\theta_c(s) \text{ if } n_c \geq 0 \\ \theta_{m,c} = \theta_m(s) \text{ if } n_c \leq 0 \end{cases} \quad (4)$$

The bimodal equation of the unsaturated permeability is also given as:

$$\begin{cases} n_{total} = n_0 + n_c \\ n_c = CIF_v - \underbrace{\Delta n}_{shrinkage} \end{cases} \quad (5)$$

Where the is defined as volumetric cracks intensity factor:

$$CIF_v = \frac{(area\ of\ cracks).hc}{Total\ volume\ of\ the\ sample} \quad (6)$$

In this case the porosity variation according to equation (7a):

$$n_c = CIF_v - \underbrace{\Delta n}_{shrinkage} \quad (7a)$$

So, the total porosity is obtained as (Eq. 7b):

$$n = n_0 + n_c \quad (7b)$$

Where n_0 is the initial porosity.
We assume that the volumetric crack intensity factor CIF_v is defined as:

$$\begin{cases} (CIF)_{surf} = \frac{Air_{crak}}{Air_{tot}} \\ (CIF)_{Volum} = \frac{V_{crak}}{V_{tot}} = \frac{h_c * Air_{crak}}{h * Air_{tot}} \end{cases} \quad (8)$$

$$Where\ \frac{h_c}{h} = \alpha,\ (0 \prec \alpha \prec 1)$$

$$\Rightarrow (CIF)_{Volum} = \alpha(CIF)_{surf}$$

Where also n_0 the initial porosity, and Δn is the variation of porosity due to the shrinkage. Its relation is as follow (Eq. 9) and:

$$\Delta n = \frac{\Delta e}{(1+e)^2} \quad (9)$$

and using the shrinkage relation (Eq. 10):

$$e = a\,\theta + b \quad (10)$$

The unsaturated permeability is also considered as bimodal function (Eq.11)

$$K_{unsat(m,c)}(s) = (1-n_c)K_{unsat(m)}(s) + n_c K_{unsat(c)}(s) \quad (11)$$

The parameters are summarized in table 1. As it can be shown in this table, only the van-Genuchten parameters are fitted from experiences performed, to determine the WRC on intact soil samples (matric).
The proposal set of equations were implemented in the COMSOL software which uses the weak Galerkin formulation. So, the continuum medium was discretized in finite volume elements and consequently the unknown analytical solution is approached by an approximative numerical one obtained for the discrete equivalent medium. Because the unknown is a scalar variable, which is the total head, the number of freedom degrees is equal to the number of nodes. Fig. 3 gives an example of three-dimensional mesh used in the current simulations.
Fig. 4 gives the evolution of the unsaturated permeability as function of n_c and Δn (as the porosity variation due exclusively to the shrinkage). The influence of shrinkage on the unsaturated permeability is significant. Considering the fissures aperture, the decrease of total porosity was clearly rewarded.

Table 1: Parameters used in the implementation of the model.

Parameter	WRC for matric	WRC (for crack's zone)	$K_{unsat(m)}$ (for matric)	$K_{unsat(c)}$ (for crack's zone)	Shrinkage (matric)
K_{sat}(m/s)	-	-	2.10^{-9}	2.10^{-6}	
n	1.66	2.08	1.66	2.08	
m	0.4	0.519	0.4	0.519	
a	2.5	0.15	2.5	0.15	
a	-	-	-	-	2.57
b	-	-	-	-	0.12

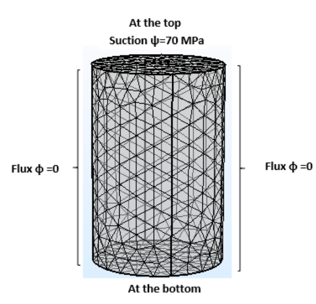

Fig. 3. Tridimensional mesh used in the numerical computing and boundary conditions.

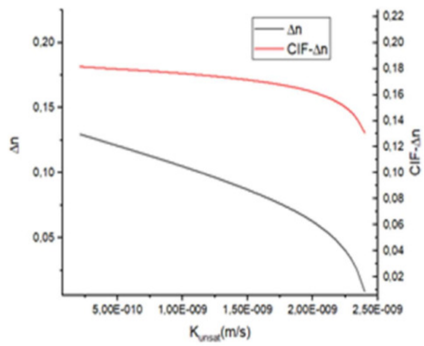

Fig. 4. Unsaturated permeability as function of porosity variation due to the shrinkage and due to the crack's growth.

B. Validation of the model

The validation of the proposal model was done as follow:

- The variation of the porosity *nc* by drainage was compared to *nc*, predicted using Eq. 7.
- the relative humidity (*HR*)measured by the two hydrometers (Fig. 2) were compared to predicted *RHs* using the constitutive model and Eq.1.

Fig. 5 gives the variation of the total porosity computed using equations (7a) and (7b).

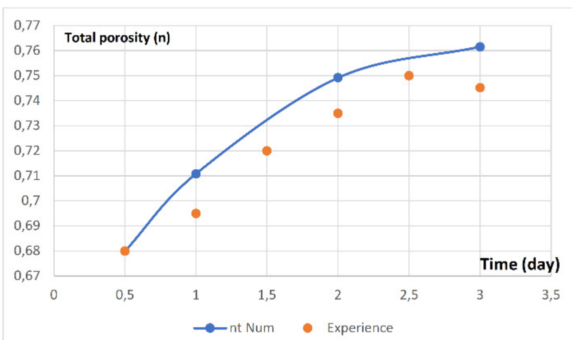

Fig. 5. Total porosity evolution under drying (including both shrinkage and crack's growth).

The comparison uses the data given by the two hygrometers (HR1 and HR2) located as it is indicated in Fig. 2 and numerical results. Figs. 6 and 7 give the trends of the relative humidity during evaporation. As it will be deduced from this comparison, the trend of HR as function of time, the capability of the model to reproduce the experience data is well highlighted.

As it can be expected, the relative humidity decreases under evaporation corresponding to the suction increase.

The validation of this model basing on the hygrometers data, gives a potential power to the proposal model to predict the relative humidity, the suction and then the gravimetric and volumetric water content profiles inside the soil columns.

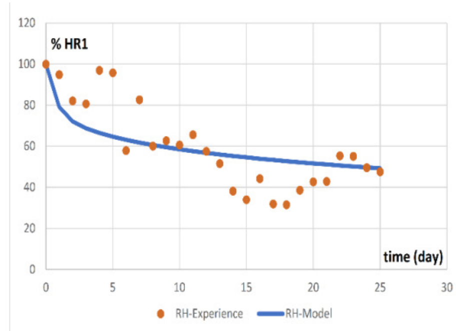

Fig. 6. Relative Humidity against time-evaporation (comparison at location of the first sensor HR1).

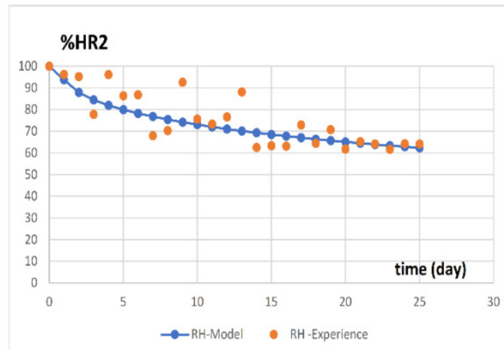

Fig. 7. Relative Humidity against time-evaporation (comparison at location of the first sensor HR2).

IV. RESULTS AND DISCUSSION: COLUMN TESTS

Different numerical simulations were performed on the columns considering two adding tests (cylindrical soil columns with a fixed diameter and high (*h*) respectively of 30cm and 60cm). The average gravimetric water content was computed for the different soil columns during the drying process (Fig. 8). For the clayey soil considered here in the experiences, the final duration of dying to reach the residual gravimetric water content of 5%, increases from 6days for sample with h=10cm, to 29 days for soil column with h=30cm and 50 days for h=60cm (Fig. 8).

So, it is clear that the numerical expertise quantifies the consuming time needed for each clayey sample depending on the high of soil column.

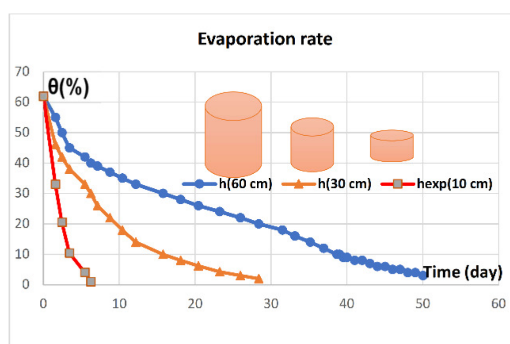

Fig. 8. Average Gravimetric water content against time-evaporation for different soil-columns.

To determine the profile of the gravimetric water content across the sample, two times were fixed which corresponded respectively to the half of CIF and maximum CIF. In fact, the CIF curve as presented in figure 9 corresponded to the area cracks measured using the image analysis from the top of sample of h=10cm.

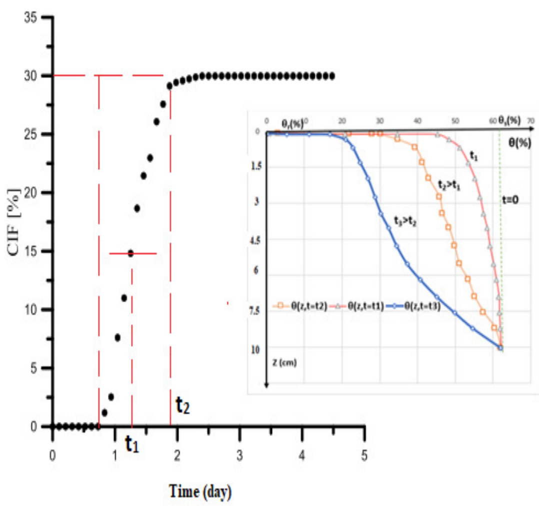

Fig. 9. Evolution of the area' intensity factor (experimental results).

Figs. 10 and 11 present the profiles of the gravimetric water content for respectively soil-columns of h=10cm and h=60cm.

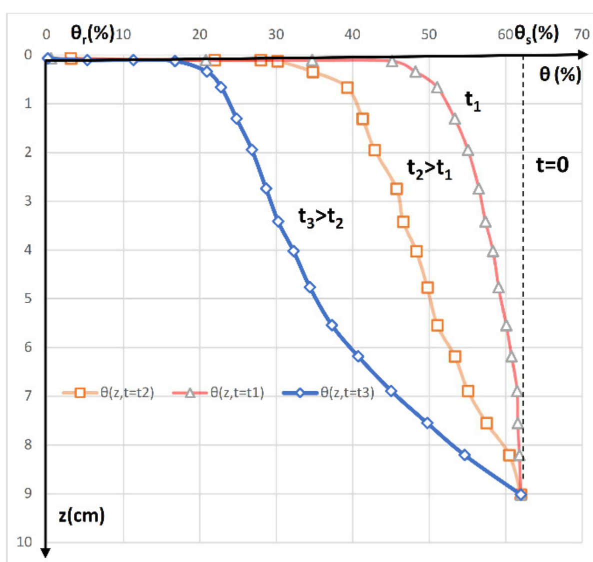

Fig. 10. Gravimetric water content profiles for three times in the total duration of drying (h=10cm), t1= 1.25 day, t2= 1.75 day, t3= 3 days.

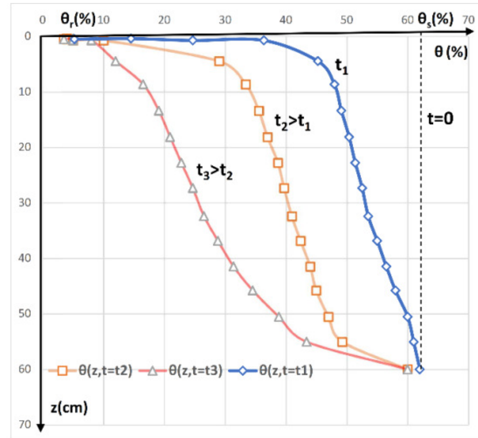

Fig. 11. Gravimetric water content profiles for three times in the total duration of drying (h=600cm), t1=5 days, t2= 7 days, t3= 12 days.

To simulate the effect of the crack's depth hc on the evolution of the average gravimetric water content during the time-evaporation (time-drying), simulations were performed considering three crack's depths, where a= 0.1; a= 0.2 and a= 0.5.

Fig. 12 shows the influence of depth of cracks which affects the duration of the evaporation to approach the value of residual water content of 5%. Obviously, more the depth hc is important (tends to the height of the sample), fastly it is the duration of evaporation. However, when the value of water content approaches the residual water content the effect of crack's depth is wiped out.

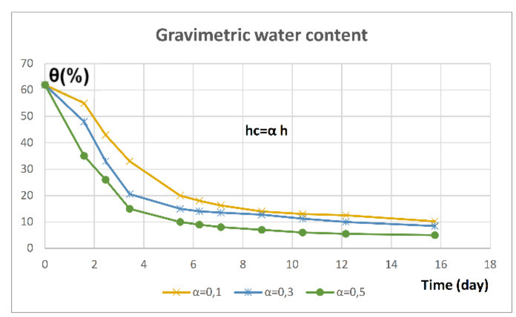

Fig. 12. Gravimetric water content profiles for three crack's depths (case of soil column with h=10cm).

V. CONCLUSION

This paper presents a hydraulic model for deformable soils by shrinkage. The constrained shrinkage induced a crack network which was quantified by the intensity factor CIF. Two intensity factors were introduced, the area and the volumetric CIF_{surf} and CIF_{volum}. The shrinkage deformation and the crack's growth affected the total porosity. Thus, the porosity was computed using the CIF measured by image analysis from the top of the samples in environmental chamber with relative humidity controlling and the shrinkage by measuring the volume change. Aiming to simulate more repetitive experiences and particularly resolve the difficulty to perform evaporation tests in soil-columns, proposal model is presented. This model including the variation of porosity and its influence on both water retention and unsaturated permeability, was tested and the results were compared with experiences, particularly in terms of the gravimetric water content and suction values. The good accordance between the numerical and experimental results gave an improvement to use the proposal model. Thus, this model was used to simulate the water content profiles and the duration kept to assure the total drying of soil-columns with different heights. This gives a guideline for the experiences to design with columns particularly for clay and silt.

The model can be extended to the open systems, such a case of evaporation of water from layers in the soil in the field.

VI. FUTURE SCOPE

The future scope is to study the cracks relation between network of cracks and size of samples, and their influence on the moisture water distribution. An application in the field to study a case study will be a future challenge.

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Conflict of Interest. Authors declare that there is no any conflict of interest associated to this study presented in this paper.

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