Numerical Modelling of Desiccation Cracking of Clayey Soil by Using Cohesive Fracture Method

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Abstract. This paper presents a numerical study on the desiccation cracking process of clayey soils. The initiation and propagation of cracks are investigated using a finite element code including damage-elastic cohesive fracture law to describe the behaviour of cracks. The coupling between the hydraulic behaviour (moisture transfers in the soil matrix and in the cracks) and the mechanical behaviour (volume change of the soil matrix and development of cracks) is also considered in the code. The results of laboratory test performed on a clay soil, taken from the literature review, are used to evaluate the numerical modelling. The results show that the code is able to reproduce the main trends observed experimentally (*i.e.* the shrinkage related to drying, cracks development).

Keywords: Unsaturated soil · Evaporation · Desiccation cracking · Cohesive fracture · Damage

1 Introduction

Desiccation cracking is a common phenomenon in soils and rocks. It involves a gradual moisture content reduction induced by evaporation from geo-material surface. The reduction of moisture content is accompanied by invading of air in the soil pores, increasing of suction and effective stress, and soil shrinkage. Shrinkage due to the desiccation from the soil surface in restrained condition (by frictional boundary condition, concentration of stress or heterogeneity of soil, *etc.*) induces an increase of tensile stress which generates the formation of cracks network when this stress reaches the tensile strength [1–3]. Due to the hydro-mechanical nature of formation and propagation of desiccation cracks, this process influences various soil properties: changes the permeability of soil, as well as the soil compressibility and decreases the mechanical strength. That could be one of the reasons for the instability of earth structure and becomes now a great challenge in engineering geotechnical domain. The hydro-mechanical coupling is one of the difficulties in the modelling of desiccation cracks that was neglected in various works.

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In the present work, a hydro-mechanical model is developed to simulate the desiccation cracking of a clayey soil using cohesive fracture method. Damage-elastic behaviour of cohesive fracture [4] was used to model the initiation and propagation of cracks. The FEM code Porofis [5], for POROus FISsured media, is used to simulate the laboratory desiccation tests reported by Sanchez et al. [6]. The results allow investigating not only the evolution of stress, strain and hydric state (suction, degree of saturation) at different locations in the soil specimen, but also the development of cracks during desiccation.

2 Gouverning Equations

This section presents briefly the governing equations of hydraulic and mechanical problems, more details can be found in [5, 7]. In the present model, the soil is represented as a homogenous porous medium containing a family of cohesive cracks. The volumetric forces and gravity effects are not considered in this study.

2.1 Cohesive Crack Representation

In the Finite Elements Method enriched by Joint elements (JFEM) used here, the cohesive crack elements are represented by 4-nodes interface elements. The joint elements are placed in the mesh on predetermined paths corresponding to potential crack propagation. For the mechanical problem, it is necessary to split the nodes on discontinuity lines and create joint elements in order to allow displacement discontinuities across fractures. But, in the hydraulic problem, at least for the fractures considered here with infinite transversal conductivity, and consequently with continuous pressure across the fracture, there is no need to split the nodes because the pressure has the same value on the two sides of the fracture. The specific mesh for this purpose is prepared with commercial tools GID and DISROC dedicated for meshing fractured media. One of the limitations of cohesive crack method is that the crack locations and pathways need to be predefined. However, this limitation can be addressed by proving a multiple unbiased potential crack with a high density and therefore the spacing between cracks will be minimised. This latter approach is chosen in the current work.

2.2 Hydraulic Behaviour

The hydraulic diffusion process in a homogeneous unsaturated porous material representing the soil is simulated. The flow in the soil around the cracks is governed by Darcy's law while the flow in the cracks is governed by the cubic law [8] and they satisfy the mass conservation condition. During desiccation, the suction evolution is related to the degree of saturation by the Van Genuchten model. The equation that allows determining the flow in the soil matrix with an assumption of incompressible fluid can be then written as follows:

$$div(\frac{k}{\rho g}\nabla p) = C_M \frac{\partial p}{\partial t} + r \tag{1}$$

with $C_M = S\left(\frac{1}{N} + \frac{\phi S'}{S}\right)$, $r = S\frac{\partial \varepsilon_v}{\partial t}$, k is the soil hydraulic conductivity, g is the gravity acceleration, N is the Biot modulus, S' is the derivative dS/dp calculated from the water retention curve.

For the cracks, the transversal conductivity between two crack walls is infinitely high. This implies that the pressure is continuous between two opposite faces of the crack and the pressure takes the same value p for a given point along the crack line. The equation, which allows calculating the pressure for every location $\underline{s}$ along the crack surface, can be written as below:

$$\nabla_s.(c\partial_s p) = r^{mf} + r^f \tag{2}$$

where $r^{mf} = \|\underline{v}\|.\underline{n}$; $r^f = \frac{\partial e}{\partial t}$,

In this equation, $\nabla_s.()$ designates the divergence in the crack. The fluid-crack mass exchanges are taken into account by the jump of fluid velocity across the crack $\|\underline{v}\|$ by presenting the discontinuity with values $\underline{v}^+$ and $\underline{v}^-$ for two faces of the crack. $\underline{n}$ is the normal unit vector to the fracture surface.

2.3 Mechanical Behaviour

For the mechanical problem, the initiation and the propagation of crack are modeled by placing the cohesive cracks represented by joint elements. The effective stress is formulated to describe the mechanical behavior of the soil matrix while the failure criterion of the cohesive cracks is based on total stress. In fact, if the cracks are considered as very big size pores, suction in these pores would be negligible, thus it is reasonable to consider their failure in terms of total stress. The continuity of total stress is ensured at the interface between the matrix element and the joint element.

The soil matrix is assumed to be an isotropic elastic linear material governing by the following equation:

$$\underline{\underline{\sigma}} + (Sp)\underline{\underline{\delta}} = \mathrm{C} : \underline{\underline{\varepsilon}} \tag{3}$$

The elastic damage of cohesive crack law [4] is used to describe the initiation and the propagation of cracks. In this model, a damage variable d is added in order to represent the process of damage through the decrease of crack stiffness and the evolution of yield surface. Under the effect of evaporation, the tensile stress increases with suction corresponding the increase of normal stress of cohesive cracks. The initiation of cracks could be considered as the breakage of bonds by degradation of the crack stiffness when the tensile stress reaches the tensile strength. The following equation is used to simulate the cohesive damage crack behavior:

$$\underline{\sigma} = (1 - d)\underline{\underline{R}}\underline{u} \tag{4}$$

where $\underline{\sigma}$ is the stress vector on the matrix/crack interface surface, $\underline{n}$ is the normal unit vector on this surface, $\underline{\underline{R}}$ is the crack stiffness tensor. The crack opening (e) changes with the deformation from the initial value e_0 to: $e = e_0 + u_n$ with u_n is the normal component of the displacement discontinuity u through two crack's wall.

2.4 Coupling Hydro-Mechanical

The coupling between the mechanical and the hydraulic problems is performed by a sequential resolution of both of the problems and the interactions between them. For each time increment, the hydraulic problem is calculated by solving the Eq. (1) and Eq. (2). The outputs correspond to the soil suction, degree of saturation and hydraulic conductivity of soil. These values are then used as inputs for the mechanical problem. For the matrix, the hydro-mechanical coupling Eq. (3) allows updating the effective stress in the soil matrix. For the cracks, the fluid pressure resulting from the resolution of the hydraulic problem is introduced in the mechanical problem Eq. (4) for calculating the crack opening. Reciprocally, the matrix and the cracks deformations resulting from the resolution of the mechanical problem are then introduced into the hydraulic problem through the source term r related to the volumetric strain of the matrix in Eq. (1) and r^f in Eq. (2) representing the crack opening evolution. Besides, the crack opening e is used to update the hydraulic conductivity of crack following the cubic law [8] which implies that when the crack is mechanically opened, its hydraulic conductivity increases quickly and potentially conducts more fluid through it.

3 Numerical Simulation

3.1 Geometry and Model Parameters

The hydro-mechanical finite element code presented above is used to simulate the desiccation experiments reported by Sanchez et al. [6]. In this test, a circular plate of organic silt (30% sand, 57% silt and 13% clay) of 100 mm in diameter and 13 mm in thickness was first prepared at the slurry state and then air-dried. By using the 2D profile laser technique, various soil characteristics (volume change, water loss, crack development, *etc.*) were observed during drying in that work.

In order to simulate this test, a 2D mesh with plane strain condition shown in Fig. 1 is used. Its width is equal to the diameter of the sample (100 mm) and its height is equal to the initial height of the sample (13 mm). The experimental observation showed that there are 4 cracks (for a typical cross section) after 24 h of drying and these cracks are propagated vertically in depth. As mentioned above, a great unbiased number of cracks and pathways can be introduced in FEM. The crack development will be dictated by the behaviour of the model. In the present work, in order to optimize the calculation cost while ensuring an adequate mesh density, 100 vertically oriented cohesive cracks were distributed regularly with a distance of *1* mm in the mesh (see Fig. 1). For the mechanical boundary conditions, the displacements at the bottom, the right and left sides are fixed while the top of the mesh (representing the soil surface) is free to move. For the hydraulic boundary conditions, no flux was allowed at the bottom, the right and left sides of the mesh. On the top of the mesh, a homogenous flux, calculated from the evaporation rate estimated from the test was imposed. This applied evaporation isn't constant and changes with the suction on the top surface as the following function:

$$\begin{cases} E_a = E_p & \text{if } |s| \leq |s_0| \\ E_a = E_p \exp[-\alpha(s - s_0)] & \text{if } |s| > |s_0| \end{cases} \quad (5)$$

where E_a is the actual applied evaporation; E_p is the potential evaporation rate which represents the evaporation capacity of the soil in a completely saturated condition, s is the actual suction at the surface and s_0 is a suction of the onset of the second phase in the evaporation process where the evaporation rate decreases quickly, α is a curve coefficient. The Table 1 presents the soil properties, cohesive crack parameters and evaporation condition used in the model.

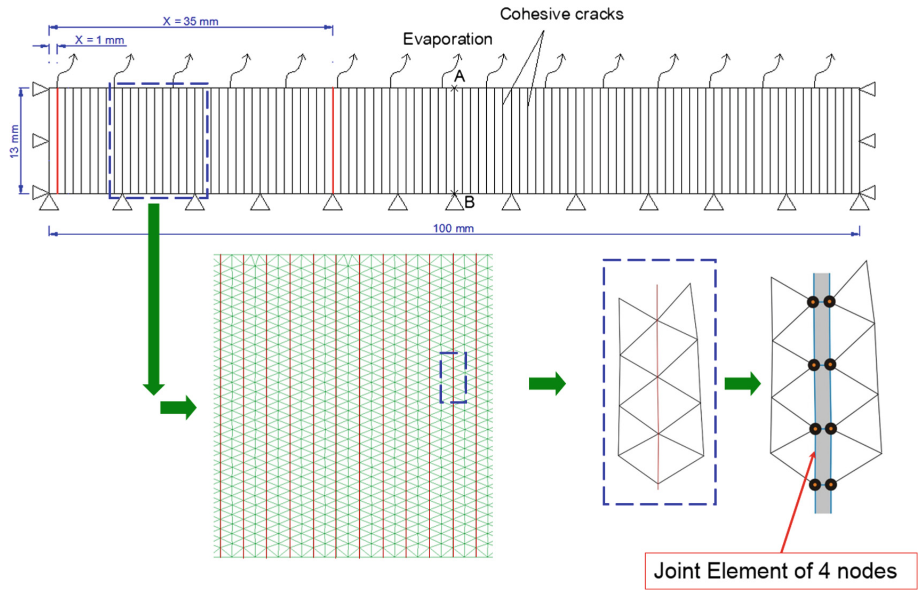

Fig. 1. Geometry and boundary condition

Table 1. Model parameters

Soil	E (MPa)	ν (−)	k_s (m/s)	Water retention curve (Van Genuchten model)				
				α (MPa^{-1})	n (−)	m (−)	S_r (−)	
	1	0.3	10^{-8}	9.81	1.60	0.375	0.02	
Crack	R_{tt} (MPa/mm)	R_{nn} (MPa/mm)	$R_{tn} = R_{nt}$ (MPa/mm)	σ_R (MPa)	C_{coh} (MPa)	φ (°)	β (−)	e_0 (mm)
	1	10000	0	0.09	0.08	30	1	10^{-3}
Desiccation rate	E_p (mm/h)	α (−)	s_0 (MPa)					
	0.3	1.857	0.3					

3.2 Results

The Fig. 2 presents the morphology evolution of the specimen during drying. It can be observed that the proposed model could reproduce two main phases observed in the experimental test. At the beginning of the test, only the settlement at the soil surface was observed without cracking (*i.e.* with t = 3 h). The two first cracks appeared close to the two lateral walls at t = 4 h. During the next 4 h, the opening of these cracks increased and no more cracks appeared. After t = 8 h, the crack network develops very quickly and, the cracks appear with the same spacing of around 6–10 mm (t = 9 and 10 h). At t = 12 h, the specimen presents 17 cracks while 100 cohesive joints were placed in the model.

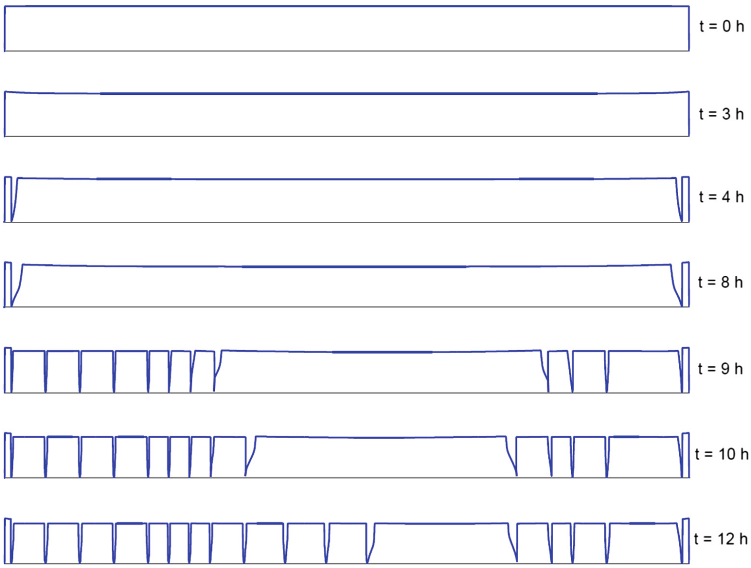

Fig. 2. Description of the cracks observed at various moments

The evolutions of suction measured at the top and at the bottom of the specimen (point A and point B in Fig. 1) are shown in Fig. 3*a*. It can be seen that the suctions at these two points are similar, showing that the suction is homogenous in the specimen during the drying test. After 12 h of drying, the soil suction reaches approximately to 0.3 MPa. The degrees of saturation calculated at these two points are also plotted in the Fig. 3*b*. It can be observed that these values are slightly lower than the average degree of saturation measured in the experiment. However, the trend observed on the numerical simulation is similar to the one observed in the experiment: a progressive decrease of degree of saturation during drying and the degree of saturation remains high after 12 h of drying.

Two families of cracks can be identified: (*i*) the two first cracks appear close to the boundary of the soil specimen in contact with the rigid mould, which is defined as lateral gap in the experimental work; (*ii*) the cracks develop in the middle of soil

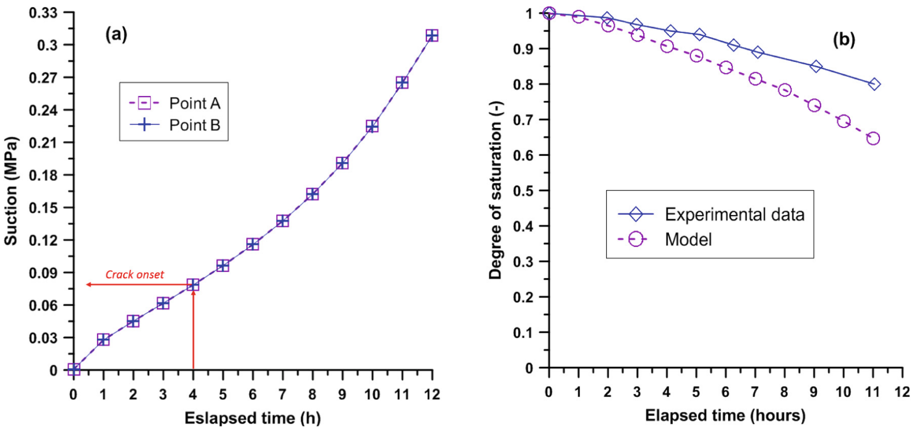

Fig. 3. (a) Suction and (b) Degree of saturation versus elapsed time. (Experimental data taken from [6])

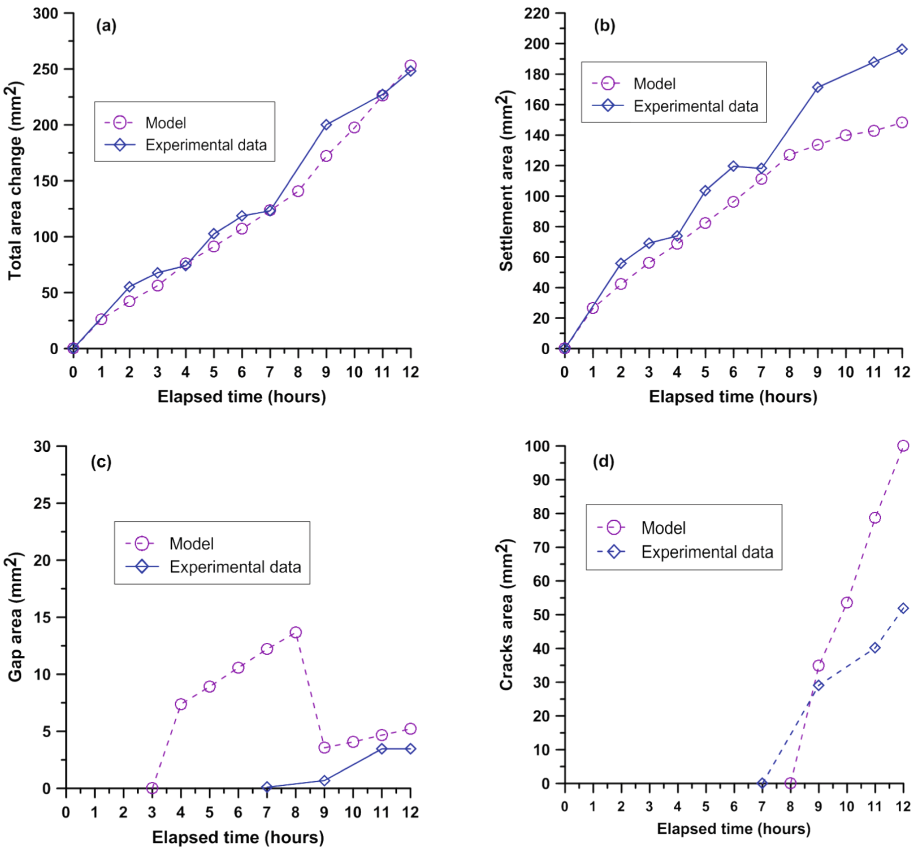

Fig. 4. Time evolution of different components of soil shrinkage: (a) Total; (b) Settlement; (c) Gap; (d) Cracks

sample, which is defined as "cracks" in the experimental work. In the experimental work, the 2D measured profiles were used to calculate the three components of soil shrinkage for a generic cross section: vertical displacement of the top surface (settlement), lateral shrinkage (gap), and cracks. These three components of the deformation mentioned above can be also determined in the simulation. The Fig. 4 presents the comparison between the numerical simulation and the experimental work for each shrinkage component. It can be seen that the results obtained by the model are in good agreement with the experimental data. In addition, it can be observed that at the beginning (t = 0–3 h), the shrinkage corresponds only to the settlement. For t = 3–8 h, the gap appears but its area remains small, and the total shrinkage area is still associated with the settlement. From t = 8 h, cracks appears quickly and there are an abrupt increase of cracks area. It can be concluded that the increase of crack area is the main cause of the total shrinkage area in this phase. Note that, in the experiment, drying was performed for 24 h while in the present work the simulation was stopped after 12 h. In the present work, a linear elastic mechanical behaviour of soil matrix is considered but this assumption is reasonable only when the soil strain remains small.

4 Discussion and Conclusions

In this study, a desiccation cracking experiment is simulated using a hydro-mechanical model where (*i*) the hydraulic diffusion under evaporation effect, (*ii*) the shrinkage of a soil sample and (*iii*) the initiation and the propagation of desiccation cracks, among others couplings, are considered. The diffusion equation includes the evolution of soil and crack hydraulic properties (degree of saturation, soil hydraulic conductivity and crack hydraulic conductivity, the mass exchange between soil matrix/cracks) and the deformation processes of the soil and the crack are equally taken into account. A finite element model, including cohesive fractures model, is used to simulate the development of cracks. The coupling between hydraulic and mechanical phenomena is performed by an iterative process passing from the hydraulic problem resolution to the mechanical problem resolution and vice versa.

A 2D plane strain model is used in the present work while the experiment was performed with a cylindrical specimen. The prime interest of this work is not a quantitative prediction of the experimental results, but a qualitative reproduction of the main trends and the crack development during drying. Various experimental studies in the literature show that the crack network would be different for the two cases: (*i*) for the case of a long bar (similar to the model in the present work) the cracks are formed successively and perpendicular to the long side of the specimen; (*ii*) for the case of a circular sample or a rectangular slab, the cracks can appear simultaneously or successively in order to create a cracks network. In the experimental work used to justify the present work, the evolution of a typical section is analysed. A 3D mesh would be then necessary to reproduce exactly the cracks pattern in this case. Even if the 3D crack pattern is not simulated in the present work, the result obtained in the 2D study allows improving the understanding on the shrinkage cracking mechanisms.

The model is able to reproduce correctly the main phases of the desiccation and the development of soil shrinkage versus elapsed time (Figs. 2, 4). At the beginning, the shrinkage is associated with settlement only. In the model, the settlement without cracking corresponds to the elastic phase of cohesive cracks in which the tensile stress increases with drying but remains smaller than the tensile strength. The damage phase begins when the tensile stress of cohesive cracks reaches the soil tensile strength and the crack is initiated. In the present work, the crack network appears quickly at t = 8.3 h. This time can be observed as the critical time in the development process of cracking. Li et al. [9] studied the desiccation cracks initiation and development at ground surface and showed that the desiccation cracks development in three stages: initial, primary and steady states. In the first stage, few cracks developed with gradually decreasing water content and a critical suction value exists for crack initiation, after which cracks appear and propagate quickly.

Despite some limitations, the results of numerical simulation show good agreement with the experimental data in terms of the hydraulic diffusion, the crack initiation, the shrinkage evolution and mostly the chronology of desiccation phases (settlement without cracking and then formation and propagation of cracks). The results of the present work indicate that the proposed hydro-mechanical coupled model using the cohesive fracture law for modelling of crack propagation can reproduce correctly the hydro-mechanical coupled phenomena related to shrinkage and crack formation during drying of clayey soils.

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