Computer Simulation of 3D Desiccation Cracks in Soils

M.A. Maedo & M. Sánchez
Zachry Department of Civil Engineering, Texas A&M University, USA

O.L. Manzoli
Department of Civil Engineering, São Paulo State University, Brazil

L. Guimarães
Department of Civil Engineering, Federal University of Pernambuco, Brazil

ABSTRACT: Cracks due to the drying process in soils have been a theme of interest over the past few years. The phenomenon of cracking in soils increases the permeability of the material and reduces its strength, which may lead a civil infrastructure to failure. Desiccation cracking in soils is a very complex problem that still needs to be properly addressed. In this paper, the desiccation cracks phenomenon is studied by considering a mesh fragmentation methodology, which considers that finite elements with high aspect ratio (*i.e.* interface elements) are responsible to reproduce the crack behaviour. An orthotropic damage model, which can emulate the orthotropic behaviour between distinct materials, is presented in this work. The main ingredients required to develop the constitutive models are presented. Therefore, in order to show that the technique is capable of reproducing desiccation cracks in soils, the drying test of a soil sample prepared in slab plates was model by using the presented technique. The crack patterns obtained from the numerical analyses were compared with the experimental ones. The results showed that the technique is able to reproduce the behaviour of dryings cracks in soils.

1 INTRODUCTION

Drying cracks in soils have been a subject of interest over the last few years. In geotechnical engineering, desiccation cracks affect the slope stability by increasing its permeability, which can degrade the strength properties of the soil (Baker 1981). In geoenvironmental engineering, barriers of slow permeability are used to contain the contamination of soil and groundwater (Kodikara and Choi 2006). The presence of cracks also impacts the performance of irrigation operations (Miller et al. 1998). To design and build more economical and safer geostructures it is essential to have a better understanding of the processes behind the formation and propagations of drying cracks in soils. In spite of the increasing volume of work related to the subject, it is still difficult to reproduce the actual 3D crack networks observed in drying soils.

Experimental and numerical works have been developed to understand the crack formation when soils are exposed to specific conditions. Laboratory tests of slurry samples subject to different conditions and with different geometries have been performed in order to comprehend the main aspects involved in the problem (Corte and Higashi 1964; Peron et al. 2009). Scaled laboratory tests, which are able to reproduce environmental conditions, have also been conducted to study the actual morphology of drying cracks (Jones et al. 2012).

In this work, solid finite elements with high aspect ratio (*i.e.* also called interface elements), which are inserted between the regular elements of the mesh during the pre-process, are used to simulate the formation and propagation of cracks (Manzoli et al. 2014, 2016; Sánchez et al. 2014). Such elements can also mimic the orthotropic behaviour between distinct materials, depending on the damage model chosen. The constitutive models of the interface elements are developed entirely in the context of continuum damage mechanics, which tends to a discrete constitutive relation as the aspect ratio increases. Therefore, the elements with high aspect ratio can be used to represent discontinuities. This technique has been called mesh fragmentation technique and the main-steps related to the insertion of interface elements in the pre-process are shown in Figure 1.

The paper is organized as follows: first, the nonlinear constitutive models used in the interface elements are presented. Afterwards, some key aspects of the analysed case are discussed (e.g. material properties, adopted mesh, and boundary conditions). Then, the crack patterns obtained from the numerical simulations are presented and compared with the experimental ones. Finally, the main conclusions from this study are explained.

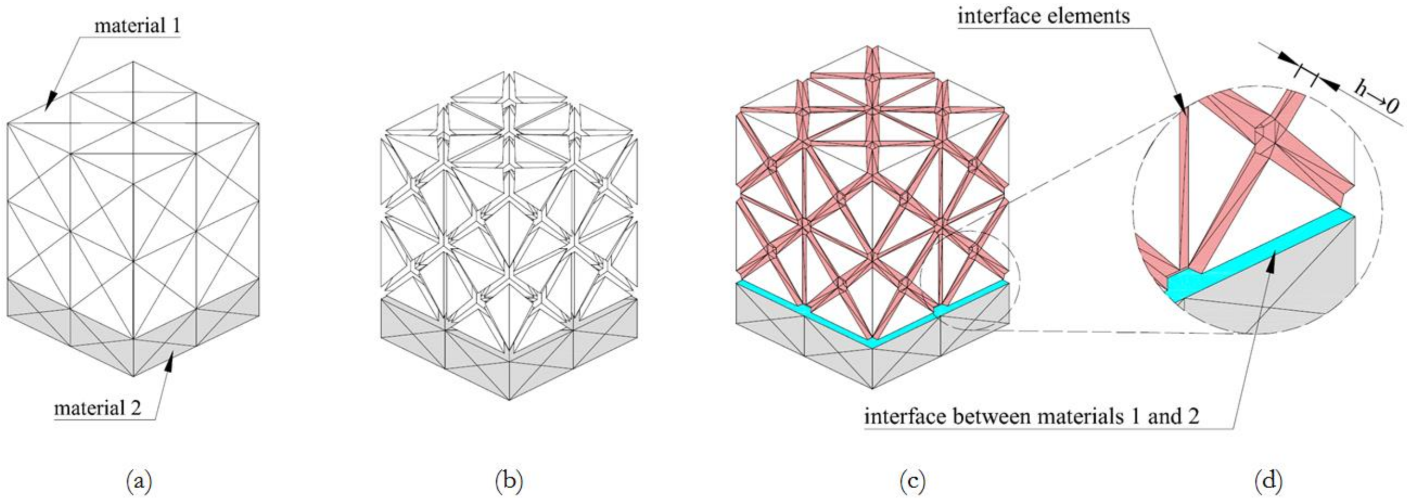

Figure 1. Main steps associated with the mesh fragmentation technique: (a) original finite element mesh; (b) the material 1 of the mesh is fragmented by separating its elements, which creates gaps between the bulk elements; (c) elements with high aspect ratio are used to fill the gaps between the bulk elements; (d) zoom showing the detail all the new elements inserted in the mesh.

2 DAMAGE MODELS

The damage constitutive models for the interface elements are presented below. But first, the kinematics of the interface elements (*i.e.* elements with high aspect ratio) is described to show that they can be used to represent strong discontinuities.

2.1 *Elements with high aspect ratio*

Let us consider a four-node tetrahedral finite element with height h, which is the distance between node 1 and its projection on the plane that contains the area A, as shown in Figure 2. Manzoli et al. (2016) showed that the strain tensor can be split into two parts as follows:

$$\boldsymbol{\varepsilon} = \tilde{\boldsymbol{\varepsilon}} + \underbrace{\frac{1}{h}\left(\mathbf{n} \otimes [\![\mathbf{u}]\!]\right)^s}_{\hat{\boldsymbol{\varepsilon}}} \tag{1}$$

where the components of $\tilde{\boldsymbol{\varepsilon}}$ depends on A and the components of $\hat{\boldsymbol{\varepsilon}}$ depends on h; $(\bullet)^s$ is the symmetric part of $(\bullet)$, $\otimes$ denotes the dyadic product,

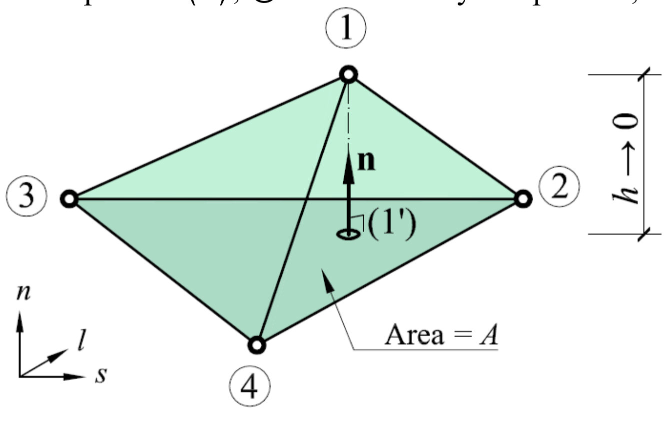

Figure 2. Four-node tetrahedral finite element

$[\![\mathbf{u}]\!]$ is the relative displacement between the node 1 and its projection on the plane that contains A and $\mathbf{n}$ is the unit vector normal to this plane.

Taking the limit as $h \to 0$, the components of $\boldsymbol{\varepsilon}$ are almost exclusively described by the relative displacement $[\![\mathbf{u}]\!]$, which becomes the measure of displacement discontinuity (Manzoli et al. 2012, 2014, 2016).

2.2 *Tensile damage model*

The constitutive equation of the tensile damage model used to describe the crack formation is:

$$\boldsymbol{\sigma} = (1 - d)\bar{\boldsymbol{\sigma}} \tag{2}$$

where $\bar{\boldsymbol{\sigma}} = \mathbf{C} : \boldsymbol{\varepsilon}$ is the effect stress tensor, d is the damage variable, $\mathbf{C}$ is the fourth order elastic tensor and $\boldsymbol{\varepsilon}$ is the strain tensor.

The damage criterion can be written in terms of the stress component that is normal to the base of the element:

$$\phi = \sigma_{nn} - q(r) \le 0 \tag{3}$$

or in terms of the effective stress as:

$$\bar{\phi} = \bar{\sigma}_{nn} - r \le 0 \tag{4}$$

The evolution of the stress-like internal variable is described by an exponential softening law of the form:

$$q(r) = f_t e^{\frac{f_t^2}{G_f E} h \left(1 - \frac{r}{f_t}\right)} \tag{5}$$

where E is the Young's modulus, f_t is the tensile strength and G_f is the mode I fracture energy of the soil.

2.3 *Orthotropic interface model*

In order to mimic the orthotropic behaviour of the interface region between the soil and the plate, the following orthotropic damage model was developed, in which the stress tensor is given by:

$$\boldsymbol{\sigma} = \bar{\boldsymbol{\sigma}}_{nsl} + (1-d_s)\bar{\boldsymbol{\tau}}_s + (1-d_l)\bar{\boldsymbol{\tau}}_l \tag{6}$$

where $d_s \in [0,1]$ and $d_l \in [0,1]$ are the damage variables and $\bar{\boldsymbol{\sigma}}_{nsl}$, $\bar{\boldsymbol{\tau}}_s$, and $\bar{\boldsymbol{\tau}}_l$ are effective stress tensors expressed as follows

$$\bar{\boldsymbol{\sigma}}_{nsl} = \begin{bmatrix} \bar{\sigma}_{nn} & 0 & 0 \\ 0 & \bar{\sigma}_{ss} & \bar{\sigma}_{sl} \\ 0 & \bar{\sigma}_{sl} & \bar{\sigma}_{ll} \end{bmatrix} \tag{7}$$

$$\bar{\boldsymbol{\tau}}_s = \begin{bmatrix} 0 & \bar{\sigma}_{ns} & 0 \\ \bar{\sigma}_{ns} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{8}$$

$$\bar{\boldsymbol{\tau}}_l = \begin{bmatrix} 0 & 0 & \bar{\sigma}_{nl} \\ 0 & 0 & 0 \\ \bar{\sigma}_{nl} & 0 & 0 \end{bmatrix} \tag{9}$$

Two damage criteria are required to simulate the orthotropic behaviour between distinct materials. Therefore, it is possible to specify that a given material has a smaller strength in a specific direction and is strong in another direction. These damage criteria can be written in terms of the strain-like internal variables, r_s *and* r_l, as

$$\bar{\phi}_s = \|\bar{\sigma}_{ns}\| - r_s \leq 0 \tag{10}$$

$$\bar{\phi}_l = \|\bar{\sigma}_{nl}\| - r_l \leq 0 \tag{11}$$

Analogous to the damage criteria, the following two damage evolution rules are also needed in the model:

$$d_s(r_s) = 1 - \frac{q_s}{r_s} \tag{12}$$

$$d_l(r_l) = 1 - \frac{q_l}{r_l} \tag{13}$$

where q_s and q_l are stress-like internal variables.

Thus, the loading-unloading condition expressed by the Kuhn-Tucker relations can be defined as

$$\bar{\phi}_{s,l} < 0, \quad \dot{r}_{s,l} > 0, \quad \dot{r}_{s,l}\bar{\phi}_{s,l} = 0 \tag{14}$$

and the consistency condition is

$$\dot{r}_{s,l}\dot{\bar{\phi}}_{s,l} = 0 \ \text{ if } \ \bar{\phi}_{s,l} = 0 \tag{15}$$

The explicit evolution law for the strain-like internal variable can be obtained from equations (10), (11), (14) and (15). Thus,

$$r_s = \max_{\tau\in[0,t]}\left[\|\bar{\sigma}_{ns}(\tau)\|, q_{s0}\right] \tag{16}$$

$$r_l = \max_{\tau\in[0,t]}\left[\|\bar{\sigma}_{nl}(\tau)\|, q_{l0}\right] \tag{17}$$

Equations (16) and (17) states that r_s and r_l reach the maximum value associated with the elastic stresses obtained during the loading-process, starting from the initial value of q_{s0} and q_{l0}, which are material properties. The stress-like internal variables are considered to be constant:

$$q_s(r_s) = q_{s0} = \beta_s \tag{18}$$

$$q_l(r_l) = q_{l0} = \beta_l \tag{19}$$

where β_s and β_l are the cohesive bond strengths of the soil-plate interface in directions s and l, respectively

3 APPLICATION CASE

The desiccation test performed by Péron et al. (2009) was simulated in order to show the capability of the technique to describe crack propagation and the orthotropic behaviour between the plate and the soil. In their experiment, a slurry soil was placed upon metallic support with parallel notches (grooves) as shown in Figure 3. Then, the soil samples were exposed to a controlled suction to initiate the drying process. Figure 3 shows the geometry, boundary conditions of the problem and crack pattern when the grooves were also considered. It is worthwhile to mention that in this work the grooves were not inserted, but an interface formed by elements with high aspect ratio were considered to model the soil-plate contact. Two studies were conducted: the first one assumes that the soil-plate contact exhibit an isotropic behaviour while the second assumes soil-plate contact with an orthotropic behaviour.

Table 1 contains all the material properties for the soil, plate, soil-soil and soil-plate interfaces used to simulate the formation of cracks during drying.

The mesh is composed by 73048 nodes and 128853 tetrahedral elements, in which 24741 are bulk elements (soil and plate) and 104112 are interface elements.

The soil (i.e. finite elements with soil material properties) was submitted to volumetric strains to represent the drying process, since the water mass balance equation was not considered.

Figures 4(a) and 4(b) show the crack pattern when the soil-plate interface is isotropic and orthotropic, respectively. Figure 5 shows photographs of final crack patterns of three samples tested by Péron

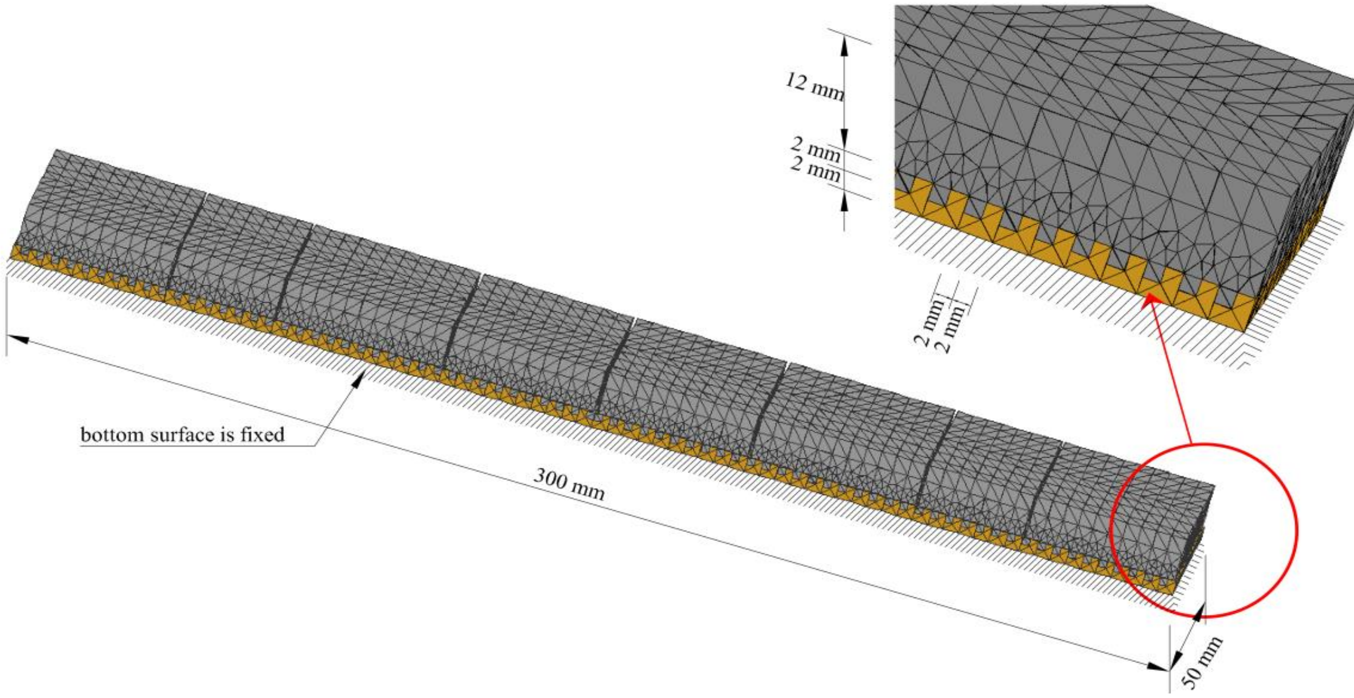

Figure 3. Geometry, boundary conditions and crack pattern of the soil sample prepared on a slab plates.

et al. (2009). By comparing the numerical result obtained with the orthotropic damage model in the interface (Figure 4(b)) with the experimental one (Figure 5), it can be seen that the technique was able to reproduce the crack pattern in accordance with the experimental test. However, the model predicts much more extensive development of irregular cracks than the experiment. Furthermore, some cracks do not propagate fully across the width of the slab in a linear manner. This occurs due to the use of unstructured meshes, which avoid alignments that could induce the formation of cracks (Manzoli et al. 2016). Therefore, unstructured meshes produces irregular cracks, although it prevents the formation of cracks developed due to the aligned of the structure meshes. In addition, crack patterns are usually not linear or aligned (Figure 5)

Table 1. Material properties

Soil (bulk) – Elastic	
Young modulus (MPa)	4.0
Poisson's ratio	0.2
Plate – Elastic	
Young modulus (MPa)	210×10^3
Poisson's ratio	0.2
Soil-soil interface – Tensile damage	
Young modulus (MPa)	4.0
Poisson's ratio	0.0
Tensile strength (kPa)	4.0
Soil-plate interfaces – Isotropic model	
Young modulus (MPa)	4.0
Poisson's ratio	0.0
Cohesive bond strength in *s*-direction (kPa)	3.2
Cohesive bond strength in *l*-direction (kPa)	3.2
Soil-plate interfaces – Orthotropic model	
Young modulus (MPa)	4.0
Poisson's ratio	0.0
Cohesive bond strength in *s*-direction (kPa)	0.96
Cohesive bond strength in *l*-direction (kPa)	3.2

4 CONCLUSIONS

A technique that consists in using finite elements with high aspect ratio to describe the crack formation and also to emulate the orthotropic behaviour between distinct geo-materials was presented. This method is entirely defined in terms of continuum mechanics concepts, and therefore, no remeshing scheme or special integration algorithm is needed. Moreover, the cracking process is governed by the geometry, boundary conditions and material properties of the material and there is no need of knowing the crack pattern a priori.

The drying test on saturated clay prepared in slab plates was model by using the proposed technique.

The crack pattern obtained from the numerical simulation shows a good agreement with the experimental one. In addition, the orthotropic model can also be used as an isotropic model by only configuring the parameters, without the need of changing the model. This was also proven by analysing the crack formation using the proposed model to simulate the isotropic soil-plate interface.

5 ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support from the National Council for Scientific and Technological Development (CNPq, proc. 234003/2014-6).

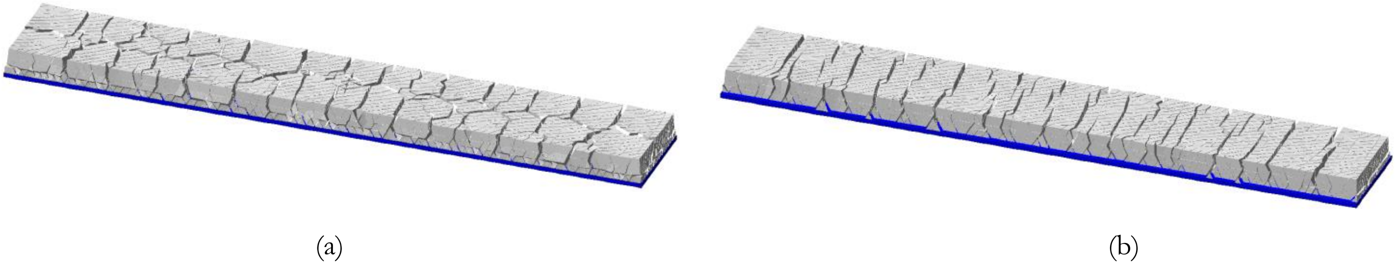

Figure 4. Crack pattern of the slab specimen, assuming: (a) an isotropic interface model; (b) an orthotropic interface model for the soil-plate interface.

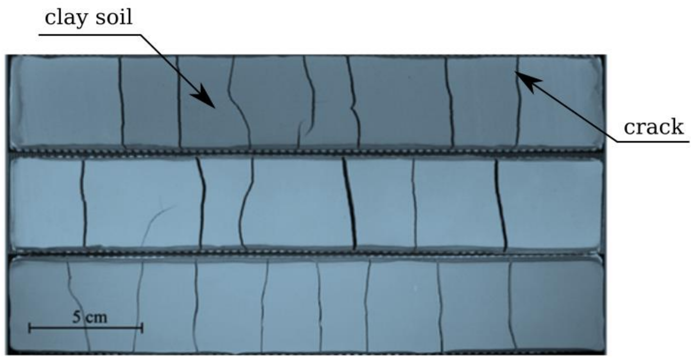

Figure 5. Experimental crack pattern obtained by Péron *et al.* (2009) during the drying test.

REFERENCES

Baker, R. 1981. Tensile strength, tension cracks, and stability of slopes. *Soils and foundations* 21(2): 1-17.

Corte, A. & Higashi, A., 1964. Experimental research on desiccation cracks in soils (No. RR-66). *Cold Regions Research and Engineering Lab Hanover NH*.

Jones, G., Zielinski, M. & Sentenac, P., 2012. Mapping desiccation fissures using 3-D electrical resistivity tomography. *Journal of Applied Geophysics* 84: 39-51.

Kodikara, J.K. & Choi, X., 2006. A simplified analytical model for desiccation cracking of clay layers in laboratory tests. *In Unsaturated Soils 2006*: 2558-2569.

Manzoli, O.L., Gamino, A.L., Rodrigues, E.A. & Claro, G.K.S., 2012. Modeling of interfaces in two-dimensional problems using solid finite elements with high aspect ratio. *Computers & Structures 94*(3): 70-82.

Manzoli, O.L., Maedo, M.A., Rodrigues, E.A. & Bittencourt, T.N., 2014. Modeling of multiple cracks in reinforced concrete members using solid finite elements with high aspect ratio. Bicanic et al., editors. *Computational Modeling of Concrete Structures* 1(1): 383-92.

Manzoli, O.L., Maedo, M.A., Bitencourt, L.A. & Rodrigues, E.A., 2016. On the use of finite elements with a high aspect ratio for modeling cracks in quasi-brittle materials. *Engineering Fracture Mechanics* 153(3): 151-170.

Miller, C.J., Mi, H. & Yesiller, N., 1998. Experimental analysis of desiccation crack propagation in clay liners. *JAWRA Journal of the American Water Resources Association*, 34(3): 677-686.

Péron, H., Hueckel, T., Laloui, L. & Hu, L., 2009. Fundamentals of desiccation cracking of fine-grained soils: experimental characterisation and mechanisms identification. *Canadian Geotechnical Journal* 46(10):1177-1201.

Sánchez, M., Manzoli, O.L. & Guimarães, L.J., 2014. Modeling 3-D desiccation soil crack networks using a mesh fragmentation technique. *Computers and Geotechnics* 62: 27-39.