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► **To cite this version:**

Thi Dong Vo, Amade Pouya, Sahar Hemmati, Anh Minh A.M. Tang. Numerical modelling of desiccation cracking of clayey soil using a cohesive fracture method. *Computers and Geotechnics*, 2017, 85, pp.15-27. 10.1016/j.compgeo.2016.12.010 . hal-01515964

**HAL Id: hal-01515964**

**<https://enpc.hal.science/hal-01515964>**

Submitted on 10 May 2017

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1 **Numerical modelling of desiccation cracking of clayey soil using a cohesive**  
2 **fracture method**

3  
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29 **Abstract.** This paper presents a numerical study on the desiccation cracking process of clayey  
30 soil. The initiation and propagation of cracks were investigated using finite element code,  
31 including the damage-elastic cohesive fracture law to describe the behaviour of cracks. The  
32 coupling between the hydraulic behaviour (moisture transfer in the soil matrix and in the  
33 cracks) and the mechanical behaviour (volume change of the soil matrix and development of  
34 cracks) were also considered. The results of a laboratory experiment performed on clay soil,  
35 taken from a literature review, were used to evaluate the numerical modelling. The results  
36 show that the code can reproduce the main trends observed in the experiment (*e.g.*, shrinkage  
37 related to drying, crack development). In addition, the numerical simulation enables the  
38 identification of other phenomena, such as the evolution of suction and stress related to drying  
39 and the development of a single crack. These phenomena are difficult to observe  
40 experimentally.

41 Key words: suction, evaporation, desiccation cracking, cohesive fracture, damage

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## 51        **1. Introduction**

52        Desiccation cracking is a common phenomenon in soils and rocks. It involves a gradual  
53        moisture content reduction induced by evaporation from a geomaterial surface. This reduction  
54        in moisture content is accompanied by the invasion of air into the soil pores, increases in  
55        suction and the effective stress, and soil shrinkage. Shrinkage due to desiccation from the soil  
56        surface in restrained conditions (by frictional boundary conditions, concentration of stress or  
57        heterogeneity of soil) causes an increase in tensile stress, which induces the formation of crack  
58        networks when the stress reaches the tensile strength ([1]–[6]).

59        Due to the hydro-mechanical nature of the formation and propagation of desiccation cracking,  
60        this process influences various soil properties. On one hand, cracks change the permeability of  
61        soil from the hydraulic point of view. On the other hand, desiccation cracking changes the soil  
62        compressibility and decreases the mechanical strength, which could be one of the reasons for  
63        the instability of earth slopes ([7]–[9]).

64        The problem of desiccation cracking in soil has been studied using both experimental and  
65        theoretical approaches. Laboratory experimental studies ([5][10][11][12]) have mainly focused  
66        on the behaviour of clayey soil when drying specimens from a saturated state. The results  
67        demonstrate the effect of specimen dimensions, boundary conditions, soil properties, and  
68        drying conditions on the formation, propagation process and morphology of the crack network.  
69        Desiccation cracking has also been observed in situ ([13][14]), where the characteristic  
70        geometry of cracks, such as depth, thickness, density, spacing, and aperture, under the actual  
71        drying conditions were investigated. The results show that the onset of cracking depends on the  
72        mineralogy of the soil, the climatic conditions (temperature, relative humidity, rainfall), and  
73        the canopy. Following Li & Zhang ([13]), crack development can be described in three stages:  
74        initial, primary, and steady state. In the initial stage, few cracks develop with gradually  
75        decreasing water content. When the water content reaches a critical value for crack initiation,

76 cracks being to develop quickly, corresponding to the start of the primary stage. As the water  
77 content approaches the shrinkage limit of the soil, cracks develop slowly and reach a steady  
78 state.

79 Using numerical methods, the initiation and the propagation of cracks have been studied based  
80 on the theory of linear elastic fracture mechanics (LEFM), discrete element method (DEM),  
81 and finite elements method (FEM) with or without cohesive fracture and interface elements.

82 The propagation of cracks in solids has been studied using LEFM [15] to explain the  
83 magnitude of the depth and the spacing between desiccation cracks. This theory has been  
84 extended to unsaturated soil ([2][16][17]) to predict the optimal depth of cracks, which is a  
85 function of the suction profile and various soil properties (e.g., tensile strength, elastic  
86 modulus, Poisson's ratio, density). Konrad & Ayad [18] used LEFM to analyse the propagation  
87 of desiccation cracks of clays under evaporation. They used the principle of the effective stress  
88 distribution [3] to take into account the distribution of stress in soil and proposed the concept  
89 of virtual stress superposition to predict the average spacing between primary cracks. LEFM  
90 considers the propagation of only one individual crack and neglects the interaction between  
91 various cracks. In addition, LEFM assumes linear elastic soil behaviour; the nonlinearity that  
92 may be present in desiccation is thus ignored.

93 DEM, which considers the soil as an assemblage of discrete elements, has good potential for  
94 the simulation of desiccation cracking and was used in previous studies ([19]–[22]). Most  
95 active clay particles gather in elementary small structures called aggregates, which in turn  
96 gather in larger aggregates at various scales ([23][24]). In DEM, the clay soil is represented as  
97 an assemblage of aggregates linked by bonds, and the aggregates are simplified as spherical  
98 grains or other geometries [21]. The drying shrinkage kinetics of clay aggregates can be  
99 simulated by applying an explicit relationship between the size of the grains and the drying  
100 duration (or the water content). As the soil dries, the contact stiffness and tensile strength of the

101 aggregates increase with increasing suction. Crack initiation corresponds to the irreversible  
102 breakage of this bond when the magnitude of the traction (or shear) force exceeds the normal  
103 (or shear) contact bond strength. In addition, the non-linear behaviour of soil can be simulated  
104 by introducing the dependences of the soil properties on suction ([19][21][22]). Simulations  
105 have enabled the investigation of the effects of the soil sample dimensions, the interface  
106 between soil/mould, and soil shrinkage parameters on the development of desiccation cracks.  
107 More recently, Hirobe & Oguni [25] proposed a model that uses FEM to simulate hydraulic  
108 diffusion and PDS-FEM (particle discretisation scheme finite element method) to solve the  
109 mechanical problem of the formation of cracks. In this model, the elasticity and fracturing  
110 behaviour are modelled using the discretisation method, which uses a pair of conjugate  
111 geometries (Voronoi and Delaunay tessellations) to estimate the displacement and strain fields.  
112 A fracture propagates along the Voronoi cell boundaries as hydro-mechanical stress evolves  
113 and exceeds the prescribed material strength. This method was used to reproduce the  
114 morphology of the crack network and the evolution of the desiccation process. The principle of  
115 this work is similar to that of Asahina et al. [26]. Both demonstrated the influence of the  
116 specimen's thickness on the spacing of the formed cracks. Despite its efficiency to simulate  
117 desiccation cracks, DEM is considered more pertinent for the specimen scale than the structure  
118 scale.

119 Soil desiccation has been studied using FEM in previous research ([27]–[29]), but the  
120 development of cracks (which involves discontinuity in the medium) was not considered. For  
121 this reason, cohesive fracture and interface elements are usually introduced in FEM code to  
122 simulate the formation and propagation of cracks during desiccation. In the work of Sanchez et  
123 al. [30], joint elements were embedded like interface elements in the boundary of tetrahedral  
124 solid elements; the cracks propagated along the boundary of these solid elements. In this  
125 numerical analysis, the effect of evaporation was introduced as the volume shrinkage of solid

126 elements, and the simulation could be observed as purely mechanical. The prime interest of  
127 this work was not to precisely reproduce the experimental observations but to determine the  
128 ability of the proposed numerical technique to qualitatively capture the main trends and the  
129 crack morphologies observed for different shapes, thicknesses and desiccation conditions.  
130 Amarasiri & Kodikara [31] used cohesive cracks with a softening law that evolves during  
131 desiccation when a crack is partially open. The model reproduced the number of cracks  
132 developed with the moisture content evolution during a desiccation test but the desiccation  
133 process with hydro-mechanical coupling was not considered.

134 In the present work, a hydro-mechanical model was developed to simulate the desiccation  
135 cracking of clayey soil using a cohesive fracture method. The damage-elastic behaviour of  
136 cohesive fracture [32] was used to model the initiation and propagation of cracks. The FEM  
137 code POROFIS [33], for POROUS FISSURED media, was used to simulate the laboratory  
138 desiccation tests reported by Sanchez et al. [11]. The results enabled the investigation of the  
139 evolution of the stress, strain and hydric state (suction, degree of saturation) at different  
140 locations in the soil specimen and the development of cracks during desiccation.

## 141 **2. Governing equations**

142 This section briefly presents the governing equations of hydraulic and mechanical problems;  
143 more details can be found in [32]–[34]. In the present model, soil is represented as a  
144 homogenous porous medium containing a family of cohesive cracks. For the hydraulic  
145 problem, the body can be subjected to pressure or flux boundary conditions. For the  
146 mechanical problem, the body can be subjected to stress or displacement applied on its surface.  
147 Other volumetric forces and gravity effects are not considered for this problem. The flow and  
148 displacement fields in the body have to satisfy these boundary conditions and the constitutive  
149 equations detailed below.

## 150 **2.1. Cohesive crack representation**

151 In the finite elements method enriched by joint elements (JFEM) used here, the cohesive crack  
152 elements are represented by 4-node interface elements introduced by Goodman (1976) [35] for  
153 modelling rock joints. The joint elements are placed in the mesh on predetermined paths  
154 corresponding to potential crack propagation. For the mechanical problem, it is necessary to  
155 split the nodes on discontinuity lines and create joint elements to allow displacement  
156 discontinuities across fractures. However, in the hydraulic problem, at least for the fractures  
157 with infinite transverse conductivity considered here, and so with continuous pressure across  
158 the fracture, there is no need to split the nodes because the pressure has the same value on the  
159 two sides of the fracture. The specific mesh for this purpose is prepared using commercial tools  
160 (GID and DISROC) that are dedicated to meshing fractured media.

161 One of the limitations of the cohesive crack method is that the crack locations and pathways  
162 need to be predefined. However, this limitation can be addressed by using a multiple unbiased  
163 potential crack with a great density to minimise the spacing between cracks. This approach is  
164 chosen in the current work.

165 In this model, cohesive cracks are simulated as elements of zero thickness with a very small  
166 normal hydraulic conductivity and high stiffness at the beginning. For the mechanical  
167 behaviour of joint elements, the cohesive fracture law [32] is applied. A damage variable  $D$  is  
168 added to represent the process of damage through a decrease in the crack stiffness and the  
169 evolution of the yield surface. Under the effect of evaporation, the tensile stress increases with  
170 suction, corresponding to the increase in the normal stress of cohesive cracks. The initiation of  
171 cracks can be considered as the breakage of bonds through the degradation of the crack  
172 stiffness when the tensile stress reaches the tensile strength.

173



174 **2.2. Hydraulic behaviour**

175 The flow in the soil around cracks is governed by Darcy's law and satisfies the mass  
176 conservation condition. To establish hydraulic diffusion, the fluid mass  $m_f$  is calculated in  
177 unit volume:

178 
$$m_f = \rho\phi S, \quad (1)$$

179 where  $\phi$  is the porosity,  $\rho$  is the fluid density and  $S$  is the degree of saturation of the  
180 medium. For a saturated medium,  $S = 1$ , and the pore pressure  $p$  takes positive values.

181 The soil suction  $s$  is the difference between the gas (vapor and air) pressure  $p_g$  and the fluid  
182 pressure  $p$  in the pore space:

183 
$$s = p_g - p \quad (2)$$

184 In the present work, gas pressure is zero. This means that in the unsaturated state,  $s = -p$ . By  
185 extending the pressure values to the negative domain, it is possible to represent, by a unique  
186 variable  $p$ , the pressure in the saturated state  $p \geq 0$  and the suction in the unsaturated  
187 condition  $p < 0$ . Upon drying, the degree of saturation  $S$  is related to suction through the  
188 water retention curve, expressed by the function  $S = f(p)$ , based on the Van Genuchten  
189 model [36]:

190 
$$\frac{S - S_{res}}{1 - S_{res}} = \frac{1}{(1 + (\alpha p)^n)^m}, \quad (3)$$

191 where  $S_{res}$  is residual degree of saturation and  $\alpha$ ,  $n$  and  $m$  are soil parameters.

192 The equation to determine the flow in the soil matrix with an assumption of incompressible  
193 fluid can be then written as follows [37,33]:

194 
$$\text{div}\left(\frac{k}{\rho g} \nabla p\right) = C_M \frac{\partial p}{\partial t} + r, \quad (4)$$

195 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 acceleration  
 196 due to gravity,  $N$  is the Biot modulus,  $S'$  is the derivative  $dS / dp$  calculated from the water  
 197 retention curve, and  $\varepsilon_v$  is the volumetric deformation. The hydraulic conductivity  $k$  decreases  
 198 during drying and is simulated as follows:

$$199 \quad k = k_s \left( \frac{S - S_{res}}{1 - S_{res}} \right)^3, \quad (5)$$

200 where  $k_s$  represents the soil hydraulic conductivity in the saturated state.

201 For cracks, the transverse conductivity (between the two crack walls) is considered as infinite  
 202 in the model, which implies that there is no pressure difference between two opposite walls of  
 203 the crack, i.e., the pressure has the same value on both faces. It could also be represented by  
 204 only one value of  $p$  at a given point along the crack line. The flow in the cracks is governed  
 205 by the cubic law with the isotropic tangent conductivity of cracks (parallel to crack walls)  
 206 denoted by  $c$ , which can be related to crack opening  $e$  and fluid viscosity  $\mu$  through the  
 207 following relation [38]:

$$208 \quad c = \frac{e^3}{12\mu} \quad (6)$$

209 The equation to calculate the pressure for every location  $\underline{s}$  along the crack surface can be then  
 210 written as:

$$211 \quad \nabla_s \cdot (c \partial_s p) = r^{mf} + r^f, \quad (7)$$

212 where  $r^{mf} = \|\underline{v}\| \cdot \underline{n}$  and  $r^f = \frac{\partial e}{\partial t}$ .

213 In this equation,  $\nabla_s \cdot ()$  designates the divergence in the crack. The velocity  $\underline{v}$  must be related  
 214 to the flow in the matrix and can be discontinuous, with values  $\underline{v}^+$  and  $\underline{v}^-$  for the two faces of

215 the crack. The term  $\|\underline{v}\| = [\underline{v}^+ - \underline{v}^-]$  represents the velocity discontinuity or the jump across  
 216 the crack surface, which expresses the fluid mass exchange between the crack and the  
 217 surrounding matrix, and  $\underline{n}$  is the unit vector normal to the fracture surface. In Eq. (7), the  
 218 source term  $r^f$  represents hydro-mechanical coupling and  $r^{mf}$  represents mass exchange  
 219 between the matrix and the crack.

### 220 **2.3. Mechanical behaviour**

221 The mechanical behaviour of the soil matrix is formulated in terms of the effective stresses  
 222 while the failure criterion of the cohesive cracks is based on the total stress. If the cracks are  
 223 considered as very large pores, the suction in these pores is negligible, so it is reasonable to  
 224 model their failure in terms of the total stress. This is in agreement with experimental  
 225 observations ([19][22]), which show a small effect of the water content on the tensile strength  
 226 of soils. This small effect is neglected in the present work. At the interface between the matrix  
 227 element and the joint element, the continuity of the total stress is ensured.

228 The soil matrix is assumed to be an isotropic elastic linear material, and the relation between  
 229 the effective stress and strain is expressed by the following equation:

$$230 \quad \underline{\underline{\sigma}} = C : \underline{\underline{\varepsilon}} - Sp\underline{\underline{\delta}}, \quad (8)$$

231 where  $\underline{\underline{\sigma}}$  is the total stress,  $C$  is the elasticity tensor,  $\underline{\underline{\varepsilon}}$  is the strain tensor and  $\underline{\underline{\delta}}$  is the  
 232 identity matrix.

233 The elastic damage of the cohesive crack law is applied using the following equation:

$$234 \quad \underline{\underline{\sigma}} = (1 - D)\underline{\underline{R}}\underline{\underline{u}} - b_f p \underline{\underline{n}}, \quad (9)$$

235 where  $\underline{\underline{\sigma}}$  is the stress vector on the matrix/crack interface surface,  $\underline{\underline{n}}$  is the normal unit vector  
 236 on this surface,  $\underline{\underline{u}}$  is the displacement discontinuity through this surface,  $\underline{\underline{R}}$  is the crack  
 237 stiffness tensor,  $b_f$  is Biot's coefficient of cracks and  $D$  is the damage variable. The

238 coefficient  $b_f$  is related to the ratio of the contact surfaces between the two walls of the crack  
 239 to the total crack surface. A value of  $b_f=1$  means the whole pressure in the crack is applied as  
 240 mechanical action on the walls, which corresponds to the case of a totally damaged crack,  
 241 without a bridge between the walls. When there is no damage ( $D = 0$ ),  $b_f = b_0$  should be very  
 242 small.  $b_f$  increases with  $D$  and reaches 1 for  $D = 1$ . We express this relationship using the  
 243 following law:

$$244 \quad b_f = b_0 + (1 - b_0)D \quad (10)$$

245 The crack aperture ( $e$ ) changes with the deformation from the initial value  $e_0$  to:

$$246 \quad e = e_0 + u_n, \quad (11)$$

247 where  $u_n$  is the normal component of  $u$ . The evolution of the damage variable  $D$  affects both  
 248 the crack stiffness and the yield surface. The yield criterion is defined by a hyperbolic surface  
 249 in the stress space, which corresponds to the following expression [32]:

$$250 \quad F(\sigma, D) = \tau^2 - \sigma_n^2 \tan^2 \varphi + 2g(D)\sigma_c\sigma_n - g^2(D)C^2, \quad (12)$$

$$251 \quad \text{with: } \sigma_c = \frac{C_{\text{coh}}^2 + \sigma_R^2 \tan^2 \varphi}{2\sigma_R},$$

252 where  $\tau$ ;  $\sigma_n$  are the tangential and normal stresses of the joint,  $C_{\text{coh}}$  is the cohesion of the  
 253 intact (undamaged) joint,  $\varphi$  is the friction angle,  $\sigma_R$  is the tensile strength of the intact joint  
 254 and  $\beta$  is a coefficient representing the material's ductility.

255 The function  $g(D)$  in Eq. (12) is defined such that the tensile strength, which is  $\sigma_R$  for the intact  
 256 interface element, tends to zero for the totally damaged element:

$$257 \quad g(D) = (1 - D)(1 - \beta \ln(1 - D))$$

258 The damage evolution law in the cohesive fracture model [32] is given by the following  
 259 relation:

$$\begin{cases} D = 0 & \text{for } u_n < u_0 \\ D = 1 - e^{-\frac{(u_n - u_0)}{\beta u_0}} & \text{for } u_n \geq u_0 \end{cases}, \quad (13)$$

261 where  $u_0 = \frac{\sigma_R}{R_{nn}}$  is the elastic displacement limit, and  $R_{nn}$  is the normal component of the  
262 joint stiffness.

#### 263 **2.4. Hydro-mechanical coupling**

264 The coupling between the mechanical and the hydraulic problems is performed through  
265 sequential resolution of the two problems and the interactions between them. The schematic  
266 view, shown in Fig. 1, represents the hydro-mechanical coupling for desiccation cracking  
267 phenomena as resolved by POROFIS. For each time increment, the hydraulic problem is  
268 calculated by solving Eq. (4) and Eq. (7). The outputs correspond to the soil suction, degree of  
269 saturation and hydraulic conductivity of soil. These values are then used as inputs for the  
270 mechanical problem. For the matrix, hydro-mechanical coupling (Eq. (8)) allows updating of  
271 the effective stress in the soil matrix. Numerically, this coupling is performed by introducing  
272 the term “free deformation”, denoted by  $\underline{\underline{\varepsilon}}^L$  in Eq. (8), under the form:  $\underline{\underline{\sigma}} = C : (\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^L)$ , in  
273 which  $\underline{\underline{\varepsilon}}^L = C^{-1}(Sp\underline{\underline{\delta}})$ . For the elastic linear isotropic model, this free deformation can be  
274 calculated as a function of the elasticity modulus  $E$  and the Poisson’ ratio  $\nu$ :

$$\underline{\underline{\varepsilon}}^L = \frac{(1-2\nu)}{E} Sp\underline{\underline{\delta}}.$$

276 problem (Eq. (7)) is introduced in the mechanical problem (Eq. (9)) to calculate the crack  
277 opening. Reciprocally, the matrix and the crack deformation resulting from the resolution of  
278 the mechanical problem are then introduced into the hydraulic problem through source term  
279  $r$ , which is related to the volumetric strain of the matrix (Eq. (4)), and  $r^f$ , representing the  
280 crack opening evolution (Eq. (7)). In addition, the crack opening  $e$  is used to update the  
281 hydraulic conductivity of the crack (Eq. (6)). This coupling implies that as soon as the crack is

282 mechanically opened, its hydraulic conductivity increases quickly and potentially conducts  
283 more fluid through it.

### 284 **3. Numerical simulation**

285 The hydro-mechanical finite element code presented above was used to simulate the  
286 desiccation experiments reported by Sanchez et al. [11]. In this test, a 100 mm diameter and 13  
287 mm thick circular plate of organic silt (30% sand, 57% silt and 13% clay) was prepared in a  
288 slurry state and then air-dried. By using a 2D profile laser technique, various soil  
289 characteristics (e.g., volume change, water loss, and crack development) were observed during  
290 drying.

291 To simulate the experiments, various data related to the tested materials were collected to  
292 determine the parameters used in the numerical model. Fig. 2 shows the water retention curve  
293 obtained for the same soil but from a compacted specimen [39]. The degree of saturation at low  
294 suction (0.001 MPa) is still significantly lower than 1 because of hysteresis. Therefore, the  
295 water retention curve used in the present work starts in the saturated state ( $S = 1$ ) for the lowest  
296 suction. Various works have found that desiccation cracks initiate at soil suction close to the  
297 air-entry value ([5][12]). The experimental data indicated an air-entry value of approximately  
298 100 kPa, so the model was fitted to the experimental data around this value. The parameters  
299 selected for the water retention curve (Eq. 3) were then:  $\alpha = 9.81 \text{ MPa}^{-1}$ ,  $n = 1.60$ , and  
300  $m = 1 - 1/n = 0.375$

301 The soil compressibility was estimated following the oedometer compression curve obtained  
302 on the same soil but in a compacted state [40]. The volumetric strain for these data is plotted  
303 versus the vertical stress for the studied soil (Fig. 3). In the present work, the soil  
304 compressibility parameters were chosen ( $E = 1 \text{ MPa}$  and  $\nu = 0.3$ ) to fit the experimental data in

305 the low stress range (up to 0.3 MPa), which should be the range of suction corresponding to the  
306 crack development.

307 The hydraulic conductivity in the saturated state,  $k_s = 10^{-8} m/s$ , was selected following the  
308 method proposed by Mesri et al. [41], which estimates the hydraulic conductivity of fine-  
309 grained soils from the void ratio, clay fraction and soil activity.

310 As explained above, the cohesive crack law was used to model the formation and propagation  
311 of desiccation cracks. The cohesive crack parameters influence the behaviour of the model,  
312 and its determination plays an important role. Several studies indicated that desiccation  
313 cracking occurs mainly in mode I ([15][16][18]). Amarasiri & Kodikara [42] presented results  
314 of fracture tests performed on beams of compacted clay at various moisture contents. A bi-  
315 linear cohesive crack law was used to model the development of bridging stress across an  
316 opening crack, which progressively decreased from the tensile strength to zero as the two  
317 faces separated. The properties of the cohesive crack (e.g., fracture energy, tensile strength,  
318 and crack opening at which the normal cohesive stress drops to zero) were determined by  
319 back-analysis. In the present work, the main parameters of a cohesive crack are: normal  
320 component of the joint's stiffness tensor  $\underline{\underline{R}} (R_m)$ , tensile strength  $\sigma_R$ , and initial crack  
321 thickness  $e_0$ . The tensile strength  $\sigma_R$  was chosen close to the air-entry value at which the  
322 crack initiated, as suggested by Peron et al.[5], Tang et al. [12], and Shin & Santamarina [43].  
323 The initial values of the normal stiffness  $R_m$  were set sufficiently high and that of the  
324 hydraulic conductivity (related to the initial thickness  $e_0$ ) was set sufficiently small to have  
325 negligible effects on the global elasticity and permeability of the model before cracking. The  
326 parameter  $\beta$  corresponds to the ductility of material and can be fitted from the experimental  
327 curves [44]. In this work, it was set equal to 1, which indicates that the tensile stress of the  
328 fracture starts to decrease at the onset of damage. The parameters  $C_{coh}$  and  $\varphi$  do not affect

329 mode I crack propagation, which is the case of the present work. However, these parameters  
330 must satisfy the inequality  $C_{\text{coh}} / \tan \varphi > \sigma_R$  for the hyperbolic surface. Therefore,  $C_{\text{coh}}$  was set  
331 to  $C_{\text{coh}} = 1.5\sigma_R \tan \varphi$ . Table 1 summarises the main parameters of soil and cohesive cracks  
332 used in the simulation.

333 To simulate the test performed, a 2D mesh in the plane strain conditions shown in Fig. 4 was  
334 used. Its width was equal to the diameter of the sample (100 mm), and its height was equal to  
335 the initial height of the sample (13 mm). The experimental observation showed were 4 cracks  
336 (for a typical cross section) after 24 hours of drying, and these cracks propagated vertically in  
337 depth. As mentioned above, in POROFIS, a large unbiased number of cracks and pathways can  
338 be introduced. Crack development is dictated by the behaviour of the model. However, in the  
339 present work, to optimise the calculation cost by always ensuring adequate mesh density, 100  
340 vertically oriented cohesive cracks were distributed regularly with a spacing of  $d = 1 \text{ mm}$  in the  
341 mesh (see Fig. 4).

342 For the mechanical boundary conditions, the displacements at the bottom, the right and left  
343 sides were fixed, while the top of the mesh (representing the soil surface) was free to move.  
344 For the hydraulic boundary conditions, no flux was allowed at the bottom, right and left sides  
345 of the mesh. On the top of the mesh, homogenous flux, calculated based on the evaporation  
346 rate estimated from the test, was imposed. The details of the determination of this flux are  
347 given below.

348 The experimental observation of soil water evaporation ([45]–[48]) from the saturated state  
349 generally indicated three main phases. The first phase corresponds to a constant evaporation  
350 rate with elapsed time. In this phase, suction develops slowly, and the soil remains in a  
351 saturated state. In the second phase, the evaporation rate decreases rapidly and soil suction  
352 increases significantly. In the last phase, the evaporation rate reaches the residual value, which



353 depends on the soil characteristics. In the present work, the evaporation rate was imposed on  
 354 the top of the mesh as a function of the suction calculated at the soil surface (see Fig. 5). To  
 355 obtain the experimental data plotted in this figure, the relationship between the evaporation rate  
 356 and the average degree of saturation of the soil specimen in the experiment was calculated  
 357 from the experiment (Fig. 5a). Then, by combining this information with the water retention  
 358 curve (Fig. 2), the relationship between the evaporation rate and soil suction was determined  
 359 (Fig. 5b). The actual evaporation rate ( $E_a$ ) was calculated based on the soil suction at the  
 360 surface, as expressed below:

$$361 \quad \begin{cases} E_a = E_p & \text{if } |s| \leq |s_0| \\ E_a = E_p \exp[-\alpha(s - s_0)] & \text{if } |s| > |s_0| \end{cases} \quad (14)$$

362  
 363 where  $E_p$  is the potential evaporation rate, which represents the evaporation capacity of soil  
 364 under completely saturated conditions,  $s$  is the actual suction at the surface,  $s_0$  is a suction of  
 365 the onset of the second phase in the evaporation process, and  $\alpha$  is a curve coefficient. Wilson  
 366 et al. [46] measured the actual evaporation rate using a drying column test. The evaporation  
 367 rate evolution showed that the first phase had a constant evaporation rate of 8 mm/day. During  
 368 the second phase, a slight decrease in the evaporation rate began when the sand surface became  
 369 visually dry. This corresponds to a water content at the sand surface of slightly less than 2%;  
 370 thus, the suction corresponding to this water content on the water retention curve was  
 371 approximately 0.5-0.6 MPa. Moreover, Wilson et al. [49] found that the actual rate of  
 372 evaporation began to decline when the value of the total suction exceeded approximately 3  
 373 MPa. This conclusion was obtained from three tested soils: clay, silt, and sand.

374 In the present work, the parameters selected by assuming the exponential form of evaporation  
 375 evolution (Eq. (14)) and by fitting the experimental curve were:  $E_p = 0.3 \text{ mm/h}$ ,  $\alpha = 1.857$  and  
 376  $s_0 = 0.3 \text{ MPa}$ . Note that  $s_0 = 0.3 \text{ MPa}$  corresponds to an average degree of saturation  $S = 0.5$

377 (following the water retention curve, see Fig. 2), which corresponds to the beginning of the  
378 decrease in the evaporation rate during drying (see Fig. 5a).

#### 379 **4. Results**

380 Fig. 6a presents the morphology of the specimen during drying. This figure is plotted from the  
381 numerical results in Fig. 6b, where the distribution of horizontal displacement was equally  
382 added. The proposed model reproduced the main phases observed in the experimental test. At  
383 the beginning of the test, only settlement at the soil surface was observed without cracking  
384 (*i.e.*, with  $t = 3$  h). The two first cracks appeared close to the two lateral walls at  $t = 4$  h. During  
385 the next 4 h, the aperture (opening) of the cracks increased and no more cracks appeared. After  
386  $t = 8$  h, the crack network developed very quickly and, the cracks appeared with the same  
387 spacing of approximately 6-10 mm ( $t = 9$  and 10 h). At  $t = 12$  h, the specimen had 17 cracks  
388 and 100 cohesive joints were placed in the model. The evolution of suction measured at the top  
389 and at the bottom of the specimen (point A and point B in Fig. 4) is shown in Fig. 7a. The  
390 suction at these two points was similar, indicating that the suction was homogenous in the  
391 specimen during the drying test. In addition, when the first crack appeared (at  $t = 4$  h), the soil  
392 suction was approximately 0.08 MPa, smaller than the air-entry value of 0.1 MPa. The suction  
393 corresponding to the rapid development of several cracks (at  $t = 8 - 9$  h) was approximately 0.2  
394 MPa. After 12 h of drying, the soil suction reached approximately 0.3 MPa. The degree of  
395 saturation calculated at these two points is also plotted in Fig. 7b. These values were slightly  
396 lower than the average degree of saturation measured from the experiment. However, the trend  
397 observed in the numerical simulation was similar to that observed from the experiment: a  
398 progressive decrease in the degree of saturation during drying with the degree of saturation  
399 remaining high after 12 h of drying.

400 In the experimental work, the measured 2D profiles were used to calculate the three  
401 components of soil shrinkage for a generic cross section: vertical displacement of the top  
402 surface (settlement), lateral shrinkage (gap), and cracks (see Fig. 8). This process made it  
403 possible to determine the three components of the deformation mentioned above from the  
404 simulation. The results of the simulation are shown in Fig. 9. At the beginning ( $t = 0 - 3$  h), the  
405 shrinkage corresponds only to settlement. For  $t = 3-8$  h, a gap appears, but its area remains  
406 small, and the total shrinkage area is still related to settlement. From  $t = 8$  h, cracks appear  
407 quickly, and there is an abrupt increase in crack area. The increase in crack area is the main  
408 cause of shrinkage area in this phase. In the experiment, drying was performed for 24 h, while  
409 in the present work, the simulation was stopped after 12 h. Additionally, the mechanical  
410 behaviour of the soil matrix is linearly elastic in this work. This assumption is reasonable only  
411 when the soil strain remains small.

412 In addition to the evolution of the soil parameters, which can be experimentally observed, the  
413 numerical simulation enables in depth analysis of the processes related to crack opening. Two  
414 families of cracks can be identified: (i) the two first cracks appear close to the boundary of the  
415 soil specimen in contact with the rigid mould, which is defined as the lateral gap in the  
416 experimental work; and (ii) the cracks develop in the middle of soil sample, which is defined as  
417 “cracks” in the experimental work. The mechanisms related to the opening of these two  
418 families are shown separately in Figs. 10-13.

419 Fig. 10 presents the isochrones of the normal stress, damage variable and opening of all joint  
420 elements along the line of the gap on the left side ( $X = 1$  mm). At the beginning ( $t < 3.505$  h),  
421 the tensile stresses of these joint elements increase gradually during drying, but they remain  
422 smaller than the tensile strength  $\sigma_R = 0.09$  MPa ; thus, no damage occurs. At  $t = 3.505$  h, the  
423 tensile stress of some joint elements on the top surface approaches the soil tensile strength (Fig.

424 10a). The elastic limit is reached and the damage phase begins. At this moment, the crack  
425 remains closed at the top, no opening of the crack is observed (see Fig. 10c) and the sample  
426 shows only settlement without cracking. For the next step ( $t = 3.510$  h), some joint elements on  
427 the top surface ( $Y > 12$  mm) are completely damaged, *i.e.*, their damage variable reaches its  
428 maximum value (equal to 1) (Fig. 10b). This total damage relaxes the normal stress of these  
429 joint elements (Fig. 10a). The bridge between the two surfaces of the crack is considered to be  
430 completely broken, and the crack is opened from the surface to its extremity. Fig. 10a shows  
431 that there is a stress singularity in the crack tip, which is in agreement with the LEFM [50]. For  
432 the following joint elements, normal stress continues to develop, the damage phase starts for  
433 some joint elements while others remain in the elastic phase, with damage variable equal to 0.  
434 This process is repeated in all joint elements along the crack line, and the crack opens  
435 gradually in depth (from  $t = 3.510$  h to  $t = 3.530$  h). The crack then propagates from the top to  
436 the bottom of the specimen in a short period (approximately 0.03 h). After this propagation in  
437 depth, all joint elements in the crack line are completely damaged, their normal stress  
438 decreases to zero, and the damage variable remains 1.

439 The opening of this crack ( $X = 1$  mm) during the next step of drying (for  $t = 4 - 12$  h) is  
440 presented in Fig. 11. The crack aperture continues to increase from  $t = 4$  h to  $t = 8$  h. After  $t = 8$   
441 h, other cracks appear, and the aperture of the crack decreases suddenly from  $t = 1.7$  mm to 0.3  
442 mm and remains at this value after 3 hours of drying.

443 Fig. 12 shows the isochrones of the normal stress, damage variable and opening of all joint  
444 elements along the line of the crack at  $X = 35$  mm (see Fig. 6). At the beginning of drying,  
445 from  $t = 1$  h to  $t = 8.50$  h, the tensile stress of these joint elements increases gradually while  
446 drying. At  $t = 8.50$  h, the tensile stress of the elements close to the bottom (at  $Y = 0.6-1$  mm)  
447 approaches the soil tensile strength  $\sigma_R = 0.09$  MPa but that of the other joint elements (with  $Y$

448 >1 mm) remains smaller than the tensile strength. This is the elastic phase of these joint  
449 elements, and no damage occurs. At  $t = 8.95$  h, some joint elements near the bottom of the  
450 specimen ( $Y < 4$  mm) are completely damaged, *i.e.*, their damage variable reaches its  
451 maximum (equal to 1) (Fig. 12*b*). The normal stresses of these joint elements are relaxed to  
452 zero (Fig. 12*a*). The total damage indicates that all the bridge or contact points between the two  
453 surfaces of the crack are completely broken, and the crack is opened from the first damaged  
454 element (very close to the bottom of the specimen) to its extremity (Fig. 12*c*). The process of  
455 damage is continued along the crack line, and the crack is opened gradually upward (from  $t =$   
456  $8.50$  h to  $t = 9.10$  h). This crack propagates along the crack line and is detected from the top  
457 surface at  $t = 9.10$  h. After this propagation along the thickness of the sample, all joint elements  
458 in the crack are completely damaged, their normal stress is relaxed to zero and the damage  
459 variable remains 1. Fig. 12*c* shows the evolution of the crack opening during the propagation.  
460 The crack is initiated from the element near the bottom of the sample, and there is no suction  
461 gradient in the sample (Fig. 7*a*). However, when the crack is detected from the surface, the  
462 crack aperture at the top is always larger than the one at the bottom. The top surface is free to  
463 move, while the bottom displacement is restrained by the prescribed boundary conditions. The  
464 opening of this crack during the next step of drying (for  $t = 10$ – $12$  h) is presented in Fig. 13.  
465 After propagation to full depth, the crack aperture continues to increase until  $t = 10$  h. Then,  
466 other cracks appear near this crack (Fig. 6), and the aperture of the crack decreases suddenly  
467 from  $t = 1.6$  mm to 0.3 mm.

468 Fig. 14 shows the normal stress of all cohesive cracks on the top surface for  $X = 0$ – $50$  mm. At  $t$   
469  $= 3.5$  h, the tensile stress is 0.04 MPa for  $X > 20$  mm, but it reaches 0.09 MPa at  $X = 1$  mm. At  
470  $t = 4$  h, a gap appears at  $X = 1$  mm (represented by a mark in the figure); the tensile stress of  
471 this gap is relaxed and drops to zero. The appearance of this gap induces a reduction in the  
472 tensile stress of nearby cohesive cracks. The effect of this interaction decreases with distance.

473 From  $t = 4$  h to  $t = 8$  h, no more cracks appear; thus, the tensile stress continues to increase. At  
474  $t = 8.3$  h, a crack at  $X = 6$  mm appears, decreasing the tensile stress. This phenomenon is  
475 repeated at  $t = 8.5$  h and  $t = 8.6$  h, when cracks appear at  $X = 11$  mm and  $X = 16$  mm,  
476 respectively. Interaction between cracks occurs when a new crack appears, creating a stress  
477 relief zone in the surface in which the stresses are reduced [18], while the prescribed boundary  
478 condition at the bottom of the specimen concentrates the tensile stress in this location.

479 Fig. 15 shows the evolution of the tensile stress of the cohesive crack at  $X = 35$  mm for a joint  
480 element on the top surface ( $Y = 13$  mm) and close to the bottom of the specimen ( $Y = 0.61$   
481 mm). The tensile stress of the joint element near the bottom of the specimen is higher than that  
482 of the specimen on the surface. At  $t = 8.5$  h, the tensile stress of the joint element near the  
483 bottom approaches the tensile strength (0.09 MPa) while the tensile strength of the joint  
484 element on the top surface reaches 0.06 MPa. Due to the damage cohesive crack in the model,  
485 when the tensile stress reaches the soil tensile strength, the damage process occurs and the  
486 crack initiates, as explained above.

## 487 **5. Discussions**

488 In the present work, FEM code, including hydro-mechanical coupling and cohesive crack  
489 elements, was used to simulate the desiccation cracking of soils. The matrix behaviour was  
490 assumed to be isotropic linear elastic. Elastic behaviour was also used in previous research to  
491 model desiccation cracking ([25][28]). In the present work, the elastic modulus was fitted to  
492 the experimental data in the range of low stress (smaller than 0.3 MPa, see Fig. 3). After 12 h  
493 of desiccation, the suction (and soil stress) remained in this range (see Fig. 7a).

494 Literature review ([3][15][16][18]) showed that desiccation cracking occurs essentially via  
495 mode I, indicating that cracking in soils results from the development of tensile stress. As soil  
496 undergoes drying, it exhibits a suction change, which causes the inter-particle force to increase.

497 An apparent cohesion term is thus created, and consequently, a tensile strength term. Kim &  
498 Hwang [51] attempted to directly relate tensile strength to the normal inter-particle force  
499 calculated from micro-scale considerations. Other researchers proposed direct relations  
500 between the decrease in water content and the tensile strength through experimental analysis  
501 ([22][51]). Peron et al. ([5][49]) performed desiccation tests on three soils and found that  
502 cracking initiates at the end of the first stage of drying. In the present work, the simulation  
503 results showed that the first cracks initiate at approximately 4.0 h, when suction equals 0.08  
504 MPa. At that moment, the evaporation rate is at its maximum value ( $E_p$ ), see Fig. 5.

505 A 2D mesh was used for the model in the present work (Fig. 4), while the experiment was  
506 performed with a cylindrical specimen. The prime interest of this work is not a quantitative  
507 prediction of the experimental results but a qualitative reproduction of the main trends and  
508 crack development during drying. Various experimental studies ([25][30][49][52]) show that  
509 the crack network would be different for two cases: (i) for the case of a long bar (similar to the  
510 model in the present work), the cracks are formed successively and perpendicular to the long  
511 side of the specimen; (ii) for the case of a circular sample or a rectangular slab, the cracks can  
512 appear simultaneously or successively to create a crack network. In the experiment considered  
513 in the present work, the evolution of a typical section was analysed. A 3D mesh would then be  
514 necessary to accurately reproduce the crack pattern in this case. In the present work, only a 2D  
515 mesh was used. Most of numerical studies use 2D mesh ([19][20][22][25][31]), while few  
516 works consider a 3D mesh ([21][30]). Although the 3D crack pattern was not simulated in the  
517 present work, the result obtained in the 2D study improves the understanding of shrinkage  
518 cracking mechanisms.

519 The model was able to reproduce correctly the main phases of the desiccation and the  
520 development of soil shrinkage versus elapsed time (Fig. 6,7, and 9). Initially, shrinkage is

521 associated with settlement only. In the model, settlement without cracking corresponds to the  
522 elastic phase of cohesive cracks, in which the tensile stress increases with drying but remains  
523 smaller than the tensile strength. The damage phase begins when the tensile stress of cohesive  
524 cracks reaches the soil tensile strength and crack initiation is observed. In the present work, the  
525 crack network appears quickly at  $t = 8.3$  h. This time can be observed as the critical time in the  
526 cracking development process. Li et al. [13] studied desiccation crack initiation and  
527 development of the ground surface and showed that desiccation cracks develop in three stages:  
528 initial, primary and steady states. In the first stage, few cracks develop with gradually  
529 decreasing water content, and a critical suction value exists for crack initiation after which  
530 cracks appear and propagate quickly.

531 Kodikara & Costa [6] presented two controlling factors in desiccation cracking. The first is the  
532 tensile stress distribution when the material is restrained against shrinkage. The tensile stress  
533 distribution depends on the boundary conditions and the material stiffness and dictates where  
534 the cracks initiate. The second factor is related to the flaws and/or pores within the material,  
535 where cracks can initiate at a stress level lower than the maximum stress developed within the  
536 material. Costa & Kodikara [55] observed that cracks could initiate even at suction of  
537 approximately 1 kPa for a clay slurry because of the large pores. In this work, cohesive cracks  
538 were placed equidistantly with the same parameters. In addition, there was no suction gradient  
539 in the sample (Fig. 7a). The heterogeneity of the material properties and the flaw factors are  
540 therefore neglected in this work. As a result, crack initiation depends only on the tensile stress  
541 distribution, which is mainly controlled by the boundary conditions.

542 The results obtained from the present work show that the discontinuity initially develops at the  
543 gaps (Fig. 6). This phenomenon can be explained by the normal stress distribution on the top  
544 surface at  $t = 3.5$  h (see Fig. 14), where the normal stress is highest at  $X = 1$  mm. In addition,  
545 the development of the crack network in Fig. 6 shows that the cracks progressed from the two



546 “gaps” beside the lateral boards to the middle of the sample, in agreement with the  
547 observations in [11] but not a general trend [19]. In the present work, this can be explained by  
548 the fact that when the gaps are created near the lateral boundaries, the stress field in the sample  
549 is no longer uniform and induces new cracks that preferentially progress from the lateral  
550 boundaries towards the centre of the sample. In addition, Fig. 6 shows that the crack opening  
551 depends on its location. The two lateral boards are fixed, so when two faces of a crack  
552 separate, the face closer to the boundary side presents a smaller displacement than the other  
553 side. These cracks thus present a V shape that is not symmetric and depends on their location,  
554 but the global configuration of the crack shape and location is symmetric with respect to the  
555 axis of the sample.

556 The present work showed that in some conditions cracks could develop from near the bottom  
557 of the specimen and propagate to reach the top surface. This can be explained in the model by  
558 the combined effects of boundary conditions at the bottom that cause stress concentration at  
559 these locations and the stress reduction on the top surface due to the onset of adjacent cracks  
560 (Fig. 14 and 15). In this numerical model, all the joint elements are fixed to the bottom.  
561 Therefore, the crack aperture cannot be observed from the bottom, similar to the observations  
562 in a previous experiment ([11]). Weinberger [56] studied the initiation and growth of cracks  
563 during desiccation of stratified muddy sediment and found that in the absence of surface  
564 defects, crack origins are consistently located at or near the bottom of the polygons. During  
565 drying, cracks initiated at the bottom and propagated vertically upward and laterally towards  
566 adjacent cracks. The crack propagation from the bottom to the full depth was also observed by  
567 Costa et al. [57] while testing desiccation cracking on three potato starch specimens.

## 568 **6. Conclusions**

569 In this study, a desiccation cracking experiment was simulated using a hydro-mechanical  
570 model where (i) hydraulic diffusion under evaporation, (ii) the shrinkage of a soil sample and  
571 (iii) the initiation and propagation of desiccation cracks, among others couplings, were  
572 considered. The diffusion equation included the evolution of the soil and crack hydraulic  
573 properties (degree of saturation, soil hydraulic conductivity and crack hydraulic conductivity,  
574 the mass exchange between soil matrix/cracks), and the deformation processes of the soil and  
575 the crack were equally taken into account. Finite element method code, including cohesive  
576 fractures model, was used to simulate the development of cracks. The coupling between the  
577 hydraulic and mechanical phenomena was performed through an iterative process passing  
578 from the hydraulic problem resolution to the mechanical problem resolution and vice versa.

579 Cohesive cracks were embedded into the model to simulate potential cracks. By including a  
580 large number of joint elements in the mesh, the model enables the detection of crack  
581 development during drying. The results of the numerical simulation show good agreement with  
582 the experimental data in terms of hydraulic diffusion, crack initiation, shrinkage evolution and  
583 the chronology of desiccation phases (settlement without cracking and the formation and  
584 propagation of cracks). The present work highlighted the importance of boundary conditions  
585 when studying desiccation cracking. The simulation of a desiccation test revealed that cracks  
586 could develop, in some cases from near the bottom of the specimen, and propagate towards the  
587 top surface, even if the water evaporation occurs only from the top. The results of the present  
588 work indicate that the proposed hydro-mechanical coupled model using the cohesive fracture  
589 law for modelling crack propagation can accurately reproduce the hydro-mechanical coupled  
590 phenomena related to shrinkage and crack formation during drying of clayey soil.

## 591 **Acknowledgement**

592 The Authors would like to thank Prof. Farimah Masrouri and Dr. Jean-Bernard Karzmierczak  
593 for their valuables comments.

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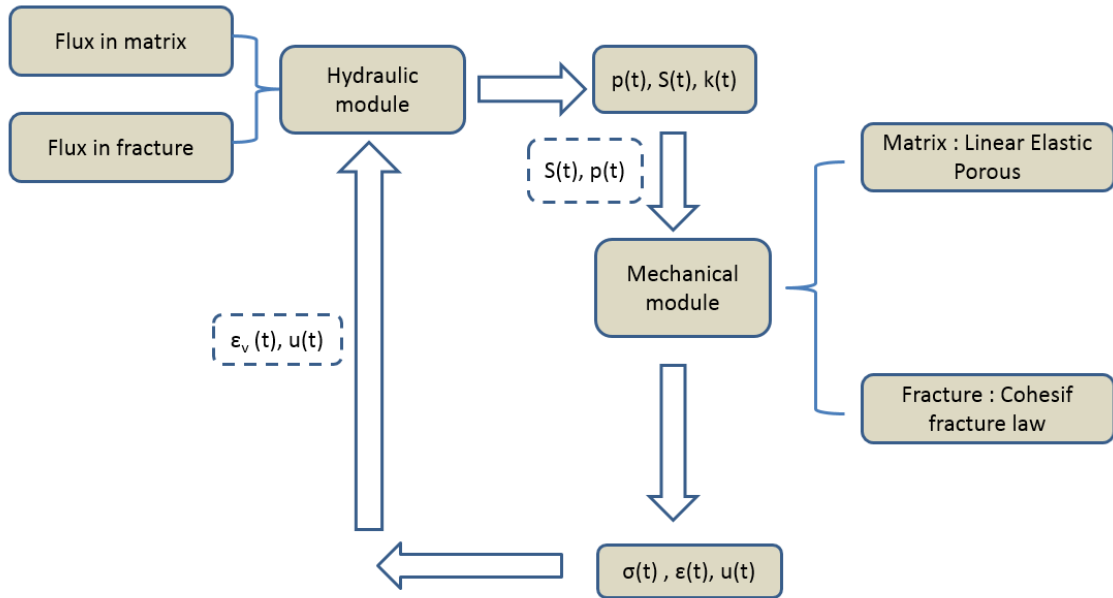
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Figure 1: Scheme of the hydro-mechanical coupling



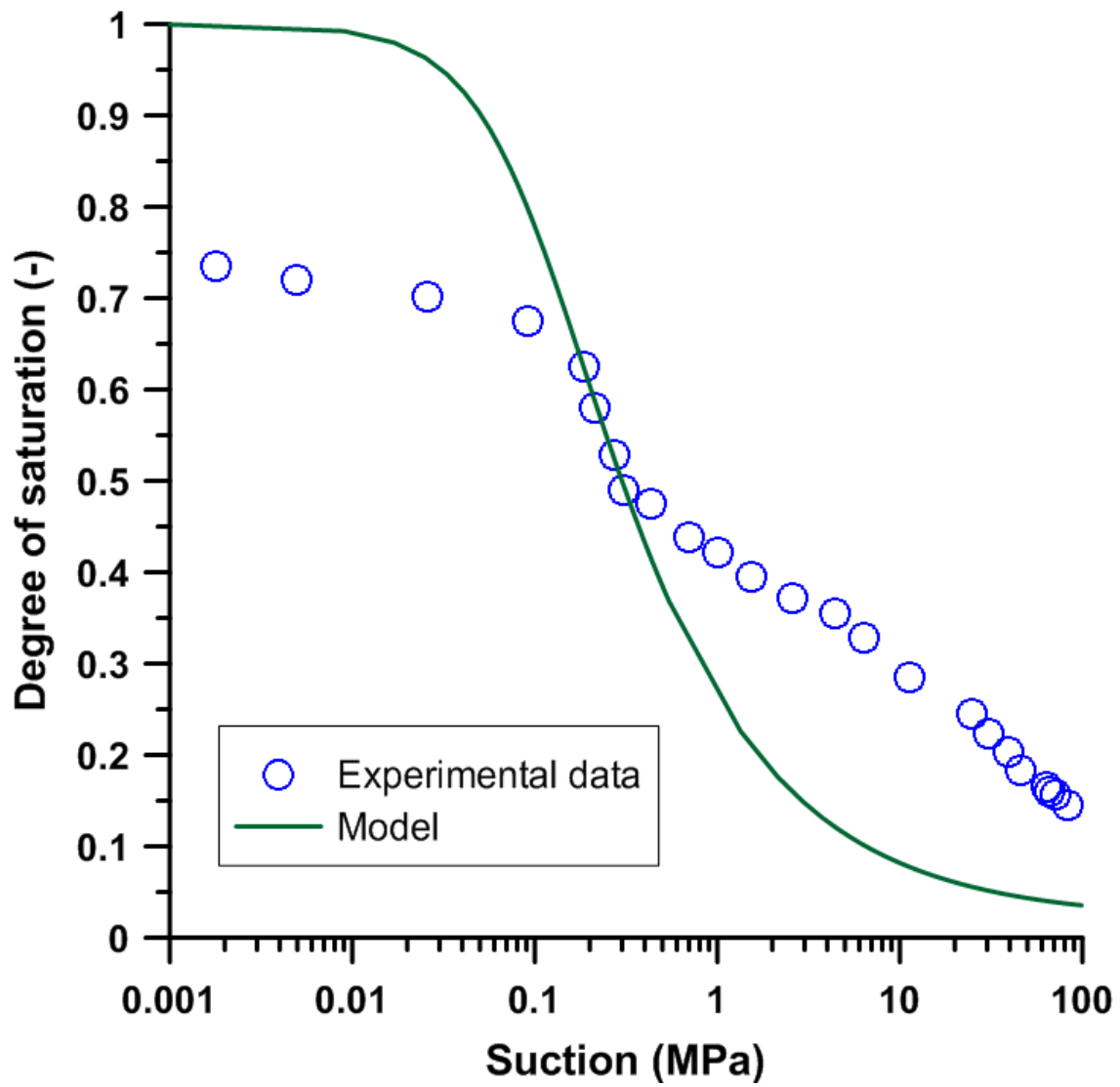
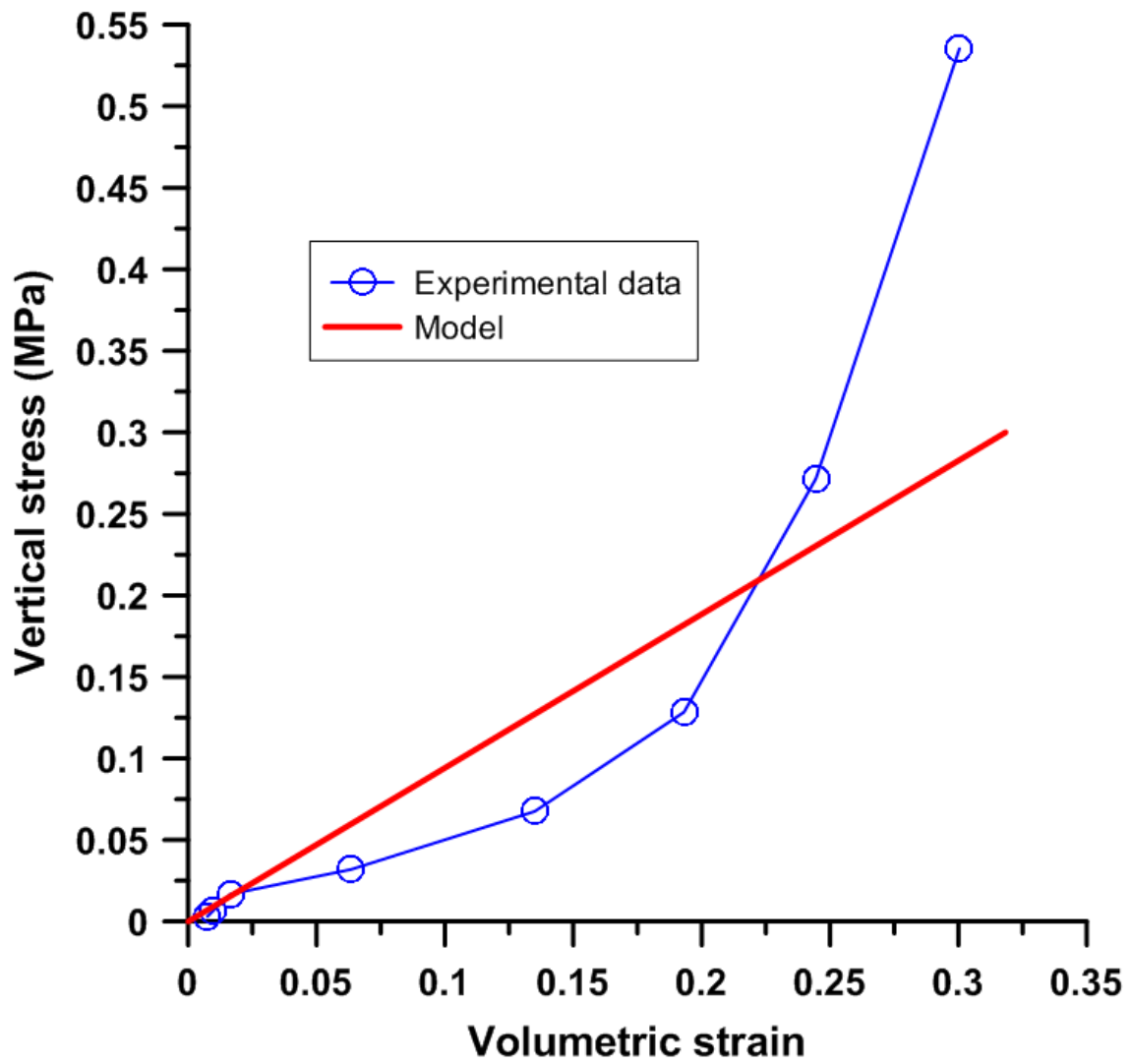


Figure 2: Water retention curve (Experimental data taken from [39])

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Figure 3: Compression curve obtained from oedometer test (Experimental data taken from [40])

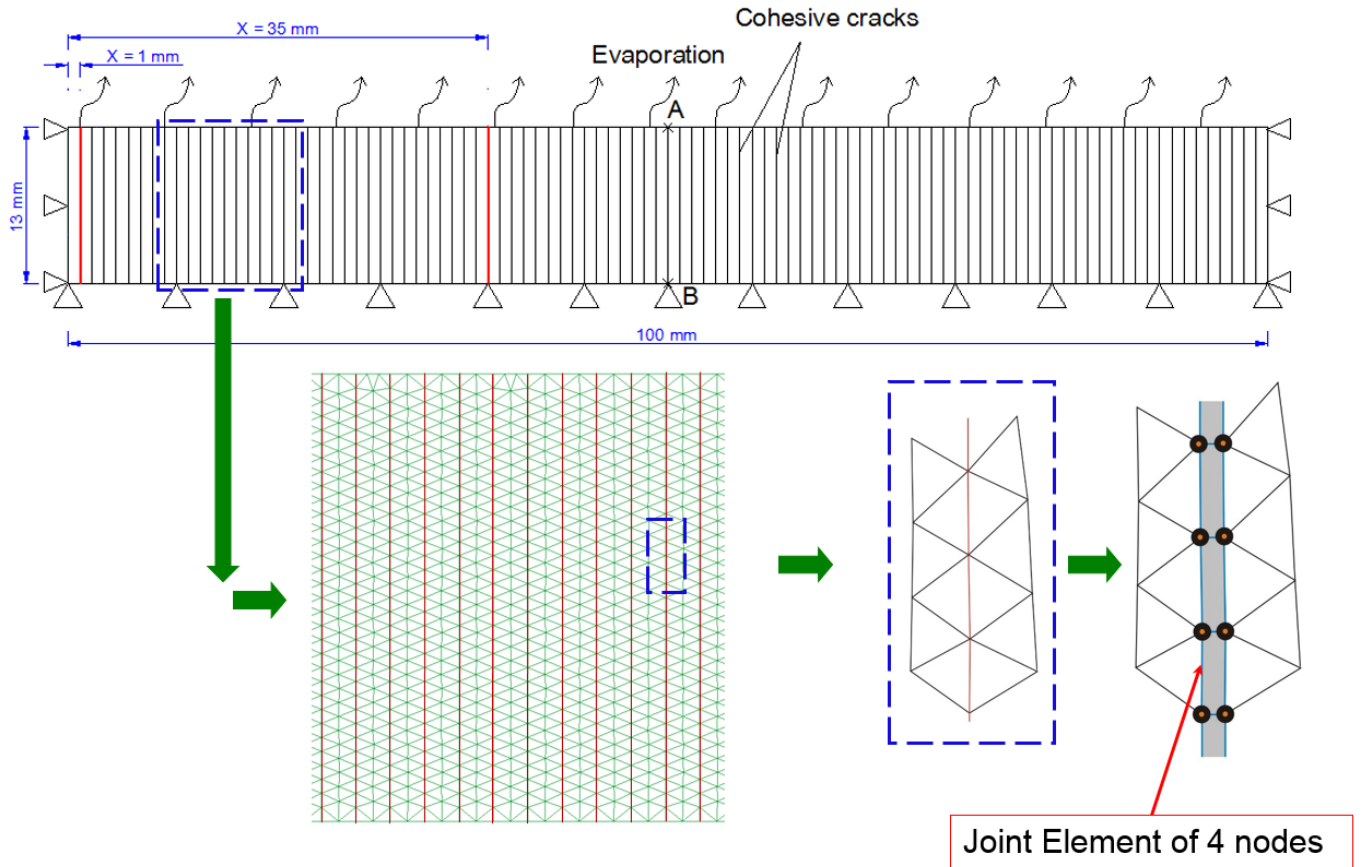
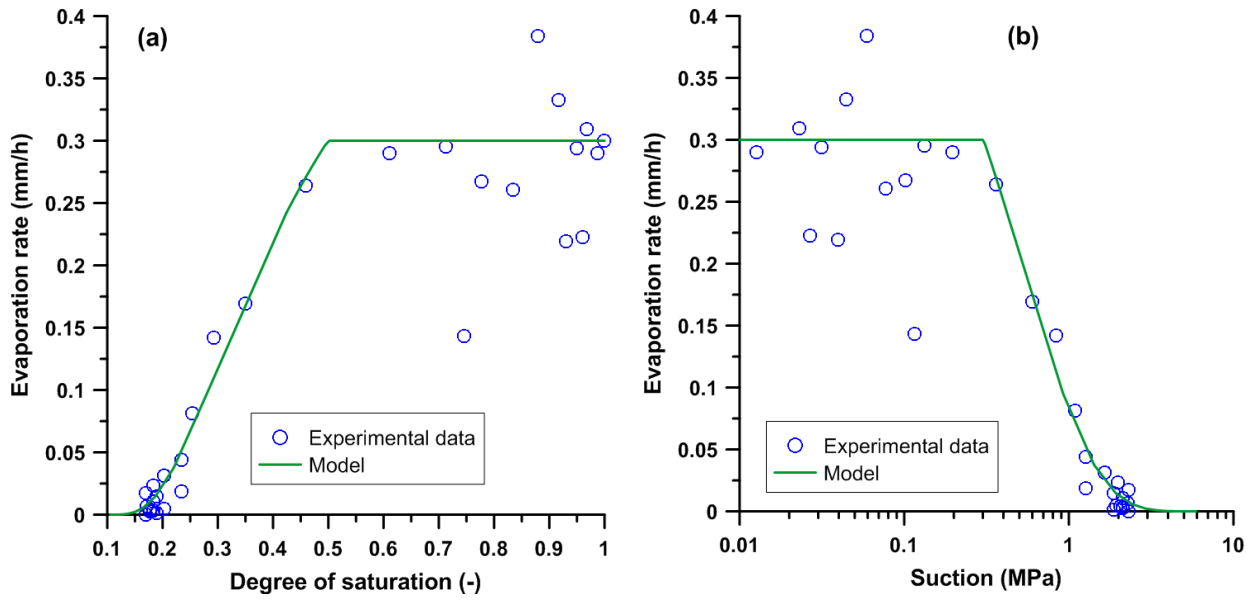


Figure 4: Geometry and boundary condition

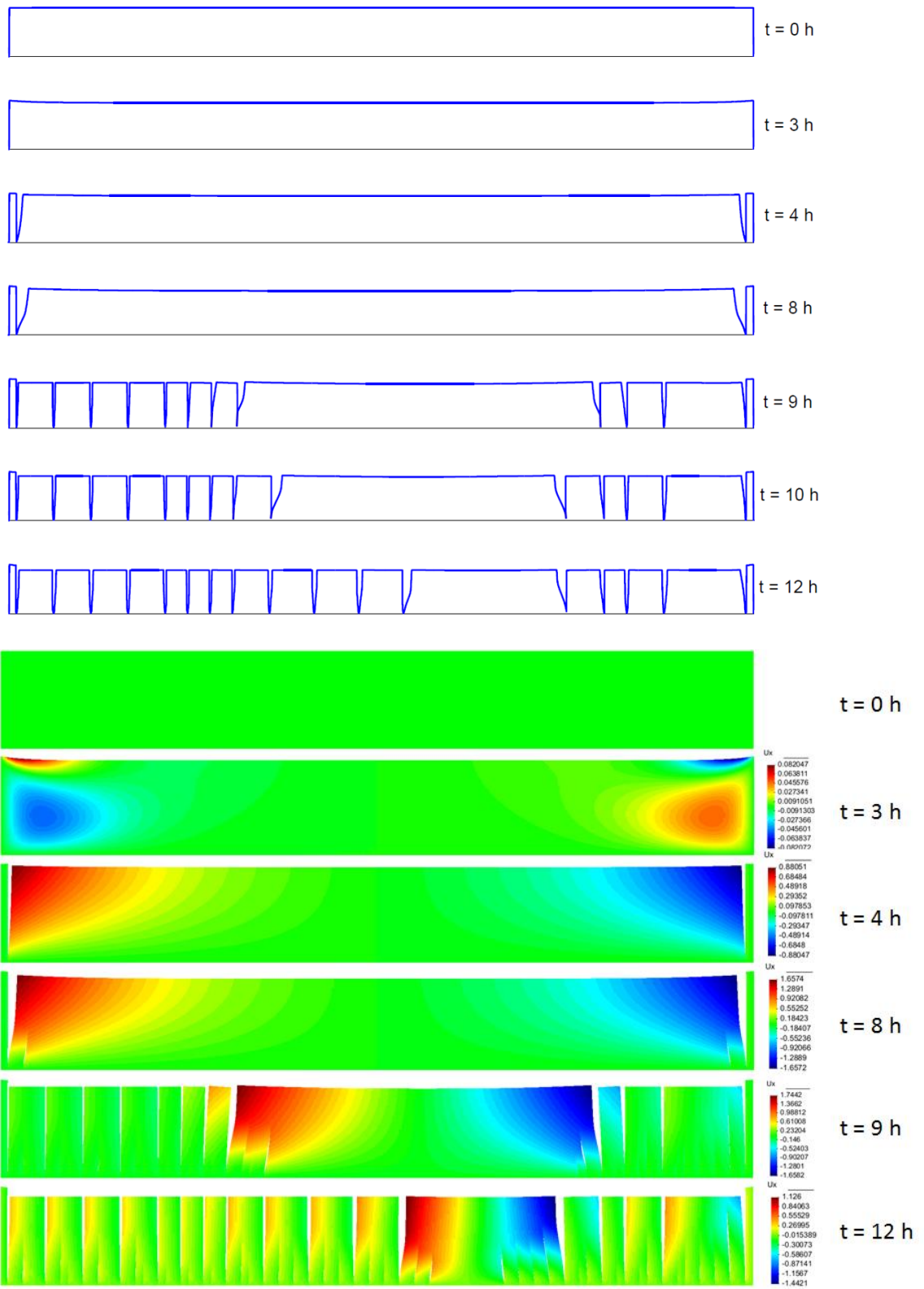
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Figure 5: (a) Evaporation rate versus degree of saturation and (b) Evaporation rate versus suction (Experimental data taken from [11])

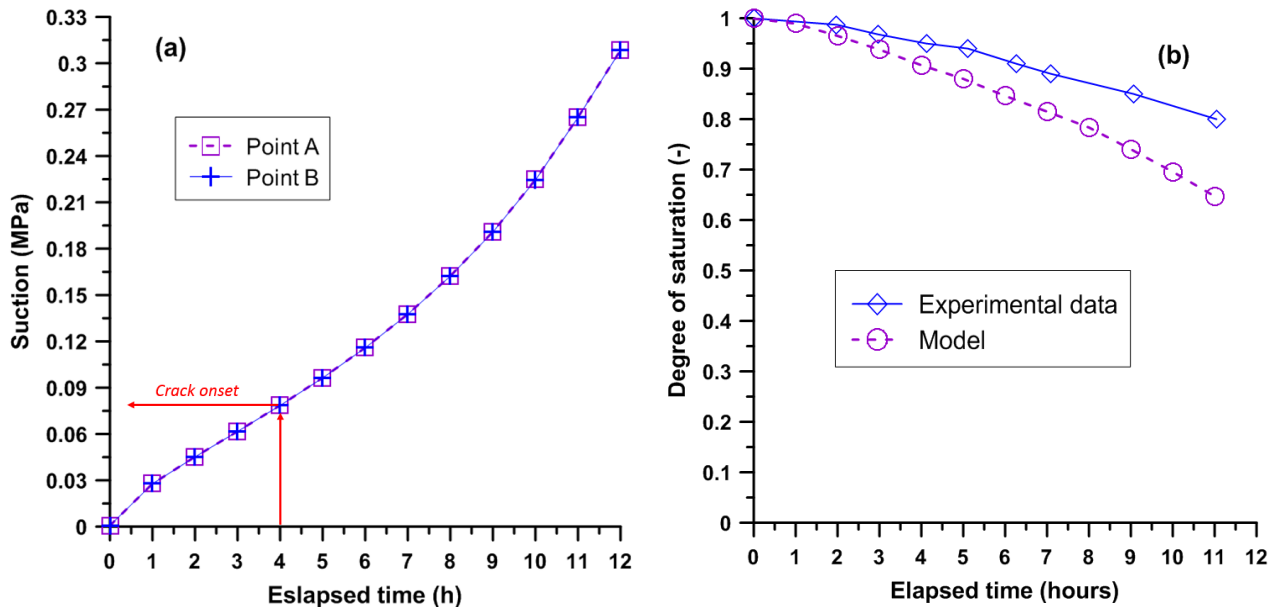
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Figure 6: (a) Description of the cracks observed at various moments and (b) Distribution of horizontal displacement

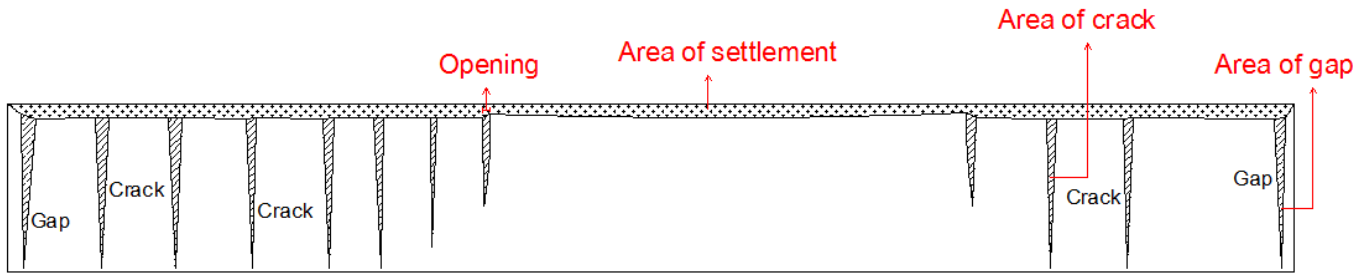
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Figure 7 : (a) Suction and (b) Degree of saturation versus elapsed time. (Experimental data taken from [11])

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Figure 8: Scheme showing the different components of soil shrinkage

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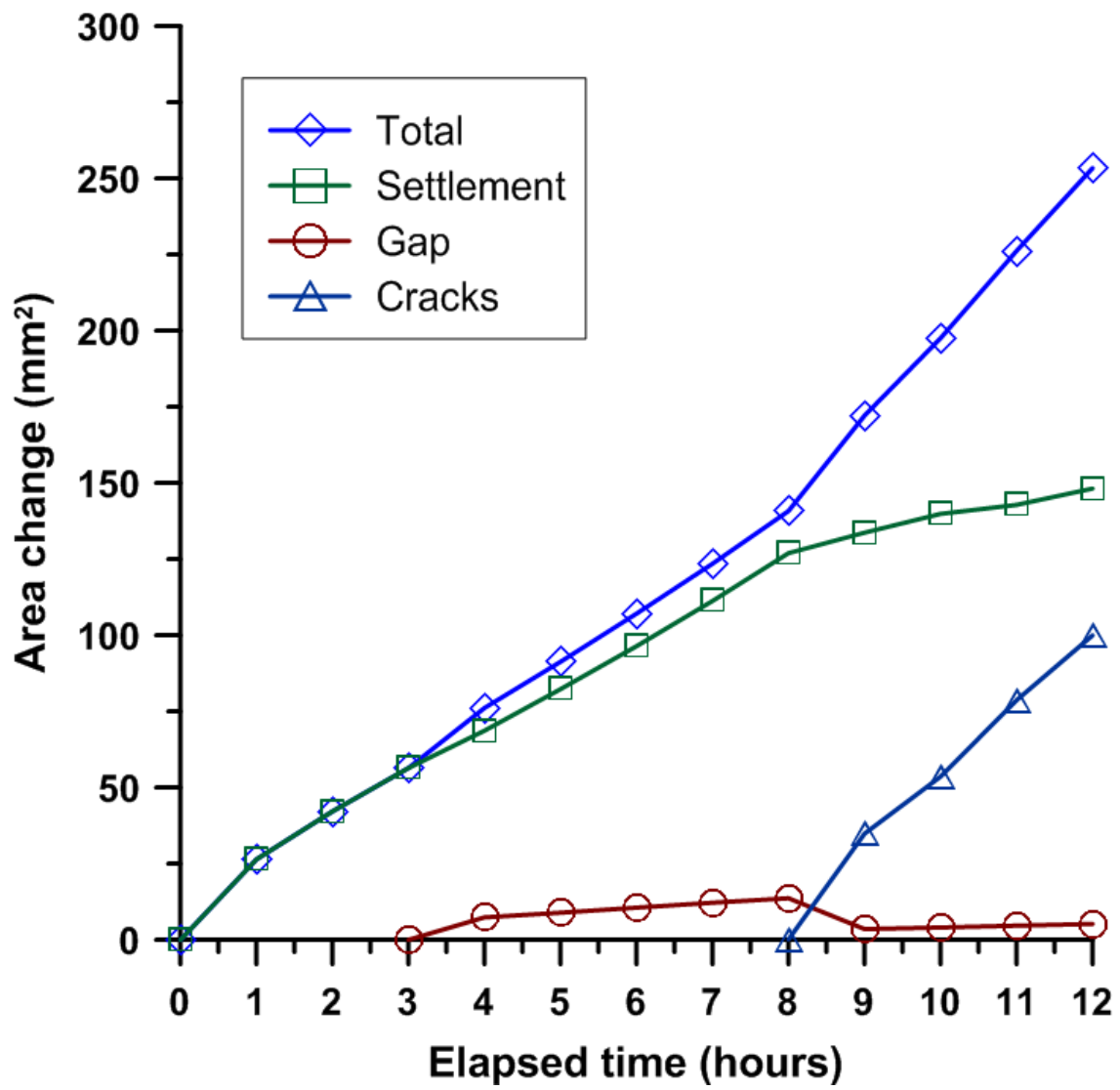


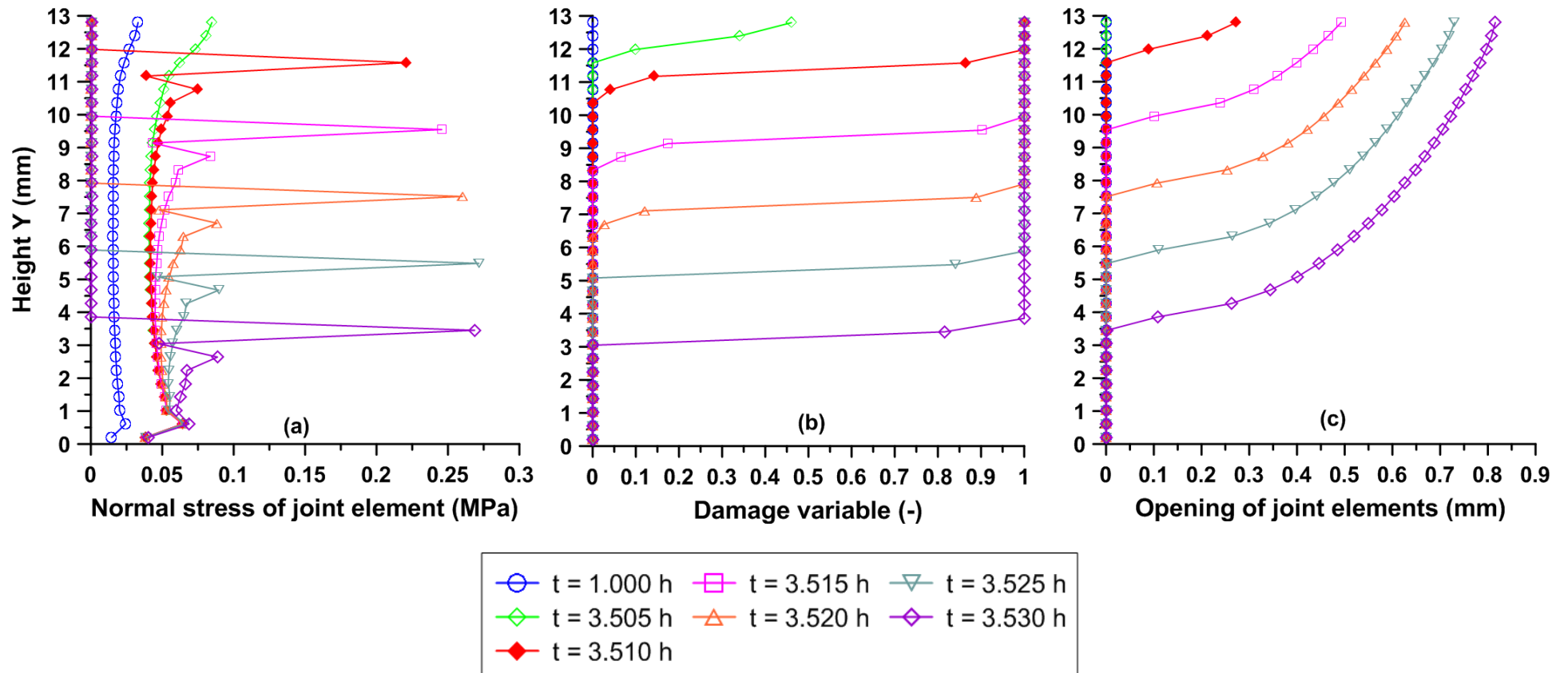
Figure 9 : Time evolution of different components of soil shrinkage

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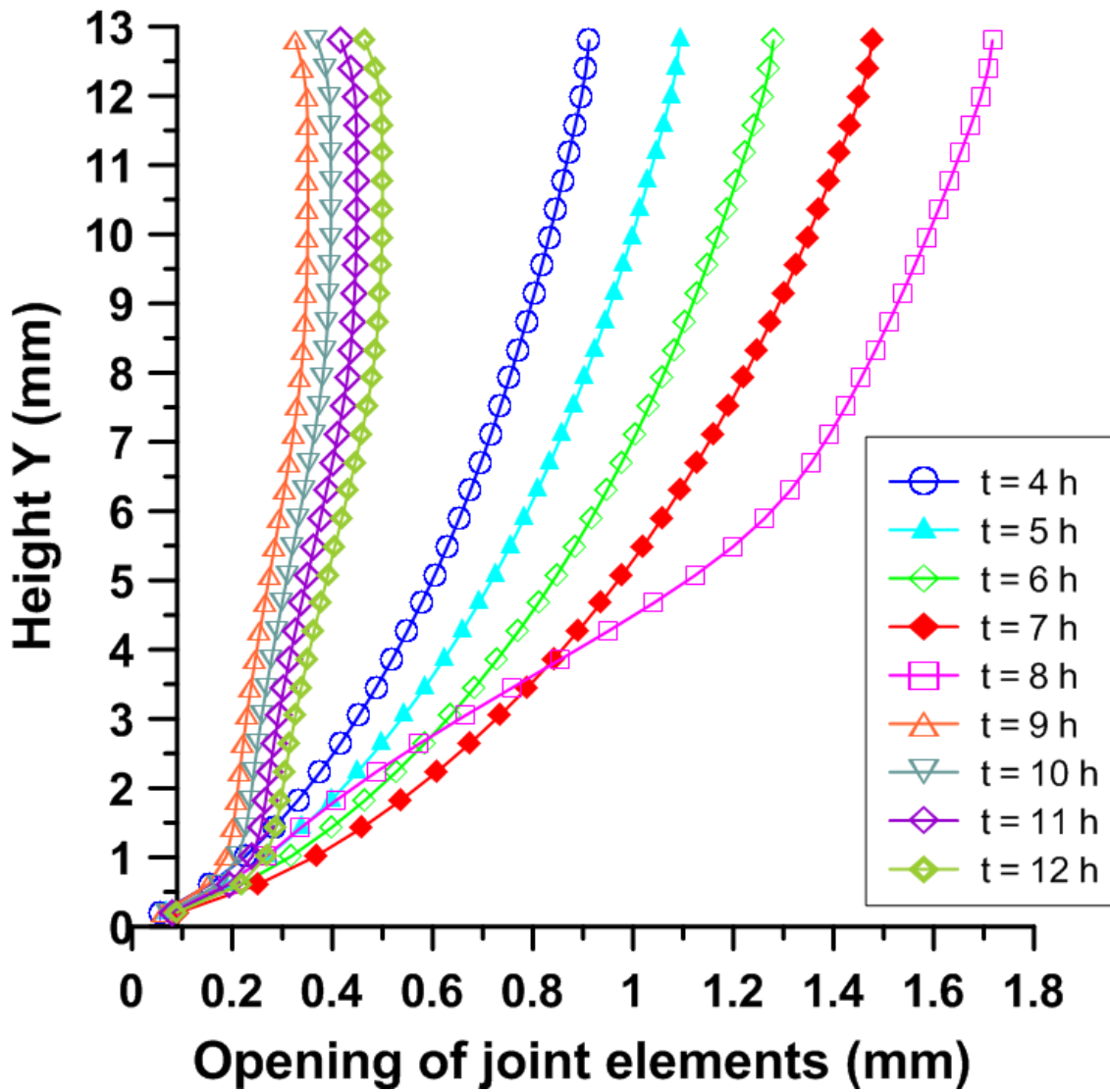
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942 Figure 10: Isochrones of: (a) Normal stress, (b) Damage variable and (b) Opening of joint elements for the gap at X = 1 mm

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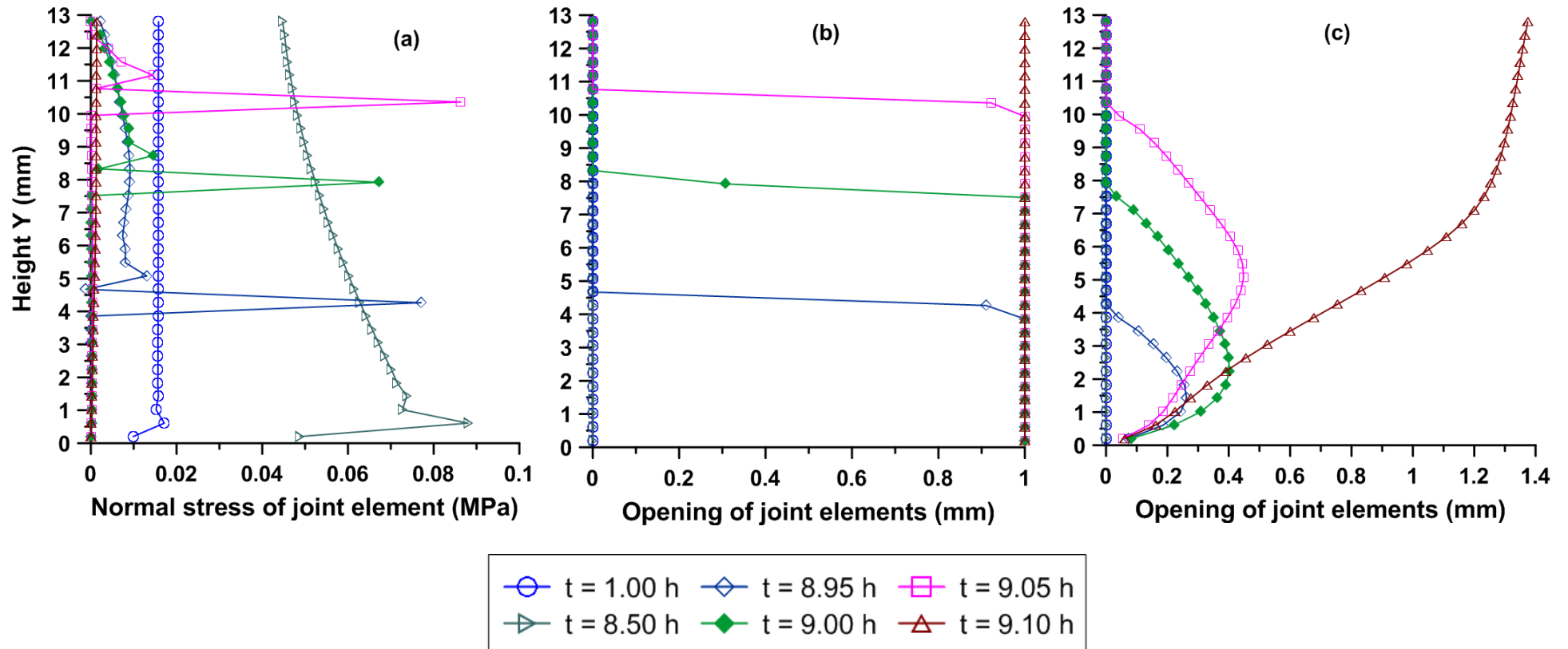


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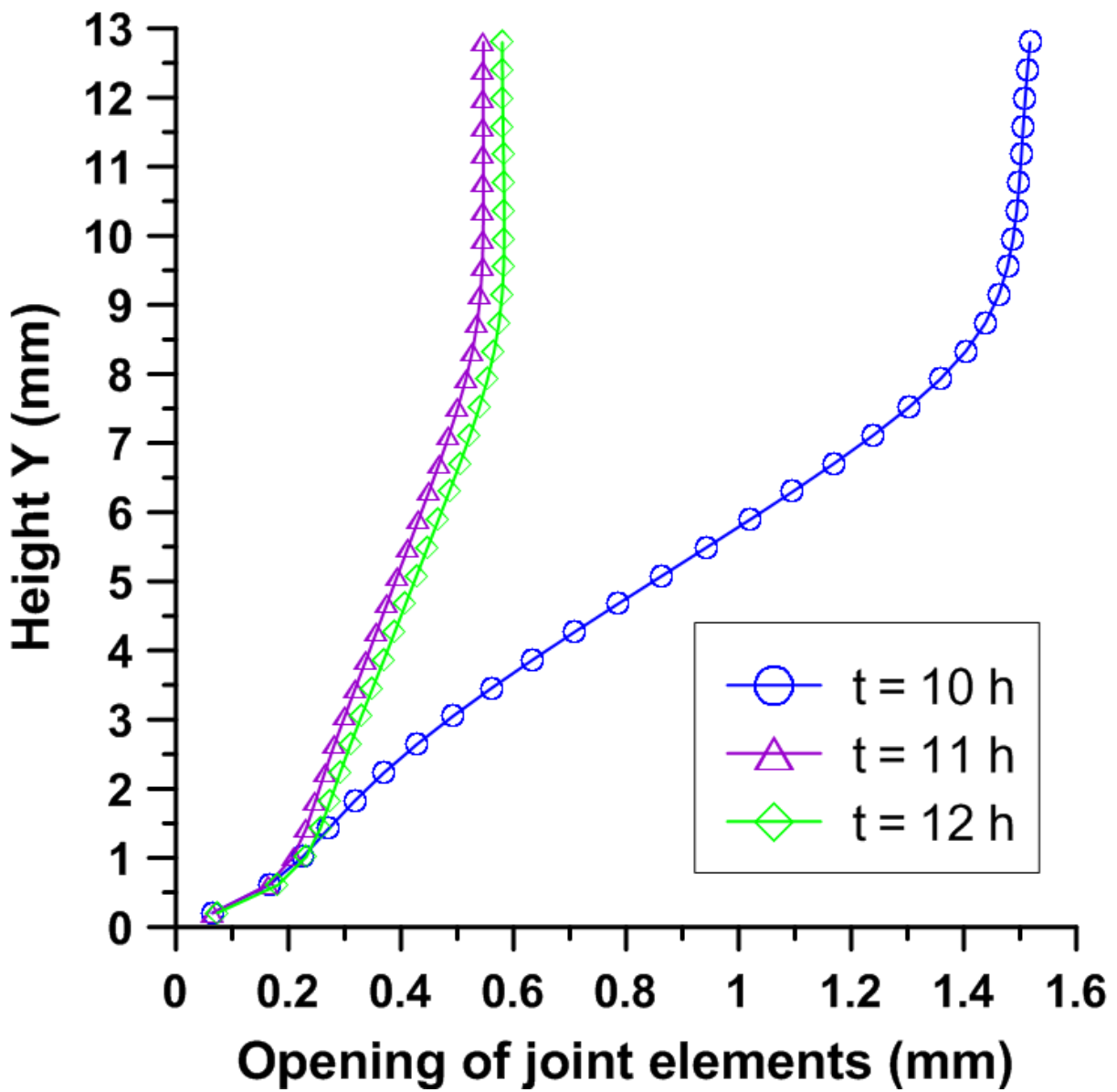
Figure 11: Opening of joint elements for the gap at X = 1 mm

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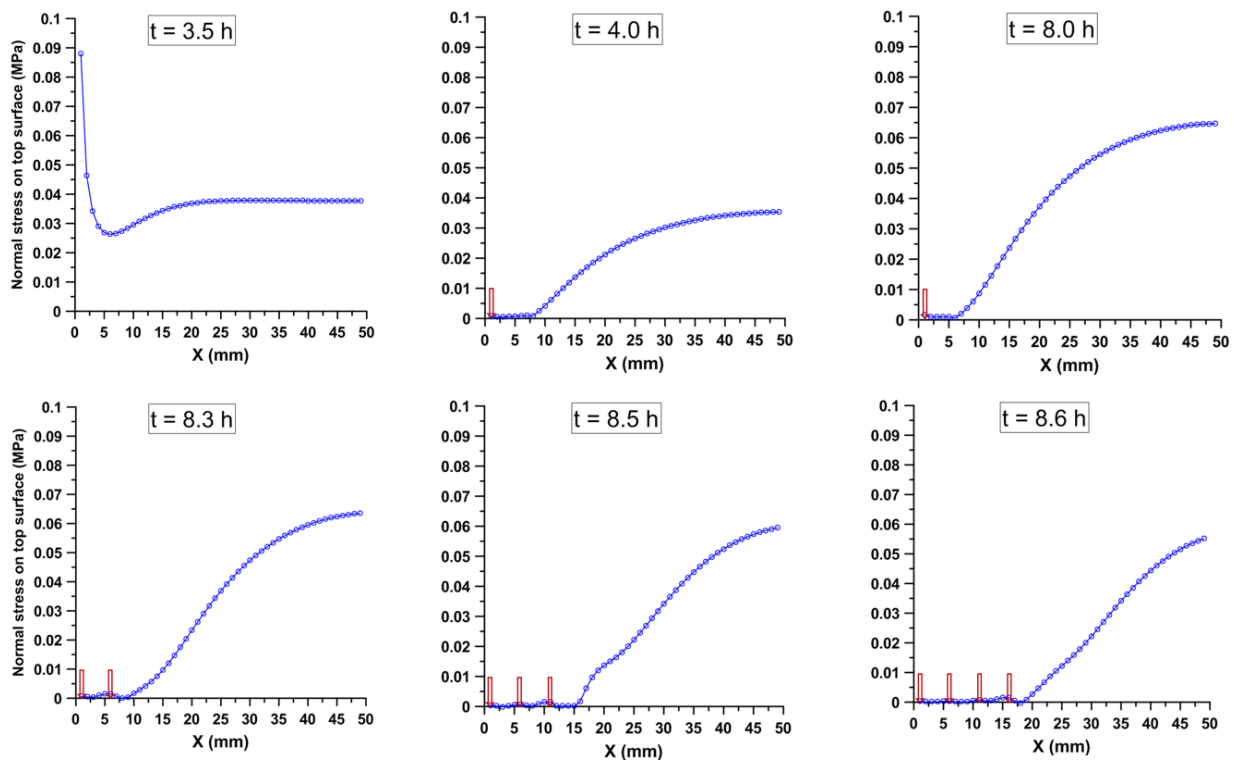
Figure 12 : Isochrones of: (a) Normal stress, (b) Damage variable and (b) Opening of joint elements for the crack at X = 35 mm



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Figure 13: Opening of joint elements for the crack at X = 35 mm

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Figure 14 : Cracks position and normal stress of a half left specimen on the top surface

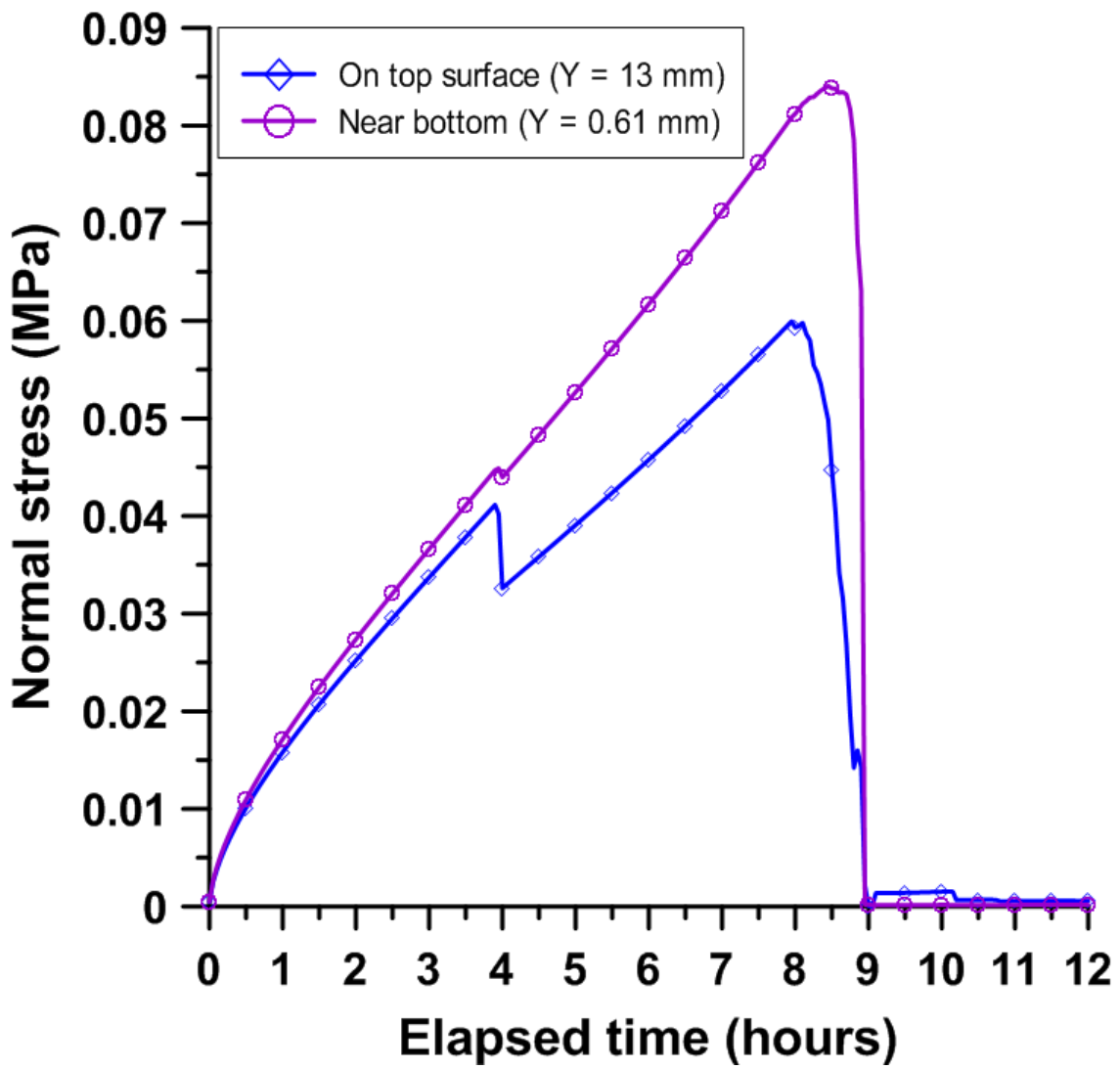


Figure 15: Evolution of normal stress of the crack at X = 35 mm

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Soil	$E$ (MPa)	$\nu$ (-)	$k_s$ (m/s)	$\phi$ (-)	$\alpha$ (MPa <sup>-1</sup> )	$n$ (-)	$m$ (-)	$S_r$ (-)
	1	0.3	10 <sup>-8</sup>	0.60	9.81	1.60	0.375	0.02

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Cracks	$R_{tt}$ (MPa/mm)	$R_{nn}$ (MPa/mm)	$R_m = R_{nt}$ (MPa/mm)	$\sigma_R$ (MPa)	$C_{\text{coh}}$ (MPa)	$\varphi$ (°)	$\beta$ (-)	$e_0$ (mm)
	1	1000	0	0.09	0.08	30	1	10 <sup>-3</sup>

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Table 1: Parameters of soil and cohesive cracks.

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