

Modelling Soil Desiccation Cracking Using a Hybrid Continuum-Discrete Element Method

Y. L. Gui, W. Hu, and X. Zhu

Abstract

Shrinkage induced crack pattern is a universal phenomenon, soil cracking due to drying shrinkage is not an exception. In geotechnical engineering, desiccation shrinkage induced cracking has a profound effect on the engineering properties of soils as it can considerably increase the hydraulic conductivity and decreases the shear strength of a soil. Thus, it poses a significant threat to the hydraulic and structural integrity of earthworks. This paper presents the application of the hybrid continuum-discrete element method to simulate soil desiccation shrinkage and cracking with a mix-mode cohesive fracture model. The applicability of the proposed approach is demonstrated through numerical simulation of laboratory and field desiccation tests. The simulation results have shown good agreements with the laboratory and field observations.

Keywords

Soil • Desiccation • Cracking • Simulation

1 Introduction

Desiccation cracking is a commonly occurring phenomenon in unsaturated soil with a high degree of saturation. Its occurrence has a significant effect on the engineering properties of soils as it can considerably increase the hydraulic conductivity and decreases the shear strength of a soil. Thus, it can pose a significant threat to the hydraulic and structural integrity of

earthworks (Peron et al. 2009), dykes (Philip et al. 2014), embankments (Peron et al. 2009; Sima et al. 2014), engineered barriers (Dixon et al. 2002; Rayhani et al. 2007) and can increase the erosion potential of surface soils (Intharasombat et al. 2007; Peron et al. 2009). Understanding of the phenomenon is also important in the field of agricultural engineering due to its role in the transportation of near-surface water, air and nutrients (Arnold et al. 2005) and its potential to increase ground water pollution (Kissel et al. 1974; Arnold et al. 2005; Gui and Zhao 2015). Even in other areas, such as food engineering (Inazu et al. 2005), material engineering (Scherer 1999; Lee and Routh 2004) and chemical engineering (Singh and Tirumkudulu 2007), a clear and robust explanation of desiccation-induced cracking also has great influence.

Many researches have been done to investigate desiccation cracking in soil by experimental study, analytical interpretation and numerical simulation. However, the insight into the phenomenon is still limited. The aim of the paper is to simulate soil desiccation cracking by employing a hybrid continuum-discrete method with a cohesive fracture model. Compared with pure continuum or non-continuum methods, the hybrid method is capable of handling multiple fracture and deformation problems in materials, a considerable advantage over other methods such as finite element method (FEM) and discrete element method (DEM). This is because the traditional FEM has a problem of handling multiple fractures, and the particle deformation is not possible to be considered in conventional DEM (Gui et al. 2015, 2016a, b, 2018) due to the particle's rigidity. In this study, the laboratory and field desiccation tests from literature are simulated. The simulation results show that the fracture model is capable of modelling desiccation cracking.

Y. L. Gui (✉)

School of Engineering, Newcastle University,
Newcastle upon Tyne, NE1 7RU, UK
e-mail: yilin.gui@ncl.ac.uk

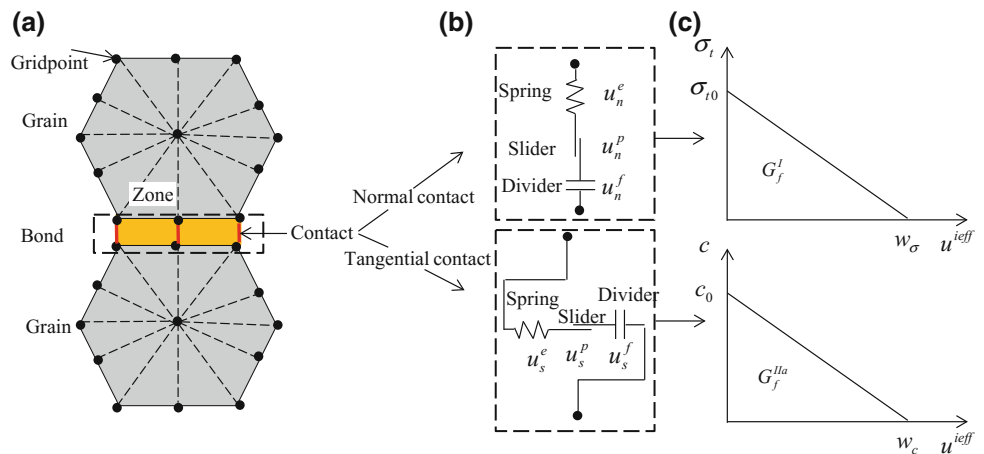
Y. L. Gui · W. Hu · X. Zhu

State Key Laboratory of Geohazard Prevention and
Geoenvironmental Protection, Chengdu University
of Technology, Chengdu, 610059, China

2 The Theory of the Model

The theory of the hybrid continuum-discrete element method can be found in Gui et al. (2015). The cohesive fracture model presented herein is an extension and application of the

Fig. 1 Sketch of the hybrid continuum-discrete element method with the mix-mode cohesive fracture model: **a** hybrid continuum-discrete element method; **b** mechanical element representation of the mix-mode cohesive fracture model and **c** constitutive model of the contact model (Gui et al. 2016b)



elastic-plastic-damage interface constitutive framework originally presented by Galvez et al. (2002). It takes into account the cohesive effect on both tension and shear. In the model, the fracture interface (i.e., cohesive contact bond between neighbouring grains) is idealised with zero thickness, in other words there is no layer of element embedded at the shared boundary of the two adjacent grains. Figure 1 illustrates the hybrid continuum-discrete element method and the fracture model used in this paper. More information about it can be found in Gui et al. (2015).

3 Modelling of Laboratory Desiccation Test

To investigate mechanism of desiccation induced shrinkage and cracking in fine-grained soils, a series of experimental tests with three different fine-grained materials including Bioley silt, Sion silt and La frasse clay were performed by Peron et al. (2009). The Bioley silt is adopted as experimental result to which the numerical simulations are compared. Three types of tests were performed: unconstrained desiccation, linearly-constrained desiccation and crack pattern tests. Only linearly-constrained desiccation tests are investigated in this simulation. For the experimental test, soil slurry prepared with a water content of 1.5 times liquid limit was poured into a mould with dimension: 295 mm (length) \times 49 mm (width) \times 12 mm (thickness), and put on a notched metallic base (Fig. 2a). The test was performed in a climate chamber with temperature and humidity controlled in a climate chamber. The temperature used was 19 °C with a variation of 1 °C. The relative humidity was 40%. Due to the existence of these notches, a constraint along the axial direction of the soil sample was created. Therefore, soil samples desiccated under linear constraint experienced paralleled one-directional cracks. These cracks were perpendicular to the sample's longitudinal direction as show in Fig. 4b. An average of 7 cracks occurred.

The linearly-constrained desiccation test was modelled using the parameters presented in Table 1. The experimental sample size (i.e., 295 mm \times 12 mm) and the shape of the notched metallic base are followed in the modelling as shown in Fig. 2a. To capture the randomness of crack initiation and propagation, Voronoi tessellation technique was adopted. The average size of the Voronoi grains was 1 mm (Fig. 2a) with total of 3760 blocks included in the soil model (excluding the block of steel base). The shared boundary of each pair of blocks was modelled using the mix-mode cohesive fracture model presented in Fig. 1. For each block, it is meshed into a few finite difference zones and they are linear elastic. For the boundary condition applied in the simulation, the bottom of the metallic base is fixed along the vertical direction while it is free along the horizontal direction. Considering the geometry of the soil sample, plane-stress mode was adopted. A total isotropic strain of 5% was applied on each zone of all soil blocks along horizontal and vertical direction, separately, during the whole simulation through 50 steps, which means an isotropic strain of 0.1% was applied on each soil grain in each step.

Figure 2 shows the desiccation cracking process at different time steps. It can be seen that the cracks generally start from the top surface of the soil model. The cracking path is generally not straight due to the discrete nature of the numerical method. It is noted that the first crack is initiated randomly and a few primary cracks are formed first. The primary soil cells bounded by the primary cracks are then segregated by the secondary cracks. At the end of the desiccation, 9 fully propagated cracks are formed which are close to the experimental result although the material properties used in the paper are not same as the real experimental parameters. Diffuse cracking which occurred at the end of the model is also observed in the simulation (right end of Fig. 2f). During the simulation, the displacement at the right end of the model was monitored as shown in Fig. 3. It can be

Fig. 2 Desiccation cracking process of Bioley silt: **a** step 0; **b** step 10; **c** step 20; **d** step 30; **e** step 40; **f** step 50 (final crack pattern) (Gui et al. 2016b)

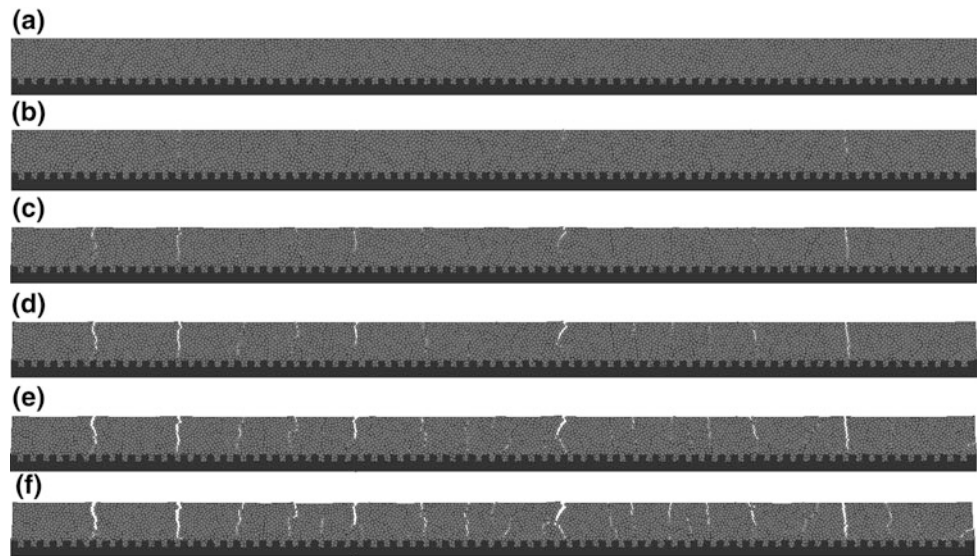


Table 1 Summary of material parameters used in the linearly-constrained desiccation simulation of Bioley silt (Gui et al. 2016b)

Property	Soil	Base
Density (kg/m^3)	1440	8000
Elastic modulus (MPa)	4.0	200×10^3
Poisson's ratio	0.2	0.2
Friction angle ($^\circ$)	20	5
Cohesion (kPa)	10.0	1.4
Tensile strength (kPa)	4.0	0.7
Fracture toughness in mode-I ($\text{kPa/m}^{0.5}$)	1.0	–
Fracture toughness in mode-II ($\text{kPa/m}^{0.5}$)	1.5	–

Note The cohesion, friction and tensile strength for the base on the above table are the soil-base interface parameters

seen that the displacement increases as the desiccation progresses. The displacement at the end of modelling is 6.64×10^{-4} m considering the symmetric geometry, the calculated strain along horizontal direction is 4.5% and it is smaller than the input strain (i.e., 5%). This can be explained by the occurrence of the cracks. More specifically, the displacement at the model end can be decreased by the occurrence of cracks. Thus, with the time progressing or with more and more cracks occurred, the rate of strain increases reduces. In order to investigate the influence of the base-soil interface properties, a soil-slab sitting on non-notched base was simulated. The obtained final number of cracks from the simulation is shown in Fig. 4. Again, the results have demonstrated the influence of base-soil interface properties on desiccation cracking.

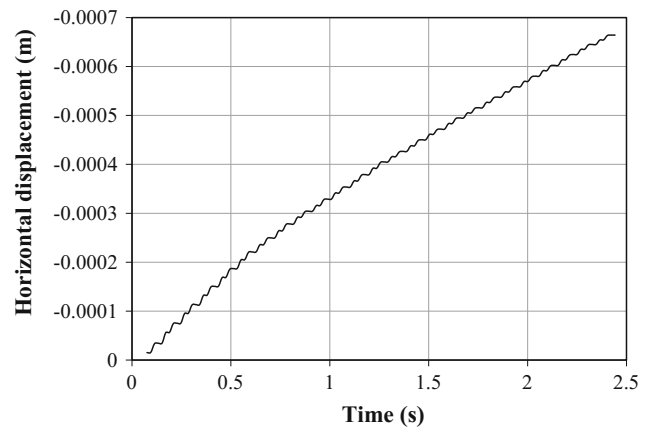


Fig. 3 Simulated horizontal displacement at the right end of the sample (Gui et al. 2016b)

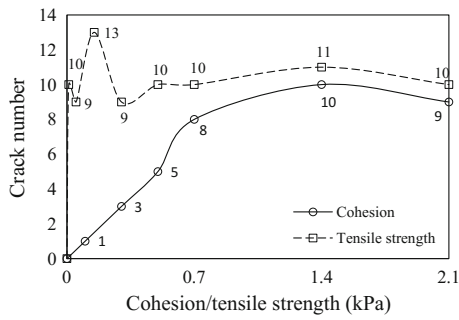


Fig. 4 The evolution of crack number with the change of cohesion and tensile strength of soil-base interface (Gui et al. 2016b)

4 Modeling of Field Desiccation Test

4.1 Numerical Model

A field experiment by excavation to three different levels from top to bottom to investigate desiccation cracking in top soil, weathered and intact clay under restrained conditions, respectively, was carried out by Konrad and Ayad (1997) at the experimental site of Saint-Alban, Quebec, Canada. In their investigation, the moisture content and suction profiles were recorded. It was found that the gravimetric water content decreased significantly in the soil close to the surface, while the deeper soil had a much smaller decrease in water content. This effect was most pronounced in the upper 40 cm. The suction profile was similar to the water content. Figure 5 show the suction profile monitored in the whole desiccation test. It was also found that desiccation cracking occurred in less than 17 h after the start of the test for both intact and weathered clays with average crack spacing of 20–24 cm for the intact clay. It was also found that horizontal crack can occur and propagate horizontally at certain

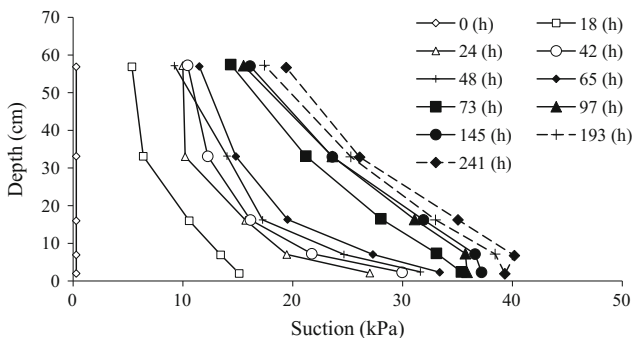


Fig. 5 The measured suction profile during the field desiccation test (Konrad and Ayad 1997)

depth in the intact clay, thereby soil wedges forming and they being easily removed.

A 2-dimensional model with length of 1.2 m and depth of 0.7 m is built, as shown in Fig. 6. Plane-stress mode is used. The model is discretized using Voronoi polygon. The interface of the polygons is treated using the cohesive fracture model. The left, bottom and right boundaries are fixed using roller boundary. The model is divided into six layers bounded by the levels where the suction history was measured in the field desiccation test. In each layer the suction is interpolated linearly. Since the soil becomes harder and harder during desiccation, the elastic modulus of the soil is calculated based on the initial suction value (289 Pa) measured in the field through the following equation (Amarasiri and Kodikara 2013).

$$E = E_0 + 24(1 - 2\nu)(s - s_0) \tag{1}$$

where E and E_0 are the updated elastic modulus and initial elastic modulus, respectively. ν is the Poisson’s ratio. s and s_0 are the updated suction and initial suction. The increase of

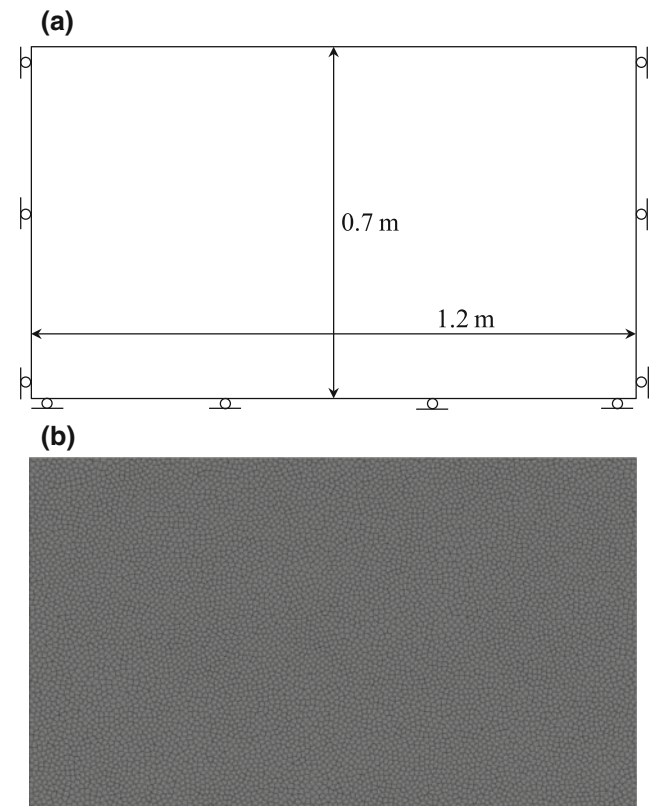


Fig. 6 a Physical model and b numerical model of the soil sample (Gui et al. 2018)

Table 2 Summary of soil parameters used in the desiccation simulation (Gui et al. 2018)

Density (kg/m ³)	1440
Elastic modulus (MPa)	5.0
Poisson's ratio	0.3
Friction angle (°)	19
Cohesion (kPa)	30.0
Tensile strength (kPa)	15.0
Normal stiffness (Pa/m)	4×10^{10}
Shear stiffness (Pa/m)	2×10^{10}
w_e (m)	1.875×10^{-6}
w_c (m)	7.5×10^{-6}

the effective stress due to desiccation is following the effective stress principle as

$$\Delta\sigma' = \Delta\sigma_{net} + \chi\Delta s \quad (2)$$

where σ' , σ_{net} and χ are the effective stress, net stress and effective stress parameter accounting the contribution of suction to the value of effective stress. During the soil desiccation shrinkage, the soil is almost saturated, even after cracking. Therefore, in this note, the effective stress parameter is set to $\chi = 1$ (Khalili et al. 2004). Due to that the value of the net stress has no change, the effective stress change is only contributed to by the increase of the suction. The initial parameters used in the modelling are listed in Table 2. During the simulation, the settlements at various depth are monitored, and the crack initiation time and crack propagation pattern are recorded.

4.2 Results and Discussions

Figure 7 shows the micro-crack initiation and propagation. It can be seen that the desiccation crack starts from

the ground surface. At some locations, the cracks initiate prior to other locations. These first occurred cracks are referred to as primary crack in soil desiccation (Fig. 4a). With desiccation progressing, more cracks (secondary cracks) are initiated within the aggregates formed by the primary cracks. The cracks propagate into the deeper level, majorly vertically. Due to the discrete nature of the method, the crack propagating path is not straight. Some of the cracks bifurcate when they propagate (Fig. 7d, e). The branches of the bifurcated cracks propagate nearly horizontally and meet each other, resulting in the formation of horizontal cracks. Therefore, soil wedges are formed close to the surface (Fig. 7f). The final crack can reach as deep as more than 60 cm from the surface. Figure 8 investigates the surface crack pattern in the field soil desiccation modelling. The parameters used are shown in Table 2. Two different shaped models are used: rectangular and circular, with roller boundary. In both simulations, desiccation-induced soil polygons are formed. However, there are more cracks are formed in the circular model.

5 Conclusions

The paper presents the numerical simulation of soil desiccation tests in both laboratory and field using a hybrid continuum-discrete element method with a mix-mode cohesive fracture model. In the simulation, the desiccation induced soil hardening is considered by adopting an empirical equation for soil elastic modulus for field desiccation test. It is found that the desiccation phenomena can be reasonably replicated, especially, the sub-horizontal crack is successfully reproduced. The present findings demonstrate that the mix-mode cohesive fracture model is able to handle desiccation induced multi-cracks in the field soil desiccation using the hybrid continuum-discrete element method.

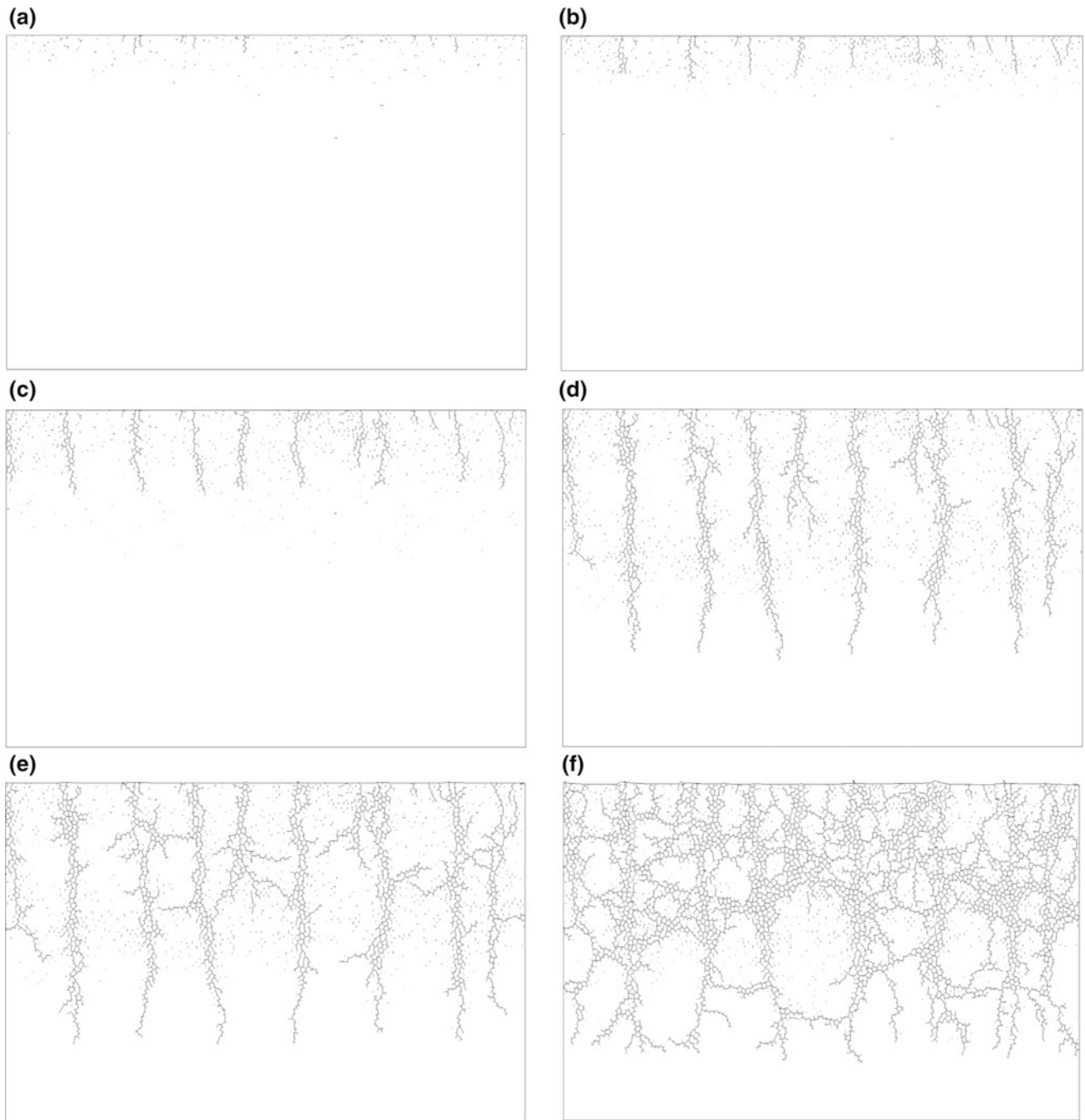


Fig. 7 Modelled micro-crack evolution during the field soil desiccation (Gui et al. 2018)

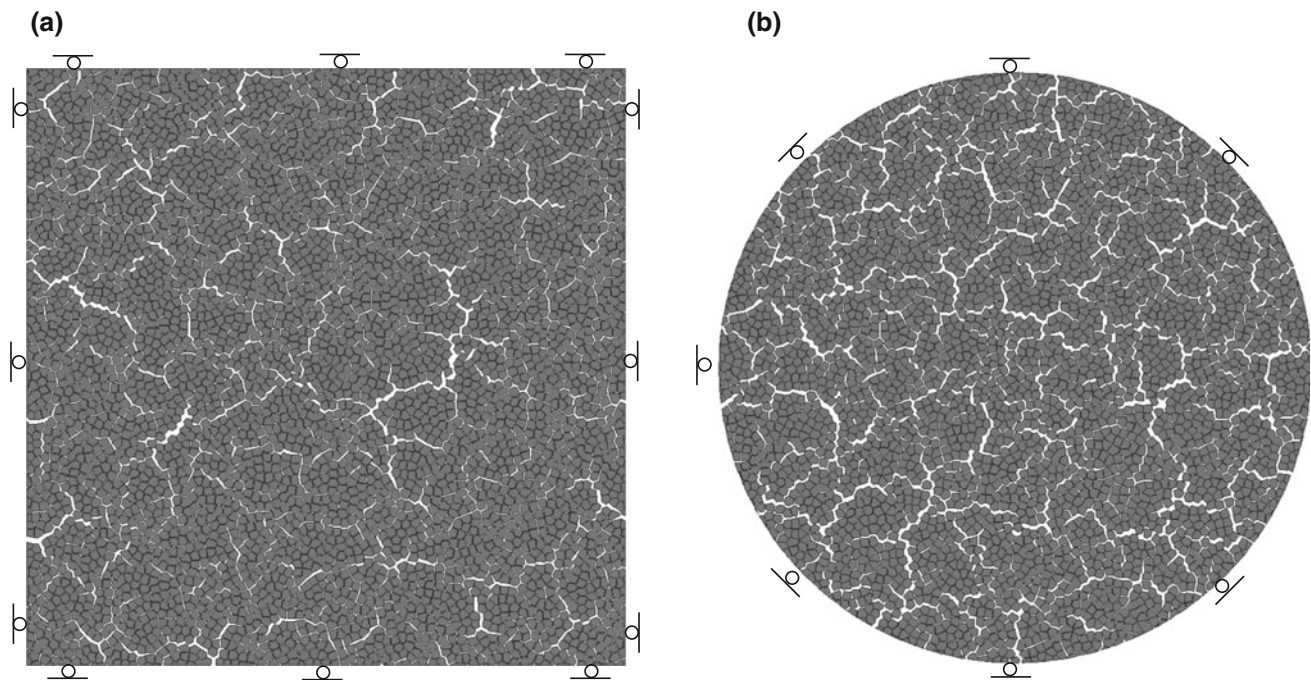


Fig. 8 Numerical final crack pattern obtained by different boundary condition

Acknowledgements Funding support from China State Key Laboratory of Geohazard Prevention and Geoenvironmental Protection, Chengdu University of Technology, via project SKLGP2016K003 is gratefully acknowledged.

References

- Amarasiri, A.L., Kodikara, J.K.: Numerical modelling of a field desiccation test. *Geotechnique* **63**(11), 983–986 (2013)
- Arnold, J.G., Potter, K.N., King, K.W., Allen, P.M.: Estimation of soil cracking and the effect on surface runoff in a Texas Blackland Prairie watershed. *Hydrol. Process.* **19**, 589–603 (2005)
- Dixon, D., Chandler, J., Graham, J., Gray, M.N.: Two large-scale sealing tests conducted at atomic energy of Canada's underground research laboratory: the buffer-container experiment and the isothermal test. *Can. Geotech. J.* **39**(3), 503–518 (2002)
- Galvez, J.C., Cervenka, J., Condon, D.A., Saouma, V.: A discrete crack approach to normal/shear cracking of concrete. *Cem. Concr. Res.* **32**, 1567–1585 (2002)
- Gui, Y., Ha, H.H., Kodikara, J.: An application of a cohesive fracture model combining compression, tension and shear in soft rocks. *Comput. Geotech.* **66**, 142–157 (2015)
- Gui, Y., Ha, H.H., Kodikara, J., Zhang, Q.B., Zhao, J., Rabczuk, T.: Modelling the dynamic failure of brittle rocks using a hybrid continuum-discrete element method with a mixed-mode cohesive fracture model. *Int. J. Impact Eng.* **87**, 146–155 (2016a)
- Gui, Y.L., Zhao, Z.Y., Kodikara, J., Ha, H.H., Yang, S.Q.: Numerical modelling of laboratory soil desiccation cracking using UDEC with a mix-mode cohesive fracture model. *Eng. Geol.* **202**, 14–23 (2016b)
- Gui, Y., Zhao, G.F.: Modelling of laboratory soil desiccation cracking using DLSM with a two-phase bond model. *Comput. Geotech.* **69**, 578–587 (2015)
- Gui, Y., Hu, W., Zhao, Z.Y., Zhu, X.: Numerical modelling of a field soil desiccation test using a cohesive fracture model with Voronoi tessellations. *Acta Geotech.* **13**, 87–102 (2018)
- Inazu, T., Iwasaki, K., Furuta, T.: Stress and crack prediction during drying of Japanese noodle (udon). *Int. J. Food Sci. Tech.* **40**, 621–630 (2005)
- Intharasombat, N., Puppala, A.J., Williammee, R.: Compost amended soil treatment for mitigating highway shoulder desiccation cracks. *J. Infrastruct. Syst.* **13**(4), 287–298 (2007)
- Khalili, N., Geiser, F., Blight, G.E.: Effective stress in unsaturated soils: review with new evidence. *Int. J. Geomech.* **4**(2), 115–126 (2004)
- Kissel, D.E., Ritchie, J.T., Burnett, E.: Nitrate and chloride leaching in a swelling soil. *J. Environ. Qual.* **3**(4), 401–404 (1974)
- Konrad, J.M., Ayad, R.: Desiccation of a sensitive clay: field experimental observations. *Can. Geotech. J.* **34**, 929–942 (1997)
- Lee, W.P., Routh, A.F.: Why do drying films crack? *Langmuir* **20**(23), 9885–9888 (2004)
- Peron, H., Hueckel, T., Laloui, L., Hu, L.B.: Fundamentals of desiccation cracking of fine-grained soils: experimental characterisation and mechanisms identification. *Can. Geotech. J.* **46**(10), 1177–1201 (2009)
- Philip, L.K., Shimell, H., Hewitt, P.J., Ellard, H.T.: A field-based tests cell examining clay desiccation in landfill liners. *Q. J. Eng. Geol. Hydrogeol.* **35**, 345–354 (2014)
- Rayhani, M.H.T., Yanful, E.K., Fakher, A.: Desiccation-induced cracking and its effect on the hydraulic conductivity of clayey soils from Iran. *Can. Geotech. J.* **44**, 276–283 (2007)
- Scherer, G.W.: Structures and properties of gels. *Cem. Concr. Res.* **29** (1999), 1149–1157 (1999)
- Sima, J., Jiang, M., Zhou, C.: Numerical simulation of desiccation cracking in a thin clay layer using 3D discrete element modelling. *Comput. Geotech.* **56**, 168–180 (2014)
- Singh, K.B., Tirumkudulu, M.S.: Cracking in drying colloidal films. *Phys. Rev. Lett.* **98**(21) (2007). <https://doi.org/10.1103/physrevlett.98.218302>