Canadian Geotechnical Journal
Revue canadienne de géotechnique

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Journal:	<i>Canadian Geotechnical Journal</i>
Manuscript ID	cgj-2016-0674.R1
Manuscript Type:	Article
Date Submitted by the Author:	03-May-2017
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Keyword:	dissication crack, shrinkage, discrete element model, crack monitoring

**Laboratory Characterization and Discrete Element Modeling of Shrinkage and Cracking
in Clay Layer**

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Abstract

The performance of a variety of geostructures such as compacted clay liners, earth dams, and pavement embankments are compromised by soil cracking. Experiments are set up to monitor the drying process of a clay layer under controlled temperature and humidity conditions. The gravimetric water content and the images are captured automatically. The volumetric shrinkage of the bentonite sample as well as the crack patterns are determined from images. The monitored volumetric strain development is used to implement the Discrete Element Model (DEM) to simulate the drying shrinkage and desiccation cracking. Model parameters are calibrated through unconfined compression tests on clay specimens at different water content. This simplified calibration procedure allows to characterize the soil behaviors in the mesoscale and bypass the complex physiochemical processes involved. The initiation and propagation of cracks

from the DEM model agree well with the phenomena observed in the laboratory experiments. The influence of boundary constraint and sample thickness on the crack patterns are analyzed, which include the use of hydrophobic coating to diminish the boundary constraint. Major features of desiccation cracking can be replicated with the computational procedures. Boundary constraint, including surface roughness and strength of boundary layer, is found to significantly influence the final crack patterns.

Keywords: desiccation crack, drying shrinkage, bentonite, crack pattern, Discrete Element Method (DEM)

Introduction

Soil cracking is a critical issue in geotechnical engineering, as it may cause damage to embankments and earth dams (Dyer et al. 2007; Kakuturu and Reddi 2006), undermine the stability of slopes (Utili 2013), deteriorate the performance of stabilized pavements (Kodikara and Chakrabarti 2005), and induce the leakage of landfill liners and covers (Daniel and Wu 1993; Albrecht and Benson 2001; Rayhani 2008; Peron et al. 2009a). Desiccation cracking, which occurs when soils are restrained while drying and undergoing volumetric shrinkage, is regarded as a critical engineering problem especially for expansive soils.

Researches show that the potential of cracking is highly related to soil properties, including shear and tensile strengths, the Poisson's ratio, compression modulus, specific surface energy, and soil suction (Morris 1992; Villar 2005; Pelot 2015). The fines content and mineral

composition largely affect the formation of desiccation cracking (Yesiller 2000; El Maarry 2015). Addition of non-swelling silica fume to clayey soils could reduce the shrink-swell behaviors (Kalkan 2009). The initiation and propagation of cracks while drying are also determined by some environmental factors. Salt concentration, relative humidity and temperature, which may significantly change the water evaporation rate, could affect the formation of desiccation cracking (Gebrenegus 2011; Hedan et al. 2014; Shokri 2015). Cyclic freezing and thawing could change the shape of the desiccation polygons (Lu 2016).

Cracking water content, or the moisture content at which crack starts to occur, varies for the same soil under different testing conditions, e.g., sample thickness, bottom contact, and evaporation rate (Nahlawi and Kodikara 2006; Tang 2011a; Zielinski 2014). Under the same testing condition, the drying process of cohesive soil can be divided into two stages separated by the air entry point (Peron 2009a). Above the point, the soil is fully saturated and the evaporation rate remains constant. Below the point, the degree of saturation is smaller than 100% and the evaporation rate decreases due to the significant increase of suction. Laboratory monitoring on clayey soil showed that 90% of the cracks took place during the constant evaporation rate period before the air entry point (Tang 2011a).

Modeling of soil cracking while drying is still challenging due to the complex influencing factors, including clay mineralogy, double layer interaction, soil suction (Anderson and Lu 2001; Santamarina 2001), and the discontinuity involved when cracking. The mesh fragmentation method, which is a further implementation of the Finite Element Method (FEM), is promising in simulating the formation of desiccation cracks (Sánchez 2014). The migration of water during drying can also be solved through weak coupled diffusion equation embedded in the FEM model (Hirobe and Oguni 2016). Besides that, the Discrete Element Method (DEM) provides an

alternative way to model the discontinuity of clayey soils while drying (El Youssoufi 2005; Amarasiri 2011; Amarasiri 2014; Gui and Zhao 2015; Gui 2016). In the DEM model, discrete polygonal-shaped blocks or spherical particles are used to simulate soils in the aggregate scale (0.1 mm ~ 10.0 mm). Some researchers also developed the particle scale model (0.1 μm ~ 10.0 μm) based on the DEM, which considers the mechanical interactions between clay particles (Anderson and Lu 2001; Katti 2009). However large dimensional modeling of clayey soils under the microscale is still challenging due to the limitation of current computational power.

Aside from considering the complicated clay particle interactions, a simplified intra-aggregate structure model may be suitable to explain most of the cracking behaviors (Chertkov 2008; Bagherieh 2009). In this model, natural soil is regarded as a medium consisted of soil aggregates, and aggregates are separated by fine inter-aggregate pores. Volume of the soil aggregate changes with water content (Tang 2011b). Based on these assumptions, the mesoscale DEM model was built to describe the cracking process (El Youssoufi 2005; Peron 2009b; Sima 2014). The formation and propagation of cracks are simulated at the aggregate level through proper scaling of particle size and careful selection of contact parameters. Experiments show that the Young's modulus and undrained shear strength of clayey soils are highly related to soil water content (Borgesson 2001; Lu and Kaya 2013; Tisato and Marelli 2013; Byun 2013; Stirling 2015). These raise difficulties in the parameter calibration of the DEM model.

Understanding the desiccation behaviors of a thin clay layer is an important initial step to understand the cracking behaviors of cohesive soils. This is relevant to the assessment and improvement of the performance of a variety of geotechnical structures such as the compacted clay liners for solid waste landfill, earth dams, and moisture stability of pavement embankments. In this study, the desiccation cracking of a thin bentonite layer is prepared in a petri dish and is

monitored in the laboratory under controlled temperature and relative humidity conditions. A DEM model is built to replicate the drying shrinkage of bentonite sample. The cracking behaviors of bentonites with different sample thicknesses and bottom constraints are compared and analyzed through laboratory experiment and numerical simulations. It is shown that the desiccation cracking of bentonite layer is highly sensitive to the initial thickness and boundary constraints (i.e., boundary roughness and boundary adhesion). The observations may offer insight on the cracking behaviors of expansive soils and therefore could lead to improved countermeasures to mitigate the cracking induced performance issues.

Laboratory Experiment

The drying process of a thin bentonite layer in a petri dish was monitored through a custom-built monitoring system under controlled temperature and humidity conditions. The measured properties of bentonite were used subsequently in the numerical model for the further analysis.

Material and methods

THERM-EX GROUT™ bentonite provided by the Wyo-Ben Inc. was used in the following experiments. Product sheet from manufacturer indicates the specific gravity of bentonite is 2.45~2.55 at 20°C, and the mean particle size is 7.0 µm measured by the particle size analyzer. The liquid limit and plastic limit are 239% and 52% respectively measured under room temperature (ASTM D4318, 2000).

Figure 1 gives the experimental setup of the custom-built cracking monitoring system.

THERM-EX GROUT™ bentonite without additional treatment was first mixed with deionized water to the initial water content of 425%. The slurry was then stirred for 30 minutes to form a uniform mixture. The well-mixed slurry was poured into a petri dish (8.0 cm in diameter) and then sealed and cured for 24 hours for fully saturation. This well-prepared sample was put in an insulated chamber under controlled temperature ($23^{\circ}\text{C}\pm 2^{\circ}\text{C}$) and relative humidity ($30\%\pm 5\%$). The gravimetric water content was tracked during the experiment through the scale reading. The initiation and propagation of cracks during drying were recorded through a camera mounted on the top. A laser displacement sensor was pointed to the center of the dish to keep measuring the vertical shrinkage.

Laboratory results

The volumetric shrinkage of bentonite clay was monitored through the video camera. Assume the sample shrinks uniformly and evenly, the volumetric strain can be obtained through the image analysis together with the thickness reading from the laser displacement sensor pointing to the center of the sample. However bentonite sample tends to crack and curl during drying due to the existence of boundary constraint and the non-uniform moisture distribution. To minimize the boundary constraint, a hydrophobic coating was sprayed on the petri dish surface. A thin bentonite layer with a thickness of 0.75 cm was prepared to diminish the moisture difference along the depth direction, and also between the center and the edge.

The monitoring result is shown in Figure 2. By applying the hydrophobic coating, the boundary constraint was minimized and only one small crack formed finally. Curling of the sample was delayed until the water content reached 22%, while in the regular petri dish the

curling water content was as large as 71%. A comparison of the final desiccated samples in the coated and uncoated dishes is given in Figure 3. It should be noted that before curling occurred, sample in the coated dish dried uniformly and the thickness can be regarded as the same. The shrinkage volume after curling ($w < 22\%$) has been corrected according to the final soil density, which was measured from three additional samples drying under the same condition.

The decrease of gravimetric water content of bentonite sample over time is shown in Figure 4. The evaporation rate (proportional to the gradient of water content curve) remains constant in the first stage but decreases as the water content drops to 150% due to the increase of soil suction. Figure 5 provides the relationship between the volumetric strain and the gravimetric water content. The volumetric strain is acquired through image analysis together with sample thickness measurement. A quadratic regression between volumetric strain (ϵ_w) and gravimetric water content (w) is given below.

$$\epsilon_w = -0.018w^2 - 0.1336w + 0.8849 \quad (1)$$

Numerical Modeling of Desiccation Cracking of Bentonite

A Discrete Element Method (DEM) model was built to simulate the formation and propagation of soil desiccation cracks. The crack pattern with different boundary conditions, including sample thickness, surface roughness, and clay-dish interface strength, has been analyzed numerically and experimentally.

Description of numerical model

Temperature and relative humidity are important factors affecting soil cracking behaviors, as they may significantly change the evaporation rate of soil samples (Rodríguez et al. 2007; Tang 2008; Tang et al. 2010). In this study, a simplified condition was assumed where a low evaporation rate is maintained during the experiment and soil sample dries uniformly. From laboratory experiments, the decreasing rate of soil water content is less than 0.1%/min even in the first few hours (Figure 4). In the DEM model, the volumetric shrinkage of bentonite was simulated through proper scaling of particle size. For spherical particles, the scaled radius can be calculated based on the volumetric strain of clay sample through Eq. (2). The quadratic regression between volumetric strain and water content (Eq. (1)) was used to calculate the scaling coefficient α_w at different water content.

$$1 - \varepsilon_w = 1 - \frac{\Delta V}{V} = \frac{(R_w)^3}{R_0^3} = \alpha_w^3 \quad (2)$$

where ε_w is the volumetric strain at a water content of w ; V is the volume of the clay aggregate; R_w is the particle radius at the water content of w ; R_0 is the initial particle radius; α_w is the scaling coefficient at the water content of w , and $R_w = \alpha_w R_0$.

The contact model between two particles is given in Figure 6. The Kelvin-Voigt model is used for both the normal and tangential directions. A frictional slider is included in the tangential direction to simulate sliding. The particle parameters characterize this contact model include: the normal and tangential spring stiffness (K_n and K_s), particle frictional coefficient (f), the normal and tangential bond strength (σ_n and σ_s), and viscous damping ratio (c). Besides the viscous damping, the PFC3D also provides the local damping, which is directly applied in the momentum equation to achieve static gravitational balance. In this paper, the viscous damping ratio is set to 0.0 for simplicity and the local damping is set to the default value of 0.7 for computational efficiency.

Calibration of particle parameters

A series of Unconfined Compression Tests (UCTs) were conducted for the purpose of parameter calibration (ASTM D2166 2013). Bentonite samples with seven different water content levels were prepared and sealed for 48 hours for moisture homogenization, and then tested accordingly. A scaled DEM sample was built to calibrate the particle parameters through inverse analysis. This simplified calibration method bypasses the complicated consideration of soil suction and clay mineral interaction, and is able to characterize the macroscale mechanical behaviors of bentonite at different water content. Figure 7 compares the UCT sample with the DEM model. The DEM model has been scaled down to a diameter of 10.0 mm and a height of 20.0 mm to improve computational efficiency. Particles in the DEM model have the same diameter of 1.0 mm. The loading velocity has been scaled according to the scale factor. The frictional coefficient between particles was calibrated through the failure plane angle. It is shown experimentally that the angle of shear plane changes little at different moisture content. In the numerical model, angle of shear plane is mainly determined by the frictional coefficient f . A frictional coefficient of 0.40 gives the most analogous result compared with the experiment (Figure 7).

The Young's modulus and unconfined compressive strength were used to calibrate particle spring stiffness and bond strength. Previous research shows the ratio of normal and tangential contact stiffness influences the Poisson's ratio of materials (Wang and Mora 2008; Liu et al. 2013). Here for this paper, the desiccation cracking of a thin clay layer can be regarded as a one-dimensional process, so that both spring stiffness and bond strength were simplified to be

the same in the normal and tangential directions ($K_n = K_s$ and $\sigma_n = \sigma_s$). The simulation results provided in the following context show this simplified method provides accurate calibrations of clay samples in terms of soil cracking simulation. Two piecewise functions have been used in the regression of stiffness and bond strength with subdomains separated by soil plastic limit ($w = 50\%$), as is shown in Figure 8a/b. A linear expression is used for the low-moisture subdomain and an exponential expression is used for the high-moisture subdomain, as is given in Eqs. (3-4).

$$K_{n/s} = \begin{cases} 3.7210 \times 10^6 - 7.2151 \times 10^6 w, & w < 50\% \\ 18962w^{-2.581}, & w \geq 50\% \end{cases} \quad (3)$$

$$\sigma_{n/s} = \begin{cases} 5.7047 - 10.3430w, & w < 50\% \\ 0.0918w^{-2.538}, & w \geq 50\% \end{cases} \quad (4)$$

where $K_{n/s}$ is the normal/tangential spring stiffness (N/m); w is the gravimetric water content, and $w = M_{water}/M_{soil}$; $\sigma_{n/s}$ is the normal/tangential adhesive strength (N).

The calibration results are shown in Figure 9. As can be seen, the piecewise function characterizes the Young's modulus and unconfined compressive strength for both high-moisture content domain and low-moisture content domain with a good accuracy. These calibrated parameters, together with the particle scaling factor α_w , have been used in the following modeling of desiccation cracking.

Numerical modeling of desiccation cracking

Mono-sized spherical particles with a diameter of 1.0 mm are generated inside a petri dish. The dish has an inner diameter of 8.0 cm and a thickness of 0.75 cm, as is shown in Figure 10. Totally 65,012 particles have been generated and balanced under gravity, and the equilibrium porosity is 0.433. A fixed ball boundary has been used on the outer layer of the bentonite sample

(Figure 10), and boundary particles with diameter 0.6 mm remain fixed during the simulation. Contacts between boundary particles and regular particles are the same as is given in Figure 6.

The desiccation process of the bentonite clay is simulated based on the losses of soil moisture. The gravimetric water content of soil sample decreases from an initial value of 425% to the residual water content of 7%. Particle size and contact parameters are assigned according to the gravimetric water content as calibrated above. Considering the discontinuity of the clay-dish interface, particles contacting with the ball boundary have a strength reduction on bond strength and frictional coefficient, while the contact stiffness remains the same, as provided in Eqs. (5-7).

$$K_{n/s,c} = K_{n/s} \quad (5)$$

$$\sigma_{n/s,c} = \beta \sigma_{n/s} \quad (6)$$

$$f_c = \beta f \quad (7)$$

where $K_{n/s,c}$ is the normal/tangential spring stiffness of particles contacting with dish surface (N/m); $\sigma_{n/s,c}$ is the normal/tangential adhesive strength of particles contacting with dish surface (N); f_c is the frictional coefficient of particles contacting with dish surface; β is the strength reduction factor. The strength reduction factor β is assumed to be 0.0 in this simulation case. Its influence on simulation results has been discussed below in details.

The simulation result together with the laboratory experiment are shown in Figure 11. In the laboratory experiment, a thin layer of 0.6-mm-diameter Nevada sand was coated on the petri dish surface to emulate the boundary condition applied in the DEM model. From Figure 11, a high consistency is observed between the numerical model and the laboratory experiment in terms of crack initiation and propagation. The first crack occurred near the weak interface between clay and petri dish ($w = 300\%$). Then major cracks generated and cut the sample into

five to six large polygons ($w = 200\%$). Minor cracks were also generated subsequently as the sample dried further, which however do not change the final crack patterns.

Influence of bottom constraint

The final crack patterns of bentonite under different surface roughness have been compared through experiments and simulations. The experimental comparison was prepared by coating a petri dish with two types of Nevada sands with mean grain sizes of 0.6 mm and 1.0 mm. The different surface roughness in the DEM model is simulated through generating different sized boundary particles (0.6 mm and 1.0 mm), as is shown in Figure 12. Other model parameters are the same as discussed previously. The initial sample thickness is 0.75 cm in both the numerical model and the laboratory experiment.

The final crack patterns of the experiments and simulations are given in Figure 13. As the surface roughness increases, bentonite clay cracks intensively, and the number of the crack polygons increases. Both the DEM model and laboratory experiment show the bottom roughness has a significant influence on the final crack patterns. A rougher surface provides a larger bottom resistance and generates a higher internal stress, which finally leads to more tensile cracks under the same condition.

The strength reduction factor β , which describes the discontinuity between clay and dish surface, changes with soil water content and is difficult to measure directly. A sensitivity study on β was conducted in order to better analyze its influence. The initial sample thickness is 0.75 cm and the sand grains coated on the dish surface are 0.6 mm in diameter. A reduction factor of 0.0 indicates that there is no particle-level bond strength and friction on the dish surface. A

reduction factor of 1.0 indicates the particle-level bond strength and frictional coefficient on the interface are the same as the inner clay particles. It should be noted that even with a reduction factor of 0.0, the rough surface still offers frictional resistance to the clay sample in the macroscale. The modeling results are given in Figure 14. Soil sample with a low bottom strength (or small β value) tends to shrinkage toward the center and is more intact at the residual water content. Compared with the experimental observations, a strength reduction factor of 0.0 was used in this paper as the baseline simulation.

Influence of sample thickness

The final crack patterns of bentonite with different initial sample thickness are compared between experiment and simulation. Three different sample thicknesses are analyzed, including 0.50 cm, 0.75 cm and 1.00 cm. The petri dish has been coated with 0.6-mm-diameter sand grains. Other parameters used in the DEM model are the same as previously discussed. The comparison between numerical model and laboratory experiment is given in Figure 15. Overall the DEM model replicates the laboratory observations well. For a thinner bentonite layer, the bottom constraint has a considerable influence on its shrinkage cracking, and the crack intensity (crack length per unit area) is much higher than the thicker sample.

Laboratory experiments conducted by other researchers also show that sample thickness has a significant influence on crack initiation and propagation (Nahlawi and Kodikara 2006; Tang 2011a). The non-uniform vertical moisture distribution and the higher surface energy required to generate crack for thicker samples are two possible explanations. In this model, moisture content of the bentonite layer is assumed to be the same throughout the sample, and the

non-uniform moisture distribution is not considered. However this DEM model replicates different crack patterns well, which may imply surface energy should play a more important role in the formation of desiccation cracking under this laboratory condition.

Conclusions

The desiccation cracking behavior of a thin bentonite layer has been studied through laboratory experiment and numerical modeling. A custom-built monitoring system was set up to evaluate the shrinkage behaviors of bentonite under controlled temperature and humidity conditions. To better estimate the shrinkage volume of bentonite clay, a hydrophobic coating was applied on the petri dish surface to diminish the bottom constraint and prevent cracking and curling of soil sample. The image analysis was used together with the sample thickness measurement to obtain the volumetric strain of bentonite at different moisture contents.

A DEM model is built to simulate the shrinking process of a thin bentonite layer under laboratory conditions. This DEM model is based on two major assumptions: 1) shrinkage of bentonite clay can be described at the aggregate level; 2) mechanical properties of the clay aggregates vary with the moisture content. Based on these assumptions, particle size in the DEM model is scaled according to the measured volumetric strain at different water content. Contact parameters of the DEM model, including particle stiffness, bond strength and frictional coefficient, are calibrated through a series of unconfined compression tests of bentonite specimens with different water contents. Using the calibrated parameters, the drying process of bentonite with different bottom constraint and thickness are simulated. The numerical model shows a high consistency with the laboratory experiment, proving its capability to predict the

316 formation of desiccation cracks of bentonite clay.

317 The experiments show that major cracks are firstly formed and dominate the shape of
318 crack polygons; minor cracks are formed subsequently as the clay dries further and cuts the
319 sample into smaller polygons. The numerical model replicates reasonably well the generation of
320 major and minor cracks. Both the experiment and numerical model demonstrate that the
321 formation of desiccation cracks is highly sensitive to the boundary constraints, including the
322 surface roughness and surface strength, and sample thickness. Drying thinner samples on a
323 tougher and more adhesive surface tends to produce more cracks. The simulation also indicates
324 that the pattern of desiccation cracks of the thin bentonite layer appears to be mainly dominated
325 by the shrinkage process rather than the non-uniform moisture distribution. Besides improving
326 material strength, reducing boundary constraint also has the benefits in the control of desiccation
327 cracks of bentonite.

328 This paper demonstrates the procedures for model building and calibration to holistically
329 simulate the process of crack initialization. Note that the water evaporation rate is only
330 heuristically considered in this work by use of monitored evaporation data, details of which
331 might have important effects on the crack development processes, e.g., distribution of soil
332 moisture, ambient temperature and humidity. This will need to be analyzed by building a more
333 advanced model, for example, by possibly coupling with a continuous model that describes
334 moisture exchange across the boundaries.

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REFERENCES

- Albrecht, B.A., and Benson, C.H. Effect of Desiccation of Compacted Natural Clays. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 127, No. 1, 2001, pp. 67-75.
- Amarasiri, A.L., Kodikara, J.K., and Costa, S. 2011. Numerical Modelling of Desiccation Cracking. *International Journal for Numerical and Analytical Methods in Geomechanics*, Vol. 35, No. 1, pp. 82-96.
- Amarisiri, A., Shannon, B., and Kodikara, J. 2014. Numerical Modelling of Desiccation Cracking in a Restrained Ring Test. *Canadian Geotechnical Journal* Vol. 51, No. 1, pp. 67-76.
- ASTM D4318-00. 2000. Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International, United States.
- ASTM D2166/D2166M-13. 2013. Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. ASTM International, United States.
- Bagherieh, A.R., Khalili, N., Habibagahi, G., and Ghahramani, A. 2009. Drying Response and Effective Stress in a Double Porosity Aggregated Soil. *Engineering Geology*, Vol. 105, pp. 44-50.
- Borgesson, L., Chijimatsu, M., Fujita, T., Nguyen, T.S., Rutqvist, J., and Jing, L. 2001. Thermo-Hydro-Mechanical Characterisation of a Bentonite-Based Buffer Material by Laboratory Tests and Numerical Back Analyses. *International Journal of Rock Mechanics & Mining Sciences*, Vol. 38, pp. 95-104.
- Byun, Y.H., Lee, J.S., Cho, S.H., and Yoon, H.K. 2013. Evaluation of Void Ratio and Elastic Modulus of Unsaturated Soil Using Elastic Waves. *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*, Paris, pp. 1089-1092.
- Daniel, D., and Wu, Y.K. 1993. Compacted Clay Liners and Covers for Arid Sites. *The Journal of Geotechnical Engineering*, Vol. 119, No. 2, pp. 223-237.
- Dyer, M., Utili, S., and Zielinski, M. 2007. The Influence of Desiccation Fine Fissuring on the Stability of Flood Embankment, FRMRC Research Report UR11.

- 362 El Maarry, M.R., Watters, W.A., Yoldi, Z., Pommerol, A., Fischer, D., Eggenberger, U., and Thomas, N.
363 2015. Field Investigation of Dried Lakes in Western United States as an Analogue to Desiccation
364 Fractures on Mars. *Journal of Geophysical Research: Planets*, Vol. 120, No. 12, 2241-2257.
- 365 El Youssoufi, M.S., Delenne, J.Y., and Radjai, F. 2005. Self-Stresses and Crack Formation by Particle
366 Swelling In Cohesive Granular Media. *Physical Review E*, Vol. 71, No. 5, pp. 1-5.
- 367 Gebrenegus, T., Ghezzehei, T.A., and Tuller, M. 2011. Physicochemical Controls on Initiation and
368 Evolution of Desiccation Cracks in Sand-Bentonite Mixtures: X-Ray CT Imaging and Stochastic
369 Modeling. *Journal of contaminant hydrology*. Vol. 126 pp. 100-112.
- 370 Gui, Y., and Zhao, G.F. 2015. Modelling of Laboratory Soil Desiccation Cracking using DLSP with a
371 Two-Phase Bond Model. *Computers and Geotechnics*, Vol. 69 pp. 578-587.
- 372 Gui, Y.L., Zhao, Z.Y., Kodikara, J., Bui, H.H., and Yang, S.Q. 2016. Numerical Modelling of Laboratory
373 Soil Desiccation Cracking using UDEC with a Mix-Mode Cohesive Fracture Model. *Engineering*
374 *Geology*, Vol. 202 pp. 14-23.
- 375 Hedan, S., Fauchille, A.L., Valle, V., Cabrera, J., and Cosenza, P. 2014. One-Year Monitoring of
376 Desiccation Cracks in Tournemire Argillite using Digital Image Correlation. *International Journal*
377 *of Rock Mechanics and Mining Sciences*, Vol. 68 pp. 22-35.
- 378 Hirobe, S., and Oguni, K. 2016. Coupling Analysis of Pattern Formation in Desiccation Cracks. *Computer*
379 *Methods in Applied Mechanics and Engineering* - accepted manuscript.
- 380 Kakuturu, S., and Reddi, L. 2006. Evaluation of the Parameters Influencing Self-Healing in Earth Dams.
381 *Journal of Geotechnical and Geoenvironmental Engineering* Vol. 132, No. 7 pp. 879-889.
- 382 Kalkan, E. 2009. Influence of Silica Fume on the Desiccation Cracks of Compacted Clayey Soils. *Applied*
383 *Clay Science*, Vol. 43, No. 3-4, pp. 296-302.
- 384 Katti, D., Matar, M.I., Katti, K.S., and Amarasinghe, P.M. 2009. Multiscale Modeling of Swelling Clays:
385 A Computational and Experimental Approach. *KSCE Journal of Civil Engineering*, Vol. 13, No.
386 4, pp. 243-255.
- 387 Kodikara, J., and Chakrabarti, S. 2005. Modeling of Moisture Loss in Cementitiously Stabilized

- 388 Pavement Materials. *International Journal of Geomechanics*, Vol. 5, No. 4, pp. 295-303.
- 389 Anderson, M., and Lu, N. 2001. Role of Microscopic Physicochemical Forces in Large Volumetric Strains
390 for Clay Sediments. *Journal of Engineering Mechanics*, Vol. 127, No. 7, pp. 710-719.
- 391 Liu, C., Pollard, D., and Shi, B. 2013. Analytical Solutions and Numerical Tests of Elastic and Failure
392 Behaviors of Close-Packed Lattice for Brittle Rocks and Crystals. *Journal of Geophysical*
393 *Research: Solid Earth*, Vol. 118, pp. 71-82.
- 394 Lu, N., and Kaya, M. 2013. A Drying Cake Method for Measuring Suction-Stress Characteristic Curve,
395 Soil-Water-Retention Curve, and Hydraulic Conductivity Function. *Geotechnical Testing Journal*,
396 Vol. 36, No. 1, pp. 1-19.
- 397 Lu, Y., Liu, S., Weng, L., Wang, L., Li, Z., and Xu, L. 2016. Fractal Analysis of Cracking in a Clayey Soil
398 under Freeze-Thaw Cycles. *Engineering Geology*, Vol. 208, pp. 93-99.
- 399 Morris, P.H., Graham, J., and Williams, D.J. 1992. Cracking in Drying Soils. *Canadian Geotechnical*
400 *Journal*, Vol. 29, No. 2, pp. 263-277.
- 401 Nahlawi, H., and Kodikara, J.K. 2006. Laboratory Experiments on Desiccation Cracking of Thin Soil
402 Layers. *Geotechnical and Geological Engineering*, Vol. 24, No. 6, pp. 1641-1664.
- 403 Pelot, D.D., Jun, S., and Yarin, A.L. 2015. Bentonite Dispersions: Transition from Liquid-Like to Solid-
404 Like Behavior and Cracking. *Journal of Non-Newtonian Fluid Mechanics*, Vol. 219, pp. 50-64.
- 405 Peron, H., Hueckel, T., Laloui, L., and Hu, L.B. 2009a. Fundamentals of Desiccation Cracking of Fine-
406 Grained Soils: Experimental Characterisation and Mechanisms Identification. *Canadian*
407 *Geotechnical Journal*, Vol. 46, No. 10, pp. 1177-1201.
- 408 Peron, H., Delenne, J.Y., Laloui, L., and El Youssoufi, M.S. 2009b. Discrete Element Modelling of
409 Drying Shrinkage and Cracking of Soils. *Computers and Geotechnics*, Vol. 36, pp. 61-69.
- 410 Rayhani, M.H.T., Yanful, E.K., and Fakher, A. 2008. Physical Modeling of Desiccation Cracking in
411 Plastic Soils. *Engineering Geology*, Vol. 97, pp. 25-31.
- 412 Rodríguez, R., Sánchez, M., Ledesma, A., and Lloret, A. 2007. Experimental and Numerical Analysis of
413 Desiccation of a Mining Waste. *Canadian Geotechnical Journal*, Vol. 44, No. 6, pp. 644-658.

- 414 Santamarina, J. C. 2001. Soil Behavior at the Microscale: Particle Forces. Proceedings of the Symposium
415 on Soil Behavior and Soft Ground Construction.
- 416 Sánchez, M., Manzoli, O.L., and Guimarães, L.J.N. 2014. Modeling 3-D Desiccation Soil Crack
417 Networks using a Mesh Fragmentation Technique. Computers and Geotechnics, Vol. 62, pp. 27-
418 39.
- 419 Shokri, N., Zhou, P., and Keshmiri, A. 2015. Patterns of Desiccation Cracks in Saline Bentonite Layers.
420 Transport in Porous Media, Vol. 110, No. 2, pp. 333-344.
- 421 Sima, J., Jiang, M., and Zhou, C. 2014. Numerical Simulation of Desiccation Cracking in a Thin Clay
422 Layer using 3D Discrete Element Modeling. Computers and Geotechnics, Vol. 56, pp. 168-180.
- 423 Stirling, R.A., Hughes, P., Davie, C.T., and Glendinning, S. 2015. Tensile Behaviour of Unsaturated
424 Compacted Clay Soils-A Direct Assessment Method. Applied Clay Science, Vol. 112-113, pp.
425 123-133.
- 426 Tang, C., Shi, B., Liu, C., Zhao, L., and Wang, B. 2008. Influencing Factors of Geometrical Structure of
427 Surface Shrinkage Cracks in Clayey Soils. Engineering Geology, Vol. 101, pp. 204-217.
- 428 Tang, C., Cui, Y., Tang, A., and Shi, B. 2010. Experiment Evidence on the Temperature Dependence of
429 Desiccation Cracking Behavior of Clayey Soils. Engineering Geology, Vol. 114, pp. 261-266.
- 430 Tang, C.S., Shi, B., Liu, C., Suo, W.B., and Gao, L. 2011a. Experimental Characterization of Shrinkage
431 and Desiccation Cracking in Thin Clay Layer. Applied Clay Science, Vol. 52, pp. 69-77.
- 432 Tang, C.S., Cui, Y.J., Shi, B., Tang, A.M., and Liu, C. 2011b. Desiccation and Cracking Behaviour of
433 Clay Layer from Slurry State under Wetting-Drying Cycles. Geoderma, Vol. 166, pp. 111-118.
- 434 Tisato, N., and Marelli, S. 2013. Laboratory Measurements of the Longitudinal and Transverse Wave
435 Velocities of Compacted Bentonite as a Function of Water Content, Temperature, and Confining
436 Pressure. Journal of Geophysical Research: Solid Earth, Vol. 118, No. 7, pp. 3380-3393.
- 437 Utili, S. 2013. Investigation by Limit Analysis on the Stability of Slopes with Cracks. Géotechnique, Vol.
438 63, No. 2, pp. 140-154.
- 439 Villar, M.V. 2005. MX-80 Bentonite Thermo-Hydro-Mechanical Characterisation Performed at CIEMAT

- 440 in the Context of the Prototype Project, pp. 1-39.
- 441 Wang, Y., and Mora, P. 2008. Macroscopic Elastic Properties of Regular Lattices. *Journal of the*
- 442 *Mechanics and Physics of Solids*, Vol. 56, pp. 3459-3474.
- 443 Yesiller, N., Miller, C.J., Inci, G., and Yaldo, K. 2000. Desiccation and Cracking Behavior of Three
- 444 Compacted Landfill Liner Soils. *Engineering Geology*, Vol. 57, pp. 105-121.
- 445 Zielinski, M., Sánchez, M., Romero, E., and Atique, A. 2014. Precise Observation of Soil Surface
- 446 Curling. *Geoderma*, Vol. 226-227, pp. 85-93.
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