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Thermo-hydro-mechanical analysis of soil strata suffered from desiccation cracking

Analyse thermo-hydro-mécanique des couches de sol souffrant de fissuration par la dessiccation

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ABSTRACT: Understanding the complex behaviour of cracked ground surface resulting from the desiccation process in swelling soils has received significant attention in recent years. The formation of these cracks is attributed to the complicated interplay between soil comprising of plastic nature and atmospheric conditions; in some cases, the influencing depth of cracking can be extended to several meters below the ground surface. Therefore, the main goal of this research is to investigate the thermo-hydro-mechanical (THM) behaviour of cracked soil strata using CODE-BRIGHT. Results indicated that crack presence led to heterogeneous moisture distribution during the drying process with more significant desiccation in crack edges and walls. In addition, the inclusion of crack into an initially homogeneous soil stratum enhanced the heterogeneous ground deformations, with the most pronounced effects observed near the cracks. Remarkably, the findings indicate that cracks display varying behaviour under diverse climatic conditions. They tend to widen more in warmer climates, and conversely, they exhibit a tendency to close during rainy periods, which can be attributed to soil swelling.

RÉSUMÉ: La compréhension du comportement complexe de la surface du sol fissurée résultant du processus de dessiccation dans les sols gonflants a suscité beaucoup d'attention ces dernières années. La formation de ces fissures est attribuée à l'interaction complexe entre un sol de nature plastique et les conditions atmosphériques ; dans certains cas, la profondeur d'influence des fissures peut s'étendre à plusieurs mètres sous la surface du sol. Par conséquent, l'objectif principal de cette recherche est d'étudier le comportement thermo-hydro-mécanique (THM) des strates de sol fissuré à l'aide de CODE-BRIGHT. Les résultats indiquent que la présence de fissures entraîne une distribution hétérogène de l'humidité pendant le processus de dessiccation, avec une dessiccation plus significative au niveau des bords et des parois des fissures. De plus, l'intégration de fissures dans un substrat de sol initialement homogène a renforcé les déformations hétérogènes du sol, les effets les plus prononcés étant observés près des fissures. Remarquablement, les résultats indiquent que les fissures présentent un comportement variable en fonction des conditions climatiques diverses. Elles ont tendance à s'élargir davantage dans les climats plus chauds, et inversement, elles montrent une tendance à se refermer pendant les périodes de pluie, ce qui peut être attribué au gonflement du sol.

Keywords: THM analysis; soil-atmosphere interaction; desiccation crack; heterogeneous deformation; geohazard.

1 INTRODUCTION

Soil deformation is a complex phenomenon influenced by various factors, including environmental conditions and soil properties. The behaviour of soils in response to changes in moisture content plays a crucial role in numerous engineering applications, from geotechnical engineering to infrastructure design (Yazdani et al., 2024). Cracks that develop within the soil matrix introduce an additional layer of complexity, altering the deformation patterns and redistributing of soil moisture and mechanical stresses (Wang et al., 2022). Understanding the deformation behaviour of soils under wetting and drying conditions is essential for predicting potential subsidence, swelling, and subsequent structural damage (Ghorbani et al., 2023). In this context, the presence of cracks further complicates the deformation mechanism, as cracks provide preferential paths that intensify evaporation and facilitate infiltration (Luo et al., 2023).

In recent years, advanced computational techniques and experimental methods have enabled researchers to delve deeper into soil desiccation cracking (Sanchez et al., 2014; Wei et al., 2016; Guo et al., 2023). Numerical simulations provide insights into the complex interplay between crack geometry, soil properties, and environmental factors. Moreover, laboratory experiments involving controlled environmental conditions contribute valuable empirical data for the validation and calibration of numerical models. Integrating these approaches facilitates a comprehensive understanding of the soil desiccation cracking mechanisms and their influencing factors. Prior studies have mainly focused on crack initiation and propagation, overlooking the complexities of how these cracks and soil surface deform under actual climate fluctuations. Hence, key aspects such as heterogeneous subsidence and swelling during warm and wet periods, induced by surface layer shrinkage and expansion, were not addressed. Furthermore, most researchs have focused on smaller scales, conducting controlled experiments on soil samples to observe crack behaviour, while larger field-scale cracks are influenced by significant climatic shifts affecting surface topography.

This study seeks to establish a more profound comprehension of the cracked soil deformation and moisture dynamics under the influence of real climate changes with THM analysis using the CODE_BRIGHT finite element program.

2 MATERIALS AND METHODS

2.1 Balance and constitutive equations

The THM model's equations employed in this study are rooted in the theoretical framework introduced initially by Olivella et al. (1994). Therefore, the model contains solid mass, water mass, energy, and momentum balance to consider the changes in soil porosity, liquid pressure, temperature, and displacements, respectively. Moreover, Fourier's and Darcy's laws are used as fundamental thermal and hydraulic constitutive equations of the model. The van Genuchten's model is also utilised to define the soil-water retention curve. In order to incorporate non-advective species fluxes within liquid phases, encompassing phenomena like water vapour diffusion in the gas phase and air diffusion in water, Fick's law is defined.

Regarding the mechanical aspect of the model, the Barcelona Expansive Model (BExM) is employed (Alonso et al., 1999). This advanced model, rooted in the Barcelona Basic Model (BBM) (Alonso et al., 1990), offers an encompassing framework to capture the sequential dynamics of soil shrinkage and swelling in response to wetting and drying cycles (Sadeghi and Ng, 2018; Ghandilou et al., 2023a, 2023b). This model can consider two levels of structure: micro and macrostructure. High suction changes experienced by fine-grained soils during climate variations induce notable alterations in both the micro and macrostructural arrangement of the soil, leading to volumetric changes. These alterations are primarily driven by the soil's response to fluctuations in moisture content (Ng et al., 2017).

At the micro level, fine-grained soils like clays have complex pore networks. As moisture declines, capillary forces dominate, leading to tighter particle packing and shrinkage. On the macrostructural scale, the cumulative microstructural modifications lead to volumetric variations. During hot, dry periods, the soil experiences notable shrinkage and subsidence, causing surface settlement. Conversely, when wet conditions return, the soil swells upon absorbing moisture, leading to surface elevation changes (Sadeghi, 2016; Ng et al., 2017).

2.2 Soil-atmosphere interactions

Soil-atmosphere interactions refer to the exchange of heat and moisture between the soil and the surrounding environment. Transfer of the moisture involves the movement of water vapour due to factors such as moisture content, temperature, and pressure gradients. The exchange of thermal energy occurs through conduction, convection, and radiation (Hemmati et al., 2012).

In analysing soil-atmosphere interactions, the fundamental theoretical framework involves gas, water, and energy fluxes. Evaporation is calculated using an aerodynamic diffusion equation, and the movement of water vapour in soil pores is induced by this evaporation. Hence, the advective flux of vapour by the gas phase is defined. Additionally, thermal energy exchanges are considered by determining sensible and convective heat flux to account for the transfer of thermal energy and internal energy of each phase (Jabbarzadeh et al., 2023; Tourchi et al., 2024).

2.3 THM model

THM analyses are conducted using the finite element program CODE_BRIGHT (Olivella et al., 1996). To cover all input parameters, the Boom clay is considered as geomaterial of the model as its THM parameters were widely reported (Alonso et al., 1998; Delahaye and Alonso, 2002; Sanchez et al., 2005; Gens et al., 2007). In addition, the meteorological data of Qom city from 2015 to 2017, including temperature, wind speed, precipitation, relative humidity, and radiation, are also used to consider climate changes effect on cracked soil deformation. This region was selected because of its vulnerability to significant subsidence caused by its arid and warm climate (Sadeghi et al., 2023).

Recent studies have provided a limited dataset regarding the dimensions of crack geometry observed in the field. While there are other experimental and numerical investigations available, they are not suitable for this study as small cracks are beyond the scope of this research. To make the most of the available data, a dimensionless parameter known as the crack ratio (C_R), which represents the ratio of crack width (C_W) to crack depth (C_D), is introduced. This parameter allows us to utilise crack dimensions from previous experimental and numerical studies as well as field observations. To select modeling scenarios, a crack depth of 1 m is chosen. The deeper desiccation cracks up to 6 m are also reported by Morris et al. (1992). To accurately determine the crack geometry, statistical analyses were conducted using a dataset of crack dimensions reported in previous studies, considering crack ratios ranging from 1% to 42%. The results of these statistical analyses indicate that the distribution of crack ratios follows a lognormal distribution, as depicted in Figure 1(a). This insight has enabled the creation of a probability density function (PDF) for the crack ratios, visualized in Figure 1(b).

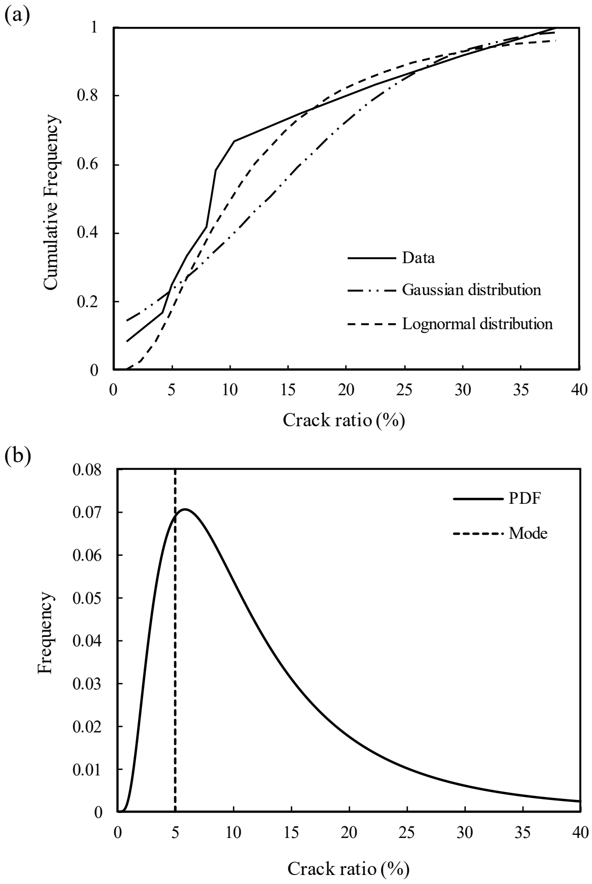

Figure 1. Statistical analysis of the crack ratio data.

Finally, the modeling scenario in terms of crack geometry was developed based on the obtained results. This scenario involves a crack with a depth of 1 m and a crack ratio of 5%, which is the peak of the PDF and shows a mode of data with the highest frequency. Once the crack shape has been established, the identified scenario is integrated into the numerical model to perform the THM analysis. This is accomplished by assigning the appropriate material properties, initial and boundary conditions. In this regard, the initial porosity is assumed to be 0.487, and the initial suction at the soil surface is set at 10 MPa. The suction value decreases linearly to a depth of 50 m, reaching a value of 0.4 MPa. Beyond this point, it declines with a different slope until it reaches the groundwater table at a depth of 90 m. To provide a visual representation, the schematic diagram of the crack geometry is depicted in Figure 2.

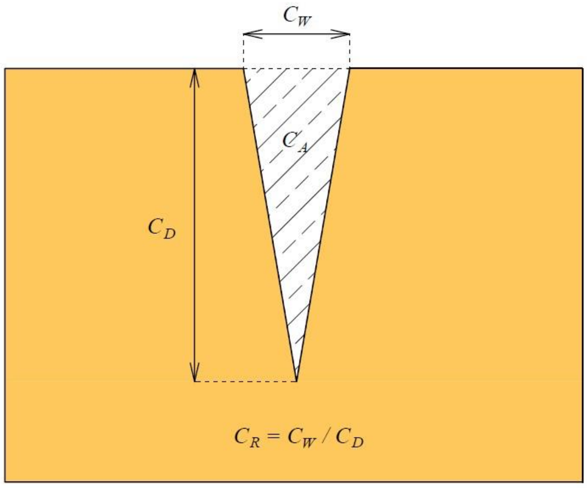

Figure 2. Schematic definition of parameters describing the crack geometry.

3 RESULTS AND DISCUSSION

3.1 Moisture distribution in the cracked soil

The soil maintains ongoing thermo-hydraulic interactions with its surrounding environment, a phenomenon that can be significantly intensified by the presence of cracks within the soil matrix. These cracks can act as conduits, amplifying processes such as water infiltration during rainfall and evaporation on warmer days. Therefore, the distribution of the degree of saturation (S_r) is visually represented in Figure 3 at three distinct time points: 100, 500, and 1000 days. These three selected days correspond to periods during the year when the weather is relatively warm, indicating the drying trend. However, the consecutive wetting-drying cycles before the chosen days have also influenced the moisture variations.

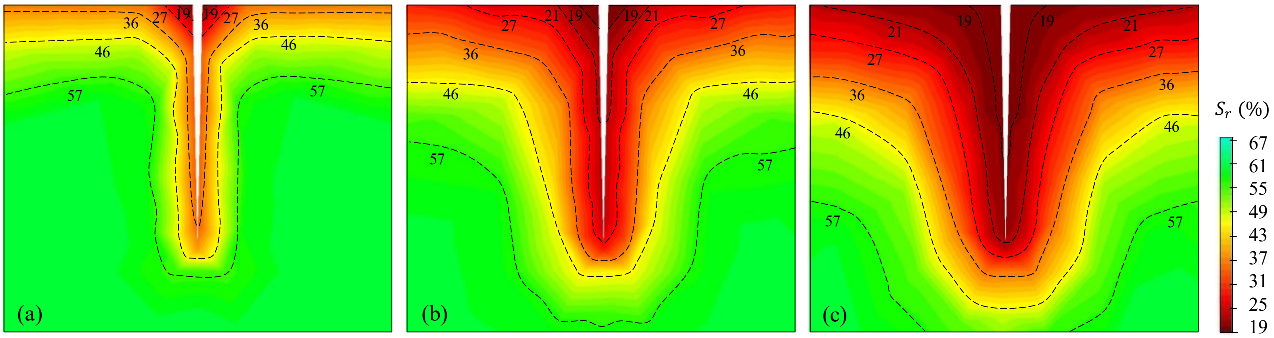

Figure 3. Spatial distribution of degree of saturation in cracked soil after (a) 100 days, (b) 500 days, and (c) 1000 days.

The results indicate that the presence of cracks leads to a heterogeneous S_r distribution, even within a homogeneous and isotropic soil layer. As illustrated in Figure 3(a), during the initial stages of the drying process, the cracked soil exhibits heightened desiccation along the edges of the cracks, while a relatively marginal drying effect is observed along the crack walls. With the progression of the drying period to the 500th day (see Figure 3(b)), the desiccation phenomenon intensifies, particularly within the cracked regions of the soil. This pattern underscores a key insight that within cracked soil, the edges and walls of the cracks are more susceptible to experiencing intensified desiccation under drying conditions. As observed, with the progression of desiccation, the contour lines deviate both horizontally and vertically away from the crack wall. This indicates that the presence of the crack exacerbates the reduction in soil moisture, both at the soil surface and in depth.

3.2 Heterogeneous deformation of the cracked soil under climate changes

The trend of moisture distribution in cracked soils can result in its non-uniform deformation under climatic variations, especially the uneven subsidence triggered by climatic warming. To explore this phenomenon, the deformed geometry of cracked soil is presented in Figure 4 for three distinct time intervals, after 100, 500, and 1000 days, compared to its initial state. As evident, the effect of soil desiccation and the consequent increase in evaporation lead to soil shrinkage and subsidence in the context of drying. This drying-induced subsidence not only affects the soil surface but also induces deformation within the crack geometry.

Notably, the findings demonstrate that the most substantial subsidence occurs along the crack edges, while the subsidence experienced by the soil surface diminishes with increasing distance from the cracks. These observations parallel the results of the moisture distribution within cracked soil, where the edges of cracks exhibited the most pronounced desiccation. Furthermore, as the drying process progresses, cracks widen and experience internal area expansion. This dynamic evolution of cracks' width and internal area alterations is visualised in Figure 5 with 100 days intervals. As evident from the results, the deformation of cracks is influenced by climatic variations in such a way that the crack deformation responds to changes in soil moisture content. With increasing soil moisture, cracks tend to expand, resulting in a reduction in their width and area. Conversely, decreasing soil moisture causes ground shrinkage, leading to their widening and increased area. As depicted in Figure 5, the changes in crack width exhibit a similar trend to those of crack area, although the variation in crack area is also influenced by the deformation of the crack walls. Consequently, this factor has contributed to a broader range of changes in crack area.

A noteworthy observation is that due to the soil's tendency to an equilibrium state, gradually the rate of the deformation diminishes. As evident, the rate of change in crack area exhibits a nonlinear relationship with time, following the trend line plotted in a logarithmic function. This proves that the deformation rate decreases nonlinearly over time. Given that the behaviour of crack width follows a similar trend as crack area, it can be inferred that the change in crack width may also follow this trend. According to Figure 5, crack with an initial width and area of 50 mm and 25000 mm^2 respectively, undergoes deformation. After 900 days, it reaches its maximum values of 114.5 mm and 55230 mm^2, indicating an increase of over twice the initial measurements. This substantial growth highlights the distinct deformation mechanism of cracked soil in comparison to uncracked soil. Coupled with climatic

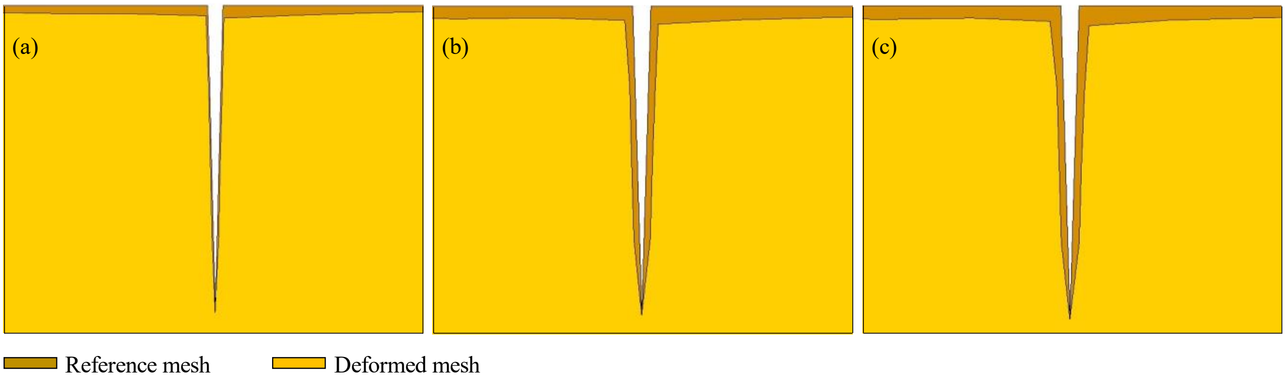

Figure 4. Heterogeneous subsidence of cracked soil under the influence of climate warming after (a) 100 days, (b) 500 days, and (c) 1000 days.

variations and global warming, which induce greater desiccation of surface soil layers, the phenomenon of soil cracking intensifies. This can result in heterogeneous subsidence of the soil surface, potentially leading to structural damages such as tilting, differential settlement, and structural cracks.

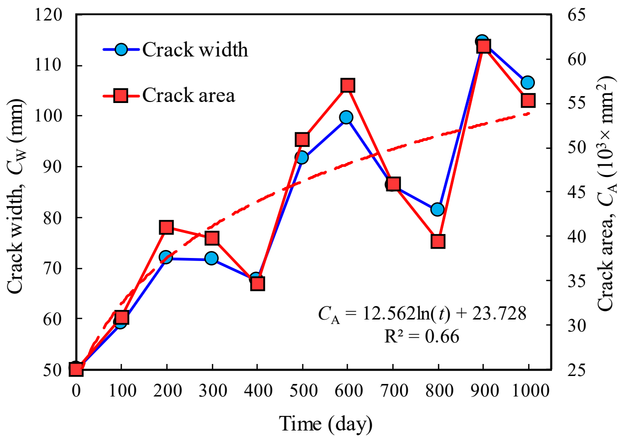

Figure 5. Variations in crack width and area with time under the influence of climate conditions.

4 CONCLUSIONS

This study focused on the THM analysis of desiccation cracked clayey strata, taking into account soil-atmosphere interaction by using real climate data from Qom between 2015 and 2017. The model incorporated various meteorological parameters like temperature, wind speed, precipitation, relative humidity, and radiation to investigate the effect of cyclic wetting-drying cycles on cracked soil behaviour. The characterization of crack geometry was achieved through statistical analysis of existing datasets from prior studies, which revealed a lognormal distribution for crack ratios. The examination of moisture distribution within cracked soil revealed a heterogeneous degree of saturation distribution. Notably, crack edges and walls experienced more pronounced desiccation, with a S_r of 19%. The behaviour of cracks under changing climatic conditions exhibited their sensitivity to moisture levels, impacting both their width and area. The findings highlighted a logarithmic trend in the changes of crack area and width, indicating a tendency toward an equilibrium state in deformation rates. Furthermore, the results underscored that cracked regions were more vulnerable to subsidence compared to uncracked areas, resulting in heterogeneous subsidence patterns in the cracked soils. Significantly, the study revealed substantial increases, exceeding twofold, in both crack width and area due to prolonged climate fluctuations.

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