Thermo-hydro-mechanical modeling of stress redistribution around deep desiccation-induced cracks in arid and semi-arid regions

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Abstract

Soil cracking primarily results from the development of tensile stresses among soil particles, caused by the shrinkage of surface soil layers during desiccation. Climate change and global warming intensify cracking in soils with high plasticity, potentially leading to irreversible damage to infrastructure and both surface and subsurface structures. Additionally, soil cracking exacerbates desiccation in the unsaturated zone, contributing to land subsidence, a major global and national issue in Iran. During the desiccation process, the stress state in cracked soils constantly changes, altering stress distribution among particles. Therefore, understanding stress redistribution in the unsaturated zone is essential as a fundamental mechanism in desiccation-induced soil cracking. In this study, thermo-hydro-mechanical modeling was employed to simulate the impact of climate changes in Qom city on a cracked soil, to investigate the transition of stresses from compressive to tensile near the cracks. Governing equations for the problem, including water and gas flow in the soil, energy transfer, and soil-atmosphere interaction, were defined in the numerical model. The results indicated that the initial compressive stress distribution in cracked soil was heterogeneous, with different stress patterns at the ground surface and crack tips. As desiccation progressed, tensile stresses emerged at the surface, crack walls, and tips, potentially leading to the propagation of existing cracks in both width and depth, as well as the initiation of new surface cracks.

Keywords

Stress redistribution, Desiccation cracks, Arid and semi-arid regions, Thermo-hydro-mechanical modeling, Unsaturated soil

1. Introduction

In arid and semi-arid regions, soils are subjected to deep and extensive cracking due to severe fluctuations in moisture content and temperature [1,2]. These soils experience cycles of wetting and drying near the atmosphere, which alter the hydro-mechanical behavior of the ground and lead to the expansion of crack networks [3-6]. Such cracks can exacerbate land subsidence and reduce the stability of engineering structures like dams, roads, and infrastructure, posing a hidden risk to their safety [7]. Previous studies have defined the mechanisms behind the occurrence and propagation of soil cracking due to desiccation of surface layers. Cracking can result from either shear [8] or tensile forces, with desiccation-induced cracks typically being tensile in nature, caused by soil shrinkage from increased suction in the unsaturated zone [9,10]. Understanding and analyzing the mechanisms of stress redistribution around desiccation-induced cracks is crucial for the design and safety assessment of engineering structures. In this context, Wang et al. [11] concluded from their analyses that stress concentration occurs at the crack tip, potentially controlling the localized propagation of cracks. However, further studies are needed

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to examine the heterogeneous redistribution of cracks under various climatic conditions. Therefore, this study aims to investigate stress redistribution around deep desiccation-induced cracks in arid and semi-arid regions through thermo-hydro-mechanical modeling. For this purpose, a finite element modeling approach was adopted, incorporating the governing thermo-hydro-mechanical equations to simulate water and gas flow, energy transfer in the porous medium, and interactions with the surrounding atmospheric environment.

2. Thermo-hydro-mechanical model

Simulations were conducted to investigate stress redistribution in cracked soil under climatic variations. For this purpose, the finite element software CODE_BRIGHT [12], with a legally acquired license, was employed. This code allows for comprehensive thermal, hydraulic, and mechanical analyses while considering atmospheric conditions, facilitating the assessment of energy and moisture exchanges between the air and soil. The fundamental equations governing this problem include the equilibrium equations, thermo-hydro-mechanical behavior equations, equilibrium constraints, and equations governing soil-atmosphere interaction. The theoretical framework adopted in this study utilized a multi-phase and multi-species approach, incorporating solid, liquid, and gas phases along with water and air species in the numerical model. Thus, the state variables (unknowns) considered were u (m), displacement; P_l (MPa), liquid pressure; P_g (MPa), gas pressure; and T (°C), soil temperature.

2.1 Theoretical considerations of numerical model

For the thermo-hydro-mechanical analysis, three mass balance equations for the solid, liquid, and energy, as well as the momentum balance equation, were considered as follows:

$$\frac{\partial}{\partial t}(\rho_s(1-\phi)) + \nabla \cdot (\mathbf{j}_s) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\left((\omega_l^w \rho_l S_l + \omega_g^w \rho_g S_g)\phi\right) + \nabla \cdot \left(\mathbf{j}_l^w + \mathbf{j}_g^w\right) = f^w \tag{2}$$

$$\frac{\partial}{\partial t}\left(E_S \rho_S (1-\phi) + E_l \rho_l S_l \phi + E_g \rho_g S_g \phi\right) + \nabla \cdot \left(\mathbf{i}_c + \mathbf{j}_{Es} + \mathbf{j}_{El} + \mathbf{j}_{Eg}\right) = f^E \tag{3}$$

$$\nabla . \boldsymbol{\sigma} + \mathbf{b} = 0 \tag{4}$$

These equations lead to the calculation of parameters such as porosity (ϕ), liquid pressure, temperature, and deformations within the porous soil medium. Convective fluxes were determined as unknowns in the balance equations through the definition of constitutive equations. To calculate the convective flow of water and gas in the porous medium, a generalized form of Darcy's law was employed. The permeability variations were related to changes in porosity using the Kozeny equation, while the van Genuchten model was applied to define the soil-water retention curve (SWRC). Additionally, Fourier's law was used to calculate heat transfer through thermal conduction, considering soil thermal conductivity as a function of saturation degree and porosity. It was assumed that thermal conductivity increases with higher degrees of saturation and lower porosity. Fick's law was adopted to define the non-convective flow of water vapor.

2.2 Geometry and atmospheric boundary condition

The crack geometry was modeled as shown in Figure 1, with parameters including width, depth, and crack ratio, defined as the ratio of crack width to depth [13]. In this study, the crack width was set to 13 cm, the depth to 100 cm, and the crack ratio to 13%, representing deep cracks. For the boundary conditions of the numerical model, the climate of Qom, a warm and arid region, was applied, including parameters such as temperature, solar radiation, wind speed, rainfall, and relative humidity.

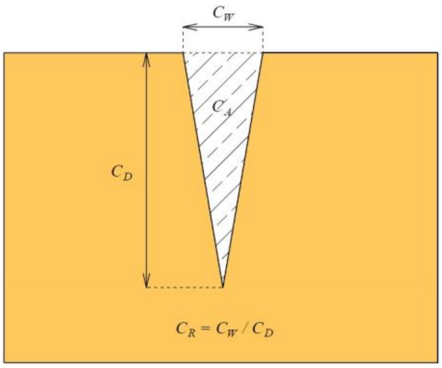

Figure 1: (a) Schematic representation of a desiccation crack showing the parameters used in the numerical model.

3. Results

The mechanism behind desiccation cracking is predominantly driven by tensile forces. Surface desiccation increases suction in the unsaturated soil zone, leading to higher tensile stresses within the soil mass. When tensile stresses exceed the soil's tensile strength, cracking occurs. Figure 2 illustrates the distribution of compressive and tensile stresses in cracked soil before and after exposure to hot and arid climatic conditions. As shown in Figure 2(a), the initial stress state is compressive due to the absence of moisture and energy exchange between the soil and the surrounding environment. The stress distribution is heterogeneous, with stress concentration occurring at the crack tip. Over time, as soil-atmosphere interactions take effect, the stress mechanism in the surface layers changes. Desiccation of the surface layers causes the stress type to shift from compressive to tensile, potentially initiating new cracks around the existing crack. With prolonged desiccation, as depicted in Figure 2(c), surface subsidence occurs due to the shrinkage of the surface layers, resulting in an uneven ground profile near the crack. Concurrently, tensile stresses increase at the crack opening and tip, potentially leading to crack propagation in both width and depth. The findings regarding stress concentration at the crack tip in this study are consistent with the observations by Wang et al. [11].

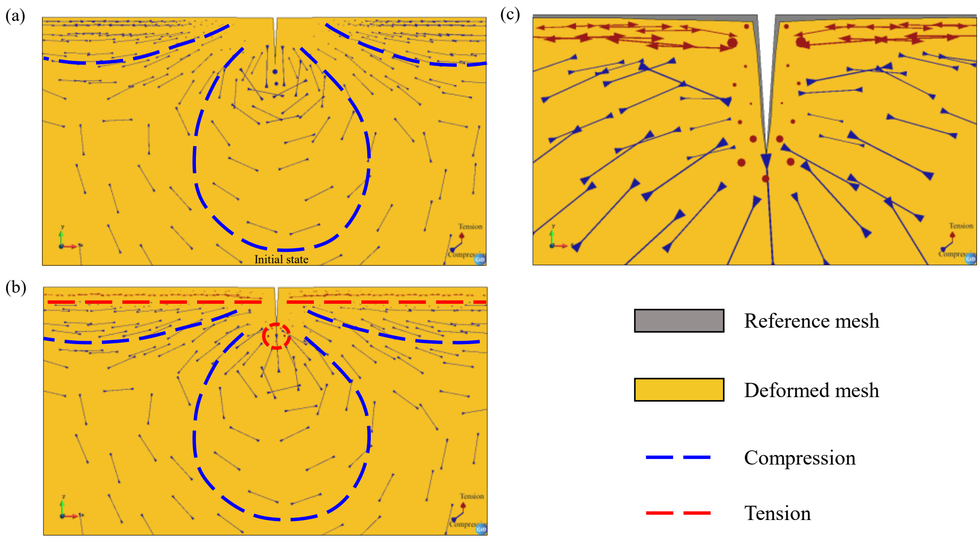

Figure 2: Tensile stress vectors near the desiccation crack: (a) initial conditions, (b) after the onset of surface desiccation, and (c) propagation of tensile stresses during the continued drying process, along with the deformation of the cracked soil

4. Conclusions

This study investigated the variations of compressive and tensile stresses in cracked soil within the hot and arid region of Qom. Soil cracking occurs as a result of surface desiccation in soils with high plasticity. The presence of cracks facilitates moisture and energy exchange between the soil and the surrounding environment, exacerbating land subsidence in the unsaturated zone. To examine this phenomenon, the finite element software CODE_BRIGHT was employed with a legally acquired license, utilizing a thermo-hydro-mechanical modeling approach to assess stress redistribution near the cracks. The results indicated that the initial stress distribution before the application of drying pathways was compressive, exhibiting a heterogeneous distribution near the ground surface and around the crack tip. As the drying process progressed, tensile stresses increased at the soil surface, particularly in the vicinity of the crack and its tip, which could elevate the likelihood of crack propagation from the existing crack tip and initiate surface cracking.

5. References

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