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Research Paper

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

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ABSTRACT

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

1. Introduction

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

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

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

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

The propagation of cracks in solids has been studied using LEFM [15] to explain the magnitude of the depth and the spacing between desiccation cracks. This theory has been extended to unsaturated soil [2,16,17] to predict the optimal depth of cracks,

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which is a function of the suction profile and various soil properties (e.g., tensile strength, elastic modulus, Poisson's ratio, density). Konrad & Ayad [18] used LEFM to analyse the propagation of desiccation cracks of clays under evaporation. They used the principle of the effective stress distribution [3] to take into account the distribution of stress in soil and proposed the concept of virtual stress superposition to predict the average spacing between primary cracks. LEFM considers the propagation of only one individual crack and neglects the interaction between various cracks. In addition, LEFM assumes linear elastic soil behaviour; the nonlinearity that may be present in desiccation is thus ignored.

DEM, which considers the soil as an assemblage of discrete elements, has good potential for the simulation of desiccation cracking and was used in previous studies [19–22]. Most active clay particles gather in elementary small structures called aggregates, which in turn gather in larger aggregates at various scales [23,24]. In DEM, the clay soil is represented as an assemblage of aggregates linked by bonds, and the aggregates are simplified as spherical grains or other geometries [21]. The drying shrinkage kinetics of clay aggregates can be simulated by applying an explicit relationship between the size of the grains and the drying duration (or the water content). As the soil dries, the contact stiffness and tensile strength of the aggregates increase with increasing suction. Crack initiation corresponds to the irreversible breakage of this bond when the magnitude of the traction (or shear) force exceeds the normal (or shear) contact bond strength. In addition, the nonlinear behaviour of soil can be simulated by introducing the dependences of the soil properties on suction [19,21,22]. Simulations have enabled the investigation of the effects of the soil sample dimensions, the interface between soil/mould, and soil shrinkage parameters on the development of desiccation cracks. More recently, Hirobe & Oguni [25] proposed a model that uses FEM to simulate hydraulic diffusion and PDS-FEM (particle discretisation scheme finite element method) to solve the mechanical problem of the formation of cracks. In this model, the elasticity and fracturing behaviour are modelled using the discretisation method, which uses a pair of conjugate geometries (Voronoi and Delaunay tessellations) to estimate the displacement and strain fields. A fracture propagates along the Voronoi cell boundaries as hydro-mechanical stress evolves and exceeds the prescribed material strength. This method was used to reproduce the morphology of the crack network and the evolution of the desiccation process. The principle of this work is similar to that of Asahina et al. [26]. Both demonstrated the influence of the specimen's thickness on the spacing of the formed cracks. Despite its efficiency to simulate desiccation cracks, DEM is considered more pertinent for the specimen scale than the structure scale.

Soil desiccation has been studied using FEM in previous research [27–29], but the development of cracks (which involves discontinuity in the medium) was not considered. For this reason, cohesive fracture and interface elements are usually introduced in FEM code to simulate the formation and propagation of cracks during desiccation. In the work of Sánchez et al. [30], joint elements were embedded like interface elements in the boundary of tetrahedral solid elements; the cracks propagated along the boundary of these solid elements. In this numerical analysis, the effect of evaporation was introduced as the volume shrinkage of solid elements, and the simulation could be observed as purely mechanical. The prime interest of this work was not to precisely reproduce the experimental observations but to determine the ability of the proposed numerical technique to qualitatively capture the main trends and the crack morphologies observed for different shapes, thicknesses and desiccation conditions. Amarasiri & Kodikara [31] used cohesive cracks with a softening law that evolves during desiccation when a crack is partially open. The model reproduced the number of cracks developed with the moisture content evolution during a desiccation test but the desiccation process with hydro-mechanical coupling was not considered.

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

2. Governing equations

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

2.1. Cohesive crack representation

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

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

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

2.2. Hydraulic behaviour

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