Computers and Geotechnics 105 (2019) 155–167

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Numerical and experimental study of initiation and propagation of desiccation cracks in clayey soils

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ARTICLE INFO

Keywords:
Desiccation cracking
Hydro-mechanical coupling
Unsaturated soils mechanics
Finite element method

ABSTRACT

This paper presents the fundamentals and the mathematical formulation to study desiccation cracking in soils based on Unsaturated Soil Mechanics as well as a numerical analysis of a previous desiccation test program. The numerical approach implemented in MATLAB is used in 2D simulations on radial sections of the cylindrical specimens and in a theoretical study of the stress field in plane strain conditions. The numerical analysis, based on two stress stare variables (total net stress and suction) is consistent and in good agreement with the experimental results, including the location of cracks and time of crack initiation.

1. Introduction

Crack desiccation in soils is an important issue because of its implications in a wide range of ground-related fields, from geotechnical engineering to agricultural land use, mining and radioactive waste storage, tailings reservoirs, gravity dams or public buildings [1–5].

The crack patterns that form as the soil dries seems to be random and unique. The cracking process in soils is difficult to reproduce numerically because many features involved are complex and yet not well understood. Formation and propagation of drying cracks in soils involve desiccation (moisture loss) and shrinkage (deformation). This is a coupled hydro-mechanical problem, further complicated because the soil has a highly nonlinear material behaviour in both, the hydraulic and the mechanical components, and most of the soil properties that play a substantial role in the cracking process change with suction or moisture content. In addition to that, boundary conditions (soil-atmosphere interactions or soil-container interactions) are difficult to handle and not yet well understood.

Two main variables that play a fundamental role in the formation and propagation of desiccation cracks are the temperature and relative humidity of the environment, but several other factors are involved in the process. In laboratory tests, specimen size, soil-container interface, drying rate and specimen's characteristics (such as heterogeneity, anisotropy, imperfections, water content, particle size, tensile strength or fracture toughness) determine how cracking develops. Additionally, in the field, the soil fabric, the location of the water table, wind velocity, solar radiation, etc. need to be considered as well [6].

When the soil is dried under laboratory conditions or in an environmental chamber, the first cracks that can be seen on the top surface of the specimen are usually boundary cracks that start at the interface between the soil mass and the container wall. These cracks propagate until the entire soil mass is separated from the wall. Soils subjected to cyclic desiccation and wetting experience several phases that start with the soil wet and usually saturated. After the first phase of evaporation, the natural tendency for the specimen is to shrink followed by cracking, resulting in a less wet soil which is usually unsaturated. After the cycle is completed, the soil in the specimen is not saturated, and additional deformation and cracking may develop [7].

The boundary conditions for this problem are complex because they may change during the analysis as the specimen conditions change. The displacement boundary conditions are governed by the friction between container and specimen. Because of the soil's water content changes during the process, the soil/container friction conditions also change and, therefore, the mechanical boundary conditions must be updated during the process. On the other hand, new cracks create new boundaries that are in contact with the environment generating changes in the hydraulic boundary conditions in terms of suction that must also be updated during the evolution of the desiccation process.

Shrinkage occurs when suction increases because of capillary effects. The capillary forces, produced by the suction increment, make the soil mass shrink reducing the size of the pores and consequently the volume of the soil specimen. This may happen in saturated, at the beginning of the process, or unsaturated conditions after a certain time. At the same time, the increasing suction increases the stiffness and the

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https://doi.org/10.1016/j.compgeo.2018.09.015
Received 17 April 2018; Received in revised form 20 September 2018; Accepted 24 September 2018

tensile strength [8–10]. If shrinkage is restricted, then cracking develops [6]. Restrictions to shrinkage may be due to three causes: (1) stress or displacement boundary conditions (e.g. friction, adherence with the soil container); (2) concentration of stresses in the soil matrix; or (3) heterogeneity, texture and soil structure [11].

Desiccation cracks appear both in saturated and unsaturated conditions [12], which is problematic when the state stress variables need to be defined. In fact, the behaviour of the soils at the beginning of the process is more similar to a liquid with no tensile strength. When the soil acquires consistency, tensile strength develops because of the increment in suction. This increment produced by the water loss induces one-dimensional vertical shrinkage at the beginning and a three-dimensional shrinkage when the soil becomes stiffer.

From the experimental point of view, several authors have studied this process since the early twentieth century [13–23] and many significant experimental and numerical contributions have been made in the last half-century [2,7,24–38]. An exhaustive state of the art can be found in the doctoral theses of M.R. Lakshmikantha and H. Levatti [7,12]. However, until the development of Unsaturated Soil Mechanics, the problem has not been analysed considering the parameters that govern the behaviour of soil in the unsaturated state, primarily suction. Tensile strength, which is suction dependent, and fracture toughness are shown to be also relevant parameters [25,31].

In the context of desiccation cracking, there are numerical approaches available in the literature based on the finite element method (FEM) [2,28,39], the finite difference method (FDM) [28], the discrete element method (DEM) [40], the distinct element method (DiEM) [41], the mesh fragmentation technique (MFT) [42], the lattice spring model (DLSM) [43]. However, there is not a consensus on how to properly simulate desiccation cracking in soils due to the number of variables, boundary conditions and complexities involved.

The model presented in this paper is formulated within the classical theories of unsaturated soil mechanics and strength of materials. The flow in deformable porous media is formulated using a coupled hydro-mechanical approach and solved using the finite element method with a $\boldsymbol{u}-\boldsymbol{p}$ formulation [44]. For the crack treatment, a release-node technique is used and simulations show the capabilities of the approach. The proposed model solves the three main physical processes involved (desiccation, shrinkage and cracking). From the initiation of the process, the initial and boundary conditions are fixed and the system evolves until the first crack appears when the tensile strength is reached. The release-node technique allows dealing with the crack propagation changing the boundary conditions at the crack surfaces.

In the present work and in order to simplify the analysis the thermal component is not considered, assuming that the process is isothermal. Also for the sake of simplicity, a nonlinear elastic constitutive model base on the stress state surface concept [45,46] is chosen, where the stress variables are suction and net stress. The hydro-mechanical coupling is obtained through the constitutive law and a non-symmetric global system of equations is obtained when solving the problem by the finite element method.

The main objective of the numerical analysis is to reproduce the time evolution of the recorded variables (suction, water content, deformation) during laboratory tests performed in recent years [12,53] and to estimate the stress evolution before and after the initiation of the cracks. The formulation presented in this work is general [48] but the implementation for the analysis is made in order to solve a radial section of a cylindrical specimen, of 80 cm in diameter and 20 cm in height. The numerical analysis is carried out to simulate the formation and propagation of the first crack, which usually appears at the interface soil-container and initiates from the upper external surface of the specimen and propagates toward the bottom along the interface.

With this technique, only the tensile strength is necessary to be determined in the laboratory. Although linear elastic fracture mechanics (LEFM) has been proposed as an approach to model desiccation cracking in soil by several authors [2,17,49,50], this technique is more complex to implement and the fracture parameters for soils are difficult to obtain because they are dependent on the water content. Apart from that, there is an increasing evidence that the Mohr-Coulomb failure criterion may apply also for this type of problems [25], but this approach will be considered in future developments.

The model presented in this paper is consistent, relatively simple and based on classical theories in the context of geotechnical engineering instead of adding additional numerical items to solve the complexity of the problem. However, complexity can be added gradually.

2. Materials and methods

The soil studied in this work is the Barcelona silty clay that has been used extensively in the past and it has been thoroughly characterized [12,47,51]. The method is based on the observation and measurement of variables during the tests followed for 2D simulations calibrated and validated with the experiment. The specimens used in the experimental program analysed here were moulded into cylindrical PVC containers of and 80 or 40 cm in diameter and 20 or 10 cm in height.

2.1. The experimental program used for the study

The tests were carried out in an existing environmental chamber [12,52] which was extensively refitted and modified to allow cyclic environmental changes [7,53]. The main features of this environmental chamber include: (a) automatic photography of the external upper surface of the specimen at pre-defined regular intervals; (b) halogen lamps to control the chamber temperature; (c) data acquisition and control system to record and drive chamber temperature and relative humidity, and suction and temperature of the soil; (d) dehumidification system to induce desiccation; (e) humidification system to induce wetting; (f) control system to combine dehumidification and humidification devices; (g) complementary data acquisition system to monitor temperature and volumetric water content of the specimens. Besides recording the images of the cracking patterns that develop on the external surface during the tests, it is possible to detect internal cracks by means of an external ground penetrating radar scanning device [7,53,54].

To prepare the tests, the dry soil was first passed through the #16 sieve (1.18 mm opening) and left at laboratory conditions for moisture stabilization. Then the specimens were made at the specified moisture content by adding distilled water. Immediately after mixing the actual moisture content was determined and the mixture was left in a humid chamber for 24 h before testing.

2.2. Mathematical formulation and numerical approach

In this paper, a hydro-mechanical model is proposed including a released node technique to simulate the desiccation cracking process.

2.2.1. Mechanical constitutive formulation

For the mechanical component of the model, a nonlinear elastic constitutive equation based on the concept of state surfaces [45,46] is chosen. For the hydraulic component, the generalized Darcy's law is used and the relation between suction and the degree of saturation is modelled using van Genuchten's closed form expression [55].

In this work, a set of two separated stress variables is introduced, the net stress and the suction [56–60]. The net stress σ^{net} (stress in excess of air pressure) and the suction s are:

$$\boldsymbol{\sigma}^{net} = \boldsymbol{\sigma} - u_a \mathbf{1} \tag{1}$$

$$s = u_a - u_w \tag{2}$$

where $\boldsymbol{\sigma}$ is the total stress tensor, u_a and u_w are the air and water pressure respectively and $\mathbf{1} \equiv \delta_{ij}$, is the identity tensor.