Computers and Geotechnics 56 (2014) 168–180

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Numerical simulation of desiccation cracking in a thin clay layer using 3D discrete element modeling

Jun Sima [a,b,*], Mingjing Jiang [b,c], Chuangbing Zhou [a]

[a] School of Water Conservancy and Hydropower Engineering, Wuhan University, China
[b] Department of Geotechnical Engineering, Tongji University, China
[c] Key Laboratory of Geotechnical and Underground Engineering of the Ministry of Education, Tongji University, China

ARTICLE INFO

Article history:
Received 17 April 2013
Received in revised form 31 October 2013
Accepted 5 December 2013
Available online 27 December 2013

Keywords:
Desiccation
Cracking
Thin clay layer
Aggregate-shrinking model
3D discrete element method

ABSTRACT

Desiccation cracking of clay soil is of critical importance in many applications, such as industrial waste containment, hydraulic barriers, road embankments, and agricultural operations. The factors that influence cracking are known qualitatively, but it is not clear how to predict the initiation and propagation of cracks. This study presents a discrete element approach to modeling desiccation cracking in thin clay layers, considering material property changes. First, an aggregate shrinkage model based on the aggregate structure of clay was proposed, and the drying shrinkage of clay soil was modeled by imposing drying shrinkage kinetics for each aggregate at the micro-scale. Second, the clay soil was represented by an assembly of aggregates linked by bonds, and desiccation cracking of the clay layer was modeled using a three-dimensional discrete element code (PFC3D), with the aid of the embedded programming language FISH. When the clay layer is sufficiently thin, the water content gradient along the section can be neglected; thus, the shrinkage kinetics are the same for all of the grains of clay. In the model based on the discrete element method (DEM), the bond strength and contact stiffness changed during drying. Their changes were determined by matching the simulation results with the experimental data. Third, the DEM approach was validated by reproducing experimental desiccation tests performed on a thin clay layer in a disk shape. The geometric parameters of surface cracks were quantified using image analysis techniques and were compared with experimental observations. Fourth, some factors of influence, such as the sample thickness, the properties of the soil–base interface, micro-mechanical parameters, and shrinkage parameters, were investigated using the DEM model. The results obtained from the DEM analyses were compared with the results of prior research in this field of study. The approach used in this study is very promising for simulating desiccation cracking in thin clay soil because the model captures the initiation and propagation mechanism of desiccation cracks. Although this study was carried out on surface cracking in a thin clay layer, the extension of this methodology is of potential benefit not only for predicting three-dimensional desiccation cracking in real clay liners but also for modeling cracking in other materials with properties that vary with water content or temperature, such as concrete and rock.

1. Introduction

Desiccation cracks are known to be formed by shrinkage of soil as moisture is lost. The presence of cracks can induce significant changes in the strength, permeability, and compressibility of soil, which can reduce the stability, serviceability, and hydraulic performance of earth structures. Therefore, desiccation cracking in clay is of critical importance in various applications, such as clay liners, dams, road embankments, expansive soil slopes, and agriculture [1–5]. As soil is a highly complex material, its cracking behavior is governed by a large number of factors, such as mineral composition, clay content, temperature, layer thickness, boundary conditions, tensile strength, elastic modulus and more [6–12]. However, while the influence of those factors on cracking is known qualitatively, it is still not clear how to quantitatively predict the initiation and propagation of cracks. With the trend toward more frequent and extreme climate events, it is urgent that a modeling method for desiccation cracking be developed.

During the last few decades, a number of researchers have made advances in the modeling of desiccation cracking [2–5,9,13–17]. Several numerical analyses based on the finite element method and linear fracture mechanics have been proposed, but the mechanisms of desiccation cracking in these methods are

* Corresponding author. Address: School of Water Conservancy and Hydropower Engineering, Wuhan University, 8 Donghu South Road, Wuhan 430072, China. Tel.: +86 21 65980238; fax: +86 21 65985210.

E-mail addresses: simajun81@126.com (J. Sima), mingjing.jiang@tongji.edu.cn (M. Jiang), cbzhou@whu.edu.cn (C. Zhou).

0266-352X/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compgeo.2013.12.003

still not completely understood. Because crack initiation and propagation involve the creation of a discontinuity, it is difficult to model the phenomenon using a continuous method. In finite element methods, the localization of crack initiation is always an issue and is generally artificially introduced by the user to reproduce the essential features of crack patterns [17]. Cracking models based on fracture mechanics are still immature and can only consider the propagation of an individual crack. Furthermore, the properties of the soil, such as the stiffness and the tensile strength or fracture toughness change with the moisture content during drying [4,5]. Some studies have analyzed cracking without taking these changes into account.

The discrete element method (DEM), which treats soils as an assembly of discrete elements [18], has been widely used in geotechnical engineering to investigate macroscopic and microscopic responses of assemblages of particles under various loading conditions [19–26]. Yao and Anandarajah [27] proposed a three-dimensional discrete element model based on cuboid particles for use in analyzing clay. Amongst the numerous approaches based on discrete elements, the DEM, which can take into account the cohesive bond between grains, is of particular interest in the study of desiccation cracking [16,17]. The cohesion increase that occurs in a soil as it dries can be captured by an increase in the cohesive force between the elements of the simulated assembly. A crack corresponds to the breakage of a cohesive bond. Some researchers have successfully simulated the vertical desiccation cracking of soil bars [4,17]. Because the crack pattern that develops at the soil surface during desiccation is more complex and of more concern in laboratory studies, it is important to further simulate the surface cracking of soil. In this study, we focus on the desiccation cracking of a thin soil layer. It should be noted that the condition of the thin clay layer is different from the real-world scenario in many respects, including the non-uniform distribution of the water content and three-dimensional cracking in the field.

This research presents a three-dimensional DEM approach to predicting the initiation and propagation of desiccation cracks in a thin clay layer, with consideration of the changes that occur in the properties of the clay material. In the approach presented, an aggregate-shrinking model is used to capture the drying shrinkage mechanism of clay soil at the micro-scale. The clay soil is represented by an assemblage of aggregates linked by bonds in a DEM model. The DEM approach was validated by reproducing the results of experimental desiccation cracking tests performed on a typical expansive clay in disk shape. Lastly, the effects of some factors, such as the sample thickness, the characteristics of the soil–base interface, and soil properties, were investigated using the DEM model.

2. Three-dimensional discrete element model

2.1. Aggregate shrinkage model

According to microscopic observations, most active clay particles gather in elementary small structures called aggregates, which in turn gather in larger aggregates at various scales, leading to a fractal structure [28,29]. Some micro-structural models have been proposed by several researchers to explain the swelling and shrinkage behavior of clay [28,30,31], which can be generally explained in terms of the swelling and shrinkage of aggregates. Because our goal was to investigate the mechanism of drying shrinkage, an aggregate shrinkage model for clay was adopted. This model is described as follows.

(1) The clay soil is represented by an assemblage of aggregates linked by bonds, and the aggregates are simplified as spherical grains.
(2) The drying shrinkage kinetics of the aggregates are simulated by imposing an explicit relationship between the size of the grains and the drying time or water content.
(3) As the soil dries, the formation of menisci causes suction to develop in the soil. The contact stiffness and tensile strength of the aggregates increase with increasing suction.

According to the aggregate structure of clay, the voids of the soil consist of inter-aggregate voids and extra-aggregate voids. In this model, the inter-aggregate voids are included in the volume of the grains, and the extra-aggregate voids are the volumes between the grains. When the shrinkage kinetics are the same for all the grains, both the inter-aggregate voids and the extra-aggregate voids decrease proportionally with the shrinking of the grains, which contributes to the decrease of the total void volume of the sample. Therefore, the shrinkage behavior of the grains is in accordance with that of the sample, and the shrinkage kinetics of the grains can be determined from the soil shrinkage characteristic curve at the macroscopic level. It is widely accepted that the shrinkage curves of natural soils are often divided into four stages [35,43]: (1) structure shrinkage, (2) normal shrinkage, (3) residual shrinkage, and (4) zero shrinkage. In the normal shrinkage stage, specimens are kept fully saturated, so the decrease in soil volume is equal to the loss of water, and the shrinkage curve is linear. Because most of the volume decrease and water loss happen in this stage during drying at the same time as desiccation cracking [9,35,38], it is the key stage that was chosen to be simulated.

A practical model for soil drying kinetics that considers the variation of the grain radius R with drying time has been proposed by El Youssoufi et al. [16] and Peron et al. [17]:

$$R = R_0 \exp\left(-\alpha \frac{t}{\tau}\right) \tag{1}$$

where R_0 is the radius at $t = 0$, α is a shrinkage parameter, and τ is the total duration of the experiment.

Eq. (1) implies a nonlinear relationship between the water content and time. When the value of alpha is small, a linear relationship can be adopted as an approximation. The grain radius R in Eq. (1) can then be expressed as a function of the water content, which is more convenient for desiccation modeling. The equation for R as a function of the water content is as follows:

$$R = R_0 \exp\left(-\alpha \frac{(w_0 - w)}{(w_0 - w_f)}\right) \tag{2}$$

where w_0 is the water content at the beginning of simulation and w_f is the final water content at the end of the test ($t = \tau$).

When the kinetics are the same for all of the grains, the shrinkage kinetics of the sample can be deduced, for small-strain conditions, for a three-dimensional sample as follows:

$$\varepsilon_v = 1 - \exp\left(-3\alpha \frac{t}{\tau}\right) \tag{3}$$

where ε_v is the volumetric deformation of the sample at the macroscopic level.

Given the relationship between ε_v or e and time, the value of alpha can be deduced from drying experimental results as follows:

$$\alpha = -\frac{1}{3}\ln(1 - \varepsilon_{vf}) \tag{4}$$

or

$$\alpha = -\frac{1}{3}\ln\left(1 - \frac{e_0 - e_f}{1 + e_0}\right) \tag{5}$$