Computers and Geotechnics 73 (2016) 179–188

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Computed tomography based numerical simulation for triaxial test of soil–rock mixture

Chang-Sheng Li, Dan Zhang *, Sha-Sha Du, Bin Shi

School of Earth Science and Engineering, Nanjing University, Nanjing, China

ARTICLE INFO

Article history:
Received 25 September 2015
Received in revised form 27 November 2015
Accepted 12 December 2015
Available online 29 December 2015

Keywords:
Soil–rock mixture
Fabric
2D mesh
Computed tomography
$FLAC^{3D}$
Digital image processing

ABSTRACT

The fabric of gravels can significantly affect the characteristics of deformation, stress field and failure of soil–rock mixture. The computed tomography (CT) was used to obtain the shape and location of gravels in triaxial soil–rock mixture samples. Based on the CT images, the typical longitudinal profiles of triaxial sample were reconstructed and the wire-frame models indicating the interfaces between the soil matrix and gravels were built through digital image processing (DIP), including image binarization, noise removal and interface detection. A mesh generator, DISTMESH was utilized to improve meshing quality, especially near the interfaces. The mesh was exported to $FLAC^{3D}$ using an interface program and 2D plane strain models with different gravel content were simulated for verification. It was found that cracks usually first appear on certain parts of the soil/gravel interfaces where the shear stress is prone to accumulate. The location of cracks have a good consistency with the results obtained by CT images. It can be concluded that the method proposed is efficient and accurate for the behavior analysis of soil–rock mixture by using numerical simulation and triaxial test with CT scan.

1. Introduction

Soil–rock mixture is a kind of inhomogeneous geomaterial with coarse and fine grains mixed up, which are the research interests in geo-engineering, such as landslides and mudflows [34,40]. The inhomogeneity and the fabric of soil–rock mixture play a significant role in the mechanical response to loading and in resistance to failure [43,32,42,6,16]. Due to the extreme difficulties in field sampling, laboratory testing and quantitatively measuring the inhomogeneity and the fabric, the mixed geomaterials are usually assumed to be homogeneous or piecewise homogeneous and their structural behavior is ignored. Vallejo and Sebastian [37] presented the application of a theoretical method developed by Hashin [11] to calculate the elastic moduli of a composite made of an elastic matrix containing large dispersed particles. Some mechanical analyses based on statistics, such as morphological or Monte Carlo random sampling methods, have also been used to simulate inhomogeneous geomaterial to simplify the modeling. In these models, the generated virtual gravels have regular shapes, such as rectangle, sphere, triangle and ellipse with which it is hard to represent the actual shape of the gravels and internal structure of natural geomaterials. In order to describe the inhomogeneity correctly, Sepher et al. [27] proposed to measure the structure of an asphalt concrete manually. Obviously, such manual measurement is time consuming and inaccurate sometimes. Yue et al. [44] put forward to photograph a cross-section of a geomaterial, then the actual inhomogeneity and fabric were obtained by digital image processing (DIP), which has been widely accepted and used in many fields, including geotechnical engineering [44,43,29,47]. With the development of computed tomography (CT) and magnetic resonance imaging (MRI), it is possible to describe the complicated internal structures nondestructively and to analyze material inhomogeneity quantitatively [23]. A stack of 2D grayscale slices which represent the fabric of the soil–rock mixture can be obtained by CT/MRI. Through image reconstruction, a 3D geometry model of the soil–rock mixture can be established. The deformation and failure process of the soil–rock mixture can be traced and analyzed by multiple scans during testing.

In recent years, attempts have been made to study the inhomogeneous geomaterial by numerical analysis. Vallejo [35] investigated the behavior of granular materials containing large particles based on laboratory and finite element method (FEM). Yue et al. [44,3,43] developed a DIP techniques to establish the actual microstructures of geomaterials, which is called DIP based finite element method (DIP-FEM). Cho et al. [4] simulated the behavior of rock by discrete element method (DEM). Jiang et al. [14] analyzed the deformation and failure mechanism of intact

* Corresponding author. Tel.: +86 25 83596387.
E-mail address: zhangdan@nju.edu.cn (D. Zhang).

http://dx.doi.org/10.1016/j.compgeo.2015.12.005
0266-352X/

sliding zone soil based on CT scanning and finite difference method (FDM). However, numerical analysis (e.g. FEM and FDM) is quite sensitive to element quality and shape, especially along boundaries or interfaces. Poor quality elements would lead to errors and convergence problems in numerical simulations [20,38]. In order to improve the meshing quality, smoothing and simplification should be adopted. Methods for meshing have been proposed in both 2D and 3D to convert imaging data into finite element models for numerical simulation [45,26,18,46,19,41]. Usually, these methods focus on generating meshes inside the objects rather than creating high quality elements on the interfaces between the soil matrix and gravels. Actually, failure of geomaterial usually occurs near the interfaces due to the significant differences of the mechanical properties. Therefore, it is necessary to generate high quality elements which can represent the actual fabric of the geomaterial to improve the accuracy and efficiency of the simulation. Some algorithms have been proposed for handling random and complex geometry [2,5,7,28]. Mostly, an extensive preprocessing and user intervention would be adopted for these methods. It is difficult to generate an adaptive mesh with good quality because the interfaces identified directly from CT digital images are rough and jagged. So, appropriate smoothing should be adopted to improve the interface quality [22]. Yue et al. [44] transferred a cluster of the edge image pixels into a closed polygon using a geometry vectorization algorithm. Different smoothness for different polygons can be achieved by setting the threshold values to remove the jagged interfaces. In addition, some free software packages, such as OOF2 were developed to automatically create an adaptive triangular mesh from a digital image. Meanwhile, for numerical simulation, it is usually desirable to reduce the number of triangles per unit area because a higher triangle density requires a higher computational cost [22]. Here, a meshing generator, DISTMESH, is utilized to automatically create an adaptive triangular mesh that takes into account the actual fabric of the soil–rock mixture. DISTMESH is an open source code, which can deal with 2D meshing [24,25].

In this paper, a triaxial test system with CT scan is introduced firstly. Typical longitudinal profiles of triaxial samples were reconstructed from the transverse CT images. By image binarization, noise removal and interface detection, wire-frame models indicating the interfaces between the soil and gravels were built. After repairing and correcting of the samples as well as interface smoothing, DISTMESH was adopted to automatically generate a high-quality mesh with small sized grid near the interfaces. Then, the meshes were transferred into $FLAC^{3D}$ using an interface program. Finally, by comparing with the CT images, the effectiveness of this method was verified. Fig. 1 shows the process from laboratory triaxial test to numerical simulation by using DIP-DISTMESH-FDM method to study the fabric characteristics of the soil–rock mixture.

2. Triaxial test with CT scan

As shown in Fig. 2, the triaxial test with CT scan includes two parts. One is the high-quality medical CT machine, the other is the triaxial apparatus, which is modified from an ordinary stress controlled triaxial apparatus to fulfill the requirements of CT scan. The confining stress and deviator stress is applied by air pressure. Before triaxial testing, the sample was scanned to obtain its initial state. During the triaxial test, the sample was scanned to record its deformation after certain level of deviator stress was applied.

The size of triaxial sample was 100 mm in diameter and 200 mm in height. The scanning step was 0.6 mm along the longitudinal direction of the sample. About 333 transverse digital images were obtained for every CT scan. The digital image is a bitmap format with size of 512 × 512 pixels, as shown in Fig. 3. The middle circular area is a transverse profile of the sample, in which the gravels particles are in light gray color and the soil matrix is in dark gray color. The fabric characteristic of the soil–rock mixture, such as size, shape, distribution and relation of the gravels at a certain section is shown clearly. In Fig. 3, a pixel approximately represents 0.3 mm in size.

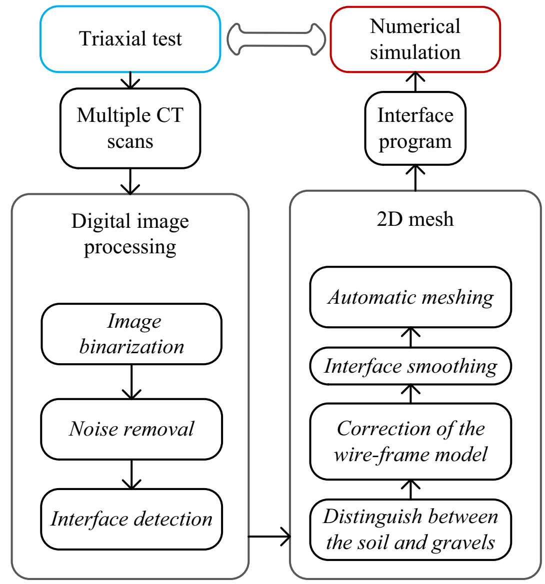

Fig. 1. CT based process to build a 2D mesh for soil–rock mixture in triaxial test.

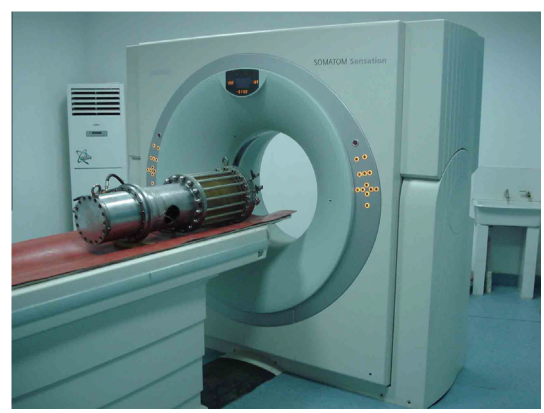

Fig. 2. Triaxial test system with CT scan.

3. Digital image processing

The digital CT image consists of a rectangular array of pixels. Every pixel in the image is assigned an integer value that defines the gray level. For the widely used “256 gray” images, the values of gray level range from 0 to 255 or for binary images with values of 0 and 1 [10]. In order to acquire the actual surface of the gravels in the soil–rock mixture, digital image processing methods, including binarization and noise removal, were adopted to obtain a high quality binary image of the soil–rock mixture.

3.1. Image binarization

A 3D model was reconstructed with a stack of the transverse CT images. The longitudinal image of the triaxial sample was obtained by cutting the model at a typical location, as the red line shown in