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Simulation of Critical State Behavior of Granular Soils with Polygonal Particles Using Discrete Element Method (DEM)

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ABSTRACT: In this study, the numerical Discrete Element Method (DEM) was applied for simulating both drained and undrained behavior of granular materials with two-dimensional polygonal particles in order to find a critical state line. For undrained behavior simulation, two methods including constant volume and cylinder methods were utilized. In the constant volume method, it was assumed that the volume of the soil remains constant during the loading due to the incompressibility of water. In the cylinder method, however, a pipe was considered among adjacent pores that provide the water transformation between them. In other words, the transmission of water among the voids can be taken into account. An undrained simulation was performed for sandy samples at the confining pressure of 200 kPa by both methods. Simulations showed that the results obtained by the cylinder method have good conformity with those of the constant volume method. A parametric study on the water compressibility was done. As the water becomes less compressible, i.e., stiffer, the stress-strain paths of both methods become closer. Also, the effect of confining pressure on the drained and undrained behavior by constant volume and cylinder methods was investigated. The results of the simulations showed that by increasing the confining pressure, the deviatoric stress and the contraction tendency increase in drained and undrained simulations. To achieve a critical state in the soil samples, the simulations were performed with a large strain level where both deviatoric stress and void ratio become constant. Then the critical state line locus, as well as its parameters, are determined. The results show that the critical state line locus does not depend on the stress path. Furthermore, the simulation method for the undrained condition has very little impact on the critical state line locus.

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1. INTRODUCTION

Many sandy soils show large deformation at large strain levels that may lead to the destruction of the structures built on them. The critical state occurs when the soil exhibits deformation with constant strength and constant volume [1]. In some studies, e.g., [2], a single critical state line has been obtained in various stress paths for sand.

Particle shape effect on strength of sand has been studied in some researches whose results showed that the behavior of sand with polygonal particles is different from sand with circular particles. The particle shape of sand obtained from the corruption of rock falling is often polygonal. This is despite the fact that in most numerical studies in the literature, circular shape is considered for the particles. In this study, the Discrete Element Method (DEM) has been used as a numerical method to investigate the strength behavior of sand with a polygonal shape.

DEM is a numerical method for studying particular assemblies. Mirghasemi et al. [3] simulated the drained behavior of assemblies with two-dimensional polygonal particles by using the linear contact law. The microscopic behavior was then studied by Seyedi Hosseininia by focusing on particle crushing [e.g., 4] and fabric anisotropy [e.g., 5]. Numerical simulation of undrained behavior of soil by DEM has been done in several studies in which, constant volume method, coupled method or cylinder method have been used. Fixing the assembly volume during the loading is the basic assumption in the constant volume method that is due to the assumption of water incompressibility. The coupled method is used to simulate water flow and particle displacement simultaneously. The third approach is the cylinder method that can be used to simulate the undr1.ained behavior of soil [6]. In this method, each pore has independent water pressure from the others. Therefore, the pore pressure difference between the adjacent pores causes the water transfer between them where the cylinders have the duty of water transfer.

In this study, the drained and undrained behavior of loose and dense sand samples containing polygonal particles at the confining pressure of 200, 400, 800, and 1600 kPa until reaching large strains were investigated. For the undrained simulation, both constant volume and cylinder methods were applied.

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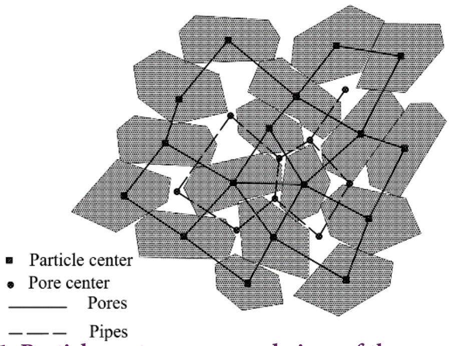

Fig. 1. Particle center, pores, and pipes of the assembly

2. INTRODUCING THE CYLINDER METHOD TO SIMULATE THE UNDRAINED BEHAVIOR OF SAND

In the cylinder method, the specifications of water among the pores such as bulk modulus and viscosity were considered and the undrained condition was simulated by hypothetical pipes that transfer water among adjacent pores. The cylinder and constant volume method algorithms have been prepared by the authors and it is added to the POLY program [3], which had been already used to simulate the drained behavior of sand with polygonal particles. The main point in the algorithm is to find the pores among the particles. Figure 1 shows the particle center, pores between the particles, pore centers and the pipes between them.

The accurate volume of pores and corresponding volume change from the previous computational cycle should be calculated. The change of pore water pressure is determined according to the water bulk modulus, initial volume and volume change of the pores [6]. The flow rate is calculated in each pore by Eq. (1):

$$q = \frac{\pi d^4}{128\mu} \frac{(u_1 - u_2)}{L} \tag{1}$$

where d and L are the diameter and the length of the pipes, respectively.

After determining the flow rate, the volume change of the pore was calculated by the sum of the volume change of the pore due to particle movements and the volume change of the water available in the pore. The force obtained by pore water pressure was applied to the particles that are adjacent to that pore and the resultant force and momentum in the particle center are calculated. By using the motion law, acceleration, displacement, and rotation of each particle were determined.

2.1. Simulations

The simulation steps are sample generation, applying confining pressure followed by deviatoric stress. The sample contains 1000 polygonal particles including different (nine) arbitrary polygonal geometries. Figure 2 shows the particles geometry. A series of particles in the sample was chosen with a scale of one, 0.8 and 0.6 relatives to the shape dimensions shown in Figure 2.

After sample generation, it was consolidated at the specific confining pressure isotropically. In the cylinder method, the initial pore pressure of 10 kPa was assigned to all of the pores and after determining soil permeability, the pipe diameter was obtained by using the results of Rothenburg and Matias study [7] that is equal to 450 micrometers. In drained and undrained simulations by cylinder method, a displacement-control loading was applied in the vertical direction while the horizontal stress kept constant. In the constant-volume method, applying strain rate to the sample boundary line in both directions were selected symmetrical to maintain the sample volume constant during loading.

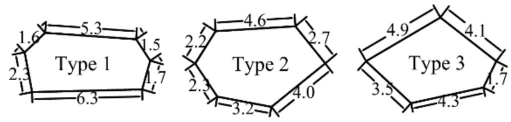

Fig. 2. geometry of three types of sample particles (dimension is in millimeter)

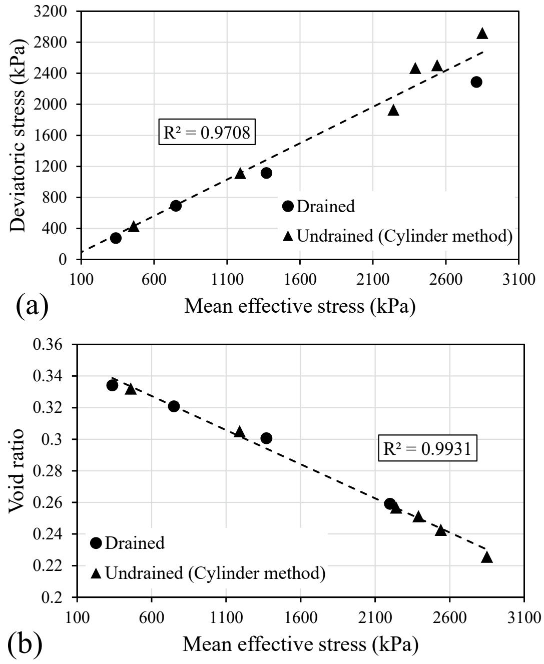

Fig. 3. Critical state line obtained by the drained and undrained (cylinder method) simulations in (a) q-p' space; (b) e-p' space

2.2. Verification of the cylinder method results

For verifying the results of the cylinder method, undrained simulation by constant volume and cylinder methods were done for the dense and loose samples at the confining pressure of 200 kPa. The obtained results showed good conformity. Also by increasing the water bulk modulus in the cylinder method, the results of the two methods got closer.

2.3. Investigation of the drained and undrained simulation results

The stress-strain path of the sample in drained and undrained simulations was investigated until reaching large strain levels. Both constant volume and cylinder methods were used for undrained simulation. The results showed that the soil strength and the volume change tendency is increased by increasing the confining pressure. Also, the method of undrained behavior simulation (either of constant volume or cylinder) has a little effect on the critical state line parameters. For example, Figures 3(a) and 3(b) show the critical state line obtained by the results of the drained and cylinder simulations in the deviatory stress versus mean effective stress and void ratio versus mean effective stress. For more complete results, refer to the main paper.

3. CONCLUSIONS

The results showed that the soil strength and volume change tendency was increased by increasing the confining pressure. Also, the results of the cylinder and constant volume methods such as strength and pore water pressure had good conformity with together. In the last section of the results, the critical state line parameters obtained by the cylinder method and constant volume method were studied. The results showed that the method of undrained behavior simulation (either of constant volume or cylinder) has a little effect on the critical state line parameter.

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