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Research Paper

Influence of the intermediate principal stress and principal stress direction on the mechanical behavior of cohesionless soils using the discrete element method

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ABSTRACT

In this paper, the Discrete Element Method (DEM) is employed to numerically explore the response of hollow cylinder specimens of granular soils under complex stress paths. Two series of numerical tests are conducted to clarify the effects of the principal stress direction α and the intermediate principal stress through the b-value on the mechanical response of granular materials. The effects of α and b-value on the non-coaxiality of the principal stress and the principal plastic strain increment directions are investigated. It is observed that b-value and α significantly affect the non-coaxial behavior of granular materials. Finally, the results are discussed and compared with those obtained from physical laboratory tests.

1. Introduction

Majority of field problems in geotechnical engineering involve three-dimensional loading conditions, that is, soil is normally subjected to three different principal stresses together with rotations of the principal stress axes. The direction α, which is the angle the major principal stress σ_1 makes relative to the vertical axis, has been used to characterize the anisotropy of materials, including inherent and induced anisotropies. In addition, in conventional tests, such as the direct shear test and triaxial test, the effect of the intermediate principal stress as given by $b = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$, which describes the three-dimensional behavior of soils, is another important factor. Furthermore, the Mohr-Coulomb failure criterion is formulated only in terms of the major and minor principal stresses σ_1 and σ_3 while ignoring the effects of the intermediate principal stress σ_2. Habib [14] was one of the first researchers to investigate the effects of b-value on the mechanical response of soils in torsional triaxial tests. However, his conclusions do not reflect the influence of b-value alone because in his tests using the hollow cylindrical apparatus, the principal stress directions were rotated such that $b = \sin^2\alpha$. The true triaxial testing system has been widely used to investigate the effects of b-value on the response of soils (e.g., [4,20,15,25,53,44]). Barretto and O'Sullivan [1] investigated the influence of the coefficient of inter-particle friction μ and b-value on the behavior of granular materials in the true triaxial test using the Discrete Element Method (DEM). However, in terms of anisotropy, the true triaxial test possesses the same limitation as does the conventional triaxial apparatus, i.e., the boundaries set by the device can translate but not rotate. No shear stress can be applied to the specimen, and the orientation of the principal stresses cannot be controlled. Therefore, the investigation of anisotropy is limited to two situations: (a) $\alpha = 0°$ and (b) $\alpha = 90°$. Hence, the full effects of α could not be fully understood, although b-value could be properly controlled.

To overcome the difficulties described above, the hollow cylindrical apparatus (HCA) was developed as a versatile tool to explore the three-dimensional anisotropic behavior of soils, including the effects of principal stress rotation. The capabilities of the HCA were extensively examined and enhanced from the 1980s (e.g., [40,39]). However, due to differences in sample conditions, sample fabrics or testing systems, the effects of b-value and the principal stress

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rotation on the stress-strain behavior have yet to be fully explored. Furthermore, there remain uncertainties in the reliability of laboratory experimental data from HCA testing, especially for complex stress paths [51].

Since Cundall and Strack [7] proposed the DEM, it has increasingly been viewed as a good alternative to physical testing when exploring the behavior of granular soils. In DEM, it is possible to prepare identical samples with no differences in the initial fabric and test them under identical loading conditions. Furthermore, DEM provides an excellent method of monitoring and extracting the micro-level data and understanding the micro-mechanical behavior of granular materials. Various investigations on the effects of intermediate principal stress have also been conducted with cubic triaxial samples using DEM and demonstrated good consistency with experimental behavior (e.g., [48,31,32,33,43]. Although the results obtained using the DEM have been positively compared against different published failure models under complex stress conditions defined by b-value and α, the predictions from DEM modeling have not been studied for many other important experimental observations. These include the complete mechanical behavior of soil in hollow cylinder testing systems and its relation to non-coaxiality [13,6]. Moreover, due to the geometry of the HCA and the introduction of the torsional stress component and different inner and outer cell pressures, the interpretation of results is not as straightforward as for cubic samples.

Three aspects of soil constitutive behavior should be clearly addressed at both the macro and micro levels: (1) the effects of intermediate principal stress; (2) the effects of the principal stress direction; and (3) the induced non-coaxiality. These factors would help researchers better interpret the experimental results from the HCA. This paper makes a contribution to the fundamental understanding of granular material response by examining the effects of the principal stress direction α and b value on the mechanical response of granular material. This paper outlines the simulation approach used in the physical HCA experiment and presents the response of cohesionless soil under various combinations of α and b-value for medium-dense and dense specimens in terms of the stress-strain relationship, dilatancy behavior and non-coaxiality. The effects of b-value on strain localization and non-coaxiality are emphasized. The results from the 3D DEM simulations are also compared to physical tests.

2. Simulation details

The DEM simulation program is divided into two series: (I) keeping $p = (\sigma_1 + \sigma_2 + \sigma_3)/3$ constant while independently varying α and b; and (II) keeping the internal and external cell pressures equal ($p_i = p_o$), which results in the condition of $b = \sin^2\alpha$. The Series I tests attempt to clarify the effects of b and α, respectively, which would induce non-uniform distributions of stresses

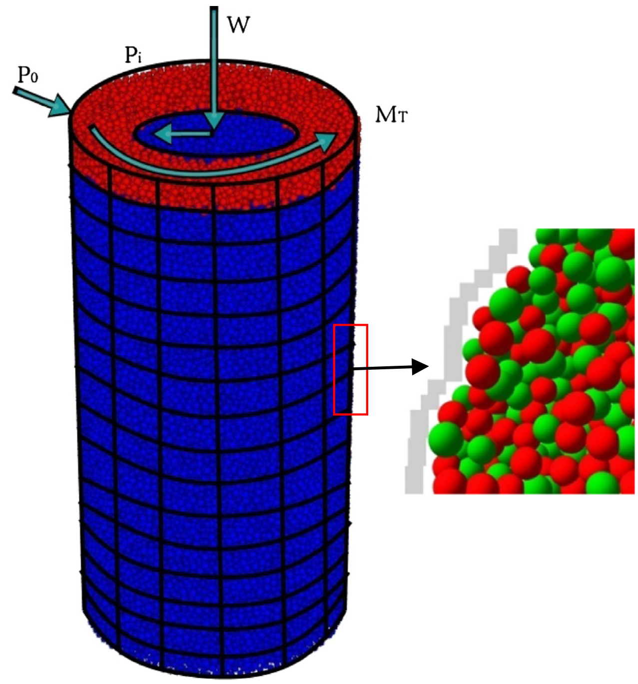

Fig. 1. 3D DEM model of the hollow cylinder sample with particle no. = 52,478.

in the sample. Many of the previous physical test results are based on the condition $b = \sin^2\alpha$, that is, $p_i = p_o$, most likely due to the control system or as a result of keeping the stress uniform across the boundary. The Series I and Series II tests could be mutual corroboration to explore the combined effects of b-value and α. Meanwhile, the stress state of the sample for the combination of α and b could be referred in Lade and Rodriguez [24]. The detailed test program is shown in Table 1.

The 3D numerical HCA tests are performed using the DEM code PFC3D (Particle Flow Code 3D) developed by Itasca [18]. A sample is prepared using an assembly of spherical particles with a uniform distribution. The "random placing" method is adopted to generate the particles. In this method, the particles are randomly generated inside the hollow cylinder mold, which can maintain the sample condition more isotropically. To reduce the simulation times during sample preparation, the particle coefficient of friction μ was intentionally set to zero temporarily so that no "lock-in" stresses were created. To accurately simulate the actual conditions of the physical tests and to reduce the calculation time in the loading sequence, many researchers have suggested that the particle size can be scaled up without significantly affecting the results of simulating the process of the two series experiments [54]. In this program, the particle diameter is scaled up 3 times, that is

Table 1
Tests program.

Test no.	b-values	α (°)	Relative density	Test condition
Series I	0, 0.3, 0.5, 0.8, 1.0	0	Mid-dense	p = constant; b-value and α are independent
	0, 0.3, 0.5, 0.8, 1.0	30	Mid-dense	
	0, 0.3,0.5, 0.8, 1.0	45	Mid-dense	
	0, 0.3, 0.5, 0.8, 1.0	60	Mid-dense	
	0, 0.3, 0.5, 0.8, 1.0	90	Mid-dense	
Series II	0.0	0	Mid-dense	$p_i = p_o$ and $b = \sin^2\alpha$
	0.067	15	Mid-dense	
	0.25	30	Mid-dense	
	0.5	45	Mid-dense	
	0.75	60	Mid-dense	
	0.93	75	Mid-dense	
	1.0	90	Mid-dense	