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Technical Paper

Experimental validation study of 3D direct simple shear DEM simulations

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Abstract

Simple shear element tests can be used to examine numerous geotechnical problems; however, the cylindrical sample (NGI-type) direct simple shear (DSS) device has been criticized for its inability to apply uniform stresses and strains, as well as for its inability to fully define the stress state of the soil during shearing. Discrete element method (DEM) simulations offer researchers a means to explore the fundamental mechanisms driving the overall behavior of granular soil in simple shear and to improve the understanding of the DSS device itself. Here, three-dimensional DEM simulations of laminar NGI-type direct simple shear element tests and equivalent physical tests are compared to validate the numerical model. This study examines the sensitivity of the DEM simulation results to sample size, contact model and stiffness inputs, and ring wall boundary effects. Sample inhomogeneities are also considered by examining the radial and vertical void ratio distributions throughout the samples. Both the physical experiments and the DEM simulations presented herein indicate that the observed material response is highly sensitive to the particle size relative to the sample dimensions. The results show that samples with a small number of relatively large particles are very sensitive to small changes in packing; and thus, an exact match with the DEM simulation data cannot be expected. While increasing the number of particles greatly improved the agreement of the volumetric and stress–strain responses, the dense DEM samples were still initially much stiffer than the experimental results. This is most likely due to the fact that the inter-particle friction was artificially lowered, during the sample preparation for the DEM simulations, in order to increase the sample density.

Keywords: Discrete element method (DEM); Laboratory tests; DSS; Three-dimensional model

1. Introduction and background

Simple shear element tests are used to study soil behavior for a number of geotechnical problems, including foundation loading, traffic/pavement loading, pile driving, slope stability, and earthquakes (Bjerrum and Landva, 1966; Randolph and Wroth, 1981; Malek, 1987). Simple shear devices aim to recreate the in situ stress state and the mode of deformation for an element of soil by applying an approximately uniform shear strain field to the sample and allowing the principal axes to smoothly rotate, a feature which is not possible in triaxial testing. The two types of experimental devices commonly used to study deformation in simple shear are the direct simple shear (DSS) device, consisting of either a cylindrical or a parallelepiped sample, and the torsional shear hollow cylinder apparatus (HCA), which uses a hollow cylindrical sample. The advantages and disadvantages of these devices have been outlined by several researchers (Saada et al., 1983; Shibuya and Hight, 1987; Talesnick and Frydman, 1991). The

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advantage of the HCA is that it allows for all three principal stresses to be directly measured and, theoretically, independently controlled. However, sample preparation is difficult. While both sample preparation and testing in the cylindrical sample DSS device, often referred to as the NGI-type device for developments made at the Norwegian Geotechnical Institute (Bjerrum and Landva, 1966), are relatively simple, several limitations have hindered its widespread acceptance (Saada and Townsend, 1981; LaRochelle, 1981; Airey et al., 1985; Talesnick and Frydman, 1991; Jardine and Menkiti, 1999).

DSS devices are not able to apply the complementary shear stresses present in the ideal simple shear case, which leads to non-uniformities across the top and bottom boundaries. While this violates ideal simple shear conditions, Franke et al. (1979) and Vucetic (1981) showed that these non-uniformities are minimized for large diameter to height ratios. Budhu and Britto (1987) also showed that the sample core is under ideal simple shear conditions. An additional limitation of the NGI-type device is the difficulty of measuring the horizontal normal stress during shearing and the fact that it does not correspond to the intermediate principal stress or the stress normal to the plane perpendicular to shearing (Budhu, 1988). These factors lead to an incomplete description of the changing stress state of the soil and require that several assumptions be made regarding the failure mechanisms in order for the strength parameters to be assessed. There is a need to examine the stresses and strains within the soil element and to determine the microscopic interactions driving the overall behavior.

Several researchers have used numerical methods to study DSS element tests in an effort to better understand the stress state and the strain distributions. Finite element analyses were performed by Budhu and Britto (1987), Dounias and Potts (1993), Bashir and Goddard (1991), and Zhuang (1993). While their studies provided insight into the mechanism of simple shear, the FEM models were limited in their ability to capture the full and complex nature of granular materials and their interactions at the particulate scale. Other researchers have used discrete element method (DEM) simulations which naturally allow granular behavior to arise through the use of very simple contact models and without the need for a complex constitutive material law (Shen, 2013; Dabeet et al., 2011; Ai et al., 2014). These studies demonstrated that DEM simulations are particularly advantageous for studying element tests on granular soils because they allow for the examination of particle-scale interactions, localized measurements of stresses and strains, and quantitative analyses of the fabric.

The documented direct simple shear DEM studies differ mainly in their treatment of the boundary conditions. In a two-dimensional DEM study, Shen et al. (2010) considered both the hinged rigid walls in the parallelepiped sample Cambridge device and the laminar walls which simulate the stack of lateral confining rings often used in the NGI-type device. Shen et al. showed that the type of boundary walls influenced the microscopic response observed, even though the macroscopic response was similar. This indicates the importance of modeling the correct boundary conditions if simulations of element tests are to be useful for examining micro-scale behavior. Ai et al. (2014) conducted a two-dimensional DEM simple shear study on non-coaxial granular behavior using a discretized wall system to limit the boundary non-uniformities imposed on the element. While these two-dimensional studies captured much of the behavior observed in granular materials in simple shear, they were not able to examine the three-dimensional response or the out-of-plane displacements which are present in real granular materials.

In a three-dimensional study, Dabeet et al. (2011) used laboratory data for glass beads to calibrate direct simple shear simulations. The stress–strain curves from simulations with various linear stiffness values were compared to experimental data to calibrate the model. The DEM model considered a single rigid cylindrical-walled sample to represent the NGI-type device used in the laboratory. While this approach is computationally efficient, it is unclear whether or not the rigid wall in this three-dimensional simulation affects the microscopic results as it does in the two-dimensional case.

If DEM simulations of simple shear element tests are to provide useful insight into the device, it is important that they be properly validated by experimental data. Validation studies consist of developing DEM models which replicate the physical conditions as accurately as possible. The size, the number, and the material properties of the particles are accurately modeled, along with the geometry, boundary conditions, and loading conditions of the system. Once the DEM simulation sufficiently resembles the macro-scale physical test results, the data recorded from the DEM simulation can be used to gain further information about the micromechanical behavior and the particle-scale response. To date, there are few, if any, documented experimentally validated three-dimensional numerical studies which replicate laminar simple shear conditions. This paper presents a study in which experimental data for monotonic DSS element tests on steel spheres were used to validate DEM model simulations. Using DEM simulations of physical element tests to study the microscopic response not only allows for improved understanding of the fundamental mechanisms driving the granular material response, but also provides the ability to better understand the DSS device itself.

2. Overview of experiments and simulations

As discussed by O'Sullivan (2014), granular assemblies are highly indeterminate systems, and DEM models can only be analytically validated for unrealistic scenarios involving ideal uniform spherical particles, lattice packings, and relatively simple deformation scenarios. For experimental validation, the physical properties of the material must be known. Steel spheres with high manufacturing tolerances and known material properties have been used successfully in previous validation studies (O'Sullivan et al., 2004; Cui and O'Sullivan, 2006), and they do not suffer from the geometrical variations that are common in glass ballotini, highlighted by Cavarretta et al. (2012). Additionally, these steel spheres are not susceptible to particle crushing, do not exhibit measurable compressible behavior at the range of stresses tested, and have relatively uniform surface