3D ANALYSIS OF FORCE CHAINS IN SAND USING FINITE ELEMENT METHOD

Wadi H. Imseeh*[1], Khalid A. Alshibli†[2]

[1]Graduate Student, Department of Civil and Environmental Engineering, University of Tennessee, USA
[2]Proffessor, Department of Civil and Environmental Engineering, University of Tennessee, USA

Keywords: Synchrotron micro-computed tomography, finite element analysis, force chains, granular materials.

Summary: 3D finite element (FE) analysis was used to model one dimensional (1D) compression of uniform silica sand. 3D images of sand particles were acquired using synchrotron computed tomography and were processed by Avizo software to generate a surface mesh. Abaqus FE code was then used to perform the simulations and calculate contact forces between particles. Experimental measurements of lattice strains and 3D images of particles reported by Cil et al. (2017) were used to validate the FE model to identify force chains within the sand specimen.

1. INTRODUCTION

It is a well-known that granular materials transmit forces at particles' contacts to form a network of force chains. Particles within force chains transmit higher contact forces than those that are not part of force chains. Photo-elastic materials have been used to visualize force chains in 2D. Numerical methods have emerged as powerful techniques to calculate stresses and strains and visualize force chains within granular materials. Discrete element method (DEM) has been widely used to measure the interaction between rigid discrete particles and model the behaviour of granular materials. On the other hand, continuum-based methods assume a constitutive model to govern the behaviour of particles and their interaction to predict the material behaviour. However, granular materials consist of individual particles that interact with each other in a complex fashion. Therefore, there is a need for a framework that can capture the morphology of individual particles and model a granular assembly. This paper uses the 3D finite element method to model the behaviour of a sand specimen based on 3D images of particles with emphasis on identifying contact forces between particles.

2. MATERIAL DESCRIPTION AND IMAGE ACQUISITION

Cil et al. (2017) conducted 1D compression experiment on a specimen composed of natural uniform silica sand. It is cylindrical in shape and measures 1 mm in diameter and 2 mm in height. 3D x-ray diffraction (3DXRD) and Synchrotron Micro-computed Tomography (SMT) scans were acquired on the specimen using beamline 1-ID of the Advance Photon Source (APS), Argonne National Laboratory (ANL), Illinois, USA. Cil et al. (2017) measured the lattice strains within individual sand particles using 3DXRD technique and SMT images helped to visualize particle interaction and fracture during the experiment.

3. FINITE ELEMENT MODELLING AND FORCE CHAINS VISUALIZATION

AVIZO Fire 9.2.0 software was used to crop each particle and generate a surface mesh with approximately 800 triangle elements per particle (Figure 1). Meshed surface images were imported into Abaqus and the triangulated surface mesh was converted into a tetrahedral mesh resulting in solid particles. An isotropic elastic material model was assigned to the sand particles with Young's modulus of elasticity and Poisson's ratio values of 91.1 GPa and 0.118, respectively (Heyliger et al. 2003). Then, particles were assembled into a discrete rigid die and bound by two discrete rigid end plates like the experimental setup that was imaged using SMT. Penalty contact formulation was adopted to define interaction properties between particles, particles-die, and particles-end plates in which slippage is constrained by a tangential friction coefficient of 0.32 and hard normal behaviour. To simulate the

* e-mail: wimseeh@vols.utk.edu
† e-mail: alshibli@utk.edu

experiment, the die and bottom end plate were fixed with zero degrees of freedom while the top end plate was permitted to move in the vertical direction with one degree of freedom. The FE simulation was divided into seating and loading phases where a seating load of 1 N was gradually applied on the top end plate in the vertical direction. Then, the top end plate was moved at a constant compressive displacement rate until the onset of force chains at approximately 0.3 mm displacement (~15% axial strain). The FE model of the specimen at multiple compression stages is depicted in Figure 2.

Abaqus/Explicit provides contact forces at surface nodes for each particle. Particles were initially examined individually at contacts. Then, nodal forces at each contact were summed up and one contact force value was assumed to act at the centre of the contact nodes. Force equilibrium of each particle was satisfied. In addition, contact forces pairs were checked to be approximately equal in magnitude and opposite in direction. As contact forces were quantified, the flow of vertical loads was tracked and the maximum contact forces were highlighted to identify force chains. Three force chains were recognized as shown in Figure 3. Cil et al. (2017) quantified two force chains experimentally based on particles with maximum principle lattice strain that were measured using 3DXRD. The two force chains that were reported by Cil et al. (2017) are also identified in the FE analysis (chains I and II in Figures 3).

References

Cil, M., Alshibli, K., and Kenesei, P. (2017). "3D Experimental Measurement of Lattice Strain and Fracture Behaviour of Sand Particles Using Synchrotron X-ray Diffraction and Tomography." *Journal of Geotechnical and Geoenvironmental Engineering, under review*.

Heyliger, P., Ledbetter, H., and Kim, S. (2003). "Elastic constants of natural quartz." *The Journal of the Acoustical Society of America*, 114(2), 644-650.

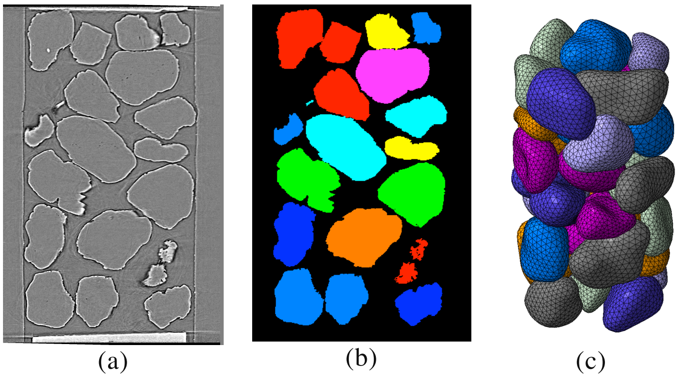

Figure 1. Vertical slice through the initial SMT scan (a) grayscale image; (b) labeled image; and (c) generated surface mesh.

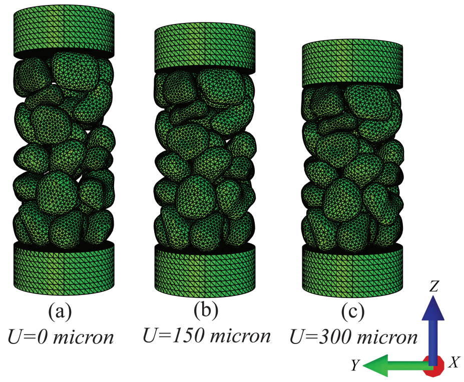

Figure 2. FE mesh of specimen. The die is hidden for better visualization (*U* refers to vertical displacement of the top end plate).

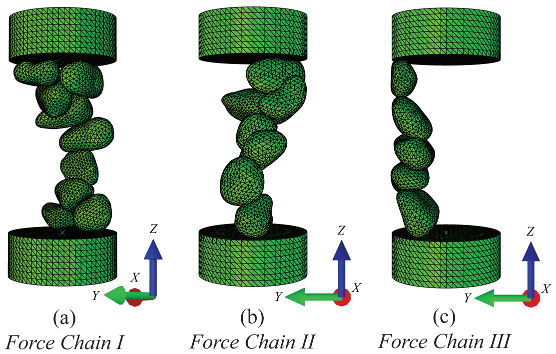

Figure 3. Force chains in FE model at 300 μm compressive displacement in which surrounding die is hidden for better visualization.