CHARACTERIZATION OF MICRO-MECHANICAL PROPERTIES OF GRANULAR MATERIALS BASED ON THE USE OF 3D-T IMAGERY AND DISCRETE ELEMENT MODELING

A Senior Scholars Thesis

by

TAM N. M. DUONG

Submitted to Honors and Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

May 2012

Major: Civil Engineering

CHARACTERIZATION OF MICRO-MECHANICAL PROPERTIES OF GRANULAR MATERIALS BASED ON THE USE OF 3D-T IMAGERY AND DISCRETE ELEMENT MODELING

A Senior Scholars Thesis

by

TAM N. M. DUONG

Submitted to Honors and Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

Approved by:

Research Advisor: Zenon Medina-Cetina
Associate Director, Honors and Undergraduate Research: Duncan MacKenzie

May 2012

Major: Civil Engineering

ABSTRACT

Characterization of Micro-Mechanical Properties of Granular Materials Based on the Use of 3D-T Imagery and Discrete Element Modeling. (May 2012)

Tam N. M. Duong
Department of Civil Engineering
Texas A&M University

Research Advisor: Dr. Zenon Medina-Cetina
Department of Civil Engineering

This study analyzes the effects of varying conditions for the assessment of micro-parameters of granular materials based on both laboratory and numerical experiments. The aim is to investigate the effects of varying micro-parameters of particle elements and the interactions between them under controlled conditions. For this purpose, a homogenous specimen is built using particles made out of steel spheres with constant diameter. The experiment where the micro-parameters are analyzed consists on assessing a simple kinematic exercise defined by the sample preparation, by the use of the dry pluviation technique, where spheres are dropped at varying heights to achieve different densities. A numerical model is built to reproduce the same experimental conditions by the use of distinct elements using PFC-3D. This allows for a direct comparison to achieving a better understanding on the assessment of micro properties of granular materials. The preliminary result demonstrates a good match between the experimental and numerical modeling in sample preparation. The outcomes of this study also permit to conduct uncertainty quantification on the assessment of the micro-parameters.

DEDICATION

I would like to dedicate this thesis to my beloved parents who are currently living in Vietnam, Mr. Thanh Duong and Mrs. Dung Nguyen. There is no doubt that without their encouragement and supports, I would never have completed this progress.

ACKNOWLEDGMENTS

I would like to acknowledge Dr. Medina-Cetina for his supports and guidance throughout the research. I would also like to acknowledge Mr. Patrick Noble, my co-worker in this study for helping me and showing me how to use PFC3D programs.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

As the result of the rapid development of computational technology, the use of Digital Image Correlation (DIC) and Discrete Element Model (DEM) techniques has become popular for many research disciplines. DIC is well-known for displacement measurements and characterizing localized material deformation by using multi camera system to capture the material displacement fields [1]. DEM is known for the capability of reproducing particles interactions for large deformation such as standardized tri-axial compression tests [2]. Improving the understanding of the micro-mechanical with respect to meso- and macro- mechanical application is currently a pressing need in geotechnical engineering. There are some preceding studies that combined DIC and DEM techniques with experimental testing results to obtain better understanding of micro-mechanical behaviors of different materials [3]-[5]. This research oriented towards the characterization of a homogeneous granular material (i.e. steel spheres) subjected to large deformations when it is characterized by the use of 3D-DIC and its DEM modeling using PFC-3D for response prediction. The purpose is to populate a database based on 3D-DIC that describes localized phenomena in granular materials and couple it with 3D-DEM models, thus to have a basic understanding of the DEM parameters to match given experimental conditions.

This thesis follows the style of *IEEE Transactions on Geoscience and Remote Sensing*.

CHAPTER II

METHODS

Specimen preparation

For the purpose of this study, specimen preparation is an important task, which would condition the failure mechanisms found in triaxial tests on granular specimens. The main goal is to produce a uniformly distributed cylindrical specimen using a homogenous particle material. Chrome steel spheres with a uniform diameter of 3 millimeters were used to form homogenous specimens in this study. According to the manufacturer, Thomson Precision Balls, the density of every single sphere is 7.8x103 kg/m^3 [6]. O'Sullivan assumed subjectively a shear modulus of $7.9\text{x}10^{10}$ Pa, a Poisson's ratio of 0.28, and the sphere boundary coefficient as 0.228 [3]. The proposed study considered testing a triaxial standard specimen at its extreme states [7], meaning the densest and loosest, assuming frictionless ends. The steel spheres were composed to make a cylindrical specimen that is enclosed in a rubber membrane while being placed in a rigid mold with a confining pressure of 58.61 kPa (8.5 psi) to hold the specimen in place. It is relevant to mention that in the literature there are several sample preparation methods which have been developed over the time such as moist tamping, dry funnel deposition, air pluviation, and water sedimentation [8]-[11].

Moist tamping is a sample preparation method that utilizes the use of compaction. As described in Ladd's study [8], several soil layers of equal mass are placed in a mold then each layer undergoes the same amount of compaction process using a tamping rod. During compaction, the tamping rod is dropped from a constant height to the center of the surface specimen at first then moving towards the periphery. The relative density of the specimen is controlled by adding distilled water to the dry soil by weight in order to produce a loose sample. However, one great disadvantage of this method is the creation of a non-uniform density distribution within the soil specimen since each layer has a different density and the preceding layers will be denser than the succeeding layers [3]. Consequently, moist tamping is not recommended for this study.

Dry funnel deposition method is usually used to create a loose sample. A funnel is placed in a mold with the spout towards the mold's bottom. After the soil specimen is poured into the funnel, the funnel is slowly raised along the axis of symmetry of the soil specimen to deposit soil in a low energy state. A denser stage can be archived by gently tapping the mold or raising the funnel faster [9]. This technique is common used to form dry, coarse-grained soil specimens. The velocity of soil poured into the funnel affects the composited density of the specimen that the faster you raise the funnel, the denser the specimen becomes.

Water sedimentation is a common sample preparation method for fine-grained soil which passes through the sieve No. 200 in a sieve analysis test. The procedure of preparing soil specimen is described by Wood et al. [9]. At short, the specimen is placed in a half-filled- of water flask and boiled about half an hour. Then the flask is filled with de-aired water and cooled down. After that, the flask is capped and rotated to mix the soil sample. The mold is also filled with de-aired water. The flask is inverted and pointed to the bottom of the mold then carefully remove the cap and slowly raise the flask to allow the soil mixture to flow out. Due to suction within the flask and the mixture in the mold, the weight of water in the mold transferred to the flask is equal to the weight of the soil specimen that flowed out. When the deposition process ends, the cap is carefully placed and then the flask is carefully removed. The remaining mixture in the flask is then dried to obtain the exact weight of the remaining soil thus archiving the weight of soil that flowed into the mold.

Air pluviation reconstitutes a soil specimen by drizzling soil particles through a set of diffuser meshes placed on top of a fall tube. The fall tube that has the same diameter of the mold rested below prevents the dispersion of the rain and promotes a uniform concentration of particles across the mold diameter. A detailed description of this method is presented in Andrew Cresswell's paper [10]. Cresswell indicated that during the air pluvation process, there was a layer of particles 3 to 4 grains thick of moving grains, called the "energetic layer". Above this layer is the bouncing zone where the grains either rebounce or are rejected from the energetic layer. The variation of the specimen depends on the rate of pouring the soil and the fall height. To obtain a specimen with uniform density, the fall height should remain constant and the pouring rate should be slow so that the soil particles have adequate time to settle and to depositional energy to archive denser configuration [11].

For the purpose of this study, which is to prepare a homogenous cylindrical specimen, the dry funnel deposition and air pluviation sample preparation methods were used. Figure 1 shows how the mold is prepared. The mold is fastened using two hoop clamps. Pressure is applied on the mold to keep the membrane in contact with the mold using a small vacuum pump. A plastic funnel of 135 centimeter diameter is placed in the mold with the spout toward the mold's bottom. Steel particles were poured into the funnel. After the spheres came to rest in the funnel, the funnel is gradually raised along the axis of symmetry of the cylindrical specimen to deposit steel particles in a low energy state, as shown in Figure 2. Ten trials of the same loose specimen were made. The weight and the specimen's dimensions, diameter and height, were recorded for each trial.

Denser specimens can be archived by using the combination of both air pluviation and dry funnel methods. Air pluviation reconstitutes soil particles by drizzling of soil particles through a set of diffuser meshes placed on top of a fall tube. The fall tube that has the same diameter of the mold rested below prevents the dispersion of the rain and obtains a uniform concentration of rain across the diameter. A fall acrylic tube with the same diameter of the mold is placed on the mold. On the top of the tube is a two-layer sieve. The funnel is placed slightly above the sieve to control the flow of the particles. Steel particles are poured into the funnel while its end is being closed. Then they are allowed to settle before the funnel's end is opened. Spheres flow through the funnel, enter the meshes and are redistributed through the acrylic vertical tube to densely form in the mold (Figure 3). With a constant flow velocity, a denser state of the specimen can be archived by increasing the tube height. The fall height is varied from having the sieve on the mold (zero fall height) to having the sieve on top of a 91.44 centimeter-height (three-foot-height) tube with increment of 15.24 centimeter (half a foot). Ten trials of each height are made and the dimensions and weight of each sample are recorded. The record of each steel specimen is used to generate a the distribution of drop height versus void ratio and drop height versus sample weight of a homogenous particle material made out of steel spheres.

Figure 1. Mold Preparation

Figure 2. Dry Funnel Composition Method

Figure 3. Air Pluviation Method

X-Ray tomography

X-Ray tomography is a recent technique based on the X-Ray diffraction analysis to retrieve the location of the steel sphere particles inside the mold. The aim to perform an X-Ray tomography is to quantify the non-homogeneity of the specimen to use as an initial condition in DEM analysis for the shearing of the specimen. This method provides an understanding of how the specimen is composed under different sample preparation methods and an observation of the non-uniformity of the specimen in terms of the volume of voids created during specimen preparation. In this study, a dense and a loose sample are prepared and placed in the CT scanner. Due to the limited space inside the machine, the sample is unable to be connected to the vacuum pump to let it stand without deforming. The scanning captures the cross section along the sample height with an interval of 1 millimeter. Figure 4 shows samples of the X-Ray scanning at different heights along the mold. All slices of x-ray images are compiled together to form a 3D specimen representation.

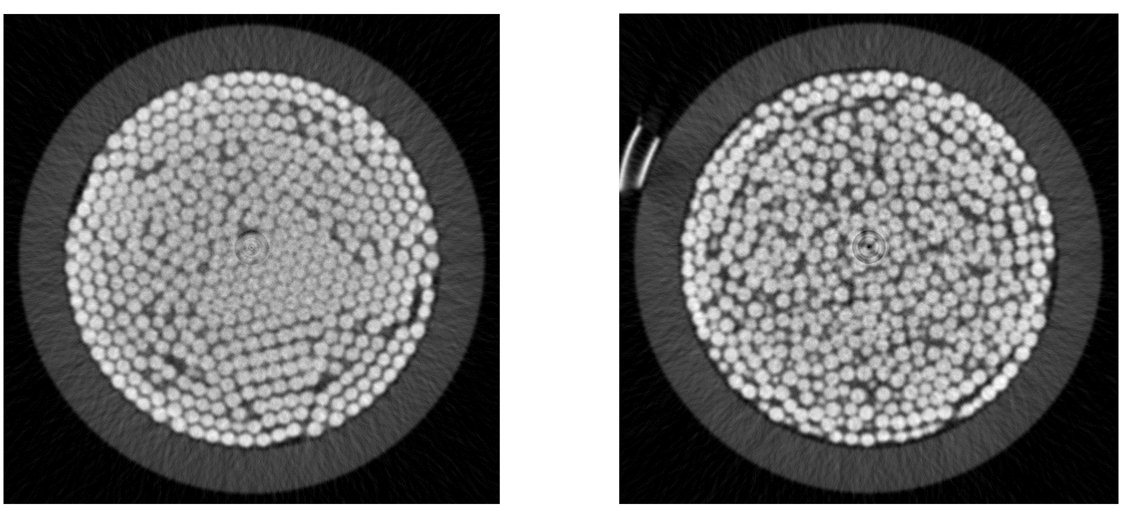


Figure 4. Samples X-Ray Scanning at the Bottom and the Middle of the Mold

Triaxial compression test

A triaxial compression test of loose and dense specimens was performed based on samples made out of steel spheres, as a way to obtain shear strength parameters of particles measuring the axial stress and axial strain of the specimen [7]. Figure 5 demonstrates a typical stress-strain curve to be obtained from the triaxial compression test of a granular material made out of steel spheres. The specimen is prepared as stated above and placed into the triaxial cell. A force transducer attached to a piston resting on the sample is used to capture the resistance of the specimen during shearing. The cell is then placed in the loading frame that connected to a displacement transducer. Both transducers are connected to the computer through a data acquisition device. The test starts as the loading frame is raised up at a rate of 1.6 millimeter per minute, while the confining pressure is still applied to the specimen. In other words, the strain rate of the triaxial test is 1.6 millimeter per minute. Figure 6 shows the set-up of the specimen prior to the triaxial test. The transducers transfer the recorded data to the computer and by the use of LabView program [12], which uses measured voltages from the transducers to get the displacement and force applied to the specimen. The end result provides adequate data to determine the strength and deformation properties of a sample composed of steel particles.

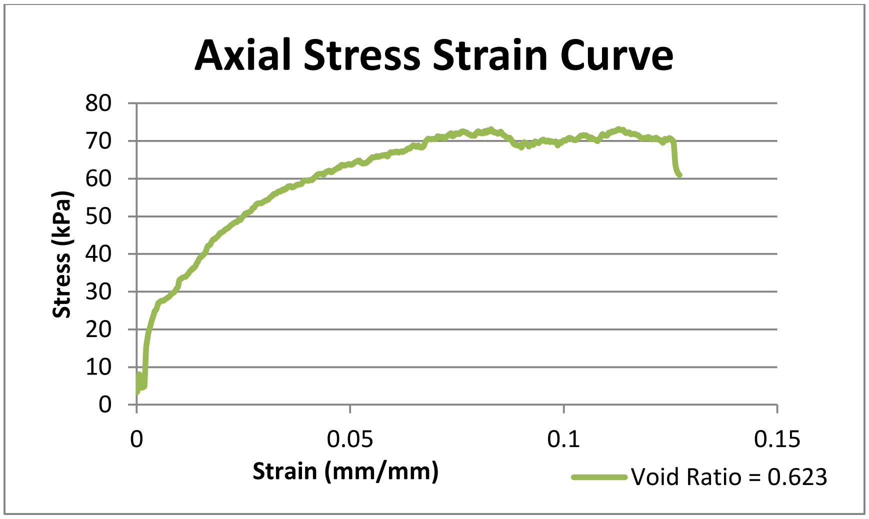


Figure 5. Stress Strain Curve for the Triaxial Test

Figure 6. Triaxial Compression Test Set-up

PFC-3D model

PFC-3D from ITASCA [13], is used to replicate the dynamic behavior of steel particles during both the sample preparation and the triaxial compression tests, using discrete element modeling. According to Cundall and Strack's study, the method utilizes an explicit numerical scheme in which the interaction of the particles is monitored contact by contact and the motion of the particles modeled particle by particle [14]. Based on the PFC-3D user manual, there are three components required to fully describe the force-displacement behavior for every contact. These components include a parallel band which are a parallel bond (slip behavior), a dashpot (stiffness) and a contact model (bonding behavior) [15]. Figure 7 demonstrates three force components at contact phase. The constitutive behavior of the balls in the simulation is associated with the contact model for the balls. A linear contact model and Hertz contact model are the two standard contact models for ball-ball contact and ball-wall contact. The linear contact model is set as the default contact model in PFC-3D. Models of specimen preparation methods for loose and dense samples are developed in PFC-3D using the same dimension and material properties, including ball diameter; normal strength and shear strength of ball; friction coefficient of ball and ball, wall and ball. The wall strengths are chosen to be a magnitude greater than the strength of the spheres. The goal is to achieve similar specimen densities for the same experimental sample preparation method. Generally, multiple walls are created and welded together to form the shape of a mold, a tube and a funnel. The sieve is replicated as meshes. There are 3500 balls generated in each simulation. Linear contact model is used in both dry funnel deposition and air pluviation models. Figure 8 shows the initial phase prior to simulate when the models are created.

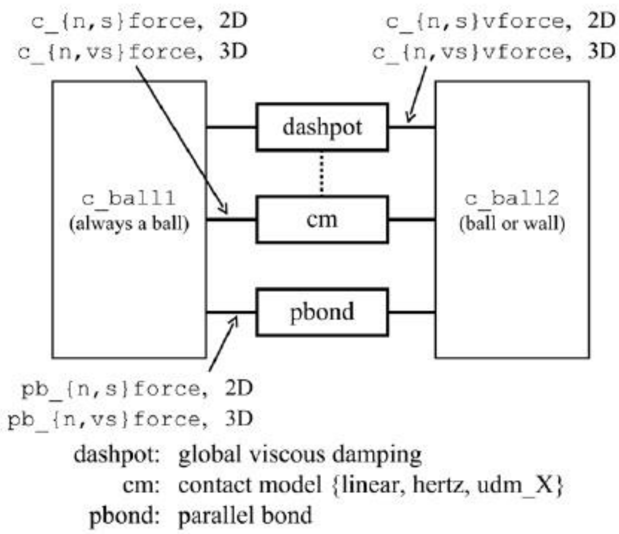


Figure 7. The Force Components at Contact Phase [15]

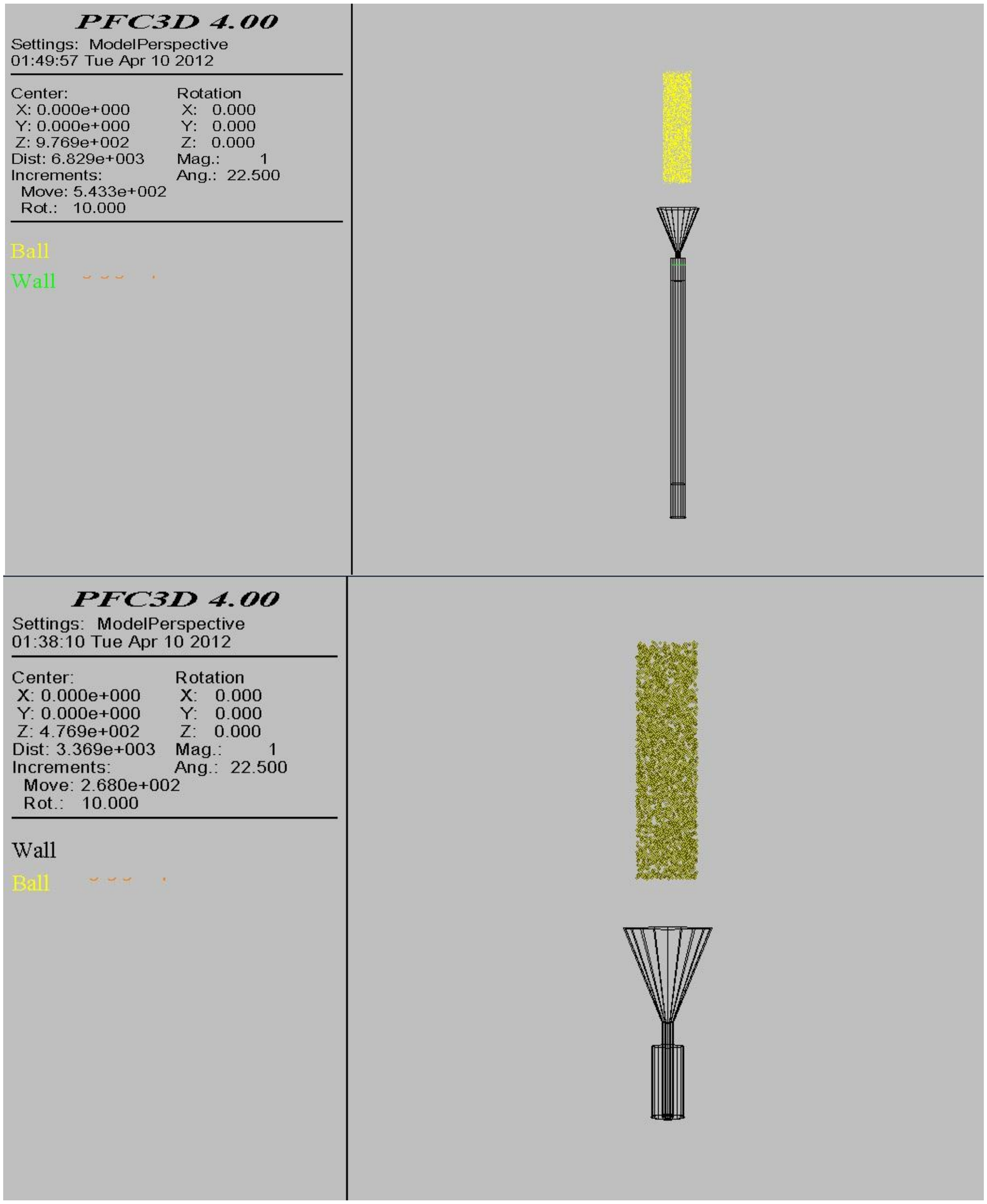


Figure 8. PFC-3D Models for Air Pluviation and Funnel Deposition Methods

CHAPTER III

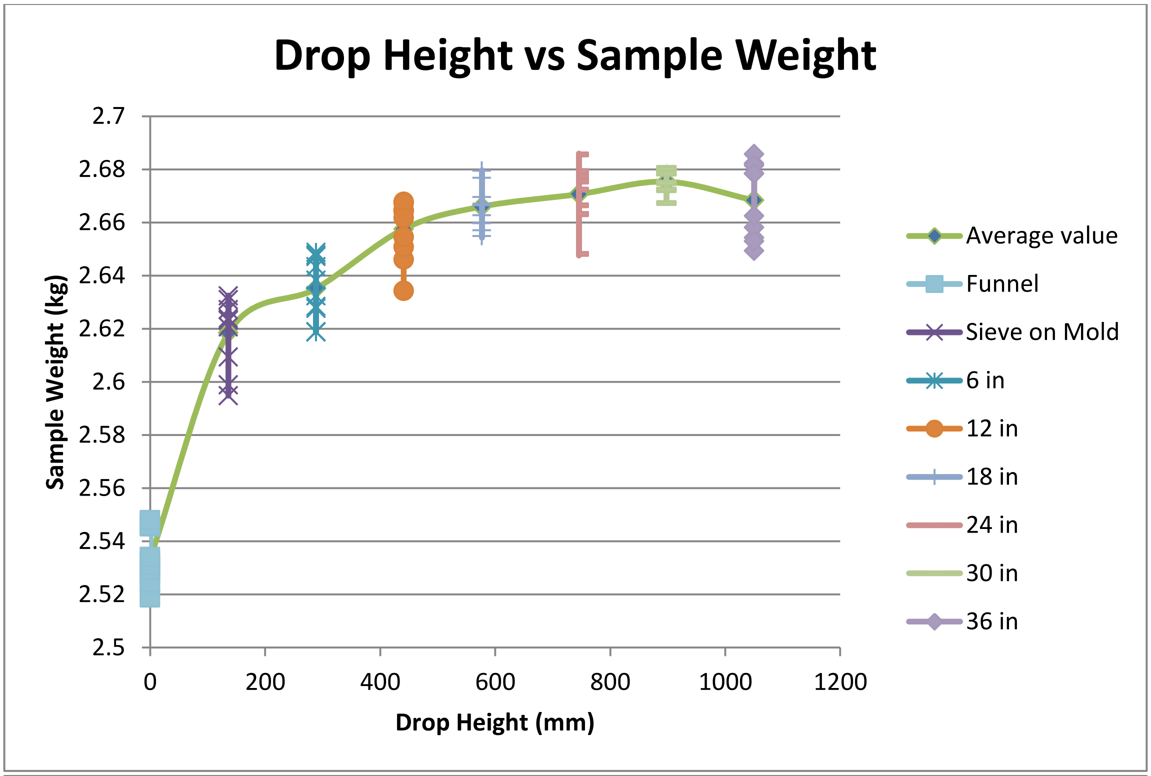
RESULTS

The experimental sample preparation using the air pluviation method for dense samples and the dry funnel method for loose samples is summarized in Table 1. Figure 9 shows the relationship between total drop height and its corresponding sample weight and void ratio. In this Figure, it can be observed that the specimen weight increases as the total drop height increases and the void ratio decreases as the total drop height increases, until an asymptotic threshold is reached. That is, the sample weight is directly proportional to the sample drop height while the void ratio and sample porosity are inversely proportional to the sample drop height up to a threshold value. The theoretical weight of dense and loose specimens calculated from material properties is 2.675 kilograms and 2.534 kilograms respectively. Comparing the experimental results of the weight of densest and loosest specimens in Table 1, the experimental method has archived a high degree of accuracy. The average weight of the loose and the dense samples achieved from the experiments are 2.5337 and 2.6707 kilograms respectively.

Table 1. Summarization of Experimental Sample Preparation Results

Total Drop Height (mm)	Average Weight (kg)	Average Void Ratio	Average Porosity
0.0	2.5337	0.633	0.388
136.0	2.6184	0.607	0.378
288.4	2.6351	0.599	0.375
440.8	2.6575	0.589	0.371
577.0	2.6660	0.577	0.366
745.6	2.6707	0.580	0.367
898.0	2.6754	0.581	0.368
1050.4	2.6683	0.580	0.367

The X-Ray images of a dense sample are compiled to form a 3D specimen representation, shown in Figure 10 and 11. Although the shape of the spheres cannot be fully identified, a number of irregular patterns can be observed throughout the image cross-section, indicating a measure of the specimen's heterogeneity. The X-Ray scanning process needs to be improved in order to have better image quality.



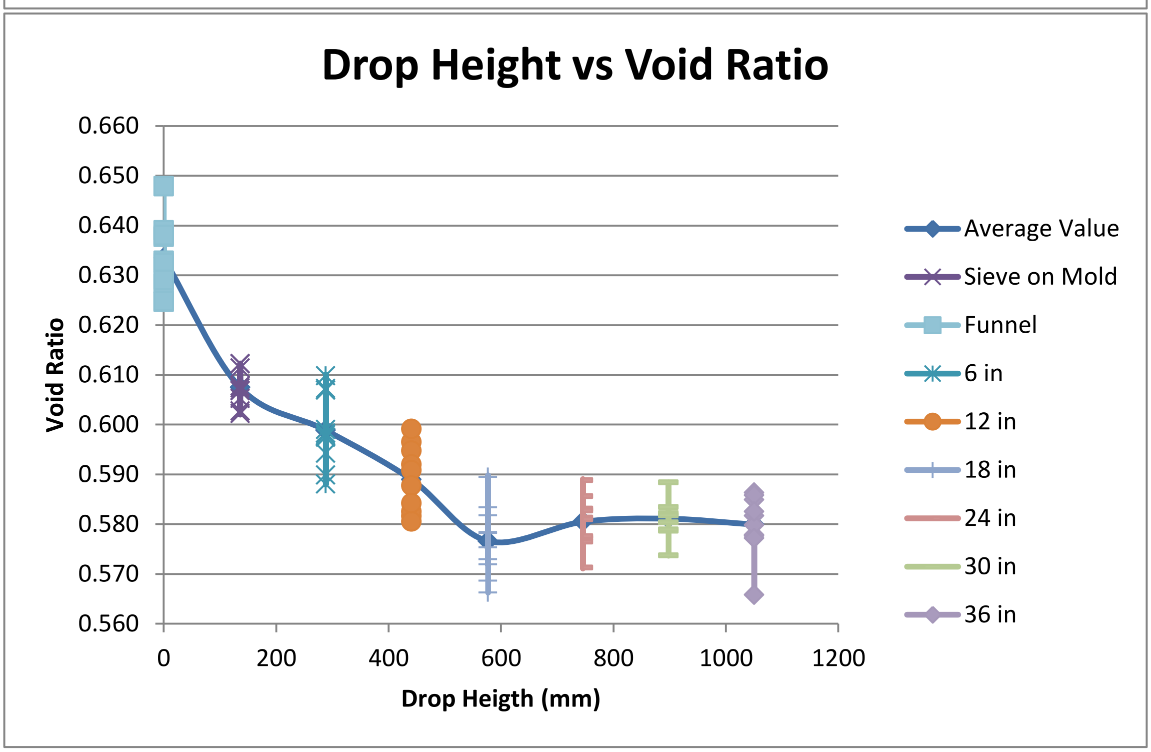


Figure 9. Plots of Drop Height versus Sample Weight and Void Ratio

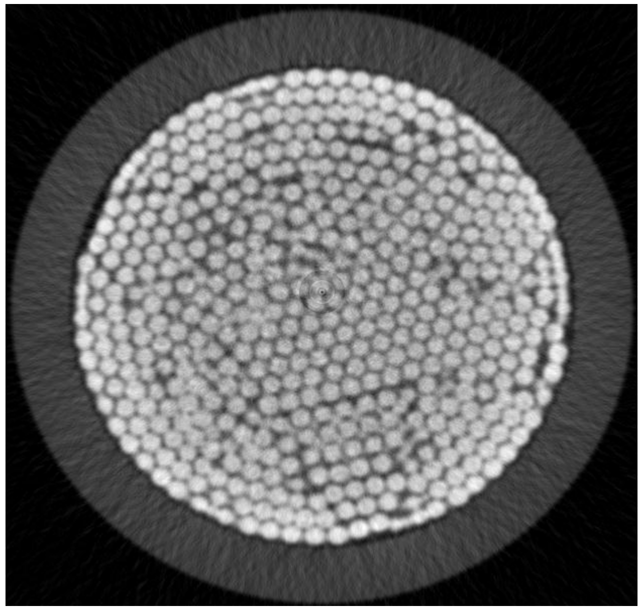


Figure 10. A Slice of X-Ray Dense Sample Image

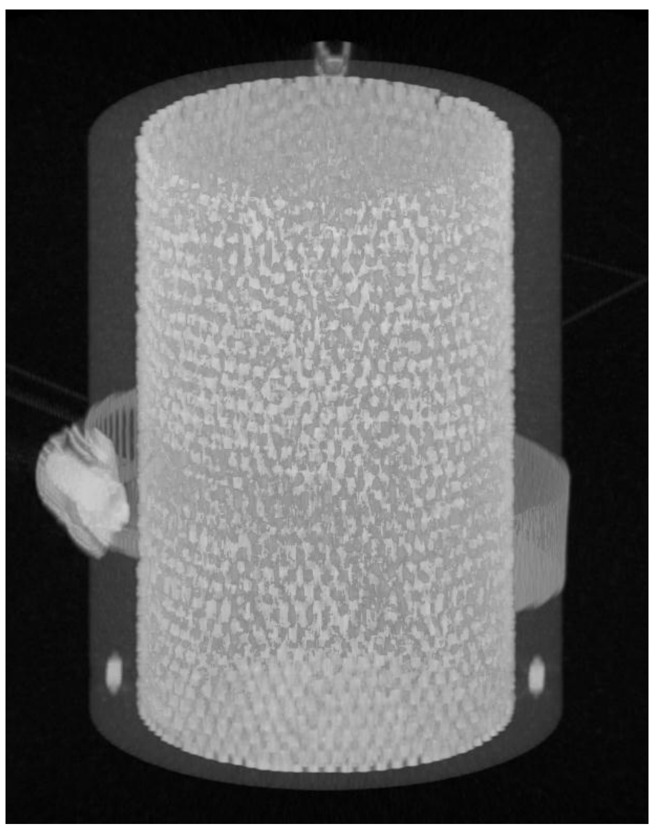


Figure 11. 3D Specimen Representation

The DEM sample preparation models for dense and loose samples are developed using the PFC-3D program. Figure 12 shows the DEM model for dense sample preparation method. The simulation is run for 20 million cycles of time steps with an average time step of 1.5E-6 seconds to completely fill the mold. Figure 13 shows a comparison of the experimental and numerical porosity at a 3 foot drop height using the air pluviation sample preparation method. To measure the constitution of the particles in the numerical model, the final numerical porosity of the bottom, middle and the top of the mold is recorded as 0.406, 0.391, and 0.391 correspondingly, as shown in Table 2. The experimental porosity for a 3 foot drop height test is 0.367. The difference between these measurements may be associated to the lack of some micro-mechanical parameters of granular material that are required to further investigate. The difference between the values could be attributed to a difference in the flow rate of particles between the numerical model and lab procedures. Due to time constraints, there is only one numerical result presented in this work.

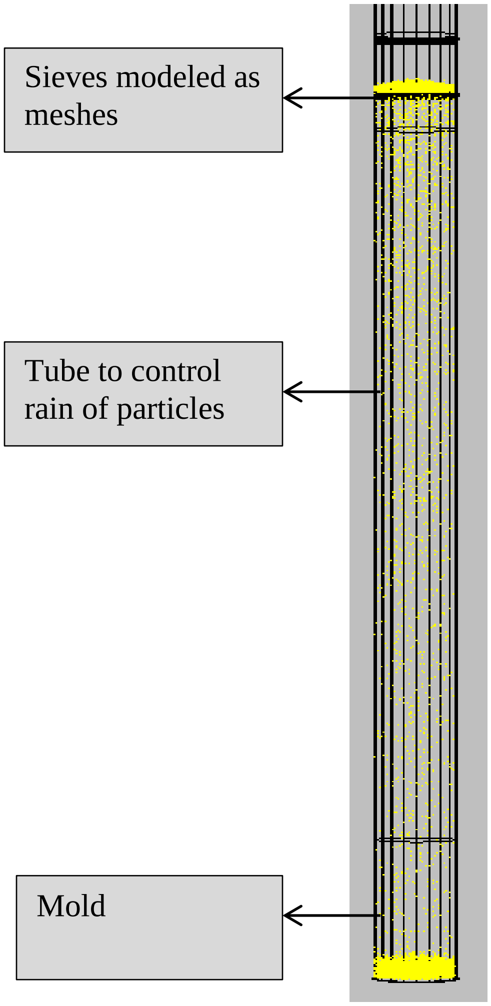


Figure 12. DEM Model for Dense Sample

Table 2. Porosity of Numerical Air Pluviation Model for 91.44 Centimeter (3ft) Tube

Time Step	Bottom Porosity	Middle Porosity	Top Porosity	Experimental Average Porosity
5.00E+05	0.866	1.000	0.999	0.367
1.00E+06	0.724	0.998	0.999	0.367
5.00E+06	0.394	0.608	0.992	0.367
1.00E+07	0.394	0.396	0.618	0.367
1.50E+07	0.406	0.391	0.393	0.367
2.00E+07	0.406	0.391	0.391	0.367

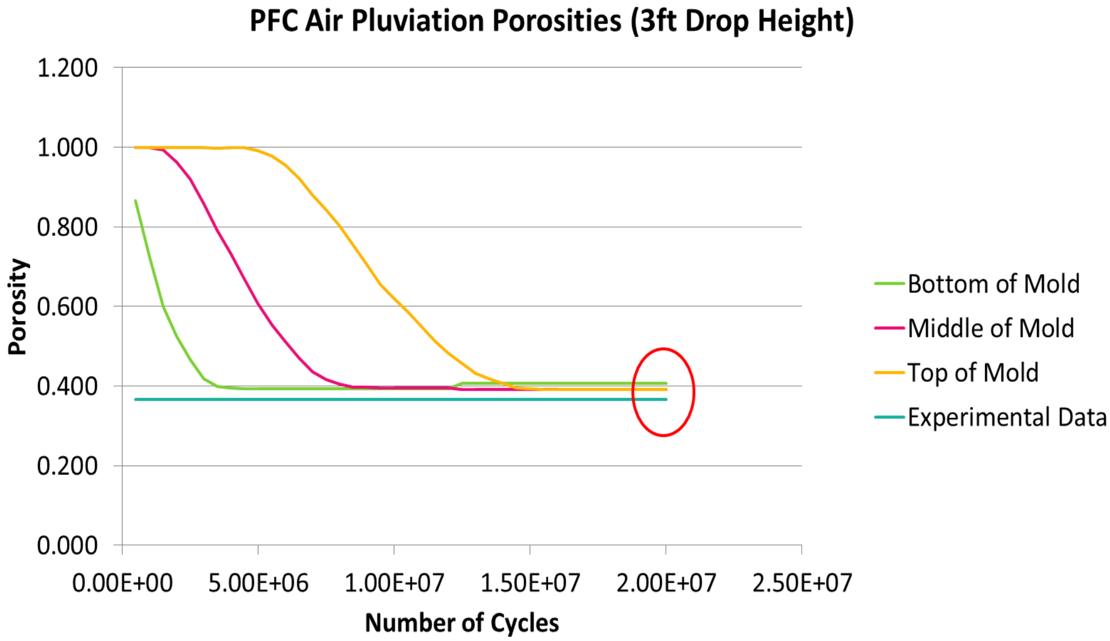


Figure 13. Comparison of Experimental and Numerical Porosity

CONCLUSIONS

A homogenous cylindrical specimen is built using both the dry funnel deposition and air pluviation methods. The experimental result shows that specimen weight relatively increases as drop height and pouring velocity increase. The loosest and densest specimen weight obtained from experiment is 2.534 kilograms and 2.675 kilograms respectively.

The image analysis demonstrates a 3D representation of the specimen to determine the homogeneity of dense samples. It can be observed from the slices of CT scan that localized heterogeneous material composition can be identified. Thus, the specimen is not perfectly homogenous. Further development of the image analysis should be conducted since sample heterogeneity is hypothesized to have a strong relation to the specimen's failure mechanism.

The PFC-3D model illustrating computational sample preparation methods replicates the dry funnel and air pluviation methods. The initial numerical result of the 3 feet drop height air pluviation sample preparation method is agreeable to the experimental sample preparation methods (Table 2). A future goal is to run the simulation for every drop height to compare the numerical porosity with the experimental porosity.

REFERENCES

[1] A. Song, Z. Medina-Cetina, and A. L. Rechenmacher, “Local Deformation Analysis of a Sand Specimen using 3D Digital Image Correlation for the Calibration of a Simple Elasto-Plastic Model,” Poster, 2012 *Geo-Congress: State of the Art and Practice in Geotechnical Engineering*, Oakland, CA, 2012.

[2] Y. B. Zhang, Z. Medina-Cetina, and H. D. V. Khoa, “Probabilistic Calibration of a Discrete Particle Model for Geomaterials,” in *Proceedings of the Geo-Frontiers Conference*, Dallas, TX, pp. 4204-4213, 2011.

[3] C. O’ Sullivan, “Micromechanics of Granular Materials Response during Load Reversal: Combined DEM and Experimental Study,” *Power Technology*, vol. 193, pp. 289-302, 2009.

[4] M. Bloom, M. J. Russel, A. Kustau, S. Mandayam, and B. Sukumaran, “Measurement of Porosity in Granular Particle Distributions Using Adaptive Thresholding,” *Instrumentation and Measurement, IEEE Transactions*, vol. 59, no. 5, pp. 1192-1199, May 2010.

[5] S. Yimsiri, and K. Soga, “Effects of Soil Fabric on Behavior of Granular Soil: Microscopic Modeling,” *Computers and Geotechnics*, vol. 38, no. 7, pp. 861-874, Nov. 2011.

[6] *Precision Ball Product Catalog*, Thomson, 2010. Available: http://www.thomsonprecisionball.com/images/pdfs/PrecisionBalls-9-26-08_loRes.pdf.

[7] ASTM Standard D4767, “Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soil*,”* ASTM International, West Conshohocken, PA, 2011, DOI: 10.1520/D4767-11, www.astm.org.

[8] R. S. Ladd, “Specimen Preparation and Liquefaction of Sands,” *Journal of Geotechnical Engineering*, vol.100, pp.1180-1184, 1974.

[9] F. M. Wood, J. A. Y., and P. V. Lade, "Effect of Depositional Method on the Undrained Repsonse of Silty Sand," *Canadian Geotechnical Journal*, pp.1525-1537, Nov. 2008.

[10] A. Cresswell, M. E. B., and R. Brown, “Determining the Maximum Porosity of Numerical Air Pluviation Model for 91.44 Centimeter (3ft) Tube Density of Sands by Pluviation,” *Geotechnical Testing Journal*, vol. 22, pp. 324-328, 1999.

[11] D. R. Sausus, D. F., and A. K. Ashmawy, "Variations in Membrane Contact Patterns of Reconstituted Sand Specimens," *Geotechnical Testing Journal*, vol. 23, pp. 522-531, 2000.

[12] National Instrument, *LabView*, 2012. Available: http://www.ni.com/labview.

[13] Itasca, *Particles Flow Code in Three Dimensions-PFC3D*, 2012. Available: http://www.itascacg.com/pfc3d.

[14] P. A. Cundall, and O. D. L. Strack, "A Discrete Numerical Model for Granular Assemblies," *Geotechnique*, vol. 29, pp.47-65, 1979.

[15] Itasca, "PFC3D 4.0 Manual," *Particles Flow Code in Three Dimensions-PFC3D*, 2012. Available: http://www.itascacg.com/pfc3d.

CONTACT INFORMATION

Name: Tam N. M. Duong

Professional Address: c/o Dr. Zenon Medina-Cetina
Department of Civil Engineering
Texas A&M University
College Station, TX 77843-3136

Email Address: m.tam91@gmail.com

Education: B.S., Civil Engineering, Texas A&M University, May 2013
Undergraduate Research Scholar
Chi Epsilon