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Preface

This Geotechnical Special Publication (GSP) contains 18 papers addressing a variety of current issues in the Unsaturated Soil, Seepage, and Environmental Geotechnics; Soi Behavior and Laboratory Testing. The technical programs for the GeoHubei International Conference struck a balance between the fundamental theories and field applications. These papers were presented at the GeoHubei International Conference held July 20-22, 2014, in Hubei, China. This GSP includes investigations and solutions from numerous countries. It expands ranges of tools that are available to engineers and scientists.

The following individuals have assisted in reviewing the papers: Marshall Addison, An Deng, Ceki Harman, G.T. Hong, Jeffrey Lee, Julie Q. Shang, Xianming Shi, Zhiming Si, Lubinda Walubita, Jingan Wang, Danny Xiao, Joey Yang, and Xiaoming Yang.

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Discrete Element Method Simulation of Granular Column Collapse

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ABSTRACT: Understanding of various natural phenomena and industrial processes such as landslides and bulk material handling requires research on the flow of granular materials. In this study, a 3-D numerical investigation of axisymmetric collapse of granular columns has been conducted using a commercial and research discrete element method (DEM) code. The simulated granular columns have an initial radius and height of 5.68 mm and 5.71 mm, respectively, rendering an initial aspect ratio (height/radius) of approximately 1.0. The columns consist of uniform spherical quartz particles with a diameter of 0.32 mm. The nonlinear particle-particle contact behavior and rotational resistance are indirectly accounted for in the DEM model. Comparison between the simulated final deposit morphology (e.g., final height and runout distance) with experimental results that are readily available in literature reveals the importance of rotational resistance in realistic simulations of granular column collapse.

INTRODUCTION

Better understanding of various important phenomena in nature (e.g., landslides) and in industry (e.g., bulk material handling) requires studying the flow of granular materials. Axisymmetric collapse of granular columns has been investigated in several experimental studies (e.g., Lube et al., 2004; Lajeunesse et al., 2004) using granular columns made up of different materials (e.g., sand and glass beads) with different aspect ratios $a = h_i/r_i$, where h_i and r_i are the initial height and radius of the granular column, respectively. The scope of these studies was to correlate the final height and runout distance of the final deposit to different factors such as properties of materials and experimental setup (e.g., aspect ratio and roughness of underlying surface).

It was observed that the final deposit morphology is dominated by the initial aspect ratio a. For $0 < a < 0.74$, a circular undisturbed region remains at the initial height; for $a > 0.74$, the final deposit takes a cone shape, which according to Lajeunesse et al. (2004) has a lower height than the initial height, while based on Lube et al. (2004) the cone preserves its original height up to $a = 1.7$ and then starts to decrease. The final runout distance based on Lube et al. (2004) depends only on the aspect ratio and initial radius and is independent of subsurface roughness. It was also noted that the inter-particle friction affects the flow pattern only in the last instant when the flow comes to an abrupt stop. On the other hand, Lajeunesse et al. (2004) stated that the grain properties and underlying surface properties play a significant role in the final deposit shape in high aspect ratios.

Several numerical simulations have been also conducted to reproduce the results of aforementioned experimental studies in both continuum and discrete element frameworks and to improve the understanding of the macro- and micro-scale behaviors of the granular flow. Chen and Qiu (2012) successfully used Smoothed Particle Hydrodynamics (SPH) method (Lucy 1977; Gingold and Monaghan, 1977) to simulate the global behavior of the flow within the continuum framework. Discrete element method (DEM, Cundall and Strack, 1979) was also utilized by many researchers (e.g., Staron and Hinch 2005 and 2007; Zenit, 2005; Cleary and Frank, 2006) to capture the discrete and micromechanical behaviors of the granular collapse.

This paper presents the results of a 3-D numerical simulation of the axisymmetric collapse of granular columns using a commercial and research DEM code, *PFC3D 4.0* (Particle Flow Code in three dimensions, Itasca 2008). The main focus is a parametric study to investigate the effect of particle rotational resistance on the final deposit morphology for a column with $a = 1.0$. In the following sections, a brief summary of the DEM model will first be presented, followed by the results of the parametric study.

DEM MODEL

Discrete Element Method (DEM) was originally proposed by Cundall and Strack (1979). In this Lagrangian method, the motion of individual particles is calculated by numerical integration of Newton's equations of motion. Contact forces are calculated based on particle overlaps using contact properties (e.g., stiffness, friction, and damping) (Itasca 2008; O'Sullivan, 2011). This section presents the DEM model used in this study.

Numerical Sample Preparation

The initial model was created by pouring 20,340 balls with a diameter of 0.32 mm into a cylindrical wall of radius r_i, and allowing the balls to settle under gravity. The column was then trimmed to achieve an initial model with radius and height of 5.68 mm and 5.71 mm, respectively, forming a specimen with $a \approx 1$. The porosity of the specimen was approximately 0.40. Fig. 1 presents the initial setup of a granular column. The cylindrical wall was then lifted with a constant velocity of 0.02 m/s to match the experimental conditions in Lube et al. (2004) and Lajeunesse et al. (2004) and then the packing was allowed to collapse over the bottom wall.

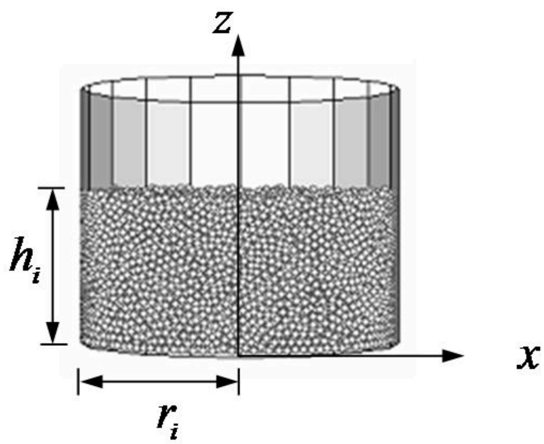

FIG. 1. Initial setup of a granular column.

Material Properties

Particles properties such as particle diameter (D), density (ρ_s), shear modulus (G), Poisson's ratio (ν), friction coefficient (μ), restitution parameters (e), and viscous damping coefficient (ξ) are summarized in Table 1. Value of e was assumed to be 0.75 (Zenit 2005) and was verified by several simple experiments conducted in this study by dropping a glass bead over various glass surfaces. The value of ξ at contact is then calculated as (Itasca 2008; O'Sullivan 2011)

$$\xi = \frac{-\ln(e)}{\sqrt{\ln^2(e) + \pi^2}} \tag{1}$$

Table 1. Material Properties used in DEM Simulation

D	ρ_s	G	ν	μ	e	ξ
0.32 mm	2650 Kg/cm^3	2.9E10 N/m^2	0.3	0.445	0.75	0.0912

Contact Stiffness

In *PFC3D* linear contact model and non-linear Hertz-Mindlin contact model can be considered to evaluate the inter-particle forces. The former is simple and computationally efficient, and is based on constant normal and tangential stiffness. The latter is widely accepted in geotechnical engineering and is an approximation of the theory of Mindlin and Deresiewicz (1953), which assumes the contact stiffness is dependent on the elastic properties of particles, overlap, and normal contact force. Due to the required computational effort, in this study a hybrid approach similar to the work of Teufelsbauer et al. (2009) was utilized, where the linear model is used for the main simulations but the contact stiffness values are calibrated based on the Hertz–Mindlin model.

The value of secant normal (k_n) and secant shear contact stiffness (k_s) between two identical spherical particles can be evaluated by (Mindlin and Deresiewicz 1953; and Itasca 2008)

$$k_n = \frac{2G \times \sqrt{2R}}{3 \times (1-\nu)} u^{\frac{1}{2}} \tag{2}$$

$$k_s = \frac{4\left[3G^2(1-\nu)R\right]^{\frac{1}{3}}}{3(2-\nu)} F_n^{\frac{1}{3}} \tag{3}$$

where R is radius of the particles; u is particle-particle overlap; and F_n is the normal contact force and can be calculated as

$$F_n = \frac{2G \times \sqrt{2R}}{3 \times (1-\nu)} u^{\frac{3}{2}} \tag{4}$$

According to Eqs. (2) through (4), in order to calculate k_n and k_s, value of u is required. This value varies within the model during the collapse. However, for computational efficiency, one average value for u is selected during the initial, intermediate and final stages of collapse based on the Hertz-Mindlin model. The obtained equivalent k_n and k_s values were later used in the linear model for the parametric study. Therefore, the proposed hybrid approach indirectly accounts for the nonlinear contact behavior and is computationally efficient. The particles in contact are acting in series; hence the ball stiffness should be taken as twice the ball-ball contact stiffness (Itasca 2008). The wall stiffness can be similarly determined based on the average ball-wall overlap, ball-wall contact stiffness, and ball stiffness. The obtained average values of u, k_n and k_s for granular column with aspect ratios of 1.0 are presented in Table 2.

Table 2. Equivalent Normal and Shear Stiffness

For balls			For walls		
u (m)	$k_n (N/m)$	$k_s (N/m)$	u (m)	$k_n (N/m)$	$k_s (N/m)$
3.07E-10	17000	14000	2.70E-10	15000	12500

Rotational Resistance

In order to consider the effect of particle shape and hysteretic behavior at contacts (e.g., micro-sliding, visco-elasticity, and plasticity), rotational resistance should be applied in DEM simulations (Wensrich and Katterfeld, 2012). This factor can be considered by either implementing resisting moments on contacting particles (e.g., Zhou et al., 1999; Wensrich and Katterfeld, 2012; Liu et al., 2012) or directly reducing the angular velocity of particles (e.g., Teufelsbauer et al., 2009). In this study, the method proposed by Teufelsbauer et al. (2009) was simplified and used to reduce the angular velocity (ω) of a particle by a constant factor. For the simulations conducted by Teufelsbauer et al. (2009), this factor was approximately 0.99. A parametric study is conducted to investigate the effect of the rotational resistance on the final height and runout distance of the granular column. Three values of the angular-velocity reduction factor: 0.99, 0.95 and 0.90 are considered, which are intended to include varying degrees of rotational resistance arising from the effect of particle shape, particle size distribution, and different test conditions between the experiments of Lube et al. (2004), Lajeunesse et al. (2004), and Teufelsbauer et al. (2009).

RESULTS AND DISCUSSIONS

During these simulations, the deposit height was continuously monitored. The final profile was achieved when the deposit height became relatively constant as shown in Fig. 2. Fig. 3 presents the final deposit profile for a typical simulation, showing the final height h_∞ and final run out distance r_∞.

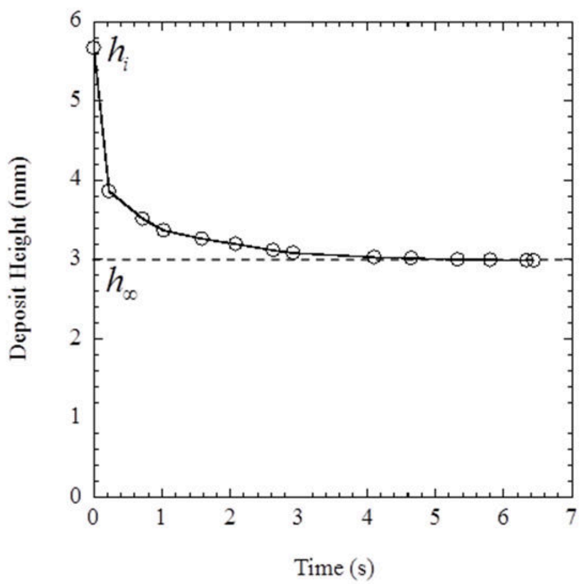

FIG. 2. Deposit height versus time.

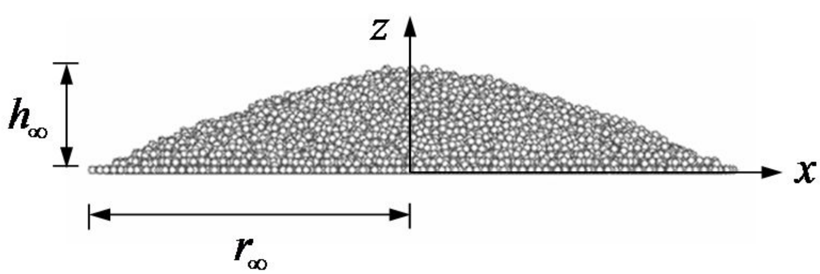

FIG. 3. Final deposit profile.