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Packing of cylindrical particles: DEM simulations and experimental measurements

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ABSTRACT

In order to achieve efficient particle packing, minimizing the space of occupation and maximizing the strength of packing, it is important to understand the best methods of fill and the effects of various particle properties, including particle shape. In this study, the packing behavior of cylindrical particles is studied via both Discrete Element Method (DEM) simulations and complementary experiments. The effects of coefficient of friction, coefficient of restitution, drop height, fill height, packing method, deposition intensity (number of particles deposited per second), container size, surface roughness, and Young's modulus are investigated. In addition, two methods of packing density analysis from DEM simulations - a center of particle method and a top grid analysis method - are introduced. It is found that the packing density increases with fill height, container diameter, coefficient of restitution and drop height and decreases with coefficient of friction, surface roughness and Young's modulus. Different packing methods are explored, and it is found that the most efficient packing scheme is to pouring particles over the whole cross-section with low deposition intensity and at a variable drop height. Finally, DEM simulation predictions for particle packing of cylinders show good agreement with experimental measurements.

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1. Introduction

Particle packing has long been a topic of interest for many theorists and experimentalists because of its importance in everyday life and in industrial processes. Tableting in pharmaceutical industries, filling up silos in storage plants, packing of fluidized beds and soil strength are just a few examples of different applications of particle packing. Understanding the parameters affecting particle packing is crucial for the achievement of the densest packing, which minimizes the space of occupation and maximizes the strength of a bulk granular material.

The packing of uniform sized spheres has been the most widely studied topic in the area of particle packing. Random packing of spheres lies between two well-defined limits: random loose packing (~0.59–0.60) and random dense packing (~0.64–0.65). To obtain random dense packing, particles are poured into a rigid container, followed by gentle vibration or shaking of the container [1,2]. The packing density of the particles is also dependent on the diameter of the container; the overall porosity decreases with increases in the spherical particle to container size ratio [3,4]. In addition, Macrae and Gray [3] studied the effects of material properties, fill height and drop height. They reported that packing density increases with coefficient of restitution and fill height and decreases with coefficient of friction and deposition intensity. In addition, they found that when spherical particles are dropped from a fixed drop height, which is a variable effective drop height with respect to the top surface of the particle bed, this leads to inefficient particle packing compare to a variable drop height in which the distance between the top surface of the particle bed and the drop height is kept constant.

In recent years, researchers have become interested in the packing behavior of non-spherical particles. Studies focusing on the packing of non-spherical particles report similar trends of wall effects on packing density. Dixon [4], Zou and Yu [5] and Foumeny and Roshani [6] developed relationships for wall effects and porosity of cylindrical particles. The packing density of non-spherical particles is also strongly affected by particle shape. Zou and Yu [7] formulated porosity – particle shape relationships for non-spherical particles. Studies dealing with non-spherical particles such as oblate spheroids showed an increase in packing density as the particle shape deviated from perfect spheres because of the increase in the number of contacts between the particles [8,9]. However, the random packing of non-spherical particles such as fibers/rods with high aspect ratio ($l_p/d_p > 10$) [10] results in lower packing density than spherical or other compact non-spherical particles [11]. In case of particles such as cylinders, there is limited research as compared to spherical particles. Since the geometry of a cylindrical particle

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contains flat and curved surfaces, it tends to give a more diverse packing density range. The packing density range for cylindrical particles have been found to be very wide (0.36–0.68) in previous work [4,6,7,12]. This packing range is also greatly affected by the treatment after/during packing. As a result of vibrations, for example, cylindrical particles start aligning vertically at the wall [13] leading to higher packing density. It has also been observed that an increase in fill height results in an increase in packing density [5]. Once a critical fill height H is reached, a constant packing density is achieved. Foumeny and Roshani [6] concluded that this effect can be neglected if the fill height to container diameter D ratio is >3.

Particle packing density has also been the topic of various simulation studies; in most cases, researchers have assumed particles to be in spherical shape. For example, Zhang et al. [14] presented a discrete element method (DEM) simulation study for spheres showing that packing density increases with drop height and coefficient of restitution and decreases with an increase in deposition intensity and friction coefficient. In addition, packing methods for spherical particles have been investigated such as pouring particles under gravity (i.e. loose packing) [15, 16], compressing the particles [17,18] and vibrating after depositing the particles (i.e. dense packing) [19,20].

However due to the strong effect of particle shape on the packing characteristics of materials, simulations of non-spherical particles have been studied more recently. The Monte Carlo method has been used to determine the influence of particle shape on the packing and segregation of a binary mixture of sphero-cylinders [9]. In the work of Williams and Philpse [21], it was shown that slightly elongated particles exhibit an increase in packing density from spheres and further increase in aspect ratio results in lower packing densities. Wouterse et al. [22] compared the packing behavior of spheroids and sphero-cylinders and demonstrated that spheroids show slightly higher packing density than sphero-cylinders. In addition, a digital packing algorithm which maps particles onto a grid was used by Gan et al. [23] to investigate the packing behavior of sphero-cylinders and the results were found to be in good agreement with previous researchers [9,21,22].

Different packing methods and their effects on packing density has been much less studied – particularly for non-spherical particles. Hence, this is the topic of the present study for a cylindrical particle shape. Specifically, the effect of fill height, fill method, and drop height on particle packing are investigated experimentally. Another aim of this paper is to present the effect of simulation variables and material properties on the predicted particle packing of cylindrical particles using DEM simulations and to compare packing predictions with experimental measurements. Simulation conditions such as the use of glued-sphere particles to represent an actual cylindrical particle and the choice of particle-particle contact model are also studied.

2. Experimental methods

In the packing experiments, uniform-shaped acrylic cylindrical particles were used with intrinsic particle density 1165 kg/m^3. The particles were of length (L_p) and diameter (d_p) 0.0340 m and 0.00635 m, respectively, (aspect ratio 5.35 and equivalent volume diameter d_v 0.0127 m) and filled cylindrical acrylic containers of diameters (D) 0.12 m, 0.16 m, 0.19 m, 0.25 m and 0.29 m, each of height 0.60 m. Packing experiments with larger acrylic cylindrical particles with the same aspect ratio (5.35) and intrinsic particle density (1165 kg/m^3) were used for the comparison with the predicted particle packing from the DEM simulations. This second set of acrylic cylindrical particles had length (L_p) and diameter (d_p) 0.0425 m and 0.00794 m, respectively, and filled the cylindrical acrylic container of diameter 0.120 m. The coefficient of restitution (0.83) for the acrylic particles was measured using a normal rebound drop test involving a high-speed camera. The coefficient of friction (0.21) was measured using a ramp and measuring its inclination. Acrylic particles were glued on two surfaces – the inclined ramp and another plank kept on top of the ramp - and the angle was measured at which the top plank started sliding on the ramp.

Eight different packing methods were employed to create the loose, random packed particle bed in the experiments:

(1) Particles of varying orientation were dropped one by one from a fixed height 0.6 m above the base of the cylindrical container and were dropped at the center of the container.
(2) Groups of particles were dropped 8–10 at a time from a fixed height 0.6 m above the base of the cylindrical container and were dropped at the center of the container.
(3) Groups of particles were dropped 8–10 at a time from a fixed height 0.6 m above the base of the cylinder. Each bunch of 8–10 particles was dropped at a different location over the cross-section.
(4) Groups of particles were dropped 8–10 at a time at the center of the container. The drop height varied such that the distance between the top surface of the particle bed and the drop height was kept constant at 0.6 m.
(5) Groups of 100 particles each were poured from a large cup at the center of the container from a fixed height 0.6 m above the base of the cylinder.
(6) Groups of 100 particles each were poured from a large cup at a different location over the cross-section from a fixed height 0.6 m above the base of the cylinder.
(7) Particles were poured continuously via a large bucket at the center of the container from a fixed height 0.6 m above the base of the cylinder.
(8) Particles were poured continuously via a large bucket over the entire cross-section from a fixed height 0.6 m above the base of the cylinder.

All packing experiments were repeated five to six times. The resulting packing density in the experiments was determined using the image analysis method (discussed in Section 5). Error bars show one standard deviation from the average value of the repetitions of the same experiment.

3. DEM particle representation and contact models

Simulations of particle packing of cylindrical particles were performed using the discrete element method (DEM) technique. In DEM, the dynamics of discrete particles is modeled and the overall system behavior is determined as a result of individual particle interactions. The trajectories of individual particles are tracked such that the translational and rotational displacements of each particle are incremented at fixed time steps. The motion of particles is determined by integrating equations governed by Newton's second law of motion. The net force acting on an individual particle i comprises of two forces: a gravitational force $m_i g$ and a particle - particle contact force F_{ci}. The translational and rotational motion of particle i is governed by following equations:

$$m_i \cdot \frac{dv_i}{dt} = F_{ci} + m_i g \quad (1)$$

$$I_i \cdot \frac{d\omega_i}{dt} - (I_i \cdot \omega_i) \times \omega_i = T_i \quad (2)$$

where m_i is the mass, I_i is the moment of inertia matrix, v_i and ω_i are the translational and angular velocities, respectively, of the particle i. T_i is the torque, which is generated due to both tangential and normal contact forces for the non-spherical particles.

Explicit time integration of these equations using a central finite difference scheme with fixed time step Δt gives new positions and velocities of individual particles. From these values of the individual particles, new particle – particle forces can be calculated. DEM particles are

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