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Discrete element modelling and experimental validation for the falling process of dry granular steps

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ABSTRACT

This paper presents an experimental validation of discrete element method (DEM) simulation for falling process of dry granular steps. Three chute slopes were considered in the study. The corresponding physical experiments were carried out in our previous study. The DEM simulations matched well with the experimental results regarding the external flow characteristics such as flow regimes, surface profiles, final deposit angles, velocity profiles at the sidewall, receding upper granular surfaces and flow rates. Subsequently, the DEM simulations were used to explore the internal flow patterns of the granular collapse, including translational velocity profiles and angular velocity profiles inside the granular assembly. According to the DEM simulation results, a mixed velocity profile (an upper convex and lower concave profile) appears in the central part of the chute, whilst the velocity profile follows a sidewall-stabilized heap (SSH) rheology (a concave profile) near the sidewall. The chute inclination facilitates the transformation from the SSH rheology to the mixed velocity profile in a narrow channel. The DEM simulations not only verify the experimental observation but also enhance the understanding of flow patterns induced by the collapse of dry granular steps.

1. Introduction

The collapse of a granular column is a simple experiment, but aesthetically exhibits many interesting phenomena and successfully provides geophysical and astrophysical applications. Lube et al. [1] explored the dynamics of static and flowing regions by the collapse of rectangular columns of sand into a wide horizontal channel. The growth rate of the static area is independent of the initial height in the free-fall phase, whereas the static area increases linearly with time and depends on the height-width aspect ratio in the later spreading phase. The non-dimensional deposition rate is a linear function of the aspect ratio. Balmforth and Kerswell [2] experimentally investigated the collapse of granular columns inside rectangular channels with four different granular media. The power laws properly describe the relationship between the final deposit and the initial aspect ratio, and their proportionality coefficients are affected by the sidewalls and the frictional properties of granular material. Lajeunesse et al. [3] conducted the experimental study on the collapse of a glass-bead column over a horizontal surface. The velocity measured at the sidewall varies linearly with depth in the flowing layer and decreases exponentially with depth near the static layer. Lacaze et al. [4] performed a quasi 2D collapse test of granular column and a discrete element simulation to study the flow behaviour of polypropylene spheres over a horizontal substrate. A predominantly linear velocity profile was found in the moving layer over an evolving static pile, and the runout distance increases with the increasing aspect ratio in a power-law relation. Staron and Hinch [5] presented 2D discrete element simulations of the collapse and spreading of circular disk columns onto a horizontal plane. The final shape of the deposit depends only on the initial aspect ratio of the column. The normalized runout distance versus the aspect ratio also follows a power-law relation.

Due to the limitation of measurement technology, most experimental studies focused on external flow behaviours of granular collapse. Consequently, the internal flow characteristics are by far still inadequately understood. On the other hand, the Discrete Element Method (DEM) [6–9] has been a promising tool to examine the internal physical quantities, while the careful experimental validations of DEM simulation are less reported. This paper presents a 3D DEM simulation for the falling process of dry granular steps. Our research rationale is as follows: the DEM simulation is first validated with the corresponding experimental results, and is then used to probe the internal flow characteristics of granular collapse. To achieve a quantitative validation, the particle properties required for DEM simulation were not just given, but measured from our developed laboratory testers. Several important modelling aspects regarding the DEM simulation, such as the contact force model, critical time step, particle generation and input parameters, were carefully defined. The external flow characteristics of granular steps during collapse, including flow regime, surface profile, final deposit angle, velocity profile at the sidewall, receding upper granular surface and flow rate, were analyzed. The comparison between the DEM simulation and experimental results was

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made and discussed. The internal flow characteristics, such as translational velocity profile and angular velocity profile inside the granular assembly, were also analyzed in this paper.

2. Description of the systems

2.1. Physical model and discrete element modelling

The physical model of dry granular steps filled in an inclined chute subjected to sudden lateral collapse is schematically shown in Fig. 1. The model is established to study the flow behaviour of granular materials during avalanche. The chute has a length of Li, a height of H and a width of W, which is inclined at θ from the horizontal. The granular materials used in this study were white spherical polystyrene beads. The discrete element method (DEM) with soft contact approach was used to model the granular assembly in this study. The theory of the DEM can be found elsewhere *e.g.* Cundall and Strack [10] and will not be elaborated here. Several important modelling features however need to be clarified below, including the contact force model, critical time step, particle generation and input parameters.

The simplified Hertz–Mindlin contact force model (HM visco-elastic contact force model) (Tsuji et al. [11]), as shown schematically in Fig. 2, was adopted in this study. This contact force model has a non-linear spring, a non-linear dashpot and a frictional slider in the tangential direction as well as a non-linear spring and a non-linear dashpot in the normal direction. The particulate system energy is dissipated through contact friction and contact damping. The tangential contact force is limited by the Coulomb friction law and some energy is always dissipated in overcoming friction. Contact damping operates on the relative velocities at the contacts and is modelled as dashpots acting in the normal and tangential directions. The damping ratio is related to the coefficient of restitution. The required parameters for this contact force model are the Poisson's ratio ν, Young's modulus E (or shear modulus: $G=E/2(1+\nu)$), particle-surface and inter-particle friction coefficients (μ_w, μ_p), and particle-surface and inter-particle restitution coefficients (e_w, e_p). A multiplier of 0.20 was applied to the Rayleigh critical time step [12] for all DEM simulations. This value was found to be sufficient to achieve numerical stability without excessive computational cost [13,14].

The polystyrene beads were randomly generated inside the space of the chute. They were all assigned an initial zero velocity and then allowed to fall under gravity to achieve the initial filled state. The particles were deemed to have settled down when the kinetic energy of the system approached zero ($<10^{-8}$ J) and the mean unbalanced force approached zero ($<10^{-6}$ N), compared to a polystyrene bead weight of 2.1×10^{-3} N. After achieving the filled state, three numerical samples were prepared as follows: one was for the chute slope with $\theta=0°$, and the other two were respectively for the chute slope with $\theta=5°$ and $\theta=10°$. In the latter two samples, the whole chute was rotated about the right-bottom corner of the chute with a very slow angular speed, which prevented disturbing the packing structure. The granular avalanche down a chute was simulated by quickly removing the right wall of the chute.

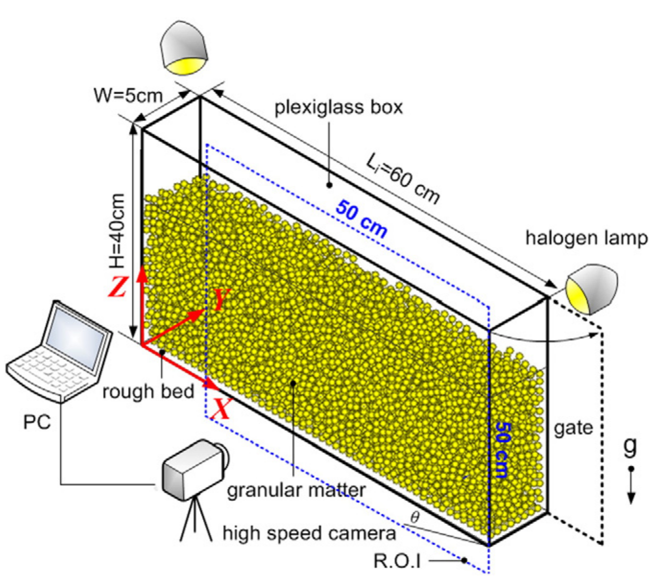

Fig. 1. Physical model and experimental setup for falling tests of dry granular steps.

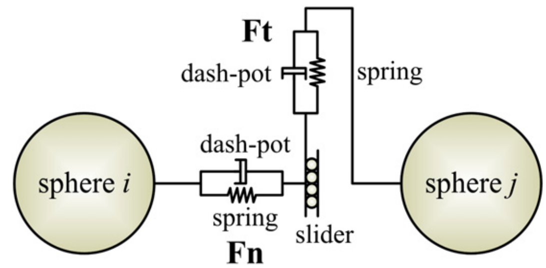

Fig. 2. Simplified Hertz-Mindlin contact force model (cited from [13]).

The DEM simulations were performed using the PFC3D code (Itasca 2010) [15], which successfully passes a set of benchmark tests at particle impact level [16] and gives confidence in modelling the particulate systems composed of tens of thousands of particles. The DEM input parameters for the polystyrene beads are listed in Table 1. To achieve a quantitative validation, the key particle properties (friction coefficient and coefficient of restitution) required for DEM simulation were not simply assumed but measured directly, which will be described in 2.2 Experimental setup. The values for the diameter, density, Young's modulus and Poisson's ratio were taken from the manufacturer in this study. The number of particles was calculated to produce a very close match with the physical experiments. The DEM simulations in this study assumed mono-dispersed particles although small particle size variation did exist in the physical experiments.

2.2. Experimental setup

The falling tests of dry granular steps have been performed in our previous study [17] and the experimental features are briefly reviewed here. The falling test setup, as also shown in Fig. 1, was devised to study the flow behaviour of granular materials subjected to sudden lateral collapse. The experimental system consisted of a rotatable chute, a high speed camera, two halogen lamps and a personal computer. The rectangular chute was made of transparent acrylic plates for visualization purpose and its length, height and width are 60 cm, 40 cm and 5 cm respectively. The chute can be rotated to the prescribed inclination angle (θ). Three chute slopes (i.e. 0°, 5° and 10°) were selected to study the influence of inclination angle on the falling process. The CCD camera was IDT MotionPro X3 PLUS with 8 GB RAM and equipped with a 50 mm Nikkor (f/1.4) lens.

Table 1
DEM input parameters for polystyrene beads.

Properties	Mean value	CoV (%)	Unit
Diameter (d)	5.8 ± 0.1		mm
Density (ρ)	2100		kg/m^3
Young's modulus (E)	3.25		GPa
Poisson's ratio (ν)	0.34		
Number of polystyrene beads ($\theta=0°$ and 5°)	9000		
Number of polystyrene beads ($\theta=10°$)	12000		
Bead-wall static friction coefficient (μ_w)	0.43	8.3	
Bead-bead static friction coefficient (μ_p)	0.38	7.9	
Bead-wall restitution coefficient (e_w)	0.66	7.6	
Bead-bead Restitution Coefficient (e_p)	0.69	7.2	