Powder Technology 297 (2016) 144–152

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Numerical study of gravity-driven dense granular flows on flow behavior characterization

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ARTICLE INFO

Article history:
Received 14 August 2015
Received in revised form 2 February 2016
Accepted 4 April 2016
Available online 9 April 2016

Keywords:
Dense granular flow
Gravity-driven
Flow regime
Statistical criterion
Discrete element method
High temperature gas-cooled reactor

ABSTRACT

A wide range of gravity-driven dense granular flows are studied numerically by using the discrete element method and statistical analysis. Intermittency and avalanche phenomenon of slow granular flows are illustrated clearly. Through analyzing time-energy data of flows with different velocities, the transformation of flow behavior from quasi-static to kinetic regimes is observed. More importantly, a general statistical rule on time-energy distribution of dense granular system under gravity is suggested. Based on this rule, the gravity-driven dense granular flows can be characterized quantitatively and categorized into three sub-regimes according to their primary features.

1. Introduction

Gravity-driven dense granular flow is prevalent in various industrial applications. Hoppers, silos and reactors adopted in agriculture and chemical industry utilize this efficient, economical and reliable flow to make the production process easy. However, due to its different features from common fluid flows and its complicated behavior, the gravity-driven dense granular flow is yet to be understood. Over the past 20 years, in addition to some specific experimental studies [27,31,36,45], the discrete element method (DEM) [3,7,10] has been widely adopted to better understand granular flows. The DEM method has been employed to investigate various industrial applications, including hopper and silo facilities [11,19,22,28,44], where the simulation results show good quantitative agreement with industrial data. DEM modeling has been also carried out to investigate some of the complicated characteristics of granular materials [14], like non-spherical particles [9,16,17,34], particle cohesion [1], particle deformation [18], dense random packing mechanism [43], and granular mixing [8,25]. These studies help to improve the design and efficiency of granular systems. For instance, it is found out stagnant regions appearing in silos should be reduced to maintain flow uniformity [21]; the particle-arches study [15] helps to predict hopper-discharge flow rate [29] and explain flow-rate fluctuation [35]; silo quake and silo music during particle-discharging are studied to prevent silo failure [27,37]; and friction effect is verified to be one of the critical factors which can determine flow patterns in silos [12,41]. In order to guarantee the desired uniform flow pattern in a silo, applying flow-corrective insert [38], modifying hopper configuration [13], and sensibly reducing particle-wall friction are adopted.

Gravity-driven dense granular flow is a special form of flow that lies between static solids and continuous fluids. The complexity of such flow comes from random particle behavior and intense particle–particle interactions. Although gravity-driven dense granular flow is widely utilized, there are limited studies that describe its characteristics. Moreover, the underlying physics is not comprehensively investigated.

Although gravity-driven dense granular flows are common and useful flows in modern industry and natural world, they only represent a part of flow regimes of granular materials. According to Campbell's studies [4–6], granular flows can be divided into two global regimes, elastic and inertial. The elastic regime is dominated by force chains and is divided into the elastic-quasi-static regime and the elastic-inertial regime depending on whether there is a noticeable dependence of the stresses on the shear rate. The inertial regime, which is free of force chains and has stresses that scale with the square of the shear rate, can be divided into the inertial-non-collisional regime and the inertial–collisional (or rapid-flow) regime depending on whether the dominant particle interaction is binary collisions. Moreover, Campbell also introduced a dimensionless parameter that governs the ratio of elastic to inertial effects that is defined by $k^* = k/(\rho d^3 \gamma^2)$; where $k, \rho, d,$ and γ represent inter-particle stiffness, solid density, particle

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http://dx.doi.org/10.1016/j.powtec.2016.04.002
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diameter and shear rate, respectively. By setting solid concentration v and dimensionless stiffness k^* as y-coordinate and x-coordinate, Campbell drew a complete flow map for flow of granular materials (refer to Fig. 1). An important conclusion can be drown from the flow map. At solid concentrations v larger than 0.6, one cannot leave the elastic regimes by changing k^* (usually by changing shear rate γ), and can only have transition between elastic–quasi-static and elastic–inertial regimes. Furthermore, out of a laboratory environment, it is difficult to reach elastic–inertial regime at high solid concentration, because it mostly asks for extremely large shear rate. Therefore, at high solid concentrations, the elastic–quasi-static regime which covers the common useful gravity-driven dense granular flow needs to be investigated.

However, the current flow regime division is not detailed enough and does not consider some of the distinct flow behaviors within the elastic–quasi-static regime. For instance, dry and powder-like materials in an hourglass can smoothly flow similar to liquids, but the gravity-driven dense pebble flow in high temperature gas-cooled reactor (HTGR) [23,32,42] in nuclear engineering behaves differently with apparent flow discontinuity [39]. HTGR is regarded as a promising candidate of generation IV [24,30] advanced nuclear systems for its excellent inherent safety. HTGR adopts the configuration of pebble bed reactor whose core is composed of randomly packed graphite-coated fuel pebbles. When a pebble bed reactor runs in a circulating way, new pebbles are loaded from top of the core and used pebbles are discharged from the bottom at the same rate, hundreds of thousands of fuel pebbles move downward under gravity with a very small velocity around 1.0×10^{-4}–1.0×10^{-3} m/h. This forms the special very slow granular flow in pebble bed reactors. Due to the very small average velocity, the overall flow shows a significant intermittence. For most of the time, the system is static, but the static state is disrupted by different sizes of pebble avalanches at random times and locations.

One of the applications of the slow dense granular flow is the pebble flow in HTGR which shows the importance of more detailed investigation on such flow. Therefore, this work aims to further describe gravity-driven dense granular flow by studying its major flow regime characteristics through numerical simulations. The phenomena of pebble avalanche and flow intermittence are illustrated in detail. A new general statistical criterion on time-energy distribution of gravity-driven dense granular flow is proposed to subdivide the elastic-quasi-static regime, which may help to characterize dense granular flows under gravity.

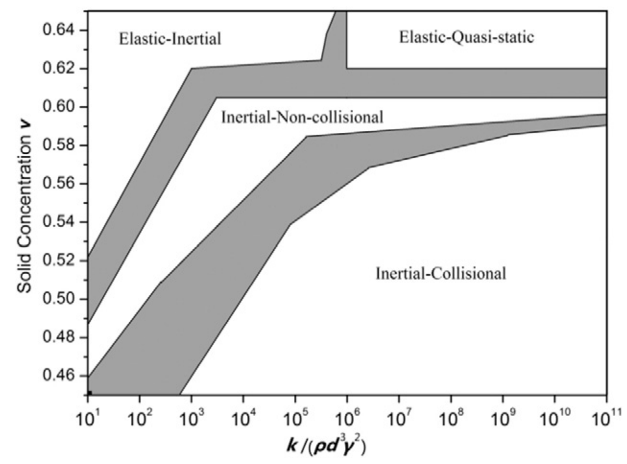

Fig. 1. Campbell's flow map of granular materials (particle surface friction $\boldsymbol{\mu} = 0.1$).

2. Numerical description

2.1. Discrete element method

In discrete element method (DEM), granular materials are discretized to a collection of unique “discrete elements” [7,10]. This numerical method is widely utilized for simulation of granular dynamics [20,25,26]. Each particle is traced deterministically by the Newton's law of motion, and interactions between particles are governed by contact models. In general, the governing equations of each particle are shown as follows:

$$m_i \frac{dV_i}{dt} = \sum_{j=1}^{n} F_{ji}^C + F_i^e + F_i^g \tag{1}$$

$$I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{n} r_{ij} \times F_{ji}^C + M_i^e \tag{2}$$

where m_i, I_i, V_i and ω_i are the mass, moment of inertia, translational and rotational velocities of element ‘i’, respectively. F_{ji}^C is the contact force from element ‘j’ to ‘i’. F_i^e and M_i^e are respectively the force and moment from the environment (not considered here). F_i^g is the gravity force and r_{ij} is the vector pointing from element ‘i’ to ‘j’.

The contact force F_{ji}^C can be decomposed into two parts: the normal contact force F_{ji}^{cn} and the tangential force F_{ji}^{ct}, which are given as follows:

$$F_{ji}^{cn} = -k_n \cdot \Delta u_{ij}^n + \beta_n \cdot V_{ji}^n \tag{3}$$

$$F_{ji}^{ct} = -k_t \cdot \Delta u_{ij}^t + \beta_t \cdot V_{ji}^t \tag{4}$$

$$\left| F_{ji}^{ct} \right|_{\max} \le \mu \left| F_{ji}^{cn} \right| \tag{5}$$

where k and β represent the stiffness and damping coefficients; μ is the friction coefficient; Δu_{ij} represents the deformation, and V_{ji} represents the relative velocity of two contacting particles. ‘n’ and ‘t’ denote the normal and tangential components respectively. Fig. 2 is the sketch of contact forces acting on each particle based on the most widely adopted soft-sphere contact model (spring-slider model), which is also utilized in our simulations. Spring and slider are used to simulate normal and

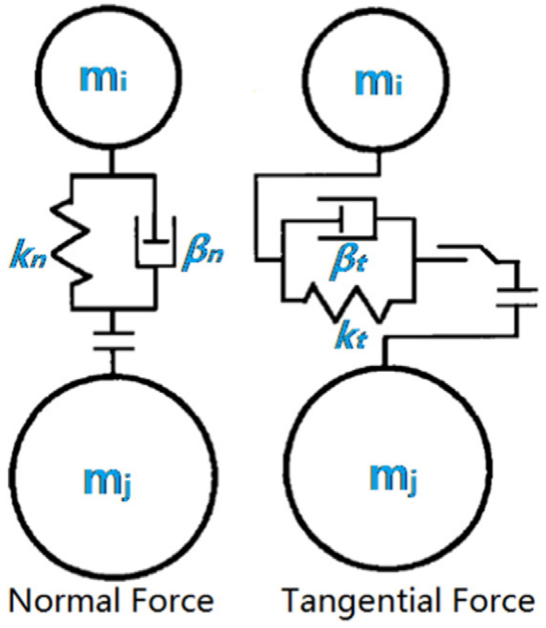

Fig. 2. Spring–slider contact model in DEM simulation.