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Flow characteristics and stresses on cylindrical objects immersed in a flow of inelastic hard disks

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ABSTRACT

Granular flows have some applications in industry and nature which can be described and modeled similarly. Debris flow, snow avalanches and landslide are examples of natural events along with silos, hoppers and fluidized beds as industrial cases where flows of grains usually encounter with solid objects. In this paper, cylindrical objects of different radii with controllable surface roughness are exposed to a stream of inelastic hard disks in the absence or presence of gravity. A granular shock wave is developed around the solid object whose features are dependent of different geometric and physical parameters. In simulations, the event-driven algorithm has been used with binary inelastic collisions. The surface of cylindrical object is either smooth or covered by hard disks as the same ones in the main stream. Stresses due to successive collisions are calculated in normal and tangential directions at the surface of cylindrical object. Voronoi tessellation is performed to visualize the packing density in particle level. Results revealed that the coefficient of restitution has considerable effect on the features of granular shock wave where gravity displayed mild influence. However, the presence of gravitational acceleration raises the stress with a quadratic function though the ratio of stress and the flow pattern reaches to steady state fairly quickly. The surface roughness in the same order as the flow particles size yields a double amount for stresses in comparison to a perfectly smooth surface. The smaller object size was also found to tolerate larger force fluctuations with a weaker quality of flow branching. For local stresses, the peak value of fluctuations can reach 5 times greater than its mean.

1. Introduction

Granular materials consist of solid grains interacting only through surface to surface contacts or collisions. Numerous studies have been made on the physics of granular materials that is a strange state of matter with multiple behaviors similar to solids, liquids and gases under different circumstances [1]. Beside pure scientific views of granular flow practical applications are also demanded. In this context, the confrontation of solid objects with stream of grains has significant practical outcomes. For example, circular pipes for heat transfer purposes are immersed in fluidized beds in contact to solid grains [2]. The pattern of granular flow around the pipe substantially controls the efficiency of heat transfer. In addition, the quality of the surface of the pipe such as its roughness can alter the residence time of grains near the pipe surface as well as the shear stress over the pipe. Hence, highly-roughened surface may increase the residence time of grains in favor of heat transfer between the pipe and granular stream. As another practical application, insertion of a series of fixed solid obstacles in the granular stream can prevent flow problems of jamming and arching [3]. Such obstacles also facilitate mixing of grains which is tremendously needed in handling and processing of powders in industrial plants. Amarouchene et al. [4] performed classic experiments for two-dimensional granular flows around obstacles with different shapes. They observed shock waves developed in upstream of obstacles. The anatomy of the sand dune was explained using particle tracking method, where a parabolic shape was observed around the obstacle with a triangular core of non-flowing or slowly-creeping sand. They observed a nonlinear velocity profile between the triangle and the parabola. Granular flows around obstacles display complex behaviors manifested as specific flow pattern with dense regions within the shock wave while behind the obstacle could be empty (particulate vacuum). The high rates of energy dissipation and the connection of the constitutive equations to various properties of grains and other flow parameters explain the source of great discrepancies between the behavior of granular flows and the ordinary fluid flows. Therefore, the role of experiments is very critical in understanding the influence of different parameters. On the other hand, experiments may not be able to reveal the details as much as needed. Thus computer simulations have been considered as an effective alternative to study the detailed behavior of the granular flow.

Computer simulations were performed before [5] and after [6, 7] the experiments of Amarouchene et al., in which the formation of triangular core in the upstream of the obstacle was neither observed nor reported. In fact, the anatomy of the dune was not specifically

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Nomenclature

d_p	Particle diameter
D	Object diameter
e	Coefficient of restitution (COR)
e_0	Reference value of COR
$\mathbf{g}$	Gravitational acceleration
H	Width of stream
$\mathbf{J}$	Impulse
$\mathbf{k}$	Unit vector along centerline
L	Length of stream
m	Mass
$\hat{\mathbf{n}}$	Unit vector in normal direction
n_c	Number of particles at surface for averaging
N	Particle number
$\mathbf{p}$	Velocity change in a collision
$\hat{\mathbf{t}}$	Unit vector in tangential direction
t	Time
V_n	Impact velocity
V_y^0	Initial particles velocity in stream
$\mathbf{V}$	Velocity vector
δt	Time interval for stress calculation
ε	Roughness of cylindrical surface
ϕ	Solid volume fraction
γ	Shear rate
μ	Stresses ratio
θ	Angle around object
ρ	Particle density
σ	Stress

Subscripts

1,2	Angular positions around object
av	Averaged value
i,j	Particle indices
N	Normal
T	Tangential

discussed and investigated in those simulations. The importance of the study of the dune anatomy is associated with the role of energy dissipation in formation of the dune. The obstacle is the source of energy dissipation where the free stream of particles is the source of energy to maintain the steady flow and also make up part of the dissipated energy in the downstream of the obstacle.

Another important parameter in the system is the surface roughness of obstacle. It is not studied in earlier investigations [4–7] or in recent study [8]. The surface roughness of the obstacle can be considered as a control parameter for the quality of the shock wave and the downstream flow of grains. Moreover, some parameters such as the ratio of the stream width to the obstacle characteristic length and the distance between the obstacle center and the central line of the granular stream could be important factors in practical applications for granular flow controlling purposes. The debris flow and avalanches [3] are two examples of granular streams which hit to objects of various regular or irregular shapes in their paths. A thorough knowledge about the flow and forces is not yet achieved.

This paper presents the results of computer simulations for moderately-dense granular streams of finite width confronting with circular objects having rough or smooth surfaces. The anatomy of the front shock and the downstream flow is presented along with normal and shear stresses exerted on the object at different circumstances. The outcome of this paper not only gives better understanding of the physics of shock waves in granular flows but also is crucial for understanding the physics of destructive events of debris flows and snow avalanches. The geometric parameters used here are also set to reproduce flows that could exist in such events.

2. Computational approach

The two-dimensional (2D) geometry of simulations is shown in Fig. 1. The granular stream used in simulations is a finite rectangular region of dimensions H (width of the stream) by L (length of the stream). Monodisperse circular particles are inserted randomly within this region to create the initial configuration. The number of particles is N with the diameter of d_p. A constant, unidirectional velocity (V_y^0) is assigned for all particles in the initial configuration. The direction of initial velocity is in the negative direction of y-axis, which is the same direction as the gravitational acceleration, $\mathbf{g}$. In some simulations, gravity is absent. A cylindrical object of diameter D is located in the end of granular stream towards which grains move. Initially, the edge of granular stream is right next to the object. Particles collide to the surface of object immediately after starting simulations. The object surface can be either smooth, or rough as shown in Fig. 1(b). The roughness of the surface is created by covering it with particles of diameter ε. Note that the normal and tangential directions $\mathbf{n_i}$ and $\mathbf{t_i}$ are given for the object at any point of contact.

The computational method is based on the event-driven algorithm [9]. In this algorithm, binary instantaneous collisions can only happen in the system. Pre- and post-collisional linear velocities of particle i are $\mathbf{V}_i$ and $\mathbf{V}'_i$, respectively. The unit normal vector to the surface of disk at the point of contact is $\mathbf{k}$, which is along the centerline of colliding disks i and j directed from i to j. In this model, the relationship between the pre- and post-collisional velocities is characterized by the translational coefficient of restitution:

$$\bar{e} = -\frac{\mathbf{k}\cdot\left(\mathbf{V}'_i - \mathbf{V}'_j\right)}{\mathbf{k}\cdot\left(\mathbf{V}_i - \mathbf{V}_j\right)}. \quad (1)$$

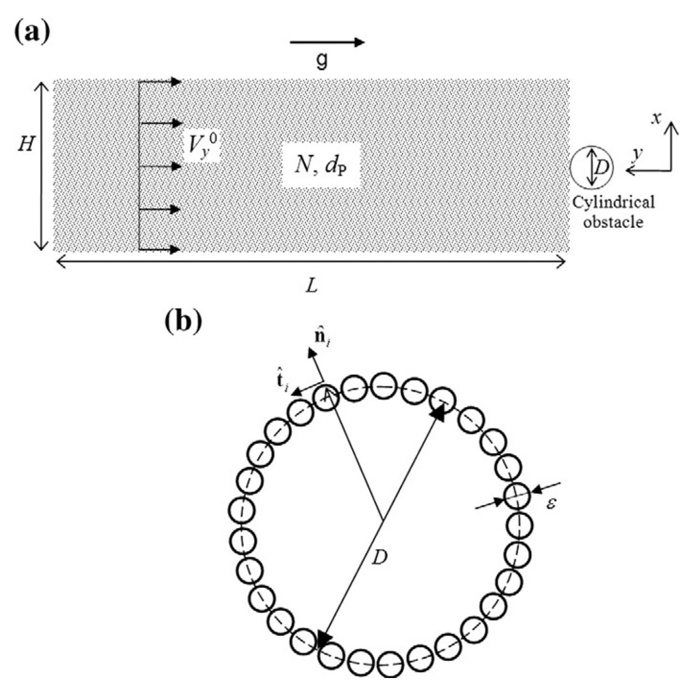

Fig. 1. Schematic representation of the simulated system. (a) Initial configuration of the system in which the granular stream of dimensions $H \times L$ is about to hit the rough cylindrical object of diameter D. The direction of initial velocity V_y^0 and the gravity g is also shown. (b) Closer view of the cylindrical object showing how the roughness of its surface is made using hard particles around the object.