Abstract

Granular flows have always fascinated researchers through its complex and mysterious behavior. Although a collection of solids, they exhibit properties like that of fluids. Flows over an inclined plane, known as chute flow, is important and popular rheometer used to test phenomenological models which will help us gain deeper insights into the physics of these materials as their relevance in nature and industrial applications are well known. Recently, an interesting phenomenon was observed where at a critical base roughness, a transition from a disordered state to an ordered state (Kumaran and Maheshwari, Phys. Fluids., 24, 053302, 2012) for particles interacting by the linear contact model. This transition is a sharp and discontinuous. The ordered state consists of well-defined 2D sheets of particles ordered in a hexagonal manner. This was reported for the linear model of contact between particles. The transition was validated for the Hertzian contact model as well, thus suggesting the universality of the phenomena irrespective of the contact model and other system parameters.

In our study of the base roughness on the flow down an inclined plane, simulations are used where the the particles are rough frictional spheres interacting via the Hertz contact law. The rough base is made of a random configuration of fixed spheres with diameter different from the flowing particles, and the base roughness is decreased by decreasing the diameter of the base particles. The transition from a disordered to an ordered flowing state at a critical value of the base particle diameter, first reported in Kumaran and Maheshwari (Phys. Fluids., 24, 053302, 2012) for particles with the linear contact model, is observed for the Hertzian contact model as well. The flow development above and below the critical base particle diameter is very different. During the development of the disordered flow for the rougher base, there is shearing throughout the height of the flow. During the development of the ordered flow for the smoother base, there is a shear layer at the bottom and a plug region with no internal shearing above. In the shear layer, the particles are layered and hexagonally ordered in the plane parallel to the base, and the velocity profile is well approximated by Bagnold law. The flow develops sin two phases. In the first, the thickness of the shear layer and the maximum velocity increase linearly in time till the shear front reaches the top. In the second phase, after the shear layer encompasses the entire flow, there is a much slower increase in the maximum velocity until the steady state is reached.

The effect of base roughness on the transition and dynamics of a dense granular flow down an inclined plane is examined using particle-based simulations. Different types of base topographies, rough bases made of frozen particles in either random or hexagonally ordered configurations, as well as sinusoidal bases with height modulation in both the flow and span-wise directions, are examined. The roughness (characteristic length of the base topography scaled by the flowing

particle diameter) is defined as the ratio of the base amplitude and particle diameter for sinusoidal bases, and the ratio of frozen and moving particle diameters for frozen-particle bases. There is a discontinuous transition from an ordered to a disordered flow at a critical base roughness is observed for all base topographies studied here, indicating that it is a universal phenomenon independent of base topography. The transition roughness does depend on base configuration and height of the flow but is independent of the contact model and is less than 1.5 times the flowing particle diameter for all the bases considered here. The bulk rheology is independent of the base topography and follows Bagnold law for both the ordered and disordered flows. The base topography does have a dramatic effect on the flow dynamics at the base. For flows over frozen-particle bases, there is ordering down to the base for ordered flows, and the granular temperature is comparable to that in the bulk. There is virtually no velocity slip at the base, and the mean angular velocity is equal to one half of the vorticity down to the base. For flows over sinusoidal bases, there is significant slip at the base, and the mean angular velocity is about an order of magnitude higher than that in the bulk within a region of height about one particle diameters at the base. This large particle spin results in a disordered and highly energetic layer of about 5-10 particle diameters at the base, where the granular temperature is an order of magnitude higher than that in the bulk. Thus, this study reveals the paradoxical result that gentler base topographies result in large slip and large agitation of particles at the base, whereas rougher topographies such as frozen-particle bases result in virtually no slip and no agitation at the base for both ordered and disordered flows.

Dense granular flows have been well described by the Bagnold rheology, even when the particles are in the multi-body contact regime and the co-ordination number is greater than 1. This is surprising because Bagnold law should be applicable only in the instantaneous collision regime, where the time between collisions is much smaller than the period of a collision. The dense granular flows down an inclined plane are also characterized by an order-disorder transition. The Bagnold rheology applies for both the ordered and disordered states, even though the rheological constants differ by orders of magnitude. The effect of particle stiffness on the rheology and the order-disorder transition is examined. It is found that the rheology crosses over from a hard-particle regime to a soft-particle regime when the stiffness of the contacts is decreased and the average co-ordination number exceeds about 2 for both linear and Hertzian contact models. The average contact energy in particle compression is small compared to the fluctuating kinetic energy of the particles in the hard particle regime, all components of the stress are proportional to the square of the strain rate, and the granular temperature is proportional to the square of the strain rate. There is equipartition between then contact energy of particle compression and the fluctuating kinetic energy of the particles in the soft-particle regime; all components of the stress are proportional to the strain rate, while the contact and kinetic energies per particle are proportional to the square of the strain rate. The scaling of the potential energy with the kinetic energy are as expected in the limit of hard particles even when the coordination number is larger than 1. However, the distribution functions for the potential energy are very different from that expected in the hard-particle model, indicating that the details of the contact regime do reflect the signatures of the soft-particle collisions. The order-disorder transition, which is a salient feature of the hard-particle regime, disappears after the cross-over to the soft-particle regime when the particle stiffness is decreased.

Experiments at very low angles of inclination reveal interesting flow regimes in the system. When the pile height is thick, a static wedge at the bottom supports flow at the top. This free surface is always inclined at the repose angle irrespective of the chute angle, provided the pile is thick enough. As the pile height drops and penetrates through the static zone, the bottom also starts to move causing a change in the velocity profiles. Thus, a transition from an erodible base configuration with a static wedge at the bottom to a flat base system is observed. The velocity profile is fit using a power law relation, vx = Azb + vslip, where vx is the streamwise velocity, z is the height from the bottom, A is a constant and vslip is the slip velocity at the base. A significant result is that the constant b is a linear function, with negative slope, of the slip velocity both for smooth bases made of glass, as well as rough bases made of sandpaper. For the rough base, we define an effective slip velocity is defined to be the extrapolated velocity to the base. These observations are supported by simulation studies as well.