Experiments on Granular Dynamics

The flow of granular materials is fundamentally fascinating because both the discreteness of the grains and cooperative "fluid-like" motion of the material can dominate flow properties in different situations. These properties manifest themselves in many natural phenomena such as avalanches, rockslides, volcanic pyroclastic flows, and spontaneous collapse of granular storage containers, all of which can have catastrophic consequences. Often the behavior of granular material can be very counterintuitive, leading to unexpected behavior such as size segregation during agitation or inelastic collapse. The economic impact of a full understanding of granular systems including predictive constitutive models of granular flow would be substantial.

The main difficulty in the description of granular flows is that the dynamics of many cohesionless particles in mechanical contact with each other is extremely complex. Since, on a large scale, granular dynamics is often similar to fluid dynamics, a possible approach is to develop continuum equations for the flow of granular materials. A *"granular fluid"* is, however, compressible and has a complicated equation of state. Thus, continuum approaches have been developed only for specific cases using significant simplifications and approximations. It is not surprising, therefore, that despite the numerous works in the field of granular flow a general description has not yet been developed. Another way to study granular flows is using molecular dynamics calculations although the complexity of granular flows has limited such calculations to spherical particles and simple particle interactions. Thus the modeling of more realistic phenomena involving the dynamics of particles with anisotropic shapes and heterogeneous size distributions is still not possible.

To address the fundamental properties of flowing granular media and the sensitivity of those flows to particle differences, we have performed experiments under controlled and reproducible conditions. In the case of the avalanche dynamics, three granular phases are present and one must understand the properties of each to understand the system. Our particular work on the dynamics of grains on a rough inclined plane (Fig. 1) has focused on three phenomena: (a) the instability of homogeneous flows and the nature of the formed patterns, (b) the rheology of a homogeneous flow, especially the role of air entrainment in fast flows and (c) the mechanisms of avalanche propagation focusing on the role of the shape of particles. Our main findings can be summarized as follows:

(a) In a wide range of the two main control parameters (plane inclination and flow rate) the homogeneous flow becomes unstable leading to the formation of a stripe pattern seen on the inset of (Fig. 1). The nature of the instability was investigated in detail.

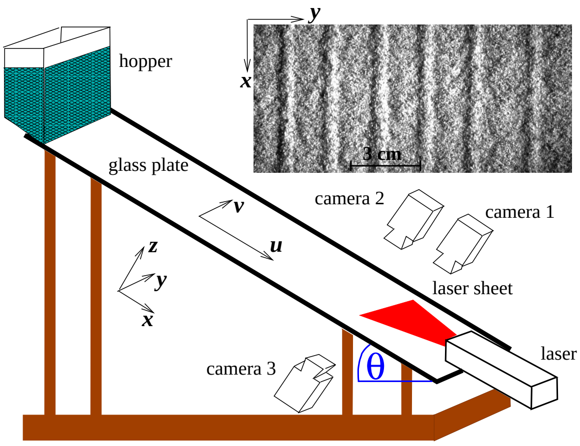

Figure 1: Sketch of the experimental setup.

The surface height profile was measured using laser deflection and the velocity field was determined simultaneously using particle image velocimetry. The time evolution of the height profile is shown in (Fig. 2) as measured by the deflection of a laser line.

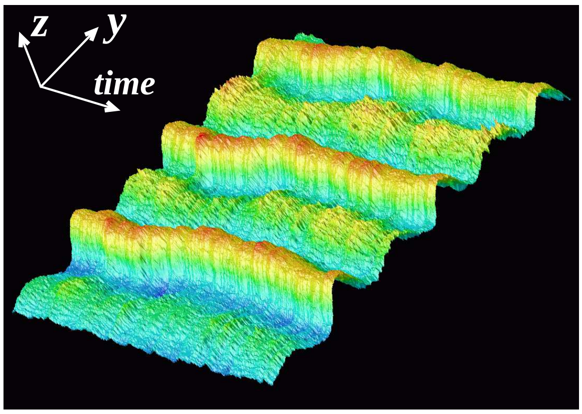

Figure 2: Time evolution of the height profile of the stripe pattern measured by the deflection of a laser line.

We have shown [1] that the lateral instability displays much greater richness than previously believed. In particular, we find that the structure of the local flow making up the stripes has height maxima for fast flowing regions, that the amplitude of the pattern evolves over downstream length scales that are 50-100 times the lateral wave length, that the flow is convectively unstable, and that secondary oscillatory instabilities can develop on long enough planes. The stationary and oscillatory regime is demonstrated in a space time plot (Fig. 3) by taking one intensity line (along y) from the movies taken with camera No. 2.

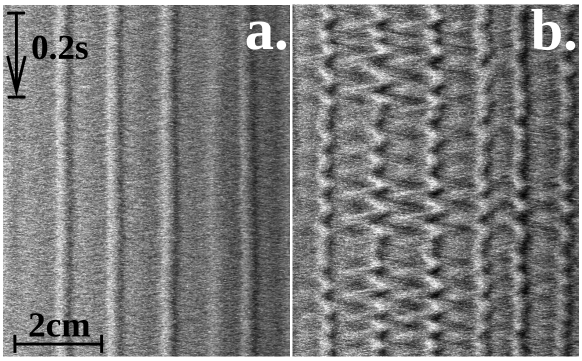

Figure 3: Space-time plot of the (a) stationary and (b) oscillatory stripes regime.

(b) For the measurement of the rheology of sand (with diameter $d = 400 \pm 100 \mu m$) a glass plate with dimensions of 190cm x 15cm that was set inside of a 20 cm diameter cast-acrylic tube. This configuration enabled us to measure the velocity of a flowing granular layer in the presence of air and in vacuum (with the pressure of $p < 1$ Millibar) with the help of fast speed (8000f/s) digital video imaging. Though the hopper discharge rate, and thereby the flow rate, is decreased by the presence of air (by about 10%), by measuring the flow thickness independently we find that even for relatively fast flows ($v \approx 3m/s$) the average flow velocity is not altered by the presence of air. For this regime, the particle velocity is in the order of the terminal velocity (velocity of free fall in air $\approx 2.7m/s$). Moreover by tracing the different regimes of the flow (homogeneous dense flow, fluidized flow, transition to waves, or stripe pattern), we found the same phase diagram in the presence of air and in vacuum. Accordingly we conclude that the presence of air does not have a detectable influence on these flows implying that the major dissipation mechanism is the collision of particles with each other and the rough bed. To quantify the nature of the dissipation mechanism the steady and accelerating flow regimes were identified and the acceleration was measured along the plane.

(c) At less steep slopes and lower incoming flux a static layer of grains builds up on the rough surface which becomes unstable above a critical thickness and avalanches form. These avalanches propagate down the plane on top of the stable static layer. The dynamical properties of the avalanches were quantitatively and qualitatively different for smooth glass beads compared to irregular granular material such as sand. For rough non-spherical grains, avalanches are faster, bigger and overturning, individual grains have down-slope speeds that exceed the front speed as compared with avalanches of spherical glass beads that are quantitatively slower, smaller and where particles always travel slower than the front speed. These two types of avalanches are demonstrated in Fig. 4, where a reconstructed height profile (measured with the deflection of a laser line) is shown for an avalanche formed by sand particles (Fig. 4a) and glass beads (Fig. 4b). Sand avalanches have a high core and two tails, which can break and form smaller avalanches. Avalanches formed by glass beads are oval shaped with a smoother relaxation of the motion on the back side.

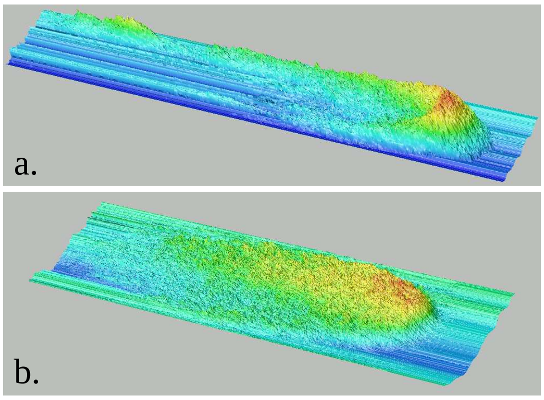

Figure 4: Reconstructed height profiles of avalanches formed by (a) sand particles (image size 7.2 *cm* x 56 *cm*); (b) glass beads (image size 12.2 *cm* x 46.8 *cm*); Vertical size rescaled by 25x in both cases.

In conclusion we would like to emphasize, that avalanches are non-universal. The quantitative differences found in the studies on the rheology of spherical beads and anisotropic particles like sand transform into a qualitatively different avalanching behavior for such materials. This dramatic change in the behavior can be captured by a simplified depth-averaged approach using the Saint-Venant equations. Taking into account the individual rheologies of the granular materials the depth-averaged equations yield a simple smooth solution (similar to flood waves in river flows) for glass beads, since the avalanche height is far below the value at which a more complex discountinous solution is found (similar to roll waves in river flows). For sand particles however the critical flow thickness is much smaller and pactically all avalanches fall into the categogy of the second type of solutions.

References

[1] T. Börzsönyi and R.E. Ecke, *submitted to Phys. Rev. Lett.*.

[2] T. Börzsönyi, T.C. Halsey and R.E. Ecke, *submitted to Phys. Rev. Lett.*.

Contact Information: Tamás Börzsönyi – Center for Nonlinear Studies & MST-10, Los Alamos National Laboratory, MS-K764, Los Alamos, NM, 87545, Phone: (505) 665-7650, email: btamas@lanl.gov.