VELOCITY PROFILES DURING GRANULAR AVALANCHES

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Summary Instantaneous velocity profiles of grain motion during glass beads avalanches are obtained with a high speed camera and by Particle Image Velocimetry (PIV) in a rotating drum set-up. When the pile is seen from above the surface velocity profile is curved with a strong slip on the two lateral smooth walls. When observed from the side, the in-depth velocity profile at the wall is found exponential with a characteristic length of two grain diameters. These profiles are time resolved (1/250 sec.) and show that their shapes are determined as soon as the avalanches start. Velocity measurements are in good agreements with global flow rate measurement deduced from the pile angle decrease.

INTRODUCTION

Understanding the rheology of granular flows is a challenging problem. One of the tool is flow visualization, however visualization of flowing granular particles is usually restricted to the outer surfaces of the piles except when using limiting MRI techniques [1] or if one limits to 2D flow [2], [3]. In the present study of intermittent avalanche flow we show that one can be confident to the surface measurements to evaluate precisely the 3D profiles.

EXPERIMENTAL SET-UP

In order to observe successive avalanches a rotating drum set-up is used. Glass spheres of diameter $d = 1$ mm half fill an horizontal cylinder of diameter $D = 17$ cm and thickness $b = 25$ mm (Figure 1). The drum is put in rotation at a very slow rotation rate ($\Omega \sim 10^{-3}$ rpm) in order to observe well separate avalanches. The drum is then almost motionless during the avalanche. During an avalanche, the mean angle of the pile decreases of about 3 degrees from the maximum angle of stability to a minimum angle in about 1 second. A high speed digital camera (500 im/s) films the pile along the cylinder axis or from above. Two successive images are processed with a PIV software in order to obtain the in-plane velocity of the grains in a close vicinity of the cylinder axis (central part of the avalanches). More details on the experimental set-up can be found in Ref. [4]. In this experiment grains are large and moves in air so we can neglect any effect of the surrounding fluid on the avalanche dynamics [5]. The finite number b/d of grains in the width of the cell affect slightly the amplitude of the avalanches as described in Ref. [6].

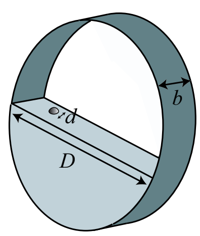

Figure 1. Scheme of the rotating drum.

INSTANTANEOUS VELOCITY PROFILES AND FLOW RATE EVALUATION

Figure 2 shows images from the side (a) and from above (b) of the grain pile together with the corresponding velocity profiles obtained by PIV and averaged on the image width.
At the lateral wall the velocity of the grains decreases rapidly below the free surface (Fig. 2a). The profile is very well fitted by an exponential with a characteristic length of the order of 2 bead diameters, and this at any time, from the very beginning to the final stop of the avalanches. No linear profile as described in Ref [2] is observed.
In the transverse direction (Fig. 2b) we observe an effect of the lateral glass wall: the velocity profile is curved, it presents a maximum in the middle plan and a large slip velocity on the boundaries. This profile can also be fitted by the sum of two exponential functions but experiments with larger gaps are necessary to demonstrate clearly this point.
The maximum velocity during an avalanche occurs in the middle plane and at the pile surface. This velocity increases progressively since the beginning of the avalanche then decreases during the second part of the avalanche. No permanent regime with constant velocity is observed in between. Typical value of the maximum velocity for the present set-up is 100 cm/s which corresponds in dimensionless form to a Froude number $u/\sqrt{gd} \approx 1$.
When the avalanche starts the profiles present very rapidly a self-similar shape and only the maximum velocity in surface or in the middle plan between the walls rescales the profiles.

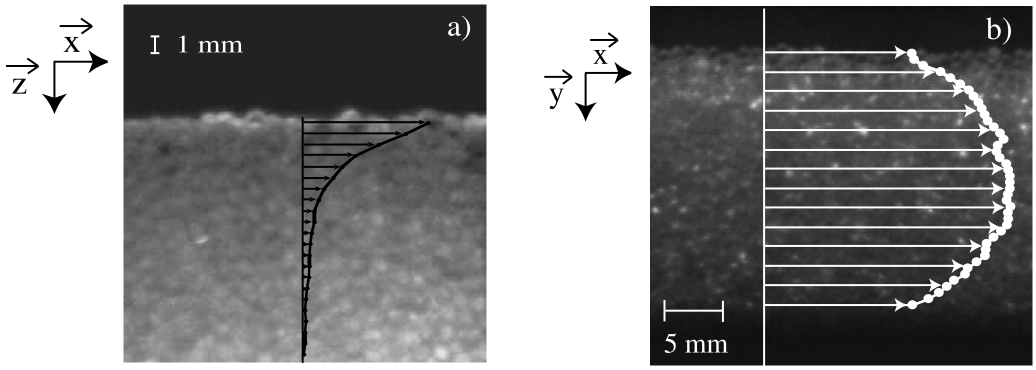

Figure 2. Images of the pile and corresponding instantaneous velocity profiles during an avalanche. (a) From the side at the front wall, (b) from above in between the walls.

From the previous measurement of the lateral and surface velocity profiles and assuming that no unexpected behavior occurs in the bulk of the avalanche, the 3D velocity profile can be written as:

$$u(y, z) = u_0(t)\ \exp(-z/\delta)\ f(y) \tag{1}$$

Integrating this profile in z and in y gives us the flow rate $Q_u(t)$ across the plane $x = 0$ perpendicular to the avalanche. This flow rate is plotted on Figure 3 as well as the macroscopic flow rate deduced from the time decrease of the pile angle θ during the avalanche and of the size of the set-up ($Q_\theta = \frac{D^2 b}{8}\,\dot{\theta}$). The agreement is excellent which indicates that the velocity profiles obtained at a lateral wall reflect well what occurs in the bulk of the avalanche.

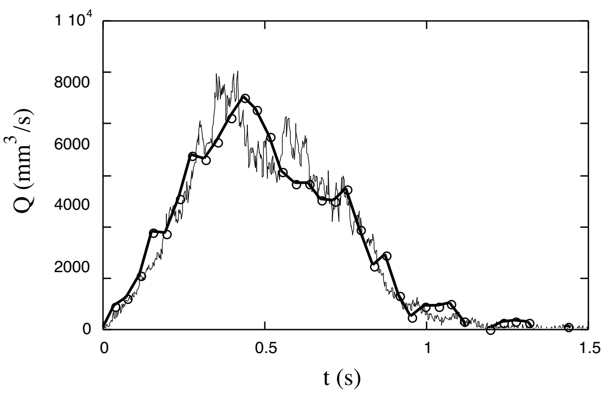

Figure 3. Time evolution of the avalanche flow rate Q based either on velocity profile (Q_u, thin continuous line) or on the time decrease of the macroscopic pile angle (Q_θ, thick line).

CONCLUSION

Velocity measurements of confined avalanches show that avalanches build an exponential velocity profile in the depth of the pile. This velocity field sets-up deeper and deeper during the flow, preserving the exponential shape. In the present set-up no saturation of the shear is observed contrary to others experiments with permanent flows [2], however it is possible that for larger set-up such linear profile near the surface would be observed even in the discrete regime of avalanche.

Furthermore we here demonstrate that flow rate measurements warrant the use of velocity fields observed at a wall to extrapolate the behavior of the grains in the bulk of a flow.

References

[1] Jaeger H.M., Nagel S.R., Behringer R.P.: Granular Solids, Liquids, and Gases. *Rev. Mod. Phys.* **68**: 1259, 1996.

[2] Bonamy D., Daviaud F., Laurent L.: Experimental study of granular surface flows via a fast camera: A continuous description. *Phys. Fluids* **14**:1666, 2002.

[3] Rachenbach J.: Granular Flows. *Adv. Phys.* **49**:229, 2000.

[4] Courrech du Pont S.: Avalanches granulaires en milieu fluide. *PhD Thesis, University Paris-XI* 2003.

[5] Courrech du Pont S., Gondret P., Perrin B., Rabaud M.: Granular avalanches in Fluid. *Phys. Rev. Lett.* **90**:044301, 2003.

[6] Courrech du Pont S., Gondret P., Perrin B., Rabaud M.: Wall effects on granular heap stability. *Europhys. Letters* **61**:492, 2003.