MEASUREMENT AND SIMULATION OF THE STREAMWISE SOLID FRACTION OF A GRANULAR HYDRAULIC JUMP IN A RECTANGULAR CHUTE

Li-Tsung Sheng*, Shang-Yu Chiu* Chih-Yu Kuo**a), Yih-Chin Tai***& Shu-San Hsiau*
*Department of Mechanics, National Central University, Taiwan
**Research Center for Applied Sciences, Academia Sinica, Taiwan
***Department of Hydraulic and Ocean Engineering, National Cheng Kung University, Taiwan

Summary We describe the streamwise flux-averaged solid fractions of steady gravity-driven dry granular flows moving over semi-circular cylinder obstacles by using an indirect measurement method. In the method, the volume flux is inferred by the velocity profile along the perimeter cross-section, combined with knowledge of the constant mass flow rate. In the flow, there is a granular hydraulic jump, which produces a strong variation of the solid fraction. The chute has a width of 5 cm wide, a length of 150 cm long, and is inclined at 30°. It is found that the perturbations in the solid fraction caused by the obstacle back-propagate into the upstream for a certain distance. To explain the solid fraction variation, we propose a continuum mixture model which contains one solid and one interstitial fluid phases. It is demonstrated that the simulation is in qualitative agreements with the experimental measurements.

INTRODUCTION

Rapid flows of granular materials on inclined surfaces are encountered in many engineering applications as well as in geophysical contexts. The mechanics of granular avalanches are, therefore, of fundamental importance in this regard. A variety of continuum models have been proposed to describe the complex behavior of granular avalanches [1]. Notably, Iverson [2] argued that the interstitial fluid can alter the behavior of the flows and its effect should be included in the constitutive laws. This intrigued a renewed interest in modeling granular flows as multiphase continua. In the continuum mixture model, the volume fraction of the constituent affects not only the distribution of the mass, momentum, etc., but also the interactions among the constituent phases [3]. When the fluid phase is air (dry particles), the volume fraction of the particles (solid fraction) becomes a measure of the mean free path between the particle contacts. Therefore the solid fraction plays an important physical role in granular avalanches. Because of its physical significance, the solid volume fraction is one of the controlling parameters in many rheology studies.

MEASUREMENTS

Measuring the solid volume fraction of granular flows however is not straightforward because of the wall and basal surface constraints. Sheng *et al.* [4] developed an interpolation scheme to infer the flux-averaged solid fraction of steady granular channel flows. With the measuring technique, this paper is aimed to measure the streamwise variation of the solid volume fraction, as well as the flow depth and velocity, of a normal granular shock in a straight rectangular chute flow, and to provide qualitative comparisons to the simulation of a continuum mixture model. The granular shock is produced by a granular flow moving over a semi-circular obstacle. Across the shocks, the flows undergo rapid changes in the flow thickness and velocity.

The experimental setup is extended from Sheng *et al.* [4]. The rectangular channel is 5 cm wide, 150 cm long and the inclination angle is set 30°. A semi-circular cylinder obstacle with 10 mm in diameter are installed at the center of the chute to generate the granular shock. The sidewalls and the bottom plate of the chute are all made of 10 mm thick transparent Plexiglas sheets through which the moving granular mass can be photographed. At the upstream end, there is a reservoir to hold the initial granular mass and a manual-operated shutter gate. White glass beads with a nominal diameter of 3 mm are used. The friction angle between the glass beads and the Plexiglas walls is about 15° and the internal friction angle of the beads is 34°. Both angles are measured by the standard Jenike Shear Tester.

A typical flow image and PIV velocity measurement at a time instance is shown in Fig. 1. A granular shock can be seen in the flow near the position of the obstacle. There is a sufficient amount ($>$ 5.7 kg) of granules in order to spread the particles over the whole image sampling window for a sufficiently long period, during which the flow is almost steady. Fig. 2 show the streamwise (depth-averaged) velocity and fluxed-averaged solid fraction. It is interesting to see that, unlike the flow depth, the flow velocity and the solid fraction have significant variation before the flow impinges on the shock generator (at $x = 40$ cm).

CONTINUUM MIXTURE MODEL

By treating air as interstitial fluid between particles, we derive a continuum mixture theory. There are continuity and momentum equations for each constituent phases. Air is allowed to enter the flow and is quantified by an entrainment

a) Corresponding author. E-mail: cykuo06@gate.sinica.edu.tw.

rate. The model equations, comprise a hyperbolicity system with four variables: the flow depth, solid fraction, and the velocities of the two constituents. The force exerted into the flow by the obstacle is measured for the simulation. Qualitative comparison with the experiments are performed and will be presented.

CONCLUSION

The streamwise variations of flow depth, velocity and solid fraction of a granular hydraulic jump flow in a rectangular chute are measured. It is found that the perturbations in the solid fraction caused by the obstacle back-propagate into the upstream for a certain distance. To explain the solid fraction variation, we propose a continuum mixture model which contains one solid and one interstitial fluid phases. It is demonstrated that the simulation is in qualitative agreements with the experimental measurements.

References

[1] Pudasaini, S. P. and Hutter, K., *Avalanche dynamics*, Springer Verlag, Berlin/Heidelberg, 2007.
[2] Iverson, R. M., "The physics of debris flows," *Rev. Geophys.*, Vol. 35, 245–296, 1997.
[3] Pitman, E. B. and Le, L., "A two-fluid model for avalanche and debris flows," *Philos. Trans. R. Soc. A-Math. Phys. Eng. Sci.*, Vol. 363, 1573–1601, 2005.
[4] Sheng, L. T., Kuo, C. Y., Tai, Y. C. and Hsiau, S. S., "Indirect measurements of streamwise solid fraction variations of granular flows accelerating down a smooth rectangular chute avalanches," *Exp. Fluids*, accepted, 2011.

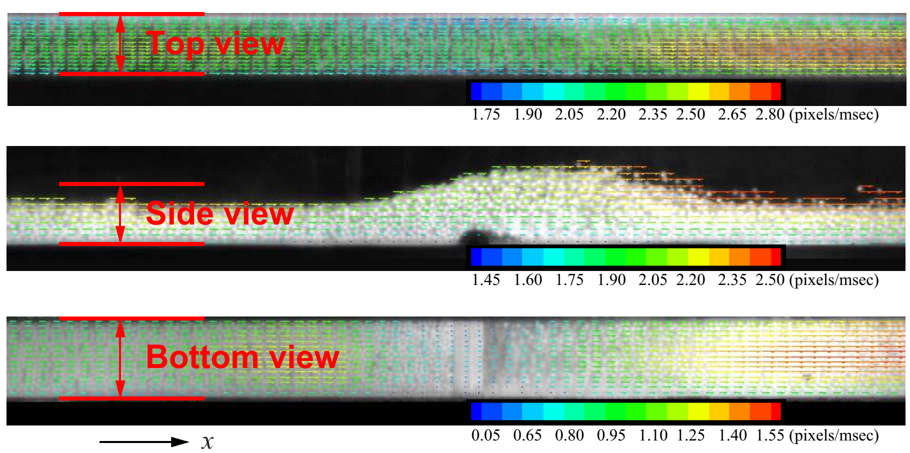

Figure 1. An instantaneous flow velocity field calculated by PIV. Panels from the top show the top, side and bottom views, respectively.

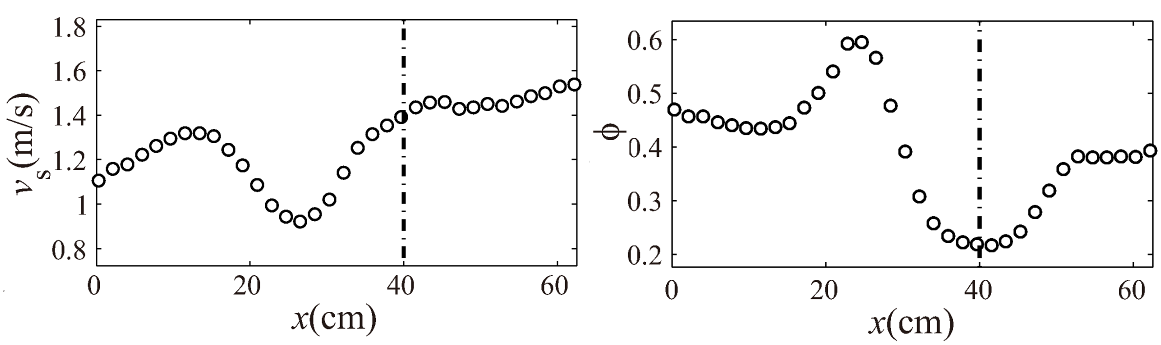

Figure 2. Measured streamwise (a) velocity and (b) solid fraction.