IN-SITU AND IMAGE-BASED FORCE MEASUREMENT OF A DRY GRANULAR FLOW DOWN AN INCLINE

Ming-Jhe Jiang & F.-L. Yang[a)]
Department of Mechanical Engineering, National Taiwan University, Taipei, Taiwan 10617, R.O.C

Summary This work attempts direct and indirect measurements for the force developed by a steady dry granular flow down an incline as it impinges and runs over an obstacle. Three load cells were implemented to achieve in-situ measurements of the impact force, the tangential friction, and the overhead normal loads. High-speed imaging technique and relevant image analysis were employed to estimate the flow density and velocity which information were further integrated into a two-dimensional control volume analysis to estimate the corresponding force components under the condition of streamwise momentum conservation. The force data obtained from the 3D in-situ and 2D indirect measurements agree well over a range of inclination angle provided that the flow is not too loose or too thin for which erroneous PTV is inevitable.

INTRODUCTION

The impact and erosion destructive force exerted on an infrastructure by a granular flow is important for homeland security. Thus, this work generates a steady dry granular flow down an incline and let it run over an obstacle to estimate the impact, the friction, and the normal force loads via in-situ load cell measurements. We also employ high-speed imaging technique to estimate the three force components via two-dimensional control volume analysis. The obtained force data are compared to evaluate the feasibility of image-based techniques on flow rheology measurements.

EXPERIMENT SETUP AND IN-SITU FORCE MEASUREMENT

As depicted in Figure 1, a laboratory-scale facility has been developed which contains a large reservoir, a chute inclined at θ=26°, and a downstream deposit container (not shown). The granular material was composed of identical POM spheres of diameter 5.9mm, to be released from the reservoir gate of 10cm height. These spheres moved along a guide onto the incline and a steady granular flow soon developed as these spheres propagated downstream under the action of gravity. A sensing module was developed by integrating three load cells with three measuring surfaces (as shown in Figure 2) and this module was installed at a streamwise distance of 30 cm down the incline (see the blue box in Figure 1). The steady flow impinged on the sensing module and climbed over it imparting *impact force* on the frontal surface and *friction force* on the top surface. Meanwhile, the overload atop the sensing module was also captured as the *normal force* load. A typical result for the temporal profiles for the module signal is shown in Figure 3(a) in which the data obtained for flow from different amounts of reservoir materials are compared. Since the material overran the sensing module was thin, the imparted friction and the normal load are of much smaller magnitude than the impact force and hence theses two components are examined in a separate figure in Figure 3(b).

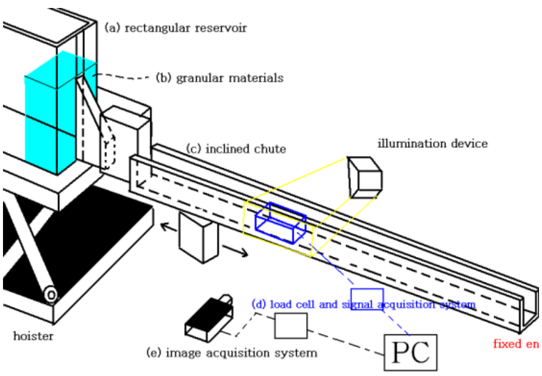

Figure 1: Experimental facility and the measuring components

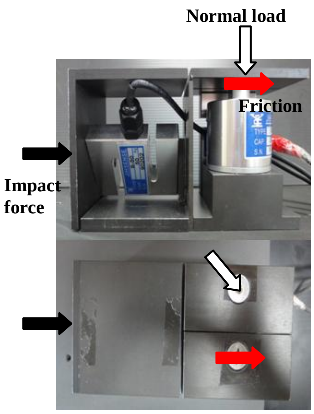

Figure 2: Sensing module (top: side-view; bottom: top-view)

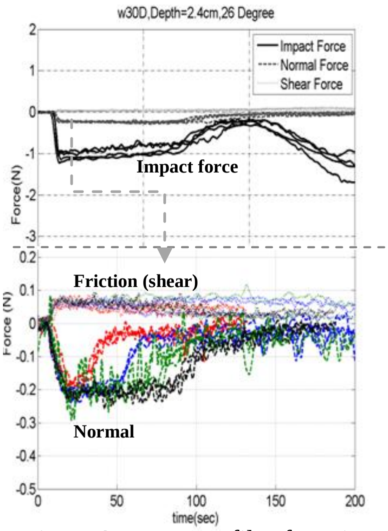

Figure 3: Force profiles from in-situ load cell measurements

IMAGE-BASED FORCE MEASUREMENT

In addition to in-situ force measurements via the load-cell sensing module, the resulting flow was also monitored by a side high-speed digital camera at 500 frames per second and the setup configuration is shown in Figure 1. One experimental image is shown in Figure 4 in which the black square area is the sensing module (note the camera rotation to meet the CCD at the incline boundary). Image analysis routine has been developed using *Circular Hough transformation method* to locate each sphere (see the inset of Figure 4) and *the method of nearest neighbor* to achieve

a) Corresponding author. Email: fulingyang@ntu.edu.tw

Particle Tracking Velocimetry (PTV). An area-weighted average scheme was employed to obtain a two-dimensional estimation of bulk properties, including its solid volume fraction, Φ, and velocity components parallel or perpendicular to the chute base, U and V. By shifting the averaging box along the flow depth, we could obtain the instantaneous depth profiles for Φ, U, and V. These information are integrated into a two-dimensional control volume analysis to estimate the bulk boundary forces as described below.
Two control volumes were defined in front and atop the sensing module as depicted in Figure 5. The integral form of mass and momentum conservation laws are transferred into a discrete form to give the three force formulae as

$$\text{Impact force } F_I = d(\phi\rho_s UV)/dt + \rho_2 A_2 (U_2)^2 - \rho_1 A_1 (U_1)^2 - \phi\rho_s g\sin\theta,$$

$$\text{Friction } F_S = d(\phi\rho_s UV)/dt + \rho_2 A_2 (U_2)^2 - \rho_1 A_1 (U_1)^2 - \phi\rho_s g\sin\theta, \text{ and}$$

$$\text{Normal force } F_N = \phi\rho_s g\cos\theta,$$

in which ρ_s represents the particle density, g denotes gravity, and V is the size of the control volume. The velocity U_1 and U_2 denotes the bulk streamwise velocity at the inlet and the exit of the control volume with the respective area $A_1$and A_2. Such force estimation is two-dimensional and hence it was multiplied by the corresponding flow width to estimate a three-dimensional force magnitude. The results for the impact force and the normal load compare very well to the actual force data over a wide range of flow conditions (various θ and reservoir packing) and one example is shown in Figure 6 and the cross data in Figure 7 (whose half-value corresponds to the normal load in Figure 3). However, since the flow atop the sensing module is too loose and rather thin, the current PTV algorithm failed to capture a physical bulk streamwise velocity and hence severe overestimation is observed from the present control volume analysis as shown in Figure 7. A manual PTV was performed and the resulting friction is around 0.11±0.05N which in much better agreement to the in-situ measurement in Figure 3.

Figure 4: (left) Snapshot of the granular flow over the sensing module; (right) the sphere located by circular Hough transformation method.

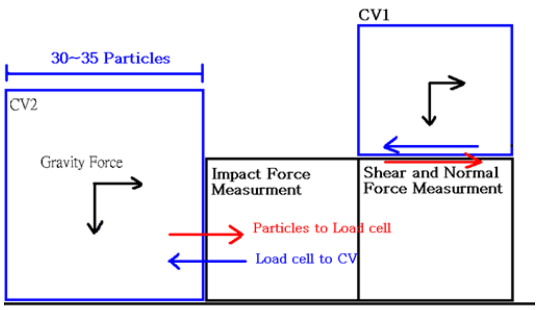

Figure 5: Illustration the two control volume employed in the current analysis.

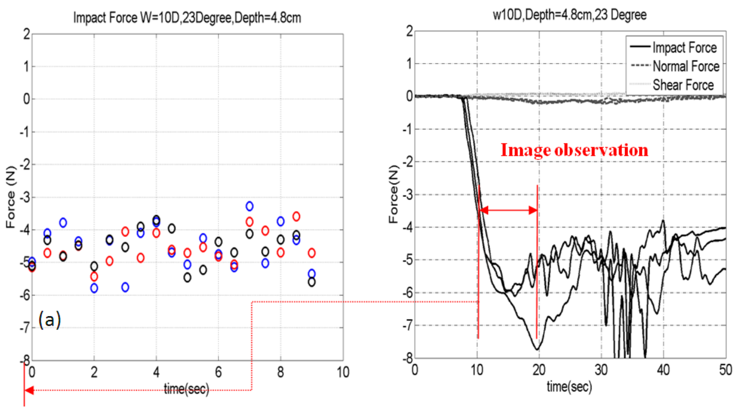

Figure 6: Impact force temporal profile. (left) from control volume analysis (b) from load-cell.

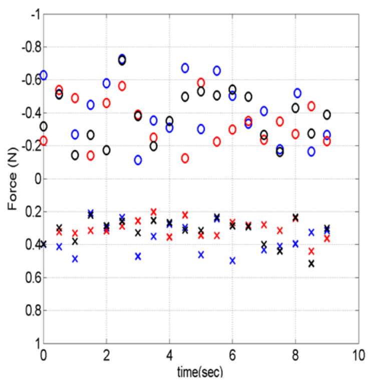

Figure 7: Friction (○) and normal load (x) estimated from current control volume analysis.

a) Corresponding author. Email: fulingyang@ntu.edu.tw