Velocity Measurement of Granular Flows Using Dynamic X-ray Radiography

François Guillard[1], Benjy Marks[1] and Itai Einav[1,2]

[1] Particles and Grains Laboratory, School of Civil Engineering,
The University of Sydney, Sydney, New South Wales 2006, Australia.

[2]Department of Civil, Environmental & Geomatic Engineering,
Faculty of Engineering Science, University College London, London WC1E 6BT, UK.

ABSTRACT Granular media are present in a wide range of industrial applications, from mining to civil engineering, including agriculture and pharmaceutical industry. Using X-ray dynamic radiography of a granular flow, we study the dynamics of a single dense intruder inside a granular material in a rotating tumbler. PIV techniques applied on the density fluctuations of the granular material are also used to measure the velocity field of the granular flow in a rotating tumbler and during the discharge of a silo.

1. INTRODUCTION

The study and prediction of granular flows are of particular interest in a wide range of industries, for material handling in mining, grain storage in agriculture or powder processing in pharmaceutical. It is therefore crucial to understand their behavior to be able to handle them efficiently, or to mix them without heterogeneities for example. However granular material can also be challenging to study with conventional experimental or numerical techniques. Numerically, to simulate each grain gives good agreement with experimental observations but is very limited by computer power to be able to simulate enough grain for meaningful and relevant result at industrial scale [1]. Experimentally, it is very difficult to have a clear description of the bulk behavior of the granular material because granular media are not transparent. Therefore only the surface of the material can be observed, and eventually the material near the walls if the container is transparent, leading to a very partial view of the actual behavior of the bulk material.

To be able to observe the inside of granular material, it is possible to use radiation that are less absorbed by the material, like X-rays or gamma rays [2]. Radiography have been used to study soil or sediments [3][4][5], granular material [6], or animal locomotion inside sand [7]. More recently, computer tomography techniques have allowed to fully reconstruct samples in three dimensions, resolving the location of each grain in space [8][9][10][11]. However, these type of tomography techniques have two main drawbacks. The first one is that most of the commonly available apparatus are limited to relatively small sample, of the order of 10 cm^3. The second one is that the full 3D reconstruction of any sample takes a long time, because images of the same sample have to be taken at different angles. Complete 3D reconstruction is therefore limited to static samples or very slow flows. This difficulty can be overcome by taking high speed images of the sample in a given orientation, which can still give a lot of meaningful informations on the behavior of the material.

We present here an X-ray facility at the University of Sydney designed to address the study of fast moving flows. This equipment allows to study locally large scale flows, with experiment size up to several meter and high-speed X-ray imaging up to 30 frames per seconds, for an indefinite amount of time. Two X-ray equipments are available to allow 3-dimensional visualization. The possibilities in term of particle tracking and particle image velocimetry of density fluctuations are presented on a rotating tumbler experiment and on the discharge of a silo.

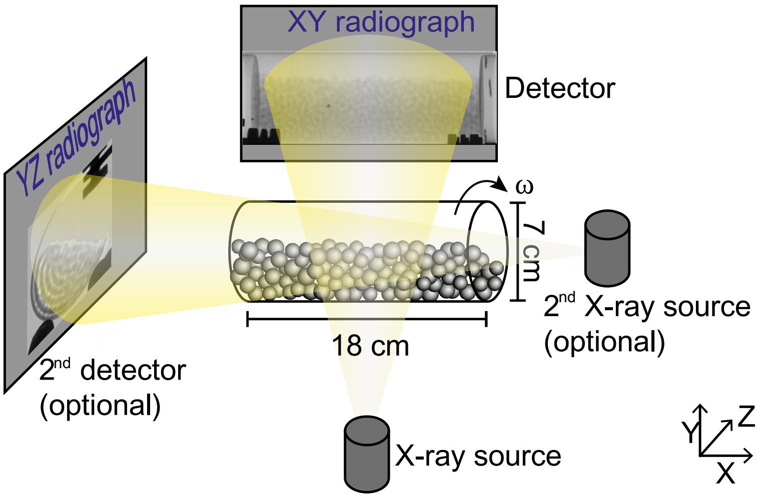

Figure 1 Sketch of the Experimental Setup

2. EXPERIMENTAL SETUP

The experimental setup is indicated Figure 1. A rotating tumbler, similar to mixing devices used in industrial application is studied. It consists of a horizontal cylinder of length 18 cm and diameter 7 cm filled with glass or plastic beads, that rotates around its horizontal axis at a velocity of $\omega = 25$ rpm. This creates a continuous avalanching of the granular material inside the tumbler. To be able to study the bulk of the granular material, the tumbler is placed between an X-ray source (X-ray tube) and a detector panel. Images are recorded at 30 frames per second, with 768×960 pixels per frame, for up to 20000 frames (11 minutes). The use of X-rays allows us to study the bulk granular material, because these radiations are less absorbed or scattered than visible light. The intensity I observed on the detector after passing through the medium is given by:

$$I = I_0 \exp(\int \mu(z) dz) \quad (1)$$

where I_0 is the intensity emitted by the X-ray tube. The integral is along the line of sight, i.e. the thickness of material traversed by the radiation, and $\mu(z)$ is the attenuation coefficient for the X-ray radiation at the energy considered, at location z along the line of sight. The attenuation coefficient is proportional to the density of the material, and also increases with the atomic weight of the material [12]. The energy and intensity of the X-rays are adapted in each experiment depending on the material studied and to the thickness of the experiment, in the range 50 keV to 225 keV, to obtain a good contrast of the images. The granular material used is either plastic polyethylene beads of diameter $d_g = 3$ mm or $d_g = 5$ mm and bulk density 920 kg.m^{-3}, or glass beads of diameter $d_g = 3$ mm and bulk density 1500 kg.m^{-3}. Steel intruder will also be used because of their very good contrast with glass and plastic in X-ray, due to their high atomic number and density.

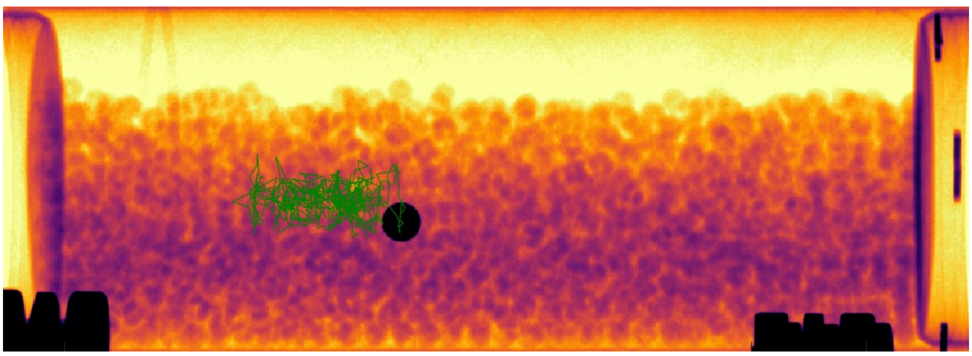

Figure 2 Trajectory of an 8mm Steel Particle (green) Superimposed on the Initial XY Radiograph.

The image obtained using the X-ray radiography technique (radiographs) can be understood as the projection of the density of the material on a plane perpendicular to the direction of the radiation. We will mainly focus on the projections on the XY plane (XY radiographs) in the following, although YZ radiographs can also be be performed at the same time thanks to a second X-ray source and X-ray detector (see Figure 1).

3. PARTICLE TRACKING IN ROTATING TUMBLER

To illustrate the effect of material variation on the radiographs, and to show the possibilities of *in situ* tracking offered by the X-ray facility, we first perform a rotating tumbler experiment with a single spherical steel intruder added in the granular medium made of plastic or glass grains. Figure 2 shows a radiograph of the XY plane and the path followed over time of a steel intruder of diameter d_i=8 mm. Several interesting features related to the interaction between the intruder motion and the granular material can be extracted. First of all, in the vertical Y direction, the intruder remains at a relatively constant position due to the effect of the granular segregation and its higher density.

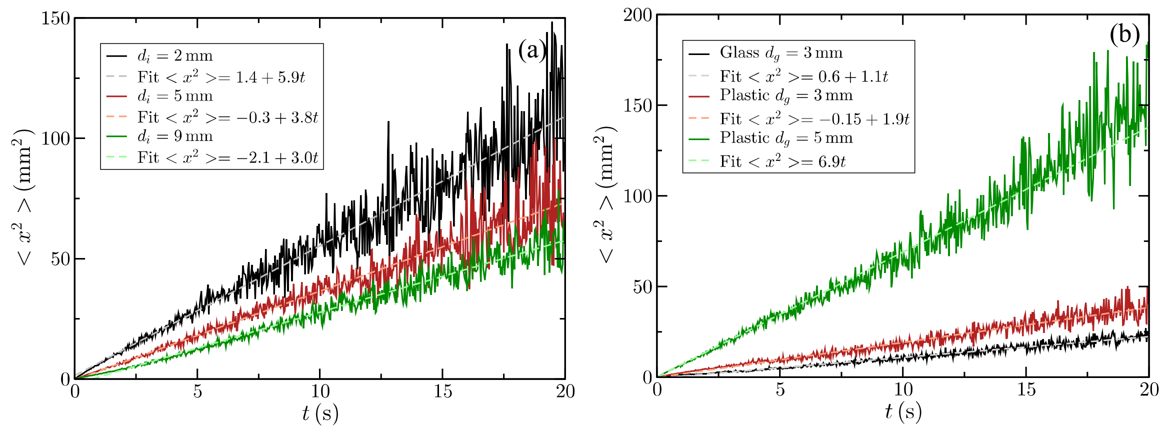

Figure 3: Mean Square Displacement Function of Time for Different Intruder Diameter (a) and Different Bulk Material (b).

Horizontally, the intruder reacts at the fluctuations of the granular medium by showing a diffusive motion in X. We study its dynamics in the horizontal plane by computing the mean squared displacement $\langle x^2 \rangle$ of the intruder over time, shown in Figure 3. The proportionality between $\langle x^2 \rangle$ and t is characteristic of a diffusive behavior, meaning that the rotating cylinder is long enough so that the intruder never goes toward the edges, and that the granular convection in the tumbler is negligible. Figure 3a also shows that the intruder moves less when its diameter is larger. On the other hand, the granular material around the intruder has a strong effect on its motion as well, as seen in Figure 3b, larger or less dense bulk grains leading to higher diffusion.
To further quantify the effect of the bulk material and intruder diameter, we define the diffusion coefficient D as [13]:

$$\langle x^2 \rangle = 2Dt \ . \tag{2}$$

Figure 4 shows the diffusion coefficient as a function of the intruder diameter. As mentioned before, the diffusion decreases with the diameter of the intruder indicating that the higher inertia of the particle is not balanced by the increase of surface area when the diameter increases. The granular medium also has a big effect on the diffusivity of the particle. When the medium is denser, the diffusivity of the intruder is smaller, whereas the diffusivity increases when the grain diameters increase. Since the diffusivity is directly linked to the fluctuations of the grains inside the granular material, the denser or smaller the grains of the material, the less fluctuations there are at constant rotating velocity of the tumbler. This can have great importance on the efficiency of mixing in rotating tumblers, and on the mixing of impurities in this kind of geometries and could have important application for industrial processes.

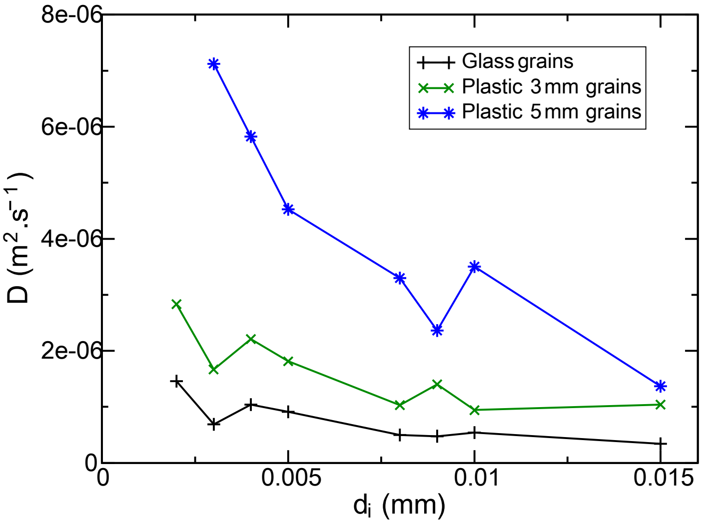

Figure 4 Diffusion Coefficient Function of Intruder Diameter for Different Bulk Materials.

4. VELOCITY MEASUREMENT BY DENSITY FLUCTUATION TRACKING

To study in more detail the flow of grains inside the rotating tumbler we would like to access the velocity field of the material. This could be achieved using different density particles used as trackers, but as seen before this type of trackers would not have the same dynamics than the rest of the flow. Another possibility to obtain the velocity field is to use the granular material itself for velocity tracking purposes. It is clear in Figure 2 that the radiograph of a granular material is not homogeneous, but shows different intensity in space depending on the local projected density of the granular material, which fluctuates in space. It is therefore possible to track these density fluctuations over time using standard Particle Image Velocimetry (PIV) technique [14], correlating patches between two images to find the most probable displacement of each patch. Figure 5 shows the result of the PIV on the YZ and XY radiographs. The typical velocity field on a cross section of a rotating tumbler is recovered in Figure 5a, with a cascading flowing layer at the surface of the flow and a rigid body rotation of the grains at the bottom of the tumbler. In Figure 5b, the velocity projected on the XY plane is plotted, showing that there is essentially no velocity in the horizontal direction, justifying *a posteriori* the absence of convection in this experiment on the timescale we are interested in. The vertical velocity v_y that is measured in the XY projection is more complicated to interpret since the grains have different velocity along the line of sight. The measured v_y actually averages the vertical granular velocity along the line of sight. This is clear in Figure 5c where the vertical velocity measured from the XY radiograph (Figure 5b) is compared with the vertical velocity averaged along the horizontal lines of sight in the YZ radiograph (Figure 5a). There is a good agreement between the two methods, except close to the top of the granular material in the tumbler because the flowing layer velocity is not properly measured by the PIV in the YZ radiograph due to fast fluctuating density. So using 2 projections it is possible to reconstruct the full 3-dimensional velocity of the granular medium, as long as the considered experiment is invariant by translation along one direction.

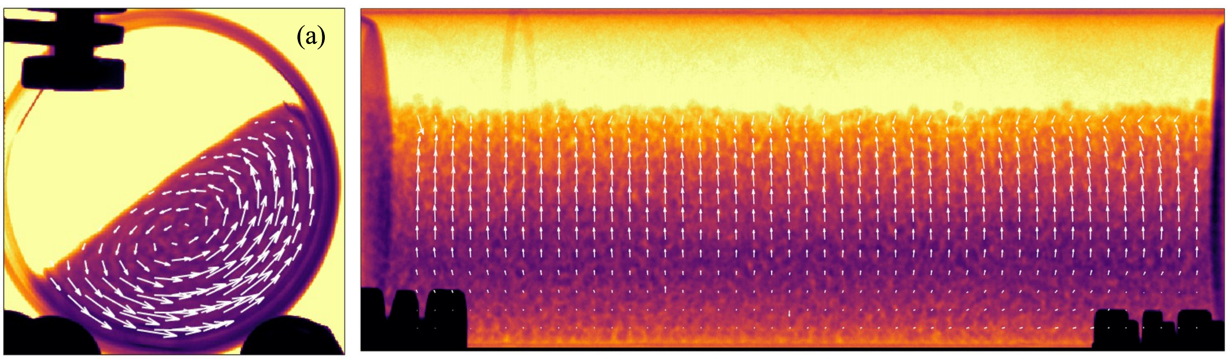

Figure 5 (a) XY Radiograph and (b) YZ Radiograph with Superimposed PIV Velocity Field.

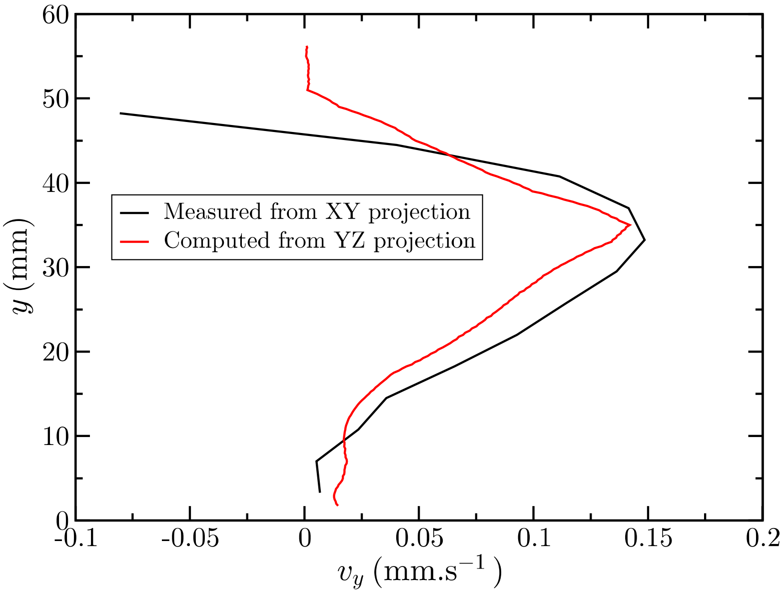

Figure 6 Comparison of Vertical Velocity Measured in XY Radiograph and Computed from YZ Radiograph.

Our method of high speed radiography allows us to study the velocity and the behavior of the granular material in rotating tumbler with good accuracy, allowing measurements of the flow and of the velocity of the granular material, either by tracking particles of different density or material, or by using directly the density fluctuations of the medium to measure its velocity.

5. VELOCITY MEASUREMENT IN SQUARE SILO

To further assess the relevance of PIV tracking of density fluctuation to measure the velocity of granular flow, we perform a silo discharge experiment. This configuration is very classic in granular media and is of interest in industry. To remain in the framework of 2-dimensional flow, we use a square silo with rectangular opening (Figure 7a) full of 1mm glass beads. Figures 7b and 7c show the velocity measurements obtained by PIV on the intensity fluctuations of the radiographs taken during the discharge. The velocities measured are coherent with the discharge rate, and show a velocity profile very similar to previous experimental and numerical observations [15].

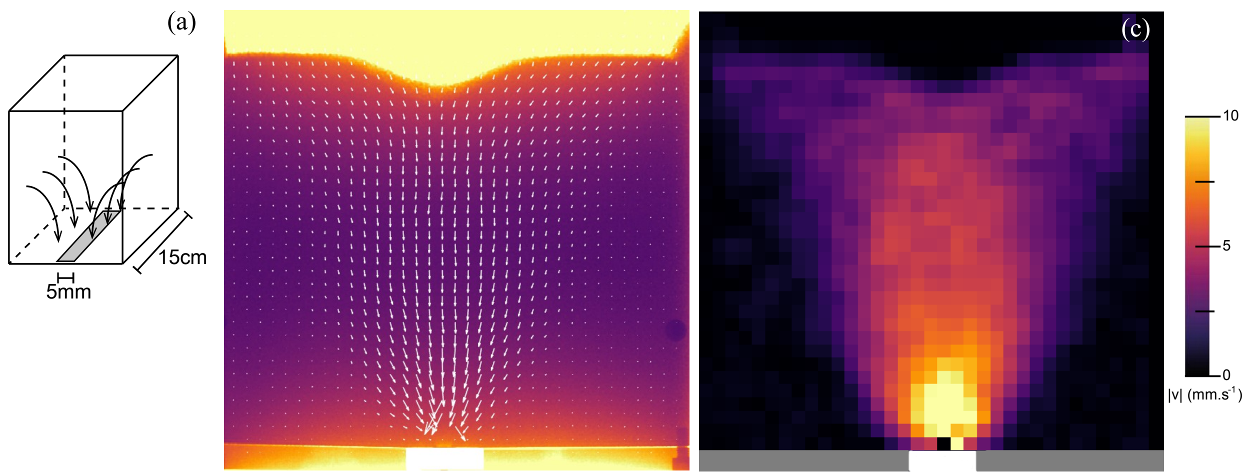

Figure 7 (a) Sketch of the Experiment (b) X-ray Image of a Silo with PIV Measurement on Top. (c) Velocity Magnitude.

6. CONCLUSION

We have presented the novel opportunities offered by the use of X-ray radiations to study granular materials far from walls or inside non transparent containers. In a rotating tumbler it is possible to track one or several intruders of different material and density, and therefore to obtain informations on their dynamics in relation with the rest of the granular material. The use of tracker particles could be extended to measure velocity of the granular medium itself, although it may be difficult to achieve trackers of same density and size than the rest of the grains with a material different enough to have a good contrast in X-ray radiography. On the other hand PIV techniques allow to follow density fluctuations of the granular material, giving the possibility to get the velocity field inside the granular material without the need of trackers, when the geometry is simple enough. These techniques open new opportunities to study bulk granular materials and could be of interest for industries in material handling or mixing for example, to have a more direct and easier view of the behavior of grains or powders during processing.

7. ACKNOWLEDGEMENT

The authors thank the ARC for grant DP160105077, funding through the Materials and Structures Research Cluster, and continuous support from the School of Civil Engineering and Faculty of Engineering & IT at the University of Sydney.

8. REFERENCES

[1] Cleary, P. W. (2000). DEM simulation of industrial particle flows: case studies of dragline excavators, mixing in tumblers and centrifugal mills. *Powder Technology*, *109*(1), 83-104.

[2] Halmshaw, R. (2012). *Industrial radiology: theory and practice* (Vol. 1). Springer Science & Business Media.

[3] Hamblin, W. K. (1962). X-ray radiography in the study of structures in homogeneous sediments. *Journal of Sedimentary Research*, *32*(2).

[4] Calvert, S. E., & Veevers, J. J. (1962). Minor structures of unconsolidated marine sediments revealed by x-radiography. *Sedimentology*, *1*(4), 287-295.

[5] Roscoe K. H. (1963). Determination of strains in soils by X-ray method. *Defense Technical Information Center.*

[6] Desrues, J. (1984). La localisation de la déformation dans les matériaux granulaires (Doctoral dissertation).

[7] Maladen, R. D., Ding, Y., Li, C., & Goldman, D. I. (2009). Undulatory swimming in sand: subsurface locomotion of the sandfish lizard. science, 325(5938), 314-318.

[8] Hall, S. A., Bornert, M., Desrues, J., Pannier, Y., Lenoir, N., Viggiani, G., & Bésuelle, P. (2010). Discrete and continuum analysis of localized deformation in sand using X-ray μCT and volumetric digital image correlation. *Géotechnique*, *60*(5), 315-322.

[9] Mueth, D. M., Debregeas, G. F., Karczmar, G. S., Eng, P. J., Nagel, S. R., & Jaeger, H. M. (2000). Signatures of granular microstructure in dense shear flows. *Nature*, *406*(6794), 385-389.

[10] Andò, E., Hall, S. A., Viggiani, G., Desrues, J., & Bésuelle, P. (2012). Grain-scale experimental investigation of localised deformation in sand: a discrete particle tracking approach. *Acta Geotechnica*, *7*(1), 1-13.

[11] Armstrong, R. T., Georgiadis, A., Ott, H., Klemin, D., & Berg, S. (2014). Critical capillary number: Desaturation studied with fast X−ray computed microtomography. *Geophysical Research Letters*, *41*(1), 55-60.

[12] Hubbell, J. H. (1982). Photon mass attenuation and energy-absorption coefficients. *The International Journal of Applied Radiation and Isotopes*, *33*(11), 1269-1290.

[13] Einstein, A. (1956). *Investigations on the Theory of the Brownian Movement*. Courier Corporation.

[14] Adrian, R. J., & Westerweel, J. (2011). *Particle image velocimetry* (No. 30). Cambridge University Press.

[15] Staron, L., Lagrée, P. Y., & Popinet, S. (2014). Continuum simulation of the discharge of the granular silo. *The European Physical Journal E*, *37*(1), 1-12.