行政院國家科學委員會專題研究計畫　期中進度報告

利用三維顆粒顯像儀分析水與土運動之研究(2/3)

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3D Particle Imaging Study of Liquid-Granular Flows and Flowslides (2/3)

NSC 91-2211-E-002-061 research project program report

Summary

The three-year research programme pursues the development of novel experimental methods for the laboratory study of debris flows and flowslides. Transparent access to the micromechanics of liquid-granular flows is sought through a combination of three components: 1) liquid and granular media with special optical properties allowing unhindered 3D imaging; 2) a tilting flume equipped with two recirculation circuits for the liquid and granular phases; 3) digital imaging algorithms allowing acquisition and analysis of the 3D particle flow field inside the bulk.

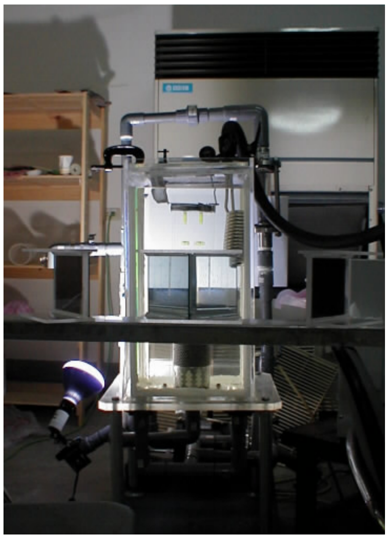
Over the programme's second year, progress has been made in all three areas. The highlight has been the successful acquisition of a set of 3D measurements of particle motions in a dense solid-liquid mixture. These measurements were made in a pilot fluidisation cell apparatus which is now fully operational. The feasibility of the measurement technique based on refractive index matching, laser marking, and stereo imaging has thus been demonstrated for the first time. A second milestone has been the completion of the large-scale double recirculation flume apparatus. Pending the solution of some technical problems, chief among them fatigue failure of the high-speed conveyer belt, the apparatus is now nearly operational. Finally, progress has been made in developing computational tools for the analysis and simulation of solid-liquid flow fields.

The results obtained and tasks remaining are detailed below under the following four headings: 1) pilot fluidisation tests; 2) double-recirculation flume apparatus; 3) three dimensional particle tracking; 4) liquid-solid flow simulations.

<u>1. Pilot fluidisation tests</u>

A successful series of pilot tests were performed using the small-scale fluidisation cell apparatus developed during the first year. The aim of these tests was threefold: to demonstrate the feasibility of refractive index matching RIM measurements; to troubleshoot materials and methods to be used later in the large scale flume; to obtain a first set of reference measurements in homogeneous flow conditions.

Through these pilot tests, the combination para-cymene / acrylic was confirmed as an excellent choice of transparent liquid-granular mixture. While the refractive indices of the liquid and solid material are already well-matched at room temperature, it was found that control of the temperature is needed to yield the best results. Precise matching of the two refractive indices, needed to minimise optical distortion, is obtained at an optimal value of 15 degrees Celsius. Temperature control is achieved by plunging a cooling circuit in the liquid bath (see Fig. 1c).



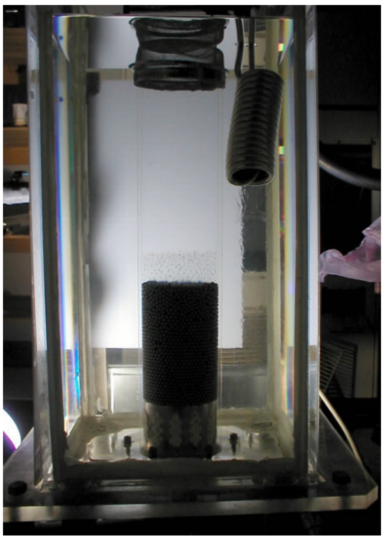


Figure 1. Fluidization cell apparatus. From left to right: a) transparent-walled device; b) lighting and stereo imaging set-up with mirror configuration; c) close-up of the inner cylindrical working section. Temperature control is achieved with the cooling coil seen on the right

Marking of the particle cores using laser etching, developed in the first year, was also found to yield excellent results. The best viewing conditions are found to be obtained using oblique backlighting, with stereo views angled at around 10 degrees. Video images obtained in such conditions yield sharply contrasted black cores on a light background. The cores are thus easily identifiable on the digital images, while at the same time being small enough to minimise occlusion effects. An example of a digital frame is shown on Fig. 2. The corresponding tracking measurements are discussed further below in section 3 of the present report.

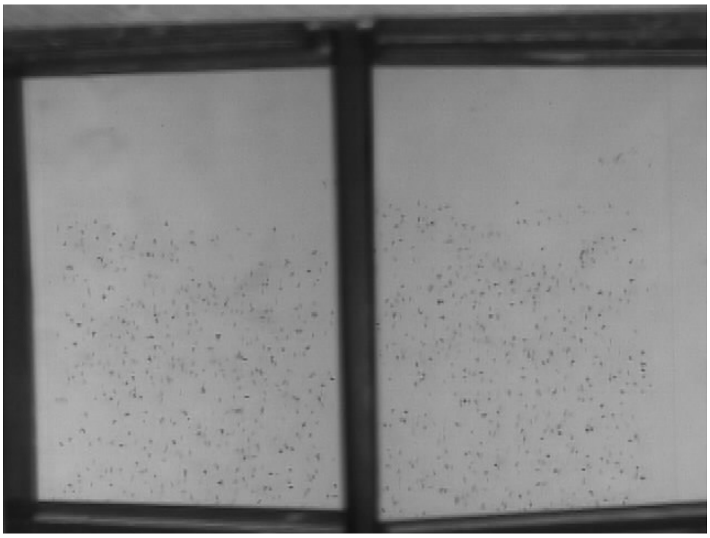


Figure 2. Sample video image of a 3D fluidisation of particles: the particle cores show up as sharp black speckles on a light background, and are identifiable in both left and right windows of the stereo image.

The tests have also highlighted various technological issues which require special care. First, wall, sealant, and piping materials must be compatible with the para-cymene liquid. The set of compatible materials was found to include acrylic, nylon, PVC, glass, stainless steel, and resin, but to exclude common sealants and plastics used for water flow experiments. Secondly, conditions of uniform liquid inflow are best approximated using a combination of expansion chamber and filtration layer of heavy particles. These results have helped guide the development of the larger scale flume apparatus discussed in the next section.

2. Double-recirculation flume apparatus

An important milestone of the full programme was reached with the completion of the large-scale flume apparatus. The double-recirculation design was implemented using materials compatible with the special RIM liquid. A view of the flume installation is shown on Figure 3. Key components include the adjustable slope, the high-speed conveyer belt for granular recirculation, and the independent pumping circuit for liquid recirculation. All three components of the device are controlled using an electronic panel. Operating parameters can be set precisely and varied over a wide range, in accordance with the design.

While the overall design was successfully implemented, difficult mechanical problems were encountered with the conveyer belt. The purpose of this belt is to entrain granular material upstream along the floor of the flume. Driven by a variable speed motor, it forms a continuous loop around the apparatus (see Fig. 3). As this belt is in direct contact with the liquid-granular mixture, its material must be compatible with the para-cymene liquid. This led to the choice of a flexible, stainless steel perforated belt entrained by solid rollers with matched pins. The original design called for a series of rollers of 10 cm diameter placed at the four corners of the flume. To form a continuous loop, the two ends of the belt must be carefully welded together.

Figure 3. Installation of the double recirculation flume.

The scheme was implemented and found successful, but only for a limited number of cycles: repeated bending of the joint as the belt curves around the rollers rapidly leads to fatigue failure (see Fig. 4). Improved endurance is obtained by subjecting the welded joint to an annealing process prior to belt installation, however joint failure nevertheless occurs after a number of cycles of the order of 1,000 to 10,000. This has forced us to reconsider the design of the belt circuit: instead of 4 small rollers at the four corners of the flume, the revised design features two large wheels of 70 cm diameter at both ends of the flume. The enlarged radius is meant to minimize bending of the belt and should allow us to gain 2 orders of magnitude in belt lifetime.

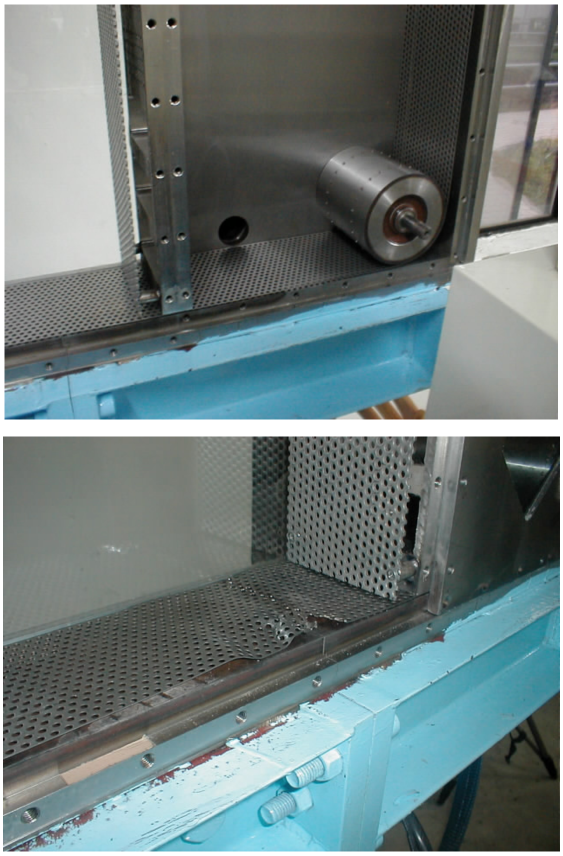


Figure 4. Fatigue failure of the welded joint of the stainless steel belt. The revised design currently being implemented replaces the small rollers at the flume corners by two wheels of large diameter.

3. Three-dimensional particle tracking

Stereo footage from the fluidization cell tests was used to derive the first set of 3D measurements of particle motions. The imaging algorithms proceed according to the following steps:

- Camera calibration (based on projective geometry) for each of the two viewpoints;
- Positioning of particle cores on 2D image frames (left and right views);
- Ray tracing and matching to position the particle cores in 3D space;
- Tracking of the particle cores in time, to obtain velocities and particle trajectories;

These algorithms have continued to be upgraded over the last year, in a cooperative endeavor pursued by our group and the University of Louvain (Belgium).

As shown on Fig. 5, preliminary results are very encouraging. A dense set of particles (of the order of 1000 particles) are successfully positioned and tracked in 3D using the above algorithms. Despite the refractive index matching and small size of the marked cores, a certain degree of occlusion remains present at such high particle densities leading to some fragmentation of the particle paths. However the track fragments are sufficiently complete to reconstitute a picture of the flow field. We expect that post-processing steps currently under development will allow us to reconnect track fragments into coherent trajectories.

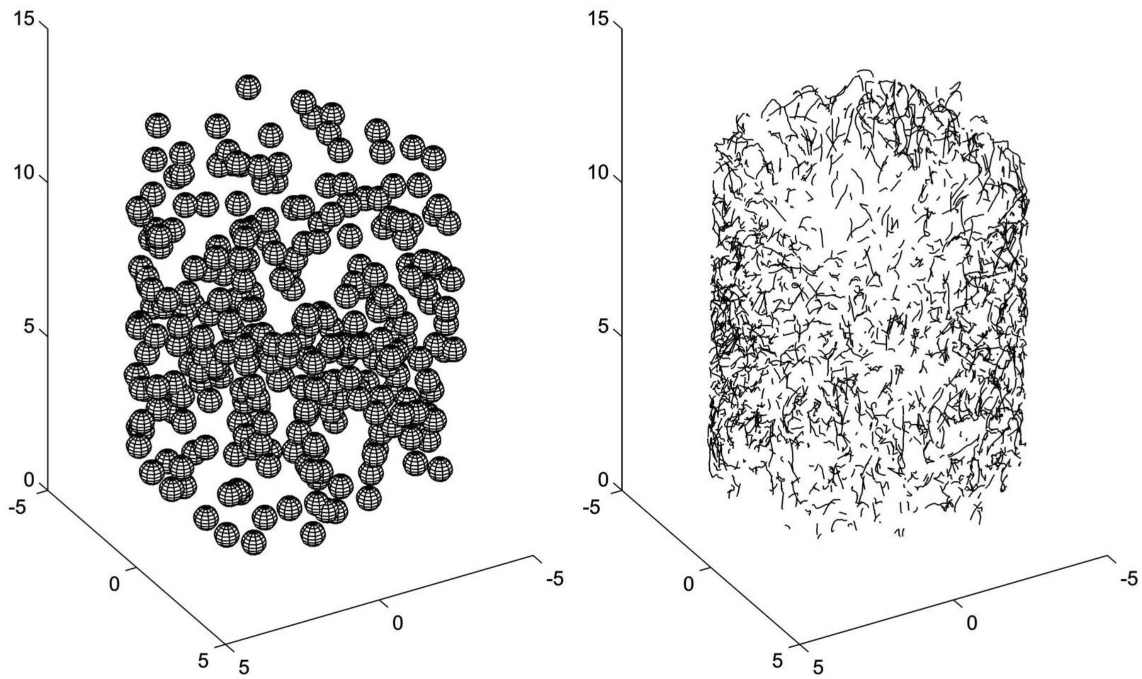


Figure 5. Preliminary 3D measurements of particle motions in the fluidization cell tests. Left: 3D particle positioning at stereoscopic ray intersections. Right: 3D particle tracks.

Thanks to the combination of RIM, laser-marking, and stereo imaging techniques, these results represent the first successful measurements of dense particle tracks at high solid fractions in liquid-granular flows. To the best of our knowledge, no comparable results have yet been documented in the literature.

4. Liquid-solid flow simulations

In parallel with the measurement effort, we have started this year to develop computational simulation tools which will facilitate the physical interpretation of the experimental results. Our efforts have focused on the development of a 3D potential flow solver describing the simultaneous motions of a large number of interacting solid spheres bathed in a liquid. The method adopted is the Method of Fundamental Solutions (MFS), a meshless approach which is particularly suitable for a flow field where solid boundaries (the surfaces of the particles) are constantly evolving. Preliminary results for 3 spheres are shown on Fig. 6.

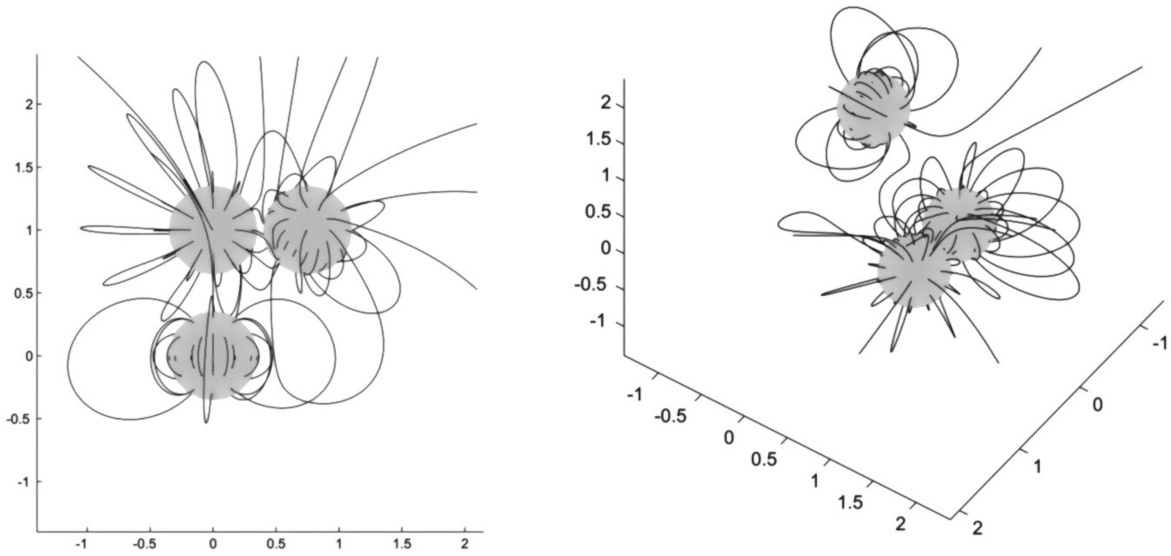


Figure 6. Calculation of the 3D potential flow induced by particle motions. Preliminary calculation involving three particles (in gray), with corresponding 3D streamlines (black lines).

By further improving both the experimental measurements and flow analysis tools, we expect to be able to probe in ever greater detail the hydrodynamic and collisional interactions within the fluidization cell. As soon as we can solve the belt problem and bring the large-scale flume on line, on the other hand, our goal will be to obtain shear flow measurements as well.