SCANNING GEOPHYSICAL HAZARDS

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Granular physics, the study of how collections of macroscopic particles behave *en masse*, helps us to model geophysical hazards like snow avalanches and landslides. Before placing trust in any predictions, we need a complete picture of how opaque grains flow. X-ray technologies provide an unobtrusive means to see beyond the surface. Whereas classical tomography does not work for moving samples, new dynamic X-ray approaches can handle genuinely flowing regimes, offering fresh insight.

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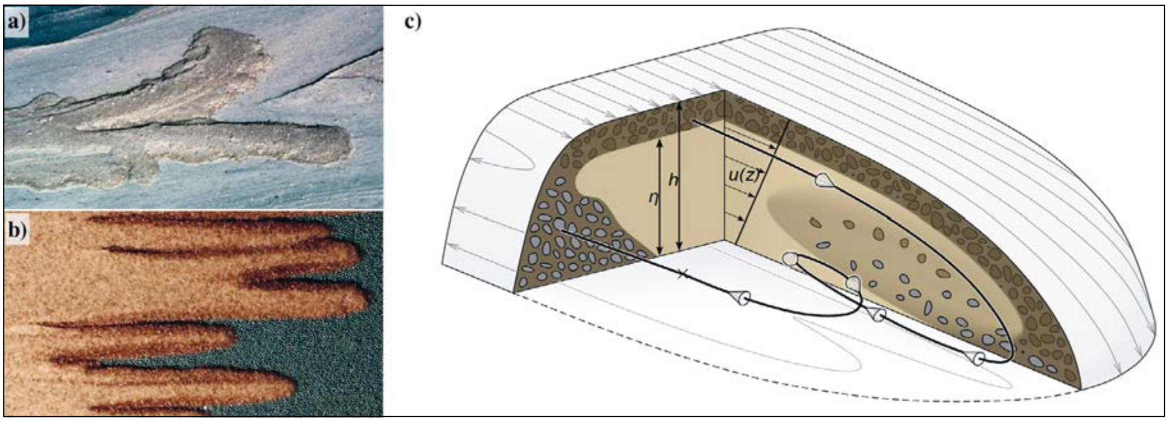
Geophysical granular flows

Geophysical hazards such as snow avalanches, debris flow landslides or volcano pyroclastic currents - fast-moving flow of hot gas and volcanic matter - can exhibit gas-like behaviour, with large powder clouds forming above the slope as well as solid-like behaviour, with grains maintaining fixed shapes in the undisturbed fringes. However, it is actually the dense flow-like regime (fig. 1a) in between the stationary and gaseous regions that causes the most damage. This has also proven to be the most difficult to decipher, and it is especially difficult to understand what goes on at the interfaces between the different zones. So, from a geophysical hazards point of view, improving our understanding of dense granular flows is an important undertaking.

Granular materials can behave like water…

Granular flows can be modelled using Newtonian fluid dynamics. This is especially true for the modelling of geophysical hazards, which are "shallow" in that the ratio of the flow thickness to downslope extent is typically small. As a result, they are amenable to depth-averaged approaches, allowing the problem complexity to be reduced by removing one spatial coordinate. Researchers have adapted the classical shallow water equations to account for the differing effective friction of granular materials to produce simple, easy-to-implement models that are still the most widely used in hazard modelling. What is more, granular flows also



▸ **FIG. 1:** Dense granular flows. a) Pyroclastic flow deposits from the 1980 volcanic eruption of Mt. St. Helens, Washington, showing two finger-like channels (source: USGS). b) Similar features observed in laboratory experiments (adapted from [2]). c) Conceptual image of the formation of such channels (source: Chris Johnson).

exhibit hydrodynamic instabilities related to those observed in water. An example is the Kapitza, or roll-wave, instability, where a fluid flow develops capillary surface waves. Similar waves have also been detected during geophysical events, as well as reproduced in small-scale granular experiments [1]. They have modelling implications because the individual pulses are more destructive than the base flow from which they develop. Another striking hydrodynamic instability in dense granular flows is finger formation (fig. 1b), where a uniformly propagating front breaks into a series of distinct channels, each travelling significantly faster and further than the uniform front. This again bears a strong resemblance to the fingering instability of viscous fluids, something we see as water runs down the outside of a window on a rainy day.

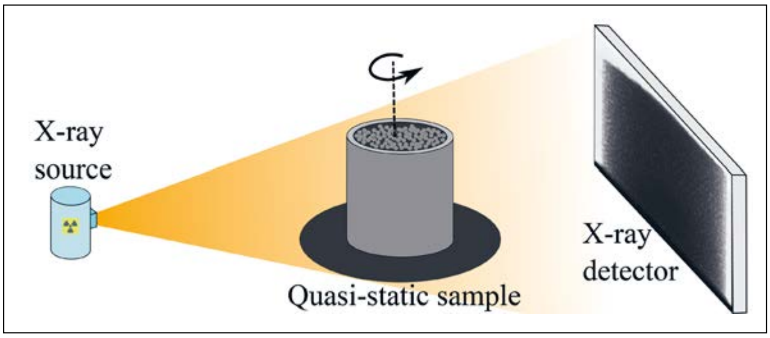
For the measurement of the velocity of a flow of granular materials the method of Particle Image Velocimetry (PIV) is used. The method was already developed in the 1980s to measure the velocity of transparent fluids. It involves the use of high-speed cameras to record successive images of tracer particles in the flow. These images are divided into 'interrogation windows', and cross-correlation analysis is employed in each window to deduce the most probable particle velocity. The tool is used to test model predictions against experimental velocity measurements and form conceptual pictures of flow mechanisms (fig. 1c).

...but things aren't always so simple

However, unlike water, granular media are highly heterogeneous with a wide range of particle shapes, sizes and material properties, that have a tendency to segregate, especially by size, which can lead to complex behaviour not present in classical fluids. The fingering instability is one such example. Whereas in classical fluids this is driven by viscosity and surface tension, in granular flows the fingers form due to particle size-segregation and increased basal friction. We therefore are forced to develop entirely new mathematical models to capture the important physical mechanisms [2]. Moreover, experimentally with granular flows optical cameras can only capture what is going on at the surface and walls and the measurements are not necessarily representative of what is really going on inside.

So how do we see inside?

A promising technique is the method of 3D computed tomography of the granular flow using X-rays as an unobtrusive method that does not require any special sample preparation. Since our ultimate aim is to measure macroscopic velocity fields, the idea is to bypass the microscopic description and directly reconstruct continuum fields. This is essentially how regular PIV works – rather than tracking each individual grain, it employs a statistical method to extract the macroscopic velocity field in each interrogation window. One can apply the principles of PIV to high-speed X-ray radiographs recorded from a single direction [5]. Combined with multiple sources and detectors a fully 3D velocity fields can be reconstructed. Such an approach was first employed in classical fluids [6], before recently being adapted to granular flows [7]. The latter method involves collecting high-speed images from three mutually perpendicular directions, and splitting each into macroscopic interrogation windows (fig. 2) For three-dimensional flows each window does not represent a single velocity - there is actually a complete distribution arising from grains at different positions in the beam path.



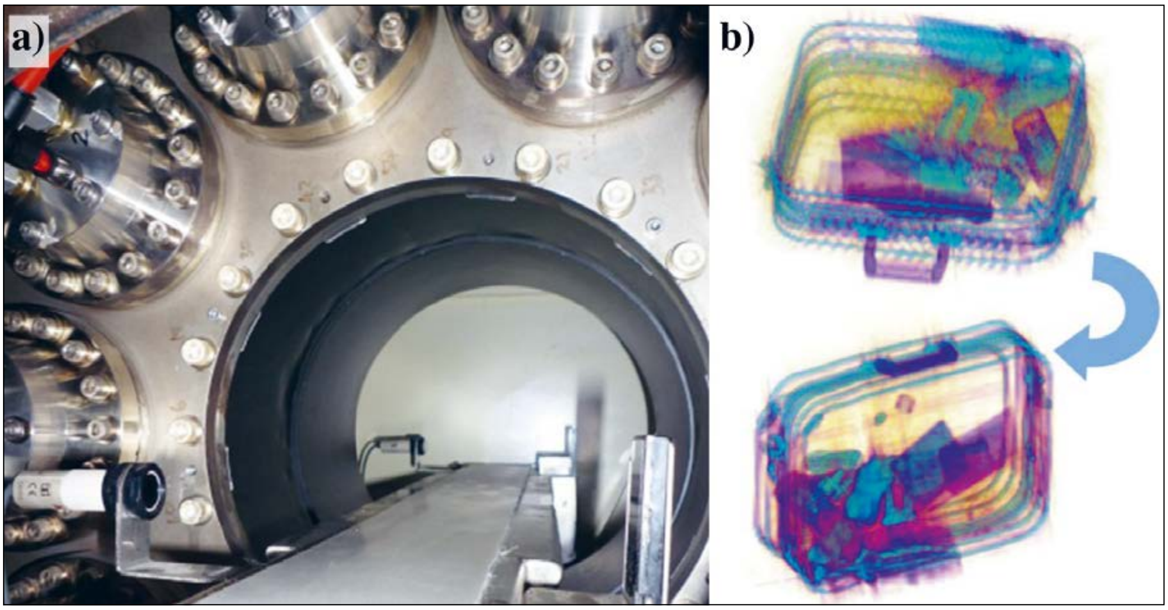
▲ **FIG. 2:** In X-ray CT the sample is typically rotated to allow radiographs to be collected from different angles.

Back to geophysical modelling

The new X-ray insights will allow us to validate continuum models with internal measurements, not just at the boundaries, and hence use small-scale experiments to make better predictions. Besides velocity fields, there are other macroscopic quantities that would be beneficial to know in 3D. The distribution of different sized particles is one such field, since particle size segregation has important implications for hazard mitigation through

INSPIRATION FROM THE AIRPORT

Some of the next generation baggage scanners currently being rolled out across the world make use of 3D tomography with multiple sources and detectors. If you've been wondering why some airport securities have suddenly decided that liquids and laptops can stay in your bag after all, it's because their new machines are now computing full 3D tomograms, as opposed to 2D radiography (fig. 3). This allows staff to easily find all items, especially when combined with automatic detection algorithms for specific objects [3]. Whilst some of these scanners resemble regular medical CT, some use a ring of sources and detectors that fire in quick succession around your bag [4], building up a 3D image one slice at a time as the conveyor continuously moves the luggage along. Could we one day see a similar approach taken in the lab to reconstruct experimental slices as grains flow through an array of sources and detectors?



▸ **FIG. 3:** a) Prototype baggage scanner that uses multiple X-ray sources and detectors (from [4]), allowing b) reconstruction of 3D images in real time (from [3]), meaning we can now leave liquids and laptops in bags at airport security.

spontaneous finger formation (fig. 1). It is certainly possible that similar reconstruction principles could be used to achieve this, allowing us to investigate segregation-mobility feedback effects from a new perspective. Currently, this is all still at the laboratory scale, and a common challenge with geophysical hazards is understanding how the granular behaviour scales up to the field. To address this researchers have conducted large-scale experiments, for example at the USGS debris flow flume [8], or installed monitoring stations to measure forces and flow heights of real events [9]. Perhaps we could also scale-up these new dynamic X-ray technologies to give the first pictures of what really goes on inside these hazards, and confirm how far our conceptual image is from the mark.

About the author

James Baker is a Postdoctoral Research Associate at the University of Sydney, Australia. He has a PhD from the University of Manchester, UK, in Applied Mathematics and an MMath degree from the University of Oxford.

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▸ **FIG. 4:** X-ray rheography. a) Flowing sample is interrogated with high-speed X-rays from three perpendicular directions. b) The velocity PDF is extracted in each window from all directions, and internal picture is reconstructed by combining different directions in process resembling a Sudoku puzzle. c) Resulting 3D reconstructions (adapted from [8]).