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Scanning geophysical hazards

Dynamic X-ray insight into geophysical hazards

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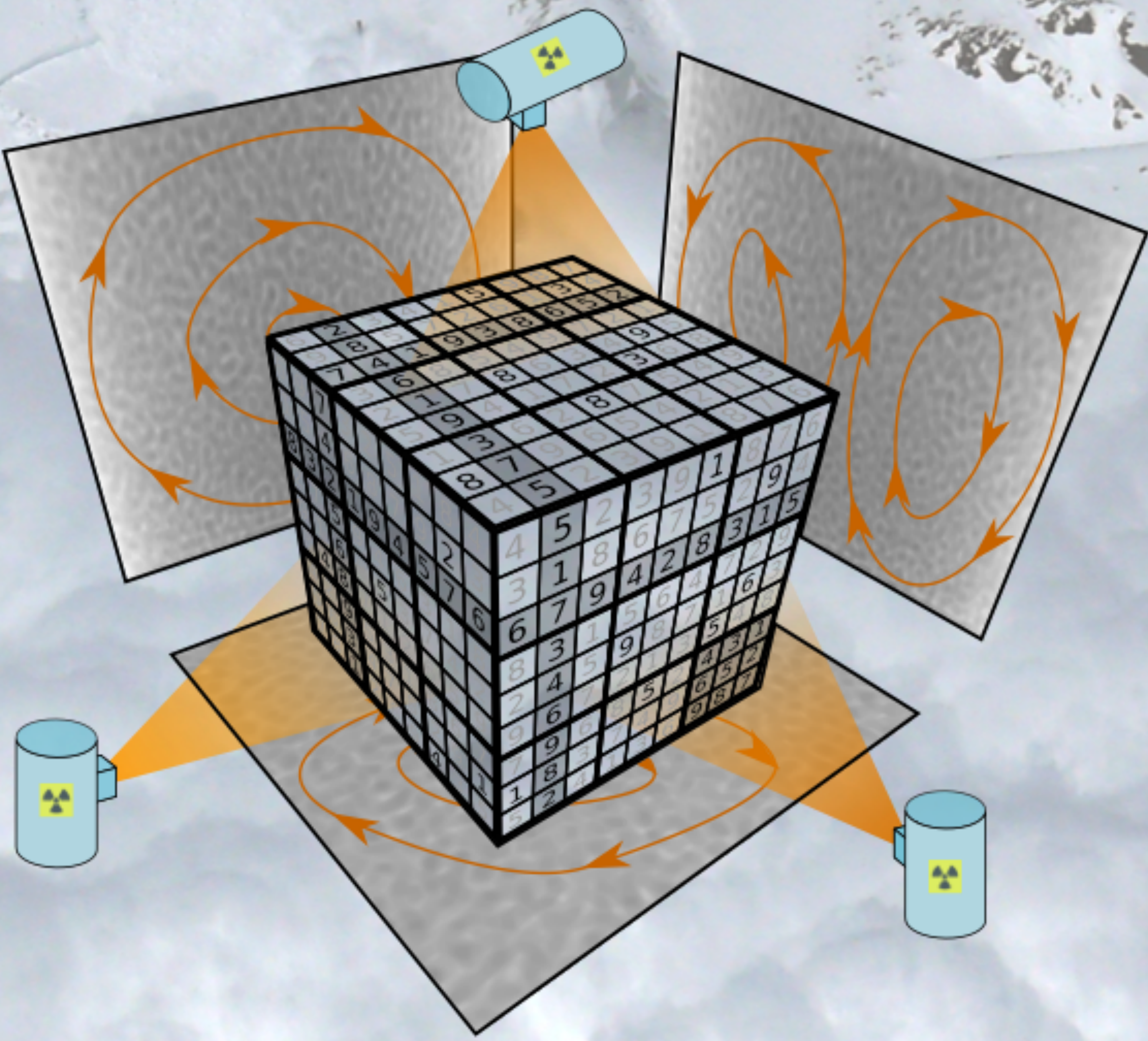

Granular physics, the study of how collections of macroscopic particles behave *en masse*, helps us to model hazards like snow avalanches and landslides. Before placing trust in any predictions, we need a complete picture of how opaque grains flow, and X-ray technologies provide an unobtrusive means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

Geophysical granular flows

Ever wondered what a snow avalanche, debris flow landslide or volcano pyroclastic current have in common? Well, these seemingly very different natural hazards are all examples of geophysical granular flows, where collections of discrete macroscopic grains (in this case snow, soil or rock), interspersed with fluid (air, water or hot gas) travel down steep mountain slopes, causing widespread destruction to anything in their path. These hazards can exhibit gas-like behaviour, with large powder clouds forming above the slope (often the first indication that something is amiss), 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. On a parallel note, granular media is also the second most commonly used industrial material (behind water), with dense granular flows popping up everywhere in the handling of pharmaceutical powders, mining minerals, and agricultural grains. The same knowledge can therefore help design industrial chutes and predict the path of environmental hazards, which has drawn many researchers to dense granular flows in the past 50 years.

Granular materials can behave like water.......

Much progress has been made in granular flows research by drawing inspiration from the most ubiquitous material of all – water. If you tip a bucket of dry sand the grains can be poured like water, and there are many more granular phenomena that have analogues in Newtonian fluid dynamics. Granular physicists can therefore borrow and adapt ideas from this classical research field. 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 exhibit related hydrodynamic instabilities to those observed in water. Take 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.

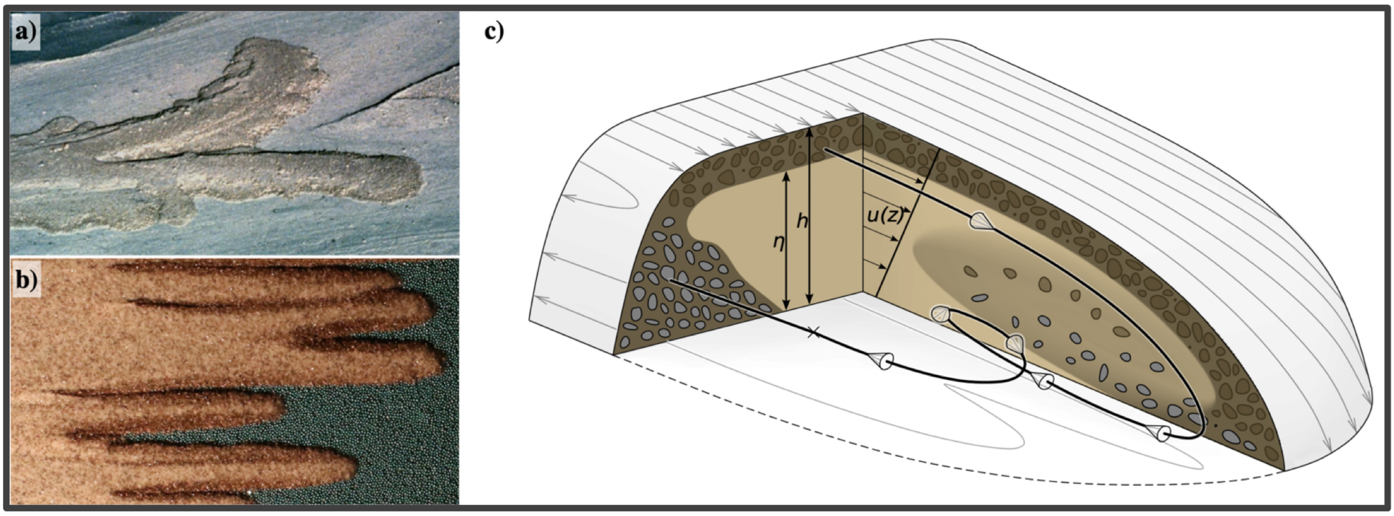

Fig. 1: Dense granular flows. a) Pyroclastic flow deposits from the 1980 volcanic eruption of Mt. St. Helens, Washington, showing two finger-like channels (source: USGS). b) Similar features observed in laboratory experiments (adapted from [2]). c) Conceptual image of the formation of such channels (source: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

We can also draw inspiration from the classical fluids community as to how to experimentally measure flowing granular materials. One method worth highlighting is particle image velocimetry, or PIV for short. This was developed in the 1980s to measure the velocity of transparent fluids. It involves seeding a liquid with tracer particles and illuminating a plane of interest with a laser sheet. A high-speed camera is then used to record successive images of the seeded fluid. These images are divided into 'interrogation windows', and cross-correlation analysis is employed in each window to deduce the most probable particle velocity, and by assumption fluid velocity. PIV has now been widely adopted in granular flow experiments, and actually has the advantage that the grains themselves act as the tracer particles and no laser sheet is required. We can therefore use this tool to test our model predictions against experimental velocity measurements, and form conceptual pictures of flow mechanisms (fig. 1c).

…….but things aren't always so simple

Unfortunately (or fortunately, depending on your viewpoint) things are inevitably more complicated because granular media are not, in fact, exactly like water. Rather than consisting of just one type of grain, they are typically highly heterogenous with a wide range of particle shapes, sizes and material properties. These constituents 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].

There are major experimental challenges as well. At the risk of stating the obvious, the majority of granular materials are opaque. Unlike water flow experiments, where the laser can highlight any part of the flow, optical cameras can now only capture what is going on at the surface and walls. Boundary layer effects mean that PIV measurements here are not necessarily representative of what is really going on inside – a problem if we want to validate 3D models.

So how do we see inside?

Not to be too disheartened, the ever-enterprising scientific community has adapted a range of methods to get around this, including refractive index matched scanning, positron emitting particle tracking and magnetic resonance imaging. Arguably one of the most promising techniques is X-ray computed tomography (CT), originally developed for the medical community. CT is unobtrusive and does not typically require any special sample preparation. It works on the principle that X-rays are attenuated by different amounts as they pass through different materials, with the intensity I recorded at the detector being approximated by the Beer-Lambert law:

$$I = I_0 \exp\left(-\int_l \mu \, \mathrm{d}l\right),$$

where I_0 is the source intensity and μ the attenuation coefficient at each point in space, a proxy for density. Since each X-ray radiograph only gives the value integrated along the path l of the beam, numerous scanning directions are used to reconstruct 3D density maps, called tomograms. In medical applications, these different directions are obtained by rotating the X-ray source and detector, but in non-medical CT, where we don't have to worry about the grains feeling nauseous, the sample itself is usually rotated (fig. 2). For stationary samples, X-ray CT allows us to visualise individual grains in fine detail. One can then deform the sample by applying an external load, scan again and track microscopic grain-level displacements between scans [3]. Such particle-level information can then be fed into macroscopic continuum-level models.

The problem with this established technology is that the process of acquiring multiple radiographs takes time. If the sample moves significantly during acquisition, which would be the case for continuously flowing grains, then CT simply won't work. It is thus restricted to quasi-static deformations. To get around this you might think we could reduce the time by spinning faster. However, another factor then comes into play. Maybe the grains don't feel nauseous during rotation, but they do feel centripetal acceleration. Specifically, the acceleration a_c felt by an element rotating with

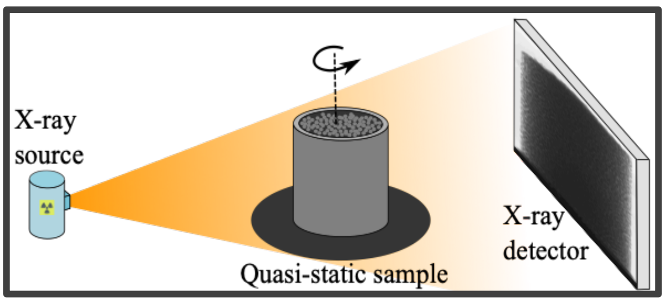

Fig. 2: In X-ray CT the sample is typically rotated to allow radiographs to be collected from different angles.

frequency f at a distance r from the centre of rotation is:

$$a_c = 4\pi^2 f^2 r.$$

For grains not to have moved too much we require $f \gg \frac{v}{\mathrm{d}x}$, where v is the particle speed and $\mathrm{d}x$ the desired spatial resolution of the reconstruction. Using modest values of v = 1 mm/s, $\mathrm{d}x$ = 1mm and r = 100 mm already gives large values $a_c > 40$g, enough to rip most samples to shreds! Thus, spinning experiments as they flow is not an option without seriously changing the dynamics.

So, is there any hope of utilising X-rays to study genuinely flowing grains? One option could be to use multiple sources and detectors. This is the approach being taken by some of the next generation baggage scanners currently being rolled out across the world. If you've been wondering why some airport securities have suddenly decided that liquids and laptops can suddenly stay in your bag after all, it's because their fancy 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 [4]. 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 [5], 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?

Another approach that has already been utilised to good effect is to forget tomograms altogether. Since our ultimate aim is usually macroscopic fields, the idea here 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 also apply the principles of PIV to high-speed X-ray radiographs recorded from a single direction [6]. Due to the integrated nature of radiography, this now gives a measure of the 'beam-averaged' in-plane velocity in each window, not just at the walls, and thus represents an improvement over optical images.

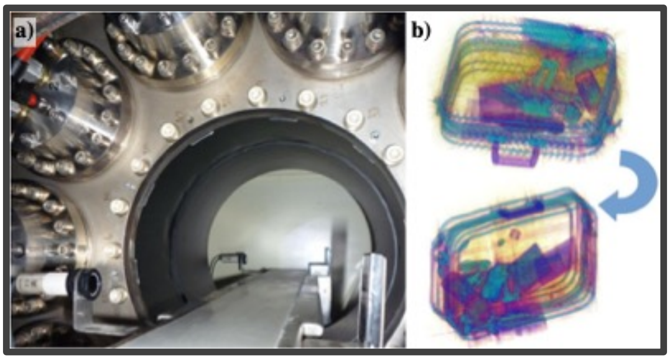

Fig. 3: a) Prototype baggage scanner that uses multiple X-ray sources and detectors (from [5]), allowing b) reconstruction of 3D images in real time (from [4]), meaning we can now leave liquids and laptops in bags at airport security.

Where does Sudoku come in?

This PIV approach can be combined with multiple sources and detectors to use X-rays to reconstruct fully 3D velocity fields. Such an approach was first employed in classical fluids [7], before recently being adapted to granular flows [8]. The latter method involves collecting high-speed images from three mutually perpendicular directions, and splitting each into macroscopic interrogation windows (fig. 4a). Now, 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. This full distribution can be extracted using convolution and correlation analysis. This gives a lot more information, but a single direction taken in isolation doesn't give any out-of-plane information. However, combining the results from two perpendicular directions results in a highly constrained system. The problem is then how to consistently arrange the two sets of observations to reconstruct the internal flow field (fig. 4b-c). This is like solving a giant *Sudoku* puzzle, since we know which elements go in each row and column but have to figure out the exact order.

Now…….back to geophysical modelling

So, where does all of this put us in the context of geophysical hazards? Well, these 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 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.

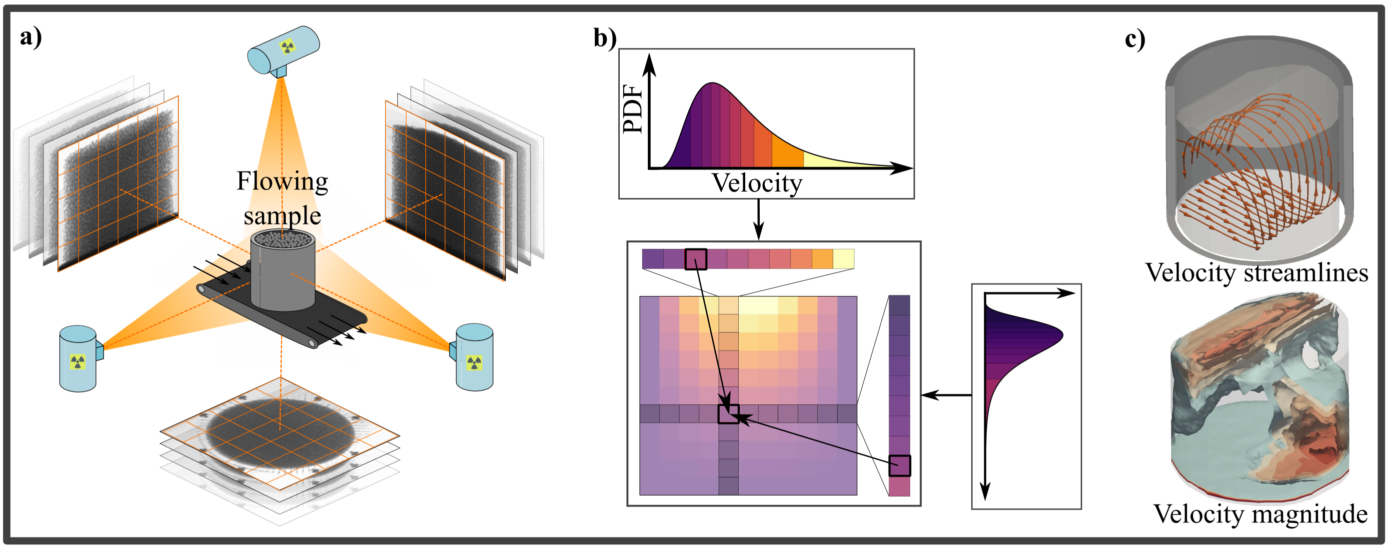

Fig. 4: X-ray rheography. a) Flowing sample is interrogated with high-speed X-rays from three perpendicular directions. b) The velocity PDF is extracted in each window from all directions, and internal picture is reconstructed by combining different directions in process resembling a *Sudoku* puzzle.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

Of course, 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 [9], or installed monitoring stations to measure forces and flow heights of real events [10]. 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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