Understanding avalanches

Avalanches kill about 150 people a year. **Christophe Ancey** and **Steve Cochard** explain how new laboratory experiments in fluid dynamics could help to reduce this number

The first half of the 1998/1999 ski season in the Chamonix Valley in France had been cold but brought little snow. When snow eventually arrived at the end of January, owners of ski resorts breathed a sigh of relief, but for many the change in the weather was to prove deadly. On 9 February, following a storm and several uninterrupted days of snowfall, a huge avalanche descended on the village of Montroc, destroying 20 houses and killing 12 people in their chalets. The next few weeks saw thousands more avalanches across the Alps and another 70 people killed.

Although 1999 was a bad year for avalanches, with some 200 people killed worldwide, it was not exceptional. The growth in winter sports has led to a significant increase in avalanche deaths over the last few decades, and in the 2005/6 season over 300 people lost their lives. Indeed, this past winter has seen some 55 killed in the French Alps alone.

For well over a century, scientists have been studying avalanches to try to improve predictions of when they will occur and to optimize defences against them. But we still do not know precisely what combination of physical conditions gives rise to avalanches and what exactly governs the way they flow. To tackle this problem, several groups of researchers are attempting to recreate avalanches in the laboratory and outdoors, in the hope that data from their experiments will allow them to build sophisticated computer models of exactly what happens in an avalanche.

Better models needed

Most catastrophic avalanches follow the same basic principle: fresh snow accumulates on the slope of a mountain until the gravitational force at the top of the slope exceeds the binding force holding the snow together. A solid slab of the surface layer of snow can then push its way across the underlying layer, resulting in an avalanche. Typically, avalanches travel for a few hundred metres, but they can move up to 15 km and achieve velocities as high as 200 to 300 km h^{-1}. They can also pack an incredible punch – up to several atmospheres of pressure. At Chamonix, for example, an avalanche destroyed a concrete barrier 7 m high and 1.5 m thick.

Unfortunately, our ability to predict when avalanches will occur is limited because the weather conditions that give rise to them are far from clear cut. For example, both significant rises and falls in temperature can trigger an avalanche. It is also difficult to construct defences against avalanches because we only have a limited understanding of how they flow. Building walls to either stop or divert avalanches requires a knowledge of how far a potential avalanche is likely to travel, how fast it will be travelling when it reaches the barrier and how broad it will be, for example. But predicting these things is still quite hit and miss.

Devastating
Rescue teams try to find victims of an avalanche that hit the village of Montroc in the Chamonix Valley in France in 1999. The avalanche killed 12 people and destroyed 20 houses.

One simple model, first proposed in the 1920s and still used in a modified form by engineers today, assumes that avalanches behave like sliding blocks. A more realistic generation of models, first put forward in the 1970s by Soviet researchers Sergei Grigorian and Margarita Eglit, relies instead on an analogy with flash floods and uses equations that describe the motion of water waves.

All current numerical models of avalanches use the water-wave analogy, but they still do not provide a rigorous physical description of avalanches. One particular problem is that snow generates much more friction (and therefore dissipates more energy) as it travels over a surface than water does. Whereas the coefficient of friction for flowing water has a standard value (based on the viscosity of water), each avalanche has a different coefficient. Since in most avalanche-prone areas there are no historical measurements of avalanche parameters, the only way of calculating the coefficient for a particular potential avalanche is to extrapolate the values from the measurements of past events that are likely to have similar characteristics. This extrapolation requires good physical intuition and many years' experience of studying avalanches.

It has therefore become increasingly clear that researchers need more physical information if they are to make their models more realistic. In the 1990s researchers in Norway, Switzerland and elsewhere set up systems to collect data about variations in the velocity, depth and mass of avalanches that are triggered under controlled conditions. Unfortunately, the techniques used to measure these parameters are limited. By

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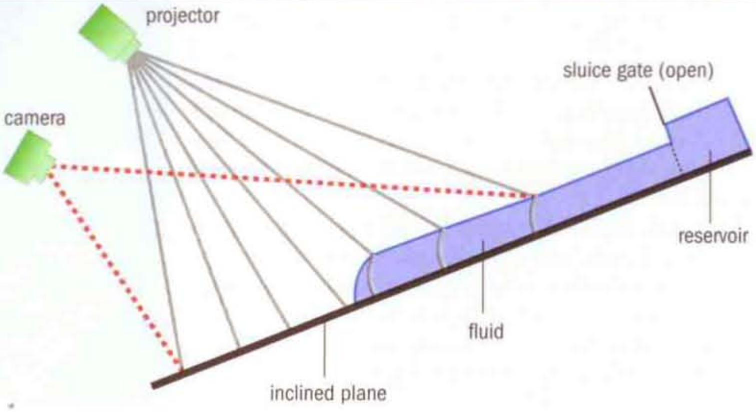

Measuring avalanches A prototype sensor (above left) used to make measurements of an avalanche's velocity, temperature, density and other parameters has been developed by scientists at the Ecole Polytechnique Fédérale de Lausanne in Switzerland. These sensors are encased inside high-resistance polycarbonate shells and can be dropped onto the mountainside by helicopter from where they relay data to a central computer using radio waves. Meanwhile, the present authors have developed an experiment (above right) that involves releasing a polymeric gel onto an inclined plane in order to simulate the motion of an avalanche down a mountainside. A camera records the distortion of a series of lines projected onto the fluid by a projector (right).

processing video images of a moving avalanche we can obtain useful information on the shape and velocity of the avalanche. But often these measurements relate only to the airborne cloud of snow that surrounds the avalanche and not to the slower moving, and more significant, core. While non-intrusive methods such as Doppler radar can provide information on the core, deciphering the signals from such systems is difficult.

To overcome these limitations, our colleagues Edoardo Charbon and Luciano Sbaiz at the EPFL in Switzerland are developing egg-sized sensors. The plan is that a helicopter will drop some 20 to 30 sensors along a snow-covered slope to track the velocity inside an avalanche and provide other information that has not previously been available, such as temperature and density. These sensors, which will be located using triangulation techniques and relay data to a central computer, will also be much cheaper than existing detectors and can therefore be distributed more widely, including at high altitudes. The researchers hope to be able to carry out experiments with real avalanches in a couple of years.

Turning to the lab

Even with such advanced sensors, however, there are inherent drawbacks in measuring real avalanches. For example, triggering and controlling an avalanche is difficult. Also, it is possible that almost all of the egg-sized sensors will remain above ground and will not be whipped up into the core of the avalanche as hoped. Even then, the snow is likely to strongly attenuate the electromagnetic signals emitted by the sensors and so limit the data that emerge from the experiments. More fundamentally, researchers are at the mercy of the prevailing conditions and cannot measure the effect of a single parameter on the formation or evolution of an avalanche while holding the others constant. This is particularly problematic when trying to measure the change in an avalanche's speed over time or the variation in density across the layers of snow.

To get over these drawbacks, the present authors have chosen to simulate fluid avalanches in the laboratory, and model them using equations that can be applied to a vast range of flow phenomena, from rockfalls to rivers. To carry out the simulations we have built a platform consisting of two inclined planes: an upper plane 4 m long; and a lower, shallower, one, which is 2 m long. Into a box placed over the upper plane we pour Carbopol, a polymeric gel very much like hair gel that has similar properties to snow (we do not use snow itself as it melts too quickly). The gel is then released onto the upper plane via a quick-opening sluice gate. The fluid accelerates rapidly, at times entering a pseudo-equilibrium state where the velocity of its flow is nearly constant, and finally decelerates quite quickly after reaching the lower plane.

Unlike experiments with real avalanches, this set-up allows us to make measurements throughout the moving fluid. We can fully control the initial and boundary conditions – for example, we know that the initial shape of the fluid is rectangular, since it is contained in a box. We can also control the nature of the flowing material – its density, surface tension, viscosity etc – and the flow geometry, such as the inclination and length of the channel. In addition, we are able, in principle, to analyse highly complex, non-equilibrium, nonlinear flows, which can be generated by, for example, varying the rate at which the fluid leaves the sluice gate or using sand instead of a liquid.

However, measuring the evolution of the flow is difficult because of changes in the shape of the leading edge and the velocity of the material. To try and overcome these problems, we have developed a system consisting of a high-speed digital camera coupled to a projector. The latter illuminates uniformly spaced dark and light stripes onto the surface of the flowing fluid (see figure), and the camera records how these patterns are deformed by the moving surface, in terms of the phase shift in the pattern (i.e. the change in the relative position of the dark and light stripes). Algorithms then convert this phase shift into a thickness, with an accuracy of 0.1 mm over a surface area of $1.8 \times 1.1\,\mathrm{m}^2$. Moreover, comparing two successive images provides a measure of the change in the fluid's velocity. Preliminary tests have shown that the system performs well, but we are working to reduce the time needed to process the measurements. We hope to publish our first results later this year.

Meanwhile, Richard Iverson and Roger Denlinger at the US Geological Survey in Washington State have designed a small-scale version of our device that has an uneven surface to simulate granular flow. Their aim is to test a numerical model based on the flood analogy and in which energy is assumed to be dissipated through particle friction. Olivier Pouliquen at the University of Provence in Marseille, France, has also carried out experiments on granular avalanches in a steady state to infer the relationship between the velocity of the leading edge and the depth of the avalanche. And Kolumban Hutter and Shiva Pudasaini at the Technical University of Darmstadt in Germany used a twisted channel to investigate how a terrain's curvature affects the motion of granular masses in an avalanche.

Are we crazy?

Some scientists think that trying to mimic natural flows in small-scale experiments is doomed to failure, and that it is better to carry out intermediate-scale experiments that use natural materials. Iverson and Denlinger, for example, have built a channel 95 m long and inclined at 31° in order to simulate the flow of stones and other debris. At the Swiss Federal Institute for Snow and Avalanche Research in Switzerland, Martin Kern uses a channel 34 m in length to investigate flowing snow. Meanwhile, Yasuaki Nohguchi of Kyoto University and Jim McElwaine of Cambridge University in the UK have investigated how a dense avalanche can become airborne by releasing large numbers of table-tennis balls down a ski jump.

Given the experiments carried out so far, however, there is no clear evidence that there are scaling problems with gravity-driven flows. More fundamentally, the equations currently used for modelling natural flows hold for any scale. In this respect, it is shrewder to conduct cheaper and more controlled experiments in the laboratory. If we are not able to derive equations of flow in a well-controlled environment, there is little hope of modelling geophysical flows in the great outdoors.

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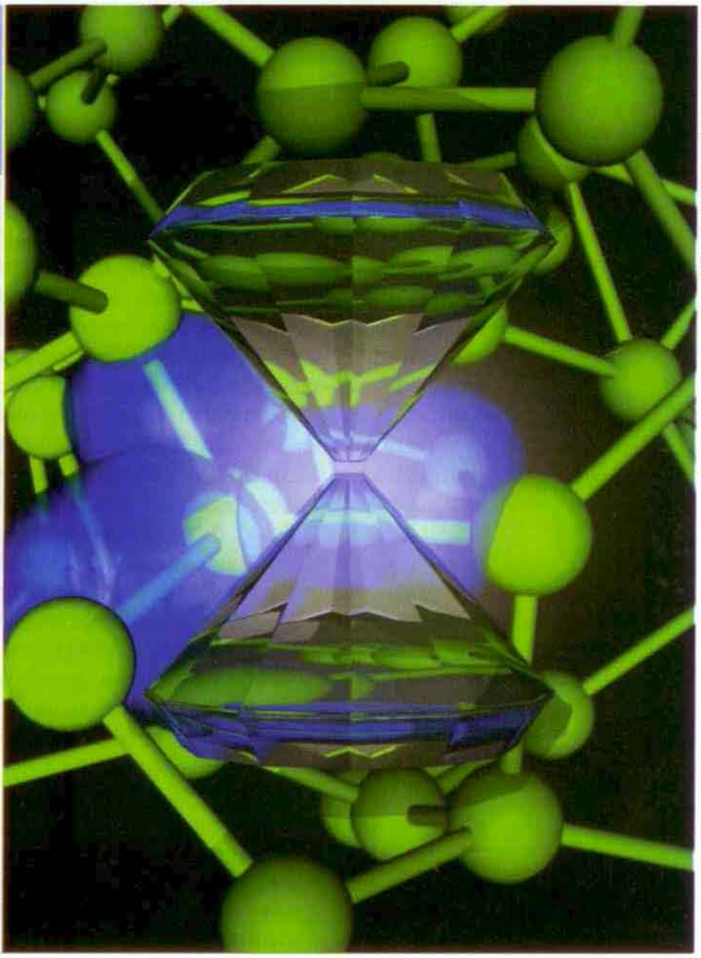

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