

The Royal Society of Edinburgh
Structures and Granular Solids
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30 June 2008

Grains of truth

You may think that pouring grain into a silo then getting the grain out is not exactly rocket science, but you would be wrong. Not only do the problems of structures and granular solids have much in common with the challenges faced by designers in the aerospace industry, but the mathematics are so complex that the world's most powerful computers have not yet come up with the answers...

In his free time, Professor Michael Rotter goes on “buckle hunts” to search for examples of damage to silos. He may spot only a slight dent or what looks like a small crack, but in the wrong place and of the wrong shape, the damage may indicate impending disaster for the structure. In turn this has implications for human safety and may involve huge sums of money when the industrial process being fed by the silo is arrested.

According to Professor Rotter, more than 60 per cent of all the materials used in industrial processes (e.g. food processing, steel making, cement, plastics and pharmaceuticals) comes in the form of small particles – powders or granular solids. Huge quantities of these materials, including plastic pellets, coal, mineral ores, maize, barley and sugar, are stored in different types of silos, and the containers suffer structural failures much too frequently.

Rotter's ultimate aim is to improve the design of containers to make them both safe and economic, but the problem is that neither engineers nor scientists properly understand the behaviour of granular solids when they flow out of a silo, or their interaction with the structures used to store them. “Solids are anisotropic and inhomogeneous,” he said – in other words, even a single type of granular solid (e.g. coal) can vary in shape, size and texture, leading to radical changes in the way it flows. Fluids, by comparison, are relatively simple to understand, mainly because they are homogeneous and uniform.

The simple fact, said Rotter, is that when it comes to storage, the containers must be able to survive the most extreme conditions and events in their lifetimes, including wind, earthquake and storing sticky solids. Quite simply, they must not fall down, buckle or burst when subjected to complex patterns of internal or external pressure, and especially under the frictional drag of the solids sliding against the wall. Moreover, the granular solids must flow out smoothly when required.

Rotter has had a passion for applied mathematics and physics throughout his career, and takes what he calls an “holistic view” of structural collapse, recognising that the individual parts of each structure affect each other strongly, so that a strength assessment based on looking at one part at a time is often quite misleading. His research focuses on problems such as plastic collapse and the effects of unsymmetrical pressures in silos. These pressures cannot yet be predicted using computational models because the appropriate equations to describe granular solid flow (like salt pouring out of a salt pot) have not yet been successfully formulated – it is not just the behaviour of the solid and the structure individually that must be modelled, but also the complex interactions between them. For example, said Rotter, the most powerful computers are capable of analysing the mechanical behaviour of about 10^6 particles inside a silo, but a typical silo contains between 10^9 and 10^{13} particles, so we still have a long way to go. The simplest route for computers to model this dynamic process is the development of a satisfactory “continuum theory of the flow of solids”, so that the huge number of particles involved do not pose a major problem. However, such a continuum theory remains elusive at the present time and is one of the big challenges for applied mathematics.

Perhaps the fact that Rotter's grandfather invented the high explosive RDX explains his fascination with the dynamics of collapsing containers filled with powder, but he also explained how his studies and career have steered him into this specialist area, via subjects such as plasticity in soil

mechanics, his Thesis on '*Continuous composite columns*' and many industrial problems involving steel and concrete structures, collapse, material failure and buckling.

Rotter uses colourful and esoteric language such as 'biaxial bending', 'elastic flexural restraint', 'flow zone geometry', 'axial compression' and 'elephant's foot' buckling, but the simple purpose of these unfamiliar concepts is to gain understanding of what goes wrong in each individual case when a structure falls down, and to prevent that problem from happening again. In Australia, where he did research after his studies in Cambridge, he analysed many real-life disasters, beginning with the bursting of a grain silo when the grain swelled with moisture uptake, fatigue cracks in a coal silo, and stress analysis of beer fermentation tanks. Industry was queuing up for practical advice.

As Rotter explained, it is hard to observe what is happening when silos burst or fall down, because the problems tend to appear very suddenly and the moment of failure is always a shock. You usually see the results of disasters when it's much too late to stop them and working out what happened just before the collapse, when all that is left is broken pieces on the ground under a huge pile of grain, is often real detective work.

The design of silos used to be based on 'rules of thumb' but Rotter not only applied mathematics and physics but also the knowledge developed by the aerospace industry, and then went on to draw up a series of international industry standards, first in Australia and later in Europe and the USA, turning academic research into practical guidelines. Later this year, for example, the European Convention for Constructional Steelwork will publish its new design recommendations on the buckling of shells under his chairmanship.

The research on shell structures always finds new applications, the latest of which are two Scottish projects. One concerns a wind tower climbing device called the 'Orangutan'; the other a new pipeline structure called the 'Helipipe' – a super high-strength steel, helically- wrapped pipeline, with a stainless steel liner for maximum strength and flexibility.

The questions facing the designer of silos are not only how to design a better structure but also how to fill the silo and empty it. How will the material flow inside the structure? Where will the pressure be greatest, and where lowest? How will the structure be stressed by complex pressure patterns? What conditions will cause catastrophic buckling failures?

Even though he has been able to transform his experiments into a set of design rules, in pursuit of "a conceptual framework for all types of structural systems", Rotter says that "neither the experiments nor the current theories are even close to correct" when it comes to real-world answers to the problems of granular solids and structures, despite all the statistical analysis and computational models devised by researchers. The reasons lie in scale effects and instrumentation difficulties in experiments, and misunderstandings in most theoretical models. Engineers and applied scientists like Rotter have advanced our understanding of structural failure, but he himself admits that phenomena such as 'shell buckling' are still tricky to analyse because very small deviations in different forms can either radically weaken the structure, leading to disaster, or have little effect, depending on the circumstances.

For the climax of his lecture, Professor Rotter brought together his different themes of granular solids flow, complex pressures on the structure and buckling behaviour of shells, to do a 'live' experiment that demonstrated the complex and unpredictable nature of silos. Using four transparent model silos filled with sand, each about one metre high, Rotter proceeded to empty them in sequence to observe the effects of symmetrical or unsymmetrical discharge. The first 'silo' emptied its sand through an outlet beneath its centre, with internal flow and a relatively even pressure pattern, producing an uneventful and safe outcome. By contrast, the other three silos were emptied from outlets that were slightly or severely off-centre, and each produced a catastrophic and disastrous collapse, shedding the sand contents all over the floor!

Rotter's final silo experiment may have gone slightly wrong, as the collapse of one silo appeared to cause some damage to its neighbour, possibly making it more likely to collapse. But after listening to his lecture, the way this happened seemed to confirm that the real world may long continue to defy the predictions of mathematical models of perfect systems, especially when it comes to structures and granular solids.

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