GRANULAR PHYSICS

A bridge to sandpile stability

Wet sand is more stable than dry sand, but exactly how this greater stability arises has been the subject of considerable discussion. Conflicting ideas are now unified by a hybrid theory that considers both surface and bulk properties of a sandpile.

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A collection of macroscopic solid grains has rather different physical properties from either a bulk solid or a liquid. For example, dry sand in a bucket can be poured like a fluid, but it can also support the weight of a rock placed on top — even if the rock is denser than the sand. Such granular materials are vital to industries ranging from mining to pharmaceuticals, and their unusual physical properties have become the subject of a growing field of research[1]. Although most of this research focuses on dry grains, every child building a sandcastle (see Fig. 1 for a spectacular example) knows that the properties of a sandpile change wonderfully when the sand is wet. The collective behaviour of wet grains is only beginning to be explored[2]. On page 50, Sarah Nowak *et al.*[3] take a notable step forward in understanding the most basic property of wet grains, providing a theory and accompanying data that clarify the role of liquid in improving the collective stability of a granular pile.

A small amount of liquid added to a dense granular material will form 'bridges' at the contact points between the grains. The surface energy of those bridges leads to an attractive force between the grains, which is absent in dry granular materials. Therefore, wetting changes a granular system from one with only repulsive intergrain interactions to one with both repulsive and attractive interactions. Given that the microscopic physical interactions are so radically changed in wet grains, it is not surprising that their macroscopic behaviour should also differ.

A granular sample has two characteristic angles: the angle of repose, which is the slope after a pile fails; and the maximum angle of stability, which is the largest slope a pile can achieve before failure occurs. The addition of even minuscule amounts of interstitial liquid to a granular material greatly increases these angles because of the cohesion between the grains[4–7], which is why sandcastles are invariably built with wet sand. But experimental results can depend on the nature of the liquid, as well as the size and surface of

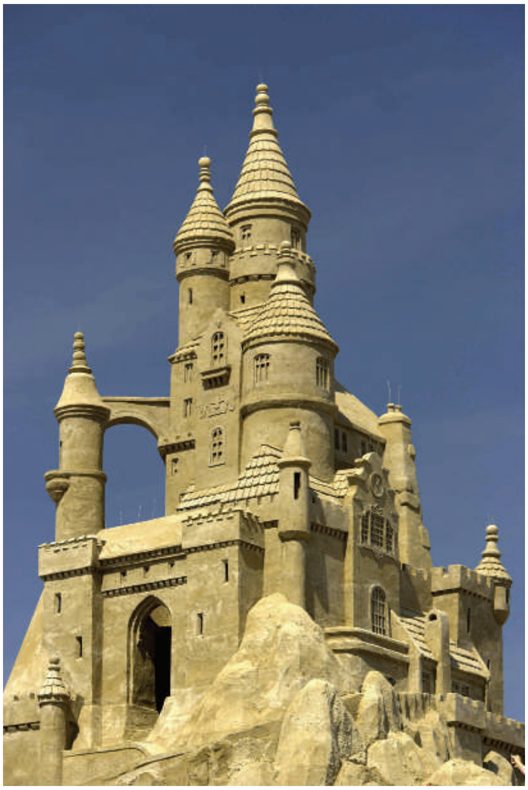
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Figure 1 Fairytale castle: wet sand required.

the grains, and the dimensions of the container used for the measurement, so a detailed understanding has been difficult to attain. Some initial data could be understood within a model based on the stability of the grains on the slope surface, whereas others seemed more explicable by models of failure within the bulk of the material.

Nowak *et al.* studied this problem with a transparent rotating drum apparatus — effectively a hollow wheel — partially filled with grains and rotated slowly around a horizontal axis. As the wheel rotates, the grains avalanche down the surface whenever the slope exceeds the maximum angle of stability, which is measured optically. The authors then developed a theoretical description of the maximum angle of stability, combining surface stability considerations with the nature of failure within the bulk of the material. They found they could fit their data exceptionally well with this hybrid theory, including data for different diameter drums, grain sizes and interstitial fluids. This is the first theory for the stability of wet materials that can quantitatively account for experimental data over such a broad range of parameters.

The work of Nowak *et al.* is an important advance in understanding static wet granular materials, which opens the door to more systematic studies of how the addition of interstitial liquid affects the dynamics of such materials. Liquid-induced effects on the dynamics are manifestly evident even on the beach; when a sandcastle falls, the grains do not move individually but in clumps, and the resulting surface is rough on a lengthscale of many grains. Recent experimental studies have begun to probe these effects, demonstrating that adding liquid alters the dynamics of grain flow[8,9], the fluidization of vibrated grains[10,11] and the segregation of grains of different size (known as the 'Brazil nut' effect)[2,12–14]. Not only do cohesive forces affect these processes, but viscous damping and lubrication can also play an important role. Even the distribution of liquid on the grain surfaces can change with time, adding further spice to the problem[15]. Intriguingly, the formation of clumps with a characteristic size, and the smooth flow observed at high liquid content[9], suggest that liquid-induced cohesion may lead to the development of a correlation length that spans many grain diameters, calling to mind connections with correlated systems found in traditional hard condensed matter. Although the whole area of granular physics is fascinating in its complexity, the emergent properties inherent in wet grains will keep researchers in the field — and on the beach — busy for many years.

REFERENCES

1. García-Rojo, R., Herrmann, H. J. & McNamara, S. (eds) *Powders and Grains 2005* (Balkema, Rotterdam, 2005).
2. Herminghaus, S. *Adv. Phys.* **54,** 221–261 (2005).
3. Nowak, S., Samadani, A. & Kudrolli, A. *Nature Phys.* **1**, 50–52 (2005).
4. Hornbaker, D. *et al. Nature* **387,** 765 (1997).
5. Fraysse, N., Thome, H. & Petit, L. *Euro. Phys. J. B* **11,** 615–619 (1999).
6. Halsey, T. C. & Levine, A. J. *Phys. Rev. Lett.* **80,** 3141–3144 (1998).
7. Mason, T. G. *et al. Phys. Rev. E* **60**, R5044–R5047 (1999).
8. Frye, K. M. & Marone, C. *J. Geophys. Res.* **107,** 2309 (2002).
9. Tegzes, P., Vicsek, T & Schiffer, P. *Phys. Rev. E* **67,** 051303 (2003).
10. Howell, D. W., Aronson, I. S. & Crabtree, G. W. *Phys. Rev. E* **63,** 050301 (2001).
11. Scheel, M., Geromichalos, D. & Herminghaus, S. *J. Phys. Condens. Matter* **16**, S4213–S4218 (2004).
12. Samadani, A. & Kudrolli, A. *Phys. Rev. Lett.* **85,** 5102–5105 (2000).
13. Duong, N. H. *et al. Powder Technol.* **145,** 69–72 (2004).
14. Li, H. & McCarthy, J. J. *Phys. Rev. Lett.* **90,** 184301 (2003).
15. Restagno, F. *et al. Phys. Rev. E* **66,** 021304 (2002).