

BRIEF COMMUNICATIONS

Liquefaction of quicksand under stress

A person trapped in salt-lake quicksand is not in any danger of being sucked under completely.

People or animals caught in quicksand find it very hard to escape¹. Here we show that quicksand acts as a trap because it becomes unstable when it is forced to move — first it liquefies, and then it collapses. But a simple sinking test demonstrates that it is impossible for a human to be drawn into quicksand altogether.

The natural quicksand that we study here consists of fine sand, clay and salt water. Rheometrical tests (Fig. 1a, b) reveal its extreme sensitivity to very small variations in stress. At rest, its viscosity slowly increases with time — a behaviour characteristic of clays^{2,3}. This reflects the formation of a fragile colloidal gel that has a random, delicately balanced structure. At higher stress, a spectacular liquefaction of the material takes place: the steady-state viscosity changes by several orders of magnitude for a variation in stress of less than 1%. The higher the stress, the more liquid the quicksand becomes, so movement by a

trapped body causes it to sink in deeply.

Why is it that, once sunk in quicksand, it is so difficult to escape? Because the apparent viscosity of quicksand increases after the initial stress-induced liquefaction, unlike that of clay or sand alone^{3,4}. After liquefaction, the quicksand is seen to segregate into a water-rich phase and a sand-rich one. The apparent viscosity increase is therefore due to the formation of sand sediment, which has a very high volume fraction ($\phi \approx 0.8$) and viscosity. It is the difficulty of moving this densely packed, wet sand that leads to trapping. Water must be introduced into the compacted sand to liquefy it, which requires huge forces: to introduce water at a speed of 1 cm s^{-1} , say, a pressure of 10^6 pascals (Pa) is needed¹, assuming a typical sand-pore size of $10 \text{ }\mu\text{m}$. To pull out a foot at this speed, a force of some 10^4 newtons is required — about that needed to lift a medium-sized car.

By mixing sand and clay in salt water, a laboratory quicksand can be created with a structure that reproduces the behaviour of natural quicksand. It is just strong enough to support the weight of an adult person¹ at a very low volume fraction of sand ($\phi \approx 0.4$): the corresponding stress of about $5 \times 10^4 \text{ Pa}$ is similar to the measured elastic modulus of quicksand (Fig. 1c). This very loosely packed sand does not collapse under its own weight owing to the yield-stress of the colloidal clay gel. However, if the delicately balanced structure is perturbed, the gel will liquefy, rendering the packing of the sand unstable and leading to collapse⁵. Salt is an essential ingredient for the collapse in laboratory and natural quicksand — the latter originates from salt lakes whose salinity is close to that of the Dead Sea. The salt destabilizes the colloidal gels, causing the colloids to flocculate², which subsequently destroys the granular network.

We also simulated someone moving in quicksand to see whether — once partially submerged — the victim would

sink helplessly beneath the surface. A sinking test⁶ was used in which the speed at which an aluminium bead (radius $r = 2 \text{ mm}$) sinks into quicksand is measured. At rest, the bead remains on the surface, although it has a higher density (ρ) than the quicksand (2.7 g ml^{-1} compared with 2 g ml^{-1}). If the whole system is mechanically shaken to mimic movement in the quicksand, the results agree with the rheological findings (Fig. 1a, b). At small amplitudes (acceleration $a < 3.16 \text{ m s}^{-2}$), the bead stays afloat; however, liquefaction occurs at larger amplitudes and the resulting low viscosity causes the bead to fall to the bottom of the container (Fig. 1d). Liquefaction is so rapid in this case that sedimentation does not have time to occur.

Viscosity values differed for the rheology and sinking experiments as the initial states were different: in the sinking test, the sample had been allowed to age to enable it to support the bead. However, the critical acceleration does give roughly the same critical stress (exerted by the bead) for liquefaction as the rheology measurement of 1.3 Pa : $\Delta p a r / 3$ was about 1.5 Pa .

The most important conclusion from the sinking experiment is that it is impossible to sink beads with a density of 1 g ml^{-1} : they continue to 'float'. As this is typically the average density of humans and animals, any unfortunate victim should sink halfway into the quicksand, but could then take solace from the knowledge that there would be no risk of being sucked beneath the surface.

A. Khaldoun*, E. Eiser†, G. H. Wegdam*, Daniel Bonn*

*Van der Waals-Zeeman Institute and †HIMS, University of Amsterdam, 1018 XE Amsterdam, The Netherlands

e-mail: bonn@science.uva.nl

‡Laboratoire de Physique Statistique de l'Ecole Normale Supérieure, 75231 Paris Cedex 5, France

1. Lamb, T. W. & Whitman, R. V. *Soil Mechanics* (Wiley, New York, 1969).
2. Van Olphen, H. J. *An Introduction to Clay Colloid Chemistry* (Wiley, New York, 1977).
3. Coussot, P., Nguyen, Q. D., Huynh, H. T. & Bonn, D. *Phys. Rev. Lett.* **88**, 175501 (2002).
4. Huang, N. et al. *Phys. Rev. Lett.* **94**, 028301 (2005).
5. Lohse, D., Rauhé, R., Bergmann, R. & van der Meer, D. *Nature* **432**, 689–690 (2004).
6. Ferroil, T., Huynh, H. T., Chateau, X. & Coussot, P. *Phys. Fluids* **16**, 594–601 (2004).
7. Batchelor, G. K. *An Introduction to Fluid Dynamics* (Cambridge Univ. Press, Cambridge, 1967).

Competing financial interests: declared none.
doi:10.1038/437635a

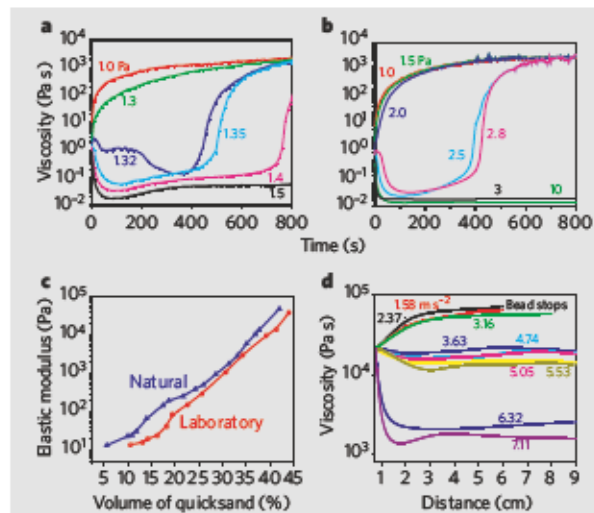


Figure 1 | Rheological and mechanical determination of quicksand properties. a, Liquefaction under shear of natural quicksand from a salt lake near Qom, Iran. Viscosity is plotted against time for quicksand (water content, 50% by weight (wt%); grain size, 50–200 μm ; clays, about 7 wt%, mostly montmorillonites; salinity, 0.1 M) for the imposed stress levels indicated in the figure. b, As a, but with laboratory quicksand (90 wt% sand, 10 wt% bentonite in salt water; total water, 50 wt%). Salinity higher than 0.02 M is necessary for collapse, which is visible as a viscosity increase after liquefaction. c, Shear elastic modulus, G' , of natural and of laboratory quicksand for different volume fractions of water, measured with a rheometer (frequency, 1 Hz; deformation, 0.1%). d, Sinking experiment, showing viscosity as a function of depth of sinking in a quicksand column (50% water) for different amplitudes of shaking. For comparison with results in a, b, we converted the falling speed into an effective viscosity by using Stokes law⁷.