Low density fragile states in cohesive powders

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We discuss the difference between cohesive and non-cohesive granular media in the context of dry quicksand, recently proposed as a new fragile state of sand. We demonstrate that weak low density configurations with properties like dry quicksand are readily formed in many common household powders. In contrast, such states cannot be formed in non-cohesive granular media such as ordinary sand.
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Sand and other granular media have the intriguing ability to exhibit properties of both fluids and solids—readily poured, yet able to hold a shape and bear weight. Recently, a report of a purported novel granular state, called dry quicksand, capable of swallowing desert travelers captured the public's imagination and was widely discussed in the popular news media.[1] Such broad interest is not surprising given that ordinary sand is capable of supporting heavy loads. However, far from being exotic and associated only with remote desert regions and carefully prepared experiments, dry quicksand's distinguishing traits are characteristic of ordinary cohesive powders, which can be found in the home and on ski slopes, asteroids,[2] and the Moon.[3]

In Ref. 1 Lohse *et al.* describe experiments in which a 2-cm-diam, 133 g ball is released at the surface of a bed of 40-μm-diam quartz grains. Without special preparation the bed supports the ball. However, after forcing air upward through the bed, which reduces the solid volume fraction ϕ to 41%, the ball sinks to a depth of about five diameters producing a jet of sand that shoots into the air.[4,5] The authors call this fragile state dry quicksand.

We were able to produce nearly identical behavior without elaborate preparation using common powders such as confectioners sugar and cake flour. We found that corn starch based Johnson's Baby Powder produced the largest jets, as shown in Fig. 1. A steel ball released at the surface of the powder ($\phi \approx 39\%$) fell to the bottom of the container, and a well-defined jet emerged. In a 30-cm-deep powder of hollow 5- 200-μm-diam glass beads, the material was so fragile that the ball bounced repeatedly on the bottom of the container. The weak low volume fraction states required for jet formation were easily prepared by gently tumbling the powder or by shaking the powder together with the ball. For all the materials we tested tapping the container on a solid surface compacted the powder, which prevented the ball from sinking.

In non-cohesive, disordered particulate media, such as ordinary sand, the low volume fraction states described are unattainable. For an idealized granular material composed of identical spheres, the volume fraction of disordered configurations is bounded by two limits: the maximum volume fraction state called random close packing with $\phi_{\mathrm{rcp}} \approx 64\%$, and the minimum volume fraction state called random loose packing with $\phi_{\mathrm{rlp}} = 55 \pm 0.5\%$. The latter state can be realized by allowing particles to settle in a nearly density-matched fluid.[6] In contrast, aeration of spherical glass beads (as small as 50 μm diameter) yields a larger minimum volume fraction of $\phi = 59 \pm 0.4\%$ independent of particle size.[7,8] It is also important to note that random configurations of ellipsoidal particles such as M&M candies have significantly higher values of ϕ_{rcp} (Ref. 9) and are expected to have correspondingly larger values of ϕ_{rlp} as well.[10]

In cohesive media fragile loosely packed states with $\phi < \phi_{\mathrm{rlp}}$ are common when the attractive forces between grains (for example, van der Waals, electrostatic, and capillary forces due to the presence of interstitial fluid) exceed the grain weight.[11] There are many reports (see, for example, Ref. 12, and references therein) of such low volume fraction cohesive powders. These materials even possess a finite tensile strength (measured, for example, in beds of 9-μm-diam toner particles with $\phi < 35\%$ achieved by aeration[12]); in contrast, in non-cohesive granular materials the tensile strength is strictly zero. Ballistic deposition can create states with ϕ as low as 15%.[13] The substantial variation in fine powder density as a function of its preparation history is characterized by the Hausner ratio, which measures the ratio of aerated to tapped powder density.[14]

For fixed attractive mechanisms and fixed material density of the particles, the transition between a non-cohesive and a cohesive material depends primarily on the particle size – cohesive powders typically have particle diameters less than 10 μm, whereas freely flowing, non-cohesive granular materials are the norm for diameters greater than 100 μm. The low $\phi \approx 41\%$ measured in Ref. 1 strongly suggests that the quartz grains used in their study were just small enough to form a cohesive powder. Low ϕ states are widely known to be weak whether they are composed of snowflakes[15] or metal particles[16] – few people would be surprised to see a measuring spoon vanish into sieved flour. The possibility of the Apollo astronauts being swallowed by loosely packed cohesive moon dust was considered a genuine risk for the first lunar landing;[3] here on Earth, it is common to sink deeply into dry powdered snow.

Studies like those of Ref. 1 have introduced the fascinating behavior of powders to a wide audience and demonstrate the still largely unappreciated and unexplored physics of

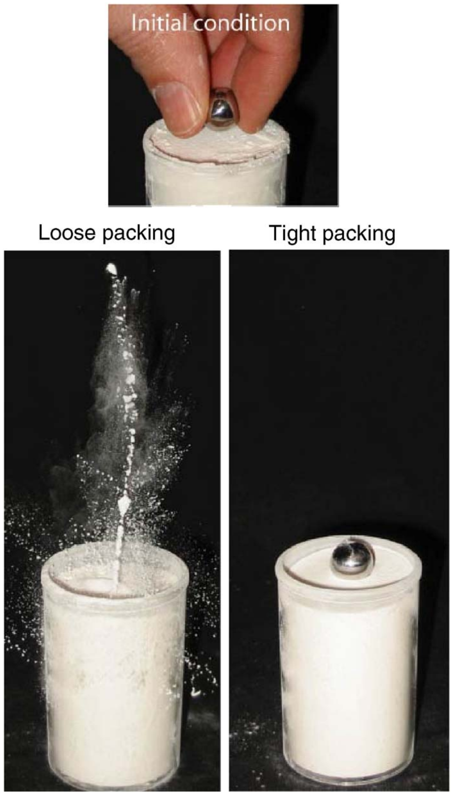

Fig. 1. A 1.27-cm-diam steel ball released (top) at the surface of a vial filled with baby powder (maximum particle diameter 45 μm) rapidly penetrates to the bottom and a jet forms (left), demonstrating that the effects obtained in dry quicksand (Ref. 1) are common in loosely packed cohesive powders. When the powder is packed by tapping the container a few times on a solid surface, it supports the weight of the ball (right). The density ratio of the loose to the tapped state (the Hausner ratio) is 0.8; the solid volume fraction of the loose state is approximately 39%. The lower images are taken about 150 ms after the release of the ball.

these common materials. There is much to learn about cohesive powders and the non-cohesive to cohesive transition, and many simple and low cost investigations are waiting to be done. For example, how does the volume fraction of the loosest possible stable state depend on the particle shape, size, and size distribution? In what way do external perturbations such as vibration or temperature variation affect volume fraction and strength? Can cohesive forces be tuned by controlling electrostatic interactions,[17] varying the amount of interstitial fluid,[18] or by creating engineered particles with adhesive hairs like those on the foot of a gecko?[19]

In summary, systems of non-cohesive particles like those found in sand dunes and sandboxes have been the subject of much recent attention and exhibit many interesting behaviors.[20] Such materials cannot form the fragile configurations necessary to create dry quicksand and other states with $\phi < \phi_{\mathrm{rlp}}$ where significant attractive inter-grain forces are essential.

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