Mechanical behavior of "living quicksand": Simulation and Experiment

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Abstract. The nature and danger of quicksand has been disputed since a long time. Despite widespread belief that humans can be swallowed or even sucked in, engineers of soil mechanics have typically asserted that, since the density of sludge is larger than that of water, a person cannot fully submerge.

We investigated a specific type of quicksand at the shore of drying lagoons. Cyanobacteria form an impermeable crust, giving the impression of stable ground. After breaking the crust a person rapidly sinks to the bottom of the field. We measured the shear strength of the material before and after perturbation and found a drastic change. The initial structure cannot be restored once it had collapsed, i.e. the material investigated shows a strong memory effect.

We simulated a model for this type of quicksand in which we constructed a tenuous granular structure representing the unperturbed soil. The initial structure consists of cohesive disks put together by ballistic deposition and settled by gravity using Contact Dynamics. We study the material behavior by determining the shear strength of the model material and by penetration tests, i.e. pushing in an object, which leads to breaking of cohesive bonds. We investigate how deep the object can be pushed in and how well the intruder is captured by the material after it collapsed above the intruder. During the penetration process we measured the relation between the driving force and the resulting velocity of the intruder.

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INTRODUCTION

The image of quicksand merciless swallowing a victim has inspired the fantasy of kids and helped writers and moviemakers to get rid of evil figures [1, 2, 3]. Is this really possible? [4, 5] This is still disputed since till today it is not even clear what quicksand exactly is [6, 7, 8, 9, 10].

The fluidization of a soil due to an increase in ground water pressure which in fact is often responsible for catastrophic failures at construction sites is called by engineers the “quick-condition” and can theoretically happen to any soil [9, 11, 12]. Is this condition, which can be reproduced on rather short time scales, equivalent to the legendary quicksands? Another way of fluidization can be vibrations either from an engine [13] or through an earthquake [2]. Recently Khaldoun *et al.* [8] have studied natural quicksand brought from a salt lake close to Qom in Iran. They found strong shear thinning behavior, and claim that the presence of salt is crucial. Their samples behaved similarly to artificial quicksand produced in the lab and no strong memory effects have been reported.

EXPERIMENTS

We investigated quicksand in the Lençois Maranhenses, a natural park in the state of Maranhão in the North-East of Brazil consisting of barchanoid dunes separated by lagoons that are pushed inland by strong winds with a velocity of 4 to 8 meters per year [14]. It is well known for its beauty as well as the presence of quicksands in which vehicles have often been trapped and oil companies have lost equipment. This quicksand appears at the shore of drying lagoons after the rain season. These lagoons, placed amidst very clean sand, have no inlet or outlet and are exclusively filled by rain water. Their bottom is covered by a soft brown or green sheet of algae and cyanobacteria.

Precisely, we performed our investigations at Lat: $2^o 28.76'$ S, Long: $43^o 03.53'$ W. Provided one does not exert on the surface a pressure higher than $p_c = 10 - 20$ kPa, it is possible to step on it and the surface will elastically deform in a very similar way to what happens when one walks on a waterbed. These deformations visibly range over tens of meters. If at some point the pressure p_c is exceeded, the surface cracks in a brittle way producing a network of tensile (mode I) cracks as seen in Fig. 1. Out of the cracks pours water. The object or person rapidly sinks inside, until reaching the bottom of the basin, which in our case could be up to one meter deep, and is then trapped within a consolidated soil. Objects less than one meter long but lighter than water like tables of wood are easily drawn inside and become nearly impossible to retrieve. We conclude that, if the basin is deeper than two meters

FIGURE 1. Typical quicksand bed at the shore of a drying lagoon in Lençois Maranhenses (Maranhão state, North-East of Brazil). Beyond a threshold pressure p_c, the crust of the quicksand breaks in a brittle way leaving a network of *mode I* cracks, and the material collapses. The maximum penetration depth for the human body was not greater than one meter.

which could possibly happen, a human being might perish.

Once the crust has broken, water and solid phase segregate. This explosion of excess pore-water and repacking of sand grains has been discussed by several authors (see [15] and refs. therein). The remaining soil shows pronounced shear thinning behavior similar to the one reported in Ref. [8] and releases a gas when strongly agitated. The original status of a crust with waterbed motion can not be recovered neither artificially nor after waiting a long time. The collapse of the quicksand is irreversible. We conclude that it is not possible to understand this quicksand by only investigating samples in the lab. One has to study it in situ because the sampling itself does already destroy the metastable quicksand condition. By placing light plates on the surface we could walk on the quicksand without visually modifying it and made various measurements before and then after the collapse. The most striking result concerns the shear strength τ measured for three different fields with a vane rheometer [16] as shown in Fig. 2. Before destroying the crust, τ is essentially constant up to the bottom of the basin and then it rapidly increases. After the system collapsed and the water came out, τ linearly increases with depth h:

$$\tau(h) = ah \,, \tag{1}$$

with $a = 1.2 \pm 0.1$ kPa/cm. We conclude from our measurements that this specific quicksand is essentially a metastable granular suspension with depth independent static viscosity. Once the collapse takes place, it becomes a soil dominated by the Mohr-Coulomb friction criterion for its shear strength.

Two questions arise: What produces the impermeable crust enclosing the fluid bubble and how is this crust formed? We investigated the material of the bottom of the lake, forming the crust and constituting the interior of the bubble physically, chemically and biologically. The most visible finding was the huge amount of living *merismopedia*, *cylindrospernopsis* and other cyanobacteria as well as of diatomacea of various types (e.g., *frustulia*) and other eukaryotes [17]. They constitute the largest fraction of mass besides the silicates of the sand. Still water and tropical weather conditions provide them an ideal environment. When the lake dries, they form the quite elastic and rather impermeable crust which hinders further water from evaporating and which therefore just stays below in the bubble. The cementing of soils by cyanobacteria and other algae has in fact already been reported in previous studies [18, 19]. We can therefore conclude that this quicksand is a living structure. We also would like to point out that we found no salt in the water which means that the presence of salt is not a necessary condition to get quicksand, as opposed to the finding of Ref. [8].

SIMULATION

We perform computational simulations with a model specially built to represent the physics of an object being pushed inside and subsequently removed from a fragile granular structure.

In our model simulation, we consider a system with width and initial height of 51 and 180 particle diameters, respectively, where periodic boundary conditions are applied in the horizontal direction. The unperturbed quicksand is modeled as a granular network consisting of cohesive disks put together through the contact dynamics technique [20, 21] and a ballistic deposition process driven by gravity, as described in Ref. [22] and shown in Fig. 3a. After the settlement of all particles, the cohesive forces between them are tuned to the point in which a

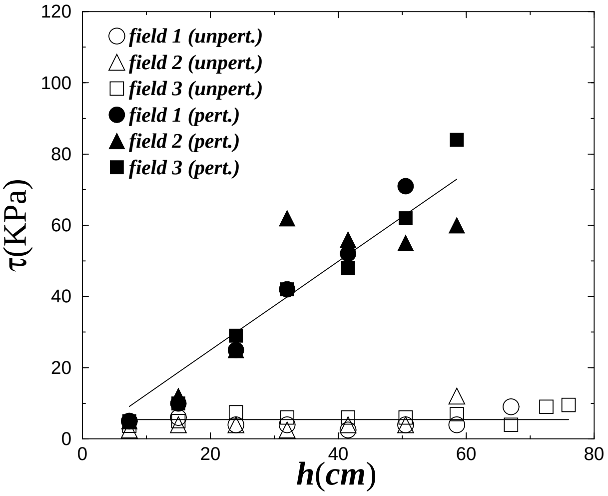

FIGURE 2. Shear strength as a function of depth before (empty symbols) and after (filled symbols) the collapse of the quicksand. The least squares fit to data of a linear function gives $\tau = ah$ with $a = 1.2 \pm 0.1$ kPa/cm after the collapse. The shear strength of the unperturbed quicksand (before the collapse) follows an approximately constant behavior $\tau \approx 5$ kPa until reaching the bottom of the basin.

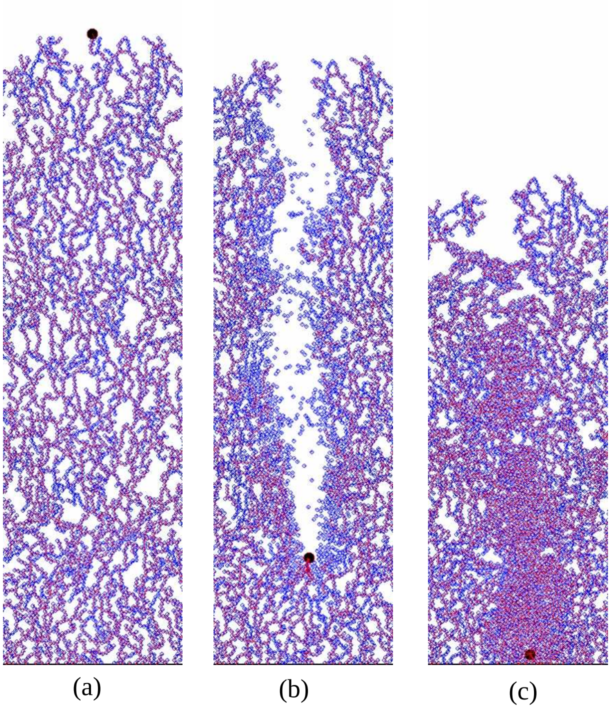

FIGURE 3. Snapshots from computational simulations showing a typical realization of the penetration process of a lighter intruder into a very loose cohesive packing. The (unperturbed) quicksand shown in (a) is modeled as a tenuous granular network of cohesive disks assembled by a gravity driven process of ballistic deposition and contact dynamics [20, 21, 22]. As shown in (b), the movement of the disk is responsible for the partial destruction of the granular structure along its trajectory. At the end of the penetration process shown in (c), the intruder rests under a much more compact mass of (perturbed) quicksand.

barely stable structure of grains is assured. This accounts for the slowly drying process of the lakes that results in a tenuous network of grains, like in a house of cards. In our model the surrounding pore water is not explicitly considered but is taken into account as a buoyant medium, thus reducing the effective gravity acting onto the grains.

We then proceed with the simulation by pushing a large disk of low density (half of the grain density) at constant force into the granular structure. In Fig. 3 we show a typical simulation of this process. As depicted, the penetration of the disk causes the partial destruction of the porous network and the subsequent compaction of the disassembled material. We observe the creation of a channel (Fig. 3b) which finally collapses over the descending intruder. At the end of the penetration process (Fig. 3c), the larger disk is finally buried under the loose debris of small particles. Since the collapse takes place in a rather short time scale compared to the formation of the quicksand, we assume that no new cohesive bonds are build up instantaneously and that broken cohesive bonds will not have time to recover during penetration.

In our simulations the density of the original packing is roughly two thirds that of the compacted material below which the intruder remains trapped. One should also note that the constant force applied to the disk must exceed a certain value to allow for penetration, otherwise the object will stay above the surface, in agreement with our field experiments. The snapshots shown in Figs. 3a-c have been obtained from model calculations with an applied force that is slightly above the penetration threshold. The further increase of the force does not lead to any substantial changes in these pictures.

Our results indicate that, if we allow for the cohesive bonds in the material to be completely restored after penetration, the force strength needed to remove the intruder disk after the penetration process can be up to three times higher than the pushing force.

CONCLUSION

Shed by bacteria in a highly unstable granular skeleton, our quicksand can catastrophically collapse and during this rapid segregation irreversibly bury objects lighter than water. Our simulations indicate that in the worst condition, one could need a force up to thtree times one's weight to get out of such morass. Fortunately basins deeper than the human size seem very rare.

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