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To cite this version:

Asmae Khaldoun, Peder Moller, Abdoulaye Fall, G. Wegdam, Bert de Leeuw, et al.. Quick Clay and Landslides of Clayey Soils. Physical Review Letters, American Physical Society, 2009, 103, pp.188301. 10.1103/PhysRevLett.103.188301 . insu-00563610

HAL Id: insu-00563610

https://hal-insu.archives-ouvertes.fr/insu-00563610

Submitted on 16 Mar 2022

Quick Clay and Landslides of Clayey Soils

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(Received 29 September 2008; revised manuscript received 6 September 2009; published 28 October 2009)

We study the rheology of quick clay, an unstable soil responsible for many landslides. We show that above a critical stress the material starts flowing abruptly with a very large viscosity decrease caused by the flow. This leads to avalanche behavior that accounts for the instability of quick clay soils. Reproducing landslides on a small scale in the laboratory shows that an additional factor that determines the violence of the slides is the inhomogeneity of the flow. We propose a simple yield stress model capable of reproducing the laboratory landslide data, allowing us to relate landslides to the measured rheology.

DOI: 10.1103/PhysRevLett.103.188301 PACS numbers: 83.80.Nb, 82.70.Dd, 83.80.Fg

Landslides kill dozens of people every year, and cause large economical damage. Different mechanisms for the onset and development of slides have been reported; however especially for clayey soils their extreme instability (''quickness'') remains poorly understood [1–3]. Such quick clays have caused many deadly landslides in countries like Canada, Russia, Alaska, Norway, and Sweden. The occurrence of quick clay landslides is usually attributed to variations in water content and/or external perturbation of the soil [3–5]. As merely one example of the latter, the infamous Rissa slide (movies are available from the Norwegian Geotechnical Institute—NGI [6]) was caused by small excavation works at a nearby farm [6].

From a fundamental point of view, there are very few studies relating soil rheology to natural phenomena such as landslides. Although some progress has been made for granular avalanches [7], there are to our knowledge no detailed investigations relating rheology of a real soil to avalanche or landslide behavior.

In this Letter we report laboratory experiments on natural quick clay samples that reveal a spectacular liquefaction of the material under flow that explains the instability. ''Laboratory landslide'' experiments in addition show that, contrary to expectation, a higher water content does not lead to more unstable soils. For high clay content, the liquefaction occurs in a thin layer of material, the rest of the clay moving as a solid block. We present a quantitative model predicting the landslide behavior, and reproduce the behavior of the natural samples by mixing different clays, water, and salt, allowing us to assess the impact on the ''quickness'' of the different constituents of the clay.

We investigate the sensitivity to external perturbations of quick clay by studying the flow behavior of samples with different water contents in a rheometer (Physica MCR300), using a vane-in-cup geometry with a roughened cup to prevent wall slip effects. The sample used is quick clay collected from about 10 m depth at Tiller, Trondheim (Norway) similar in composition to quick clays collected from other regions [2,3]. The composition, as determined by x-ray diffraction, is 70 wt % of nonswelling clays (illite, chlorite, and some kaolinite) and a few percent of swelling clays (vermiculite and montmorillonite). Primary minerals represent the remaining part. Texture analysis of the sample shows that the particles are platelike and very fine (fine silt size).

A fixed slope of a hill in nature corresponds to a fixed gravitational shear stress exerted on the sample [8]. Rheometrical tests under imposed stress (Fig. 1) reveal the extreme sensitivity of the quick clay samples to very small stress variations. At rest, the viscosity slowly increases with time, a behavior characteristic of swelling clays [8], reflecting the formation of a fragile colloidal gel. At higher stress, a spectacular liquefaction of the material takes place: the steady state viscosity changes by 6 orders of magnitude for a variation in stress of less than 1%, so that indeed a 1% variation in slope can set off a landslide. The data also show that a decrease in water content increases the stress necessary for liquefaction.

However, our laboratory landslide experiment [9] (Fig. 2) shows that this does not imply that the wetter samples cause more violent landslides. Notably, the sample with a 59% mass fraction of particles stops flowing rapidly whereas a dryer sample (61% particles), slides down the entire inclined plane. Here, only a thin layer of material liquefies, and the rest moves as a solid block over the liquefied layer. This behavior is very characteristic of quick clay landslides; the Rissa slide [6] shows that houses remain fully upright, indicating that they, too, were moving on a nonliquefied part of the soil.

This remarkable behavior is due to the fact that the gravitational stress is not the same at different depths within the quick clay layer because the gravitational stress

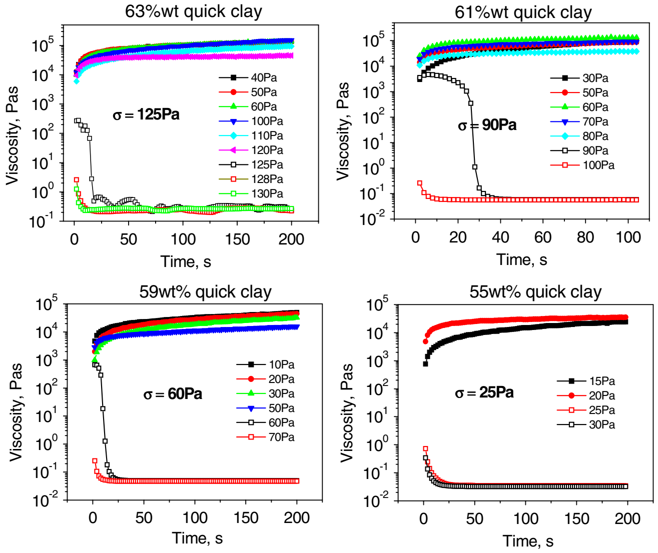

FIG. 1 (color online). Determination of quick clay rheological properties. Liquefaction of natural quick clay of different water contents under an imposed stress. Viscosity is plotted against time for the different imposed stress levels indicated in the figure. A very modest variation in the clay mass fraction is sufficient to achieve a big change in yield stress. The density of all samples is about 1.75 g/cm^3.

at a given height is due to the amount of material above this layer. From the rheology (Fig. 1) we conclude that the material is solid below some critical yield stress σ_y, and flows with a low viscosity when liquefied. For the 63% sample σ_y is so high that the material does not flow in the experiment. To the contrary, the yield stress of the 55% sample is so low that the behavior is well described as simple fluid. The remaining two samples show a much more interesting behavior which can be explained by their rheology. For a heap of height h of material of density ρ on an plane inclined by an angle with respect to the horizontal, the stress distribution is given by $\sigma(z) = \rho g(h - z)\sin(\theta)$, where z is the direction normal to the inclined plane. The gravitational stress equals σ_y on a plane (the "yield surface") parallel to the inclined plane for which $\sigma(z) = \sigma_y$. The material below that plane will flow, since $\sigma > \sigma_y$. For the 59% sample, σ_y is relatively low, and so the whole heap flows until a balance between gravitational and yield stress is achieved. For the 61% sample, σ_y is higher and the yield surface is very close to the physical surface over which it slides. Then, only a thin layer of material flows, leading to high velocity gradients, which in turn lead to a low viscosity and thus a high sliding velocity. Also, because the material hardly spreads, it takes much longer to reach mechanical equilibrium between gravity and yield stress. Thus, even though the yield stress is higher, the slide goes faster and further.

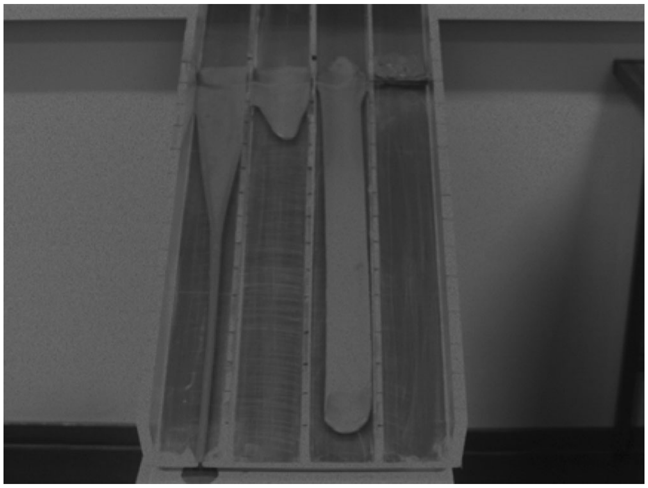

FIG. 2. Laboratory landslides. Picture of the final stage of the slides: in the four lanes from left to right the concentration of quick clay in water increases, the concentrations corresponding to those of Fig. 1. Interestingly, the landslide is much more pronounced for 61% than for 59%.

To further quantify this, a series of experiments were done, varying the plane inclination and σ_y. The experiment consists of pouring quick clay in a mold on a horizontal plate, removing the mold, and inclining the plate to different angles. Then the length of the resulting landslide and the final height of the pile are measured. Two different molds and fluid volumes were used: a 7.2 cm diameter mold with 204 cm^3 quick clay and a 12.2 cm mold with 608 cm^3 clay. The molds were removed (resulting in the pile settling a bit), the total length of the pile quickly measured, and the plate immediately inclined. The total slide length is defined as the final minus the initial length.

Figure 3(a) shows the slide length as function of the yield stress, demonstrating that the larger the inclination, the longer the slide. However, it is also observed that higher yield stresses can lead to longer slides, as was observed in Fig. 2.

Before inclination the piles for a given yield stress are identical, and after the inclination the force on the pile tangential to the substrate is proportional to $\sin(\theta)$. One would then expect the slide length to be proportional to $\sin(\theta)$, so that rescaling the slide length by $\sin(\theta)$ would collapse the data. This is indeed observed in Fig. 3(b), where also the surprising hump in slide length at 150 Pa is clearly seen. Figure 3(b) also shows the rescaled averaged data from the 608 cm^3 sample, which shows a similar peak, but at a higher stress. Figure 3(c) shows the final deposit height; for $\sigma_y < 150$ Pa, larger inclination angles indeed lead to thinner piles, as expected from the simple mechanical equilibrium between gravitational and yield stresses. However, above 150 Pa, the deposit height becomes independent of inclination angle, meaning that larger inclinations make the pile slide further, without loosing height. This is the explanation behind the surprising peak in Figs. 3(a) and 3(b): for $\sigma > 150$ Pa (190 Pa for the 608 cm^3 sample), the pile slides as a solid block,

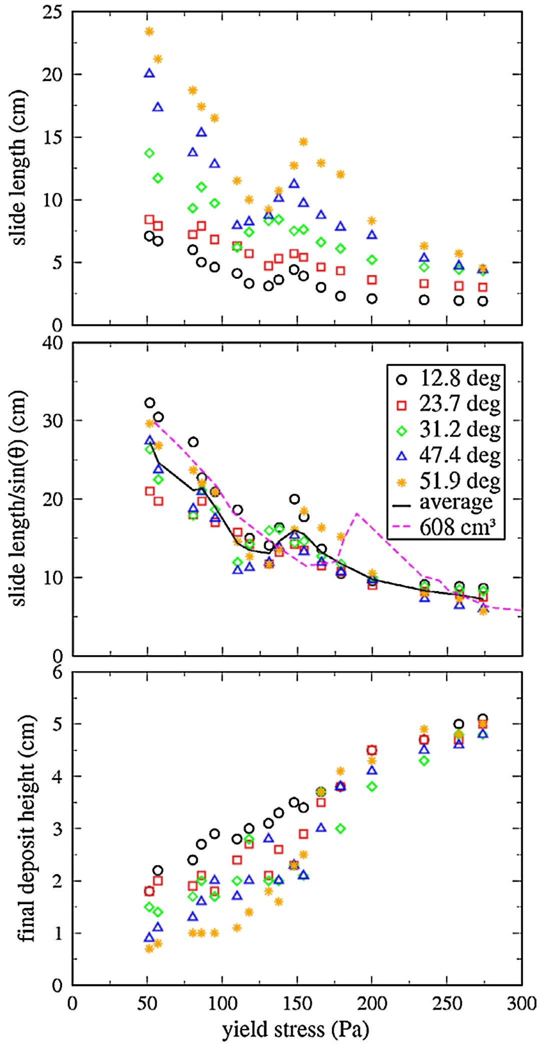

FIG. 3 (color online). Landslide experiments performed by putting a cylindrical heap of fluid on a plane and inclining the plane. All data are plotted as a function of yield stress, and most show data only from a heap of 204 cm^3. (a) gives the final deposit slide length after inclination to different angles [indicated in (b)]. (b) shows that the slide length rescales with the inclination angle, and shows also the average, rescaled data from a 608 cm^3 heap. (c) shows the final deposit height for different inclination angles.

without loosing much height. But why does this happen exactly at 150 Pa?

When the mold is removed, the pile on the horizontal plane will flatten until the $\sigma_{\text{gravitation}} = \sigma_y$. When the plane is subsequently inclined, the aspect ratio of the pile determines whether the gravitational force is (i) large enough to "pull the sliding pile apart," resulting in a spreading pile that stops soon, or (ii) too small, so that the pile slides as a whole, without losing much material, and goes far.

Consider first whether the force is enough to pull the sliding pile apart; the cohesive force holding two identical halves of the pile together is roughly $F_{\text{coh}} = \sigma_y 2Rh$ where R is the pile radius and h its height. The friction force on half of the pile is $F_{\text{fric}} = \sigma_y \pi R^2/2$. These balance at a critical pile height: $h_{\text{crit}} = \pi R/4$ and since, $V = \pi R^2 h$, $h_{\text{crit}} = (\pi V/16)^{1/3}$, yielding 3.4 cm for the 204 cm^3 sample (and 4.9 cm for the 608 cm^3 sample). So the critical pile height separating the two regimes should be about 3.4 cm (4.9 cm). Since above the transition in Fig. 3 the piles slide without thinning, the final pile height is identical to the initial pile height, so the critical pile height that separates the two regimes can be read off simply as the final pile height just when it becomes angle independent. That happens at a yield stress of ≈150 Pa and for a pile height of ≈3.5 cm (190 Pa and 4.8 cm for the 608 cm^3 sample)—in surprisingly good agreement with experiment.

Can we predict what the relation between these stresses and the height is? Considering a disk of radius R and height h on a horizontal plane with an imaginary plane through two corners of the disk, we expect the pile to hold its shape when the resisting force along this plane: $F_{\text{res}} = \sigma_y \pi R(R^2 + h^2/4)^{1/2}$ is larger than the projection of the gravitational force on the plane: $F_g = 0.5\rho g h \pi R^2 \sin(\theta) = 0.5\rho g h \pi R^2 h/(4R^2 + h^2)^{1/2}$. These two forces balance when $\sigma_y = \rho g h^2 R/(4R^2 + h^2) = \rho g h^2 (V/\pi h)^{1/2}/(4V/\pi h + h^2)$, which gives 100 and 140 Pa for the 204 and 608 cm^3 samples, respectively, in fair agreement with the measured values of 150 and 190 Pa, respectively. Considering the simplicity of the model, this is quite satisfactory. More importantly, the model correctly describes how the peak changes when the sample volume is increased by a factor 3.

This also means that we can predict the yield stress corresponding to the peak in Fig. 3(b) (slide length vs σ_y) by inserting $V = \pi R^2 h$ and $h_{\text{crit}} = (\pi V/16)^{1/3}$ in $\sigma_y = \rho h^2 R g/(4R^2 + h^2)$: $\sigma_{y,\text{crit}} = \rho g V^{1/3}(4\pi^4)^{1/3}/(2^6 + \pi^2) \approx \rho g V^{1/3}/10$ or alternatively the flowing volume corresponding to the peak: $V = (10\sigma_y/\rho g)^3$.

Thus, our model qualitatively, and to a large extent also quantitatively accounts for the "laboratory landslides." One important factor which has not been mentioned above is the role of the thixotropy of the material [8,10]. This is actually needed to ensure the very thin lubricating layer upon which the solid blocks slide. As the block slides, a tiny bit of material is ground off the bottom of the sliding block, quickly liquefying, and supplying the lubrication for further sliding. We believe that thixotropy is necessary for this since only thixotropic fluids show such extreme localization of shear.

This leaves us only with the question of what the physical origin that makes these soils so unstable is. To study this, we prepared, starting from pure components, a "laboratory quick clay" that perfectly mimics the flow behavior of a natural sample, including the sensitivity to variations of water and salt content in the sample. We start out with pure illite because it is the main component; we found it

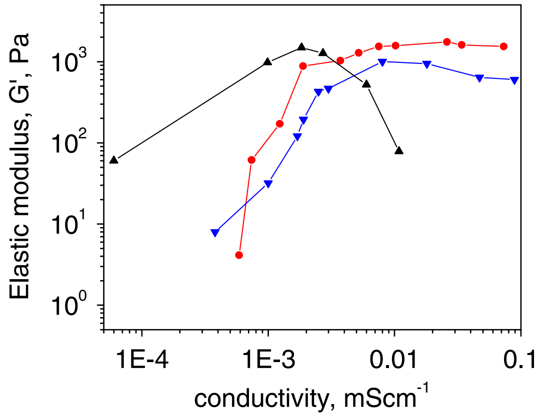

FIG. 4 (color online). Elastic shear modulus, G', of 50 wt % solid samples of natural quick clay (red circles), laboratory quick clay (blue downward triangles), and of pure illite (black upward triangles) measured with a rheometer (frequency, 1 Hz; deformation 1%) for different salt concentrations. The measured conductivity is directly proportional to the salt concentration. With no salt added, the elasticity of the natural quick clay is low. After adding a small amount of salt (0.005 g ≈ 0.006 wt % of salt) a sharp increase in the elasticity of the natural quick clay is observed. This sharp increase explains why landslides occur after leaching by rain. The sharp increase in elasticity is not observed with the pure illite. Also, in contrast to the illite suspension, the elasticity of the quick clay sample does not decrease at high salt concentration. These observations show clearly that the illite alone can not mimic the flow behavior of the natural quick clay. To mimic the behavior of the natural quick clay, "laboratory quick clay" was prepared by adding 3% of washed bentonite to 97% illite. We washed the bentonite by suspending it in water then sedimenting it by centrifugation. We repeated this cleaning process until the conductivity of the bentonite became less than 107 μS/cm. The combined illite-bentonite sample perfectly reproduces the quick clay behavior.

necessary to repeatedly wash it to get rid of dissolved salts, in agreement with the ideas of Rosenqvist [11] that in nature the "quick" properties appear after the soil has repeatedly been leached by rain. This was also the reason why, in the past, quick clay soils have been successfully stabilized by injection of salt water [12]. We find that to reproduce the stabilization by adding salt, it is necessary to add a 3 wt % of (washed) swelling clay (bentonite). The elastic properties of this artificial laboratory quick clay then perfectly match that of the natural sample as a function of electrolyte concentration. On the other hand, if no swelling clay is added, the material cannot be stabilized by salt (Fig. 4), nor be destabilized by leaching. This shows that the contribution of the few percent of swelling clays is essential for the quick clay behavior. Such swelling clays typically form colloidal gels that can liquefy tremendously under flow [9,10].

The mechanism of the quick clay landslides is then the following. On the slopes, if the material itself changes due to variations in water or salt content, or the stress on it varies due to slope variations, a thin layer of material within the soil liquefies at the bottom; the liquefaction is very pronounced due to the combined effects of the destruction of the swelling clay gel and orientation of the platelike particles of the nonswelling clays and minerals by the flow. This then leads to the rapid motion of massive amounts of solid material on top of the liquefied layer. All these features agree with field observations [5,6].

These fundamental new insights provide a starting point for modeling and predicting landslides through their rheological properties. Simple tests exist [10] for determining the yield stress of soils. In addition, experiments on inclined planes such as our laboratory landslide experiment yield a good estimate of the postyield viscosity; these two are the only parameters necessary to predict the violence and extent of landslides. In addition, the extreme liquefaction under flow, taken together with the flow inhomogeneity, explains the large distances over which quick clay landslides travel, which was an unsolved problem in geophysics [13].

We thank P. Coussot for discussions and J. Jonland for samples. This work was supported by FOM. LPS de l'ENS is UMR 8550 of the CNRS.

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