Screenings from the Soil Research Lab

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A CHILD'S GARDEN OF SHEAR STRENGTH

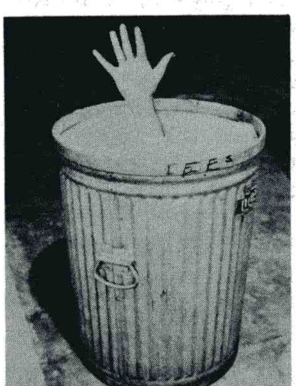
The earliest recorded example of shear strength was when a go-go girl name Delilah used sartorial wiles on a longhair named Samson, who is the good guy in this story.

Although Samson subscribed to the fad of letting his hair grow, he was no ordinary Berkeley potted plant. For example, Samson once turned loose 400 foxes with their tails set on fire.[1] He also coolly dispatched a thousand of Delilah's neighbors with the jaw-bone of an ass, and that was before slaughter by jaw-bone became commonplace, as at cocktail parties, etc., where it passes for intelligent conversation. In fact, jawbone of ass is hardly considered a lethal weapon any more.[2]

Delilah's people were sorely vexed by Samson's pranks, most especially the killing, so she took him to a trimming. It left him weak as water (this was before pollution), and Delilah's cohorts collected an eye for an eye until halted by the shortage. Thus un-eyed, Samson still made a comeback when his hair grew back -- he stood up and slew them all, including himself.[3]

Lookout, There's Quicksa...!

Another early example of shear strength was when Sir Walter (anything-for-a-laugh) Raleigh gallantly laid down his coat for Queen Elizabeth to walk on, knowing full well that underneath her royal dignity lay a large puddle of quicksand.[4] They called this the Age of Chivalry, because afterward he helped her out.[5]



"Quicksand," from the set for the movie of the same name. This shot illustrates what is meant when they say the picture is "in the can". It also confirms the kind of can.[6]

When acting force exceeds friction, real estate values perceptibly slide -- hence the term "Skid Row". Part of this slide in Des Moines was subsequently stabilized with lime. Watch for details in ASCE "Civil Engineering".

Real quicksand is not a matter of fineness or round particles, because given the right conditions any sand can be quick. The cause is water which seeps upward fast enough to lift the individual sand particles until they are no longer in continuous contact. No contact, no friction that quick!

According to the great Arabian mystic Algebra, the critical condition for quicksand is

$$i_c = \frac{G - 1}{1 + e} \cong 1.0$$

where i_c is the hydraulic pressure gradient needed

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[1] Would you believe 300?

[2] It's getting so now we even celebrate the ass. Just have a look at Congress.

[3] Now known as blind fury. Probably he had just had a round with the assessor.

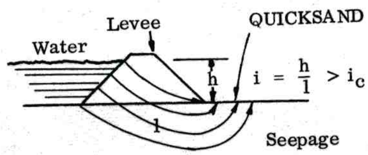
[4] A sense of humor like that could get one sent to the Tower. And so it did.

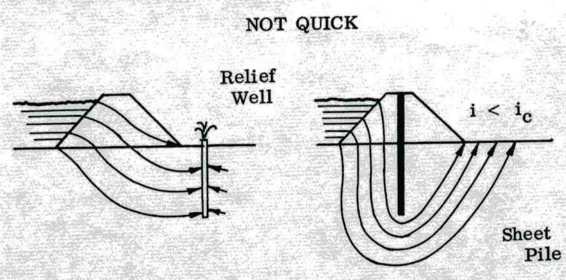
[5] He wanted his coat back.

[6] Contrary to popular misconception, it is impossible to sink over your head in quicksand unless you go in head first or wear jewelry. If you don't believe us, ask Archimedes: Buoyant force = weight of fluid displaced. Since quicksand has about twice the density of water, you will have to work at it to go in much over waist-deep.

Return to Table of Contents

to keep quick, G is the sand specific gravity and e is its void ratio. In other words to prevent quickening keep the water pressure low or increase its length of flow:





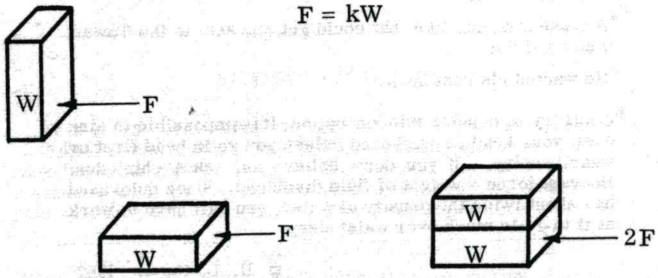
Friction Ain't Novel

It's a fact of human nature that dynamic friction generates heat which readily perks into violence. Obviously what the world needs is air conditioning plus a good shot of lubricating oil. One of the best is oil of chuckle -- it's hard to hate a clown, and man turned loose has all the instincts and bluster of top banana. Unfortunately he overlooks the humor-- if he only saw how funny he was he might ease off.

The laws of mechanical friction were discovered by the one major artist with enough talent to make it as an engineer, Leonardo da Vinci. People naturally recognized his pictures but not his vision, with the result that his discoveries on friction were forgotten for a couple centuries. Leonardo is a most unique example of a man before his time.

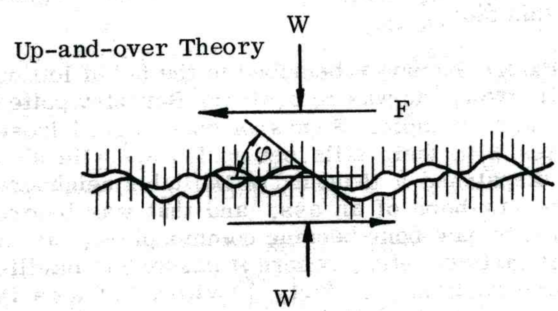
Leonardo discovered that friction depends on weight but not on contact area, something to remember before you buy wide tires. These two laws of friction were rediscovered by the French architect Guillame (Bill) Amontons in 1699, and are sometimes referred to as Amontons' Laws. They can be expressed by one equation,

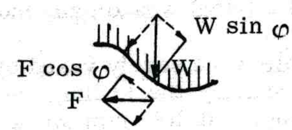
$$F = kW$$



Amontons also observed that rough surfaces make more friction, and reasoned that surficial bumps must either push down or lift over one another for sliding to occur.

The "up-and-over" model for surface friction was attractive to the mathematically inclined, particularly those inclined at the angle φ, which is known as the angle of friction. If sliding is incipient on a surface roughness inclined at an upward angle φ, the upslope component of friction must equal the downslope component of weight, or





$$F \cos \varphi = W \sin \varphi$$

$$F = W \frac{\sin \varphi}{\cos \varphi} = W \tan \varphi$$

This is the same as the previous equation with $k = \tan \varphi$, and leads to such wild utterances as "the friction angle is the angle whose tangent is the coefficient of friction." You probably knew that, but we just thought we'd throw it in.

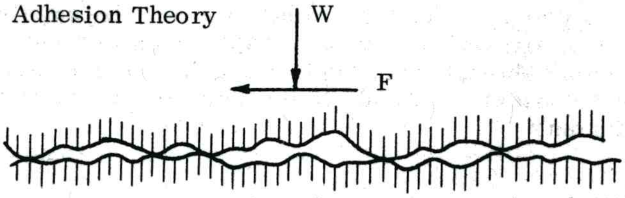
Hand Warmers

The up-and-over theory went unquestioned until the early 1800's when a British physics professor named John Leslie had a question. The British, like the French, frequently rub their hands together, albeit for different reasons. (The British do so to keep warm.) Leslie reasoned that frictional ups must be equalled by downs or the surfaces would fly apart. If ups equal downs, where is the energy dissipation, commonly in the form of heat?

The answer came in 1950 when two English physical chemists, F. P. Bowden and D. Tabor, published a modern classic, "The Friction and Lubrication of Solids."

Bowden and Tabor showed that the actual contact area between two apparently smooth surfaces is relatively tiny and is proportional to load. Friction is

Adhesion Theory



Actual contact area, $A = k_1 W$

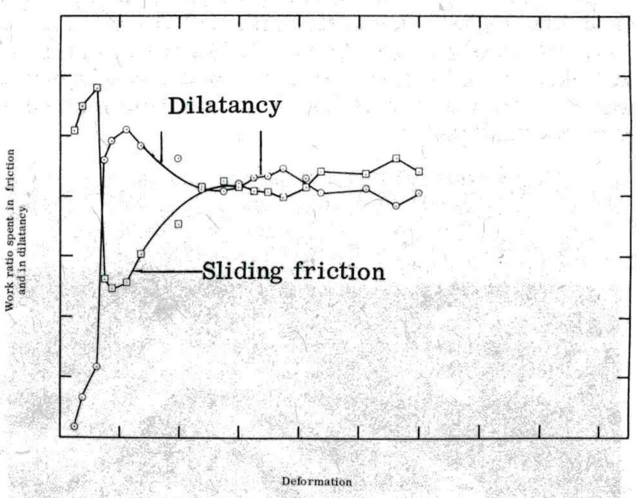
Adhesion friction, $F = k_2 A = kW$

a result of molecular adhesion between these contact areas, and still conforms to the two laws. Tearing of the molecular bonds is what causes the heating. And that, friends, is why cool characters sometimes have hot little hands. Now if we could only find a way to cool some hot little heads we could all relax and enjoy our pizza.

Dilatancy[7]

Although adhesion theory of friction has its adherents, the old up-and-over concept remains pertinent to soils. Shearing of a granular soil is analogous to rubbing two pieces of sandpaper together -- the grains interlock, preventing movement unless allowed to separate slightly.

The same sexy behavior is found in dense sandy soils -- shearing causes an increase in volume, as the grains in the shear zone slide up and over one another. Part of sand internal friction is therefore surface friction, and part is due to packing. Therefore to strengthen an argument or a sand, compact it.



Roles of dilatancy and sliding friction can be evaluated by calculating the work involved in shearing. These curves for a crushed and compacted limestone show two periods of structural readjustments (dilatancy) before failure occurred. Equations were derived by Tinoco (ISU) after the work of Rowe (England).

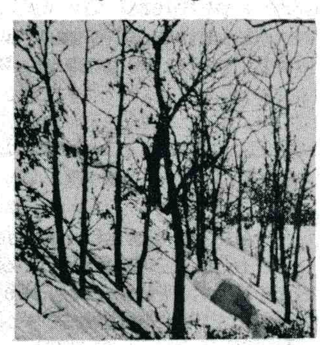
Recent tests by Youd at Iowa State indicate that vibration may reduce the critical void ratio, practical implications being in earthquake damage and in artificial compaction. Earthquakes hit hardest where cities rest on loose sand, per recent examples in Alaska and in Japan.

TILT! Aftermath of an earthquake which rumbled through Niigata, Japan, in June 1964. Vibrations reduced shear strength of the loose underlying sands, causing quicksand "boils" (right), plus extensive settlements and shear failures. For details see ASCE Jour. Vol. 93 SM3, May 1967. Photos courtesy W. G. Holtz, U. S. Bur. Recl.

Angle of Repose

A wide variety of angles of repose may be seen on beaches and sundecks, particularly since the advent of the bikini. However, for angles of repose within everybody's grasp nothing can beat the voluptuous backside of a sand dune. No falacious attempts to uplift, conceal, or expand on the true facts -- instead merely an angle generated by sliding sand.

Our real reason for getting excited is that this is a very neat way to measure internal friction, since the angle of repose equals the angle of internal friction without any dilatancy component, which might unduly bulge the bikini.



[7] Not to be confused with "dilatation", which is stress-induced volume change of a solid, or with "dilation", which is a stress-induced volume change caused by overeating.

Return to Table of Contents

Pore Pressure

On a hot day pore pressures soar, so people naturally tend to keep their distance and avoid rubbing elbows. Pore pressure in a soil also tends to prevent close contact and reduce friction, a fact recognized by the late and great soil mechanic, Karl Terzaghi. Terzaghi said in effect

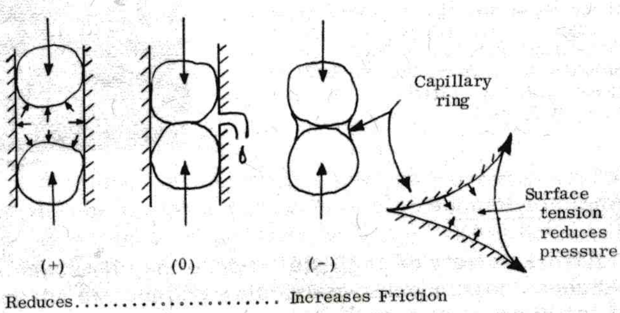
$$\tau = (\sigma - u) \tan \varphi'$$

where τ is shear strength, σ is applied normal pressure, and $\tan \varphi'$ is the "effective" coefficient of friction, i.e., after corrections for pore pressure.

This means that if you load a saturated soil but don't allow drainage, the grains don't touch any harder, and intergranular friction stays the same. The applied load is all taken by the pore water, and is reflected in pore water pressure.

Pore pressure can be either positive or negative --positive from compression of the soil structure, or negative during dilatation. Negative pore pressures are additive to the applied load, and temporarily increase shear strength.

PORE PRESSURE



The most important implication of pore pressure is in construction--build too fast and heavy, and positive pore pressures may cause catastrophe. Where problems are anticipated, pore pressures are determined by measuring water levels in vertical pipes in the ground, termed piezometers.

Students!

Graduate assistantships and fellowships are available to top students interested in graduate work in Soil Engineering at Iowa State University -- just mention "Screenings" when you write.

Question: I have a brother-in-law who smells like an Airdale because he's afraid that intergranular friction plus dilatancy might cause him to get stuck in the bathtub. Would positive pore pressures help him out?

--Anxious

Dear Anx: Yes. However in view of the enormity of the problem we would suggest that he use a shower or go to the lake.

Question: I recently drove on the beach at Ft. Lauderdale to test my car's pick-up. The pick-up was a beaut, but my car later got stuck in the sand. The next day the car was gone. Why?

--Playboy

Dear Mr. P.: Wet (not saturated) sand has negative pore pressure, primarily because of capillary action at the grain contacts. The wet sand therefore has higher shear strength, sufficient to support a car plus pick-up.

Later the sand was dry so the car became stuck, and by the next day the pick-up had probably picked up where you left off. This transient phenomenon of sin in the sand is called "apparent cohesion."

Question: Which weighs more, a bucket filled with dry sand or the same bucket filled with wet sand?

--Miss America

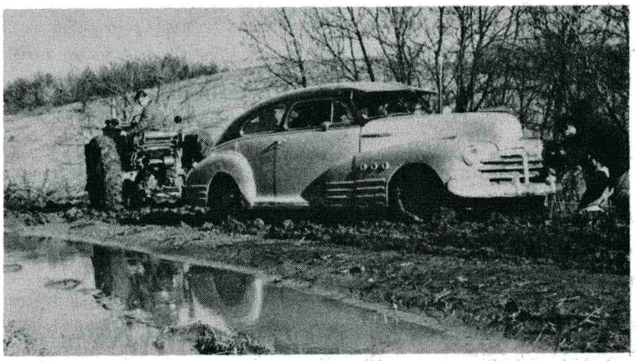
Dear Miss A.: Due to its apparent cohesion, wet sand has higher shear strength and does not pack down as easily. The bucket filled with wet sand therefore weighs less, in spite of the weight of the water. This action is known to concrete technologists as "bulking".

The March, 1964 Alaska earthquake densified lenses of loose sand, increasing pore pressure to cause liquifaction and trigger landslides. Clays also lost strength, helping the slides move along. This one moved laterally about 500 feet. For details see ASCE Jour. Vol. 93 SM4, July 1967. Photo courtesy Dr. H. B. Seed, Univ. of Calif.

Return to Table of Contents

Sticky Problems

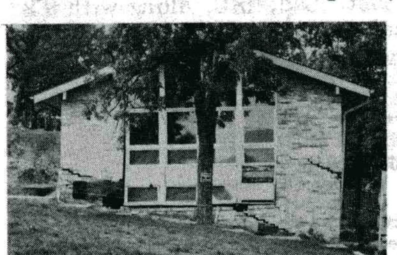
Whereas sands are notable for their grit, not to mention sliding friction, dilatancy and pore water pressure, clays pose some stickier problems. As they say in Alexandria, man with feet of clay should not try to walk on water or he may have dam dampened enthusiasm.



Wet, low-density clay is as soft as a maiden's mustache, primarily because of drippy pore pressures. Under load the water is very slow to move out because of the fineness of the pores, although eventually the water does squeeze out and allow the clay to consolidate and gain permanent adhesion-type friction. Major differences from sand are that clay gains strength much more slowly, but then retains its strength after unloading, and is said to be "preconsolidated".

Another way to make clay hard is remove the water by drying, whereupon the clay gets hard as a horse's bunion. The clay particles not only touch, they are held together because of air-water surface tension, much as in sands. Only now the particles are 1000 times smaller, have a billion times the population density, and the environment is highly changed, all of which can create a lot of surface tension and internal friction.

Direct evidence for clay grain-to-grain contact came from experiments in the 1950's by a Norwegian engineer and mineralogist, I. Th. Rosenqvist.



Look out for pushy neighbors, particularly when the land slides. Here a push from the left made the buttresses fly a little -- note the beam stuck in for temporary support.

[8] Clays were formerly believed to be held together by an aqueous "glue". Evidences were shrinkage and hardening during drying, as the "glue" presumably reduced in volume and became more concentrated.

Rosenqvist froze-dried some clays and found that they did not shrink, and he took electron micrographs that showed the clay plates touching in an edge-to-face "cardhouse" structure. This structure had been suggested earlier by Prof. T. W. Lambe during a card session at M. I. T.[8]

Floccing Together

In truth, forsooth, why does clay stay stuck? Clays are inherently attractive, proof that beauty is mainly surface chemistry determined in part by the internal crystalline structure.

Clays by nature are negative unless previously conditioned by an adverse environment, in which case Playboy would say they are more for fun than for keeps. Negative clay platelettes still have positive spots because of crystal discontinuities at the edges, and stick together edge-to-face without further ceremony. The strength and character of such flocs depends on chemistry of the system, and the extent of subsequent tightening as water is squeezed or dried out.

Slopping Apart

Although flocculation is the usual structure in clay society, a loss of chemical restraints can cause dispersion, the particles becoming free agents surrounded by water. The famous "quick clays" of Norway and Canada have been leached sufficiently that a few bumps will permanently destroy the flocculent structure and turn them into a clay soup. The resulting landslides are a real go-go.

Thixotropy and Viscosity

Much more common and less flighty than quick clays are slower ones that are termed thixotropic. Shearing of a flocculated clay temporarily breaks some flocs and reduces strength. After setting a while, new flocs are formed and the clay regains its strength--very important in driving piles, if you should ever care to drive any.

Dispersed clays--whether the dispersion is temporary due to stirring, or permanent due to their chemistry, still resist shearing much the same as water resists stirring. This resistance is proportional to the rate of shearing, and constitutes viscosity. Presumed viscous flow of soils has been termed "secondary consolidation" or "soil creep".

Return to Table of Contents

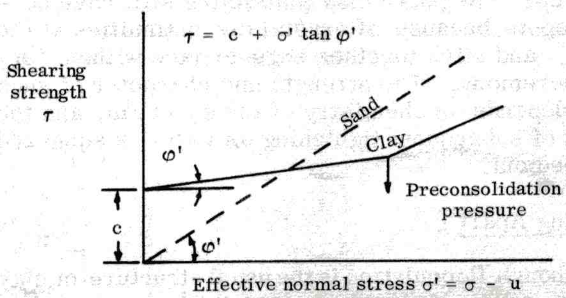
Summary: Mohr-Coulomb-Terzaghi-Hvorslev Theory

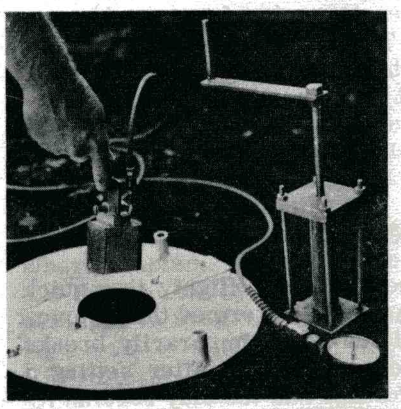
While these hypothetical mechanisms can change any day in the week, the most famous descriptive statement on soil shear strength was made in 1773 by a French military engineer, Charles A. Coulomb.[9] King Louis XIV was pushing his public works program at the time, building new roads and canals, and had found that he could not tell them apart without a road map.

Coulomb said in effect that soils probably behaved as follows:

$$\tau = c + \sigma \tan \varphi$$

This was undoubtedly a comfort to Louis, who did need comfort. It means that soil shear strength (τ) is made up of two components, cohesion (c) not dependent on normal pressure, and friction which is dependent on normal pressure (σ) and on the coefficient of friction ($\tan \varphi$). As already mentioned, this was modified by Terzaghi to include pore pressure (u):





The bore-hole shear device (new!) applies a normal force σ and then shears soil at the sides of a bore hole. The inventors claim this Handy device will produce reliable c and φ data in a mere fraction of the lab testing time. See May 1967 HRB News or write Testlab, 216 N. Clinton St., Chicago 60606

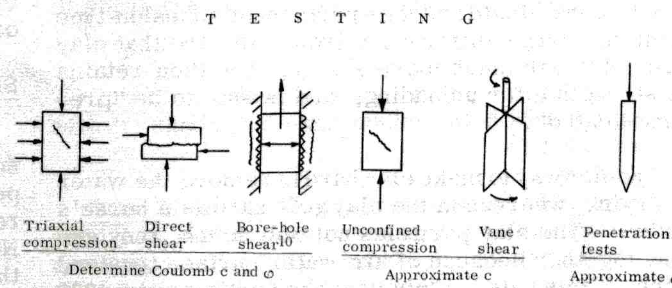
Mohr theory is used to calculate shearing strength from compression tests, where orientation of the shear plane is not known. Hvorslev emphasized the dependence of c on preconsolidation effects. In geological or chemically stabilized materials c also may be increased by cementation.

To summarize, the factors affecting soil shear strength include:

In sand and/or in clay:	Only in clay:
Grain sliding friction	Flocculation
Dilatancy	Preconsolidation
Pore pressure	Dispersion (quick clay; thixotropy)
Seepage pressure (quicksand)	Shear rate (viscosity; soil creep)
Cementation	

The result is approximately described by the Coulomb equation modified for pore pressure.

A wide variety of tests has been devised to measure soil shear strength, the primary one being the triaxial test interpreted with Mohr theory. Other tests reflect mainly Coulomb cohesion c, the friction angle φ (or φ'), or both. Vane shear, bore-hole shear, and penetration tests are performed in the field.



SCREENINGS REPRINTS

Despite popular demands, some students have reprinted Vol. 1 and 2 of the early "Screenings," hitherto safely suppressed and out-of-print for 5 years. Complaints should be addressed to Mr. Glen Ferguson, Eng. Res. Inst. Lab, ISU, along with $2 for which you will receive one set and our sympathy in a suitably cheap binding.

IN MEMORANDUM

This is the first issue of "Screenings" to have survived Ye Editor's wastebasket since the hell-wrought winter of '64, when we did one (Vol. 8) on portland cement and acquired a permanent set. Owing to other responsibilities, we anticipate that the publication will continue to be highly irregular.

IN MEMORIA
J. H. Bolton 1898-1967
"Golden Shoveller"

This issue of "Screenings" is respectfully dedicated to Prof. John H. Bolton, editor of the Iowa Engineering Experiment Station, without whose urging the first "Screenings" never would been sifted.

[9] The same Coulomb was later attracted to the current glamour field, electricity, to the extent that his name now means a large charge.

Return to Table of Contents