Screenings from the Soil Research Lab

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FOUNDATION ENGINEERING

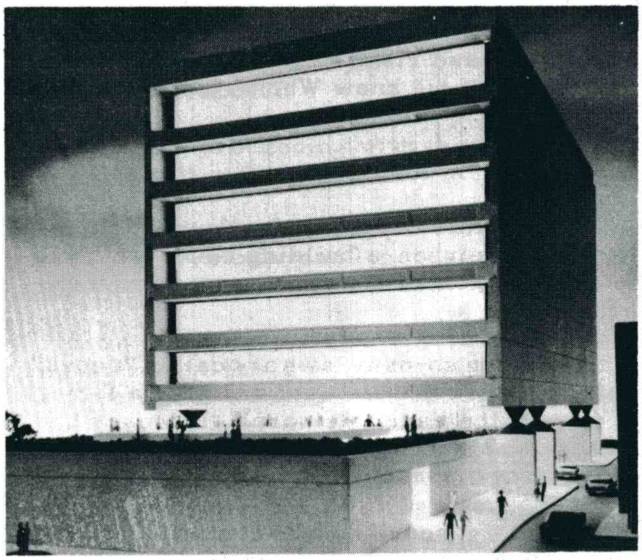
As every woman knows and most men surmise, there's more to foundation engineering than meets the eye of the casual observer.

An historic example typifying need is when Queen Cleopatra's expanding political resources got stuck in her sedan chair, just when it began to look like Burton for certain.

"Give me liberty or give me death," Cleo was heard to proclaim. The local brotherhood of sedan chair carriers was glad to oblige, they being in current high level conflict with management over increasing use of the wheel. They argued that while a wheel might do the job all right, somebody would have to go along with each one to make sure it was oiled.

Queen Cleo sat steadfast and resolute as a southern governor, unable to make a move without endangering the entire robust substructure of her economy. Eventually she got hungry enough to eat crow, but owing to her high-souled heritage she got the asp instead. She was the first Egyptian queen ever to be buried in a sitting position, all on account of being struck by the asp in her sedan.

Cleopatra, as played by Miss Lillian Russell. Her talents did not go to waist.



New building in Des Moines will stand on eight stainless steel "feet", four on each side of the building. Load is transmitted by columns to four gigantic concrete footings extending 40 feet underground.

More properly, foundation engineering pertains to design and construction of substructures for the support of buildings, dams, bridges, etc. It is probably safe to say that over 90 percent of all engineering structures are ultimately supported by soil. Those that aren't either fly, float, or fall over.

There are two reasons why foundations fail, both being ignorance. Because the ignorance is pretty evenly distributed among everybody involved, the event is often heralded as an act of God. This illustrates man's characteristic sense of fair play; we only allow ourselves to take credit for successes, whereas responsibility for a failure is automatically awarded to Higher Authority. We mean nothing personal; it's more a matter of who can and who can't be sued.

Yet every job is a calculated risk, and at worst it isn't even calculated. The problem is that soil is not something an engineer can look up in a handbook and order from the mill by number. Soil is individual. It's like progeny; you take whatever comes.

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* Vol. 6 was murdered in the crib after a single issue, designated No. 1-2. Ye olde editor wishes to be excused from any criminal responsibility for the act, on the plea of temporary sanity.

Return to Table of Contents

Anybody who would thus buy a pig in a poke should at least poke the pig. Unfortunately that still gives no guarantee the pork chops will be tender. Likewise one can poke holes in the soil and still not be sure of sameness between the holes. Maybe there's a fault, or cavern, or tunnel of an old gold mine. The only sure way would be to drill the holes overlapping, and that would leave nothing to build on. Thus some ignorance is excusable, and a calculated risk is inevitable. If things don't work out we know Who to blame.

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codes

The simplest expedient for foundation design is to rely on a building code, which is the culmination of many long years of inexperience.

The reason so many laws are called "codes" is pretty obvious, ipso facto and prima facie, not to mention esprit de corps. If Moses had gotten his instruction that way they could have built another pyramid with the stones.

Building codes can be classified by the factors they ignore. For example, a code may ignore everything but the mayor's bonus and still be binding upon the builder. A code might say make the footings a foot wide for every story the building is tall, which makes a tall story, that may subsequently shorten somewhat as the building sinks in the ground.

More commonly building codes suggest maximum allowable bearing pressures which depend on the kind of rock or soil. As you can see, this is little more than a guide because so much depends on whether a material is loose or compact, hard, medium, or soft:

Massive rock (granite, gneiss, etc.)	100
Hard layered rock (slate, schist, basalt)	40
Medium rock	20
Broken hard rock	10
Soft rock (shale, chalk, coral)	10
Broken soft rock	3
Gravel-sand-clay, very compact (glacial till)	10
Gravel or sand-gravel, compact	5
Gravel, loose	4
Coarse sand, compact	4
Coarse sand, loose, or fine sand, compact	3
Fine sand, loose	1
Silt, compact	2
Silt, loose (loess)	1/2
Clay, hard, brittle	6
Clay, medium	4
Clay, soft	1

SOIL TESTS

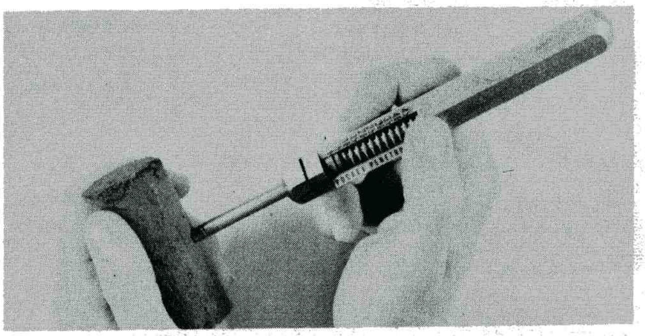
Class: Penetrometers

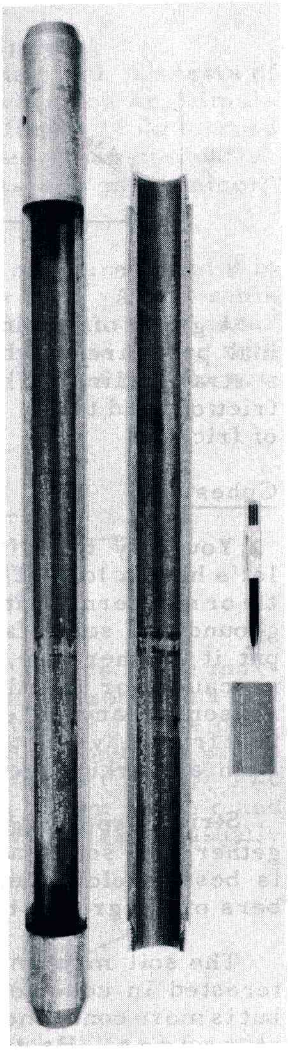
More scientific and therefore more exact than most building codes is to actually test the soil at the proposed building site. The simplest kind of test is to probe the soil to test its firmness; this comes under the general heading of Penetration Tests.

Subclass A: The Thumb. A most common type of penetration test is to jab the soil with the thumb. The rule of thumb can be: count the joints buried and read the reciprocal, which happens to be in tons per square foot. For example, half-way to the first joint is 2 Tsf. The full depth of the thumb would be two joints, or 1/2 Tsf. For lower values you use your fist, and then your foot. If you go in over your belt, yell for help; it's quicksand.

Unfortunately for science, there appears to be a widespread disparity in the lengths of thumbs, not to mention differences in weights pushing. We have been thinking of mentioning this to ASTM with an eye to issuing a suitable standard. One difference between an architect and an engineer is that an engineer knows his thumbs. The architect first looking at soil tends to get it the other way around.

Subclass PP: The Pocket Penetrometer. For the man who is all thumbs with his thumbs a pocket penetrometer may be the answer. With this little gadget you measure the force required to push a small plunger 1/4 inch into the soil. Correlations have been made with unconfined compressive strength (mentioned later) such that the scale is calibrated to read directly in tons per square foot. No guarantees, of course, but at least you read a numerical answer, and this impresses a client. Alternately you can tattoo some numbers on your thumb.





Subclass Drillrig: The Standard Penetration Test is a kind of systematized comment on how hard it is to drive a sampling tube. The system is to count the hammer blows to drive the tube one foot. Since the hammer weighs 140 pounds and must be raised and dropped 30 inches per blow, machine power is a great aid.

The sampling tube, or "spoon", also is standardized. It is 2 inches in outside diameter and only 1.4 inches on the inside. The "split spoon" therefore displaces as much as it samples, so the sample is hardly what one would call "undisturbed", although some do call it that in moments of high humor.

Various schemes have been used to convert blows-per-foot, or N values, to bearing capacity. One can take a wild stab, divide by 10 or some such, and call it tons per square foot. Another recipe is to take the square root and multiply by a grading factor which is a maximum of 1 for a well-graded loamy gravel, 3/4 for a clean gravel or loamy sand, 5/8 for clean coarse sand, and 3/8 for fine sand, silt, or clay.

The Standard Penetration Test is most reliable in sands, where N is a surprisingly good indicator of friction. The angle of friction, discussed later, is approximately $28^\circ + N/4$. Good policy is to forget the N's for silts and clays, which are more accurately tested by other means, and keep them for sands, where other tests are very tough.

Subclass Dutch Cone. A more refined type of penetration test utilizes a conical tip. Penetration is slow and steady rather than by hammering, and the resisting force gives an indication of the strength of clays in Holland. Perhaps our interpretation is a little vague, but anyway the test does work well for soft clays. A similar cone may be driven in sands to estimate friction; a disadvantage is no sample.

FAILURE THEORY

Before proceeding with the proceedings we must halt and have a brief discord.

Are you confused by stress and strain, sines and symbols and legerdemain? Well, move over; they aren't all easy as π.

In an engineer's view, stress is the force and strain is the give. Stress is when the kids yell too much; strain is when you suggest they go play in the traffic. Stress is quiet and invisible, like an inner seeping anger; strain is distortion--the frown and the fist, the sickness or the laughter.

Avoiding the Breaks

Too much stress brings a break, whether in a material or a marriage or international politics, like Russians vs. Chinese. The result is termed a failure. Failures are brutally obvious, and only a dolt would try to ignore them.

Engineers spend much of their time calculating failure stresses in advance, so they can keep actual stresses on the safe side. The stress well calculated to cause failure is divided by the actual stress to give a "factor of safety."

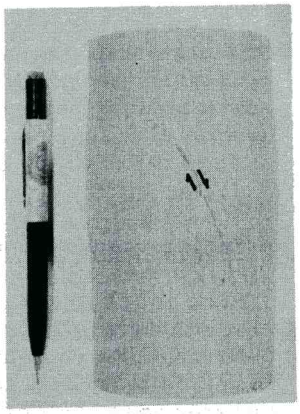
For example, lifting a 10 lb fish with a 15 lb test line means a factor of safety of 1.5, although not from the point of view of the fish. Factors of safety depend on human frailties of testing and arithmetic, and may not be entirely accurate. Maybe the fishline has a weak knot. Factors of safety are therefore termed factors of ignorance, but not in front of a client. A factor of safety less than 1.0 means you lose the fish, hook, line, and sinker.

Return to Table of Contents

Internal Friction

Foundation soils loaded in excess tend to fail by sliding along a shear plane. For example, consider the landslide; but perhaps you aren't familiar with a one-party system.

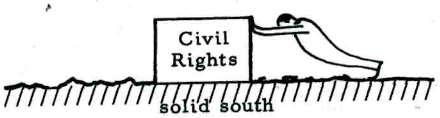
The force, if any, resisting a land or other slide is termed friction. There is very little friction apparent in a one-party election, although there may be an abundance hidden away within the party. It's the same in soils, where it is called "internal friction." In political parties it may be called internal friction, or it may be called "infernal friction" or "internal fiction," depending on whether it's in your own group or in the opposition. To the innocent spectator it's a little of both; everybody knows there's more infernal fiction in politics than in any other game except advertising.



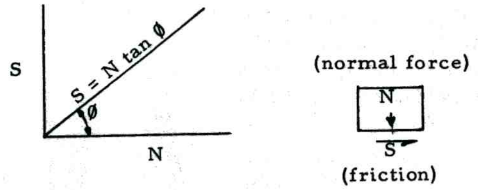
Soil sample loaded on ends fails by shear, which is resisted by soil internal friction. This sample was confined by air pressure during the test in order to increase normal pressure on the shear plane and increase friction (triaxial test). Pencil is used for writing down the results.

In any crowded urban population such as soils, internal friction is no fiction, but is proportional to the amount of confinement. In soils this is termed the normal pressure, or pressure on the shear plane. The larger the normal pressure, the greater the frictional resistance to shear. In animate populations the forces causing internal friction are a little more abstract, and include such things as neighborhood acoustics, summer comfort index, traffic jams, and dog jobs on the lawn.

FRICTION



FRICTION



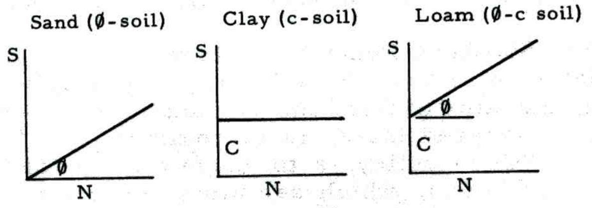
A graph of maximum friction versus normal pressure on the shear plane is ideally a straight line. The angle Ø is the angle of friction, and tan Ø, or S/N, is the coefficient of friction.

Cohesion

You may think friction is a real drag, so let's have a look at cohesion. Clays with little or no internal friction are still firm enough ground for some fancy footing work. Or to put it another way, a friction restriction is no cause for eviction. And cohesion is the reason. Many cities derive their main support from clays, not to mention other sources such as parking meters and taxing the poor.

Strictly speaking, cohesion is sticking together. In soils, as in most populations, it is best developed among the smallest members of the group, in this case clays.

The soil mechanic is not particularly interested in cohesion as a tensile strength, but is more concerned with the shear strength it causes. He therefore calls this shear strength "cohesion." That's about like calling your husband "Van" because he comes home at night loaded. A more exact term for c is "cohesive shear strength," but nobody says that.


Sand (Ø-soil) **Clay (c-soil)** **Loam (Ø-c soil)**

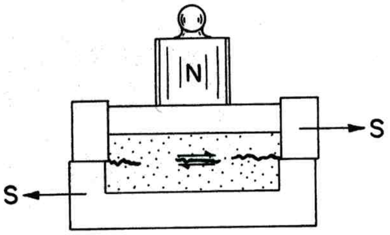
To summarize, each soil has a value of c and Ø, cohesion and angle of friction, depending on such things as size gradation, compaction, moisture content, and clay mineralogy. The c and Ø can be measured by laboratory tests on undisturbed samples.

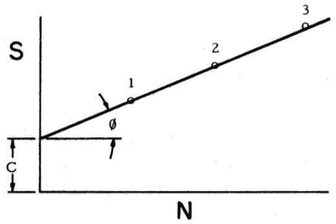
Return to Table of Contents

LAB TESTS

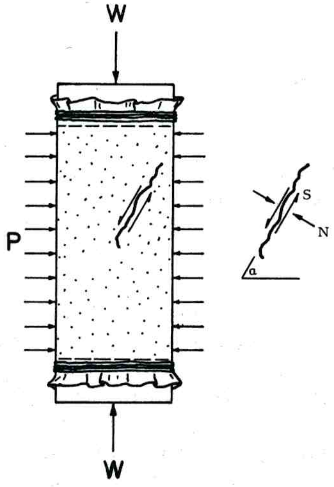
Most of us are familiar with lab tests of one sort or another, as when you are simultaneously jabbed in the finger, told to read the eye chart, and handed a sample bottle. By comparison, soil tests are much nicer; no pain and no strain.

The simplest way to measure c and Ø in a soil is the direct shear test. A soil sample is trimmed to closely fit inside a shear box. The ends of the sample are loaded with a value of N, and two halves of the box are slid apart until the soil shears. The maximum pull per unit area of the soil mass is a value of S, which together with N gives a point on the S vs. N graph. A second test with a different value of N gives another point. Two points determine the line, from which c and Ø are read directly. A third test is usually made for good measure.





A slightly more complicated way to get at c and Ø is the triaxial test, meaning you give it the ax on the third try. Here the sample is covered with an air-tight membrane and confined under pressure, much as it would be if it were still deeply buried underground. The ends are then loaded to failure.

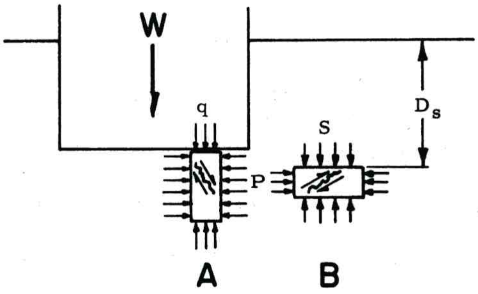


In the triaxial test the position of the shear plane is not fixed as in the direct shear test, so S and N on the shear plane vary depending on the break angle α. The α sometimes may be measured, but is more accurately found mathematically from Mohr theory. Experts say α also equals $45^\circ + Ø/2$, if you care to heed the experts. Most people do, so long as they don't have to give up smoking.

APLLPILCATIONS*

This story had better observe the literary traditions and come to a climax pretty soon before it drags out into something severe, like a textbook. This may seem a rather long route merely to find out if a building will stand still or get a move on, but these things are nice to know in advance. It's too bad the perennial human conflict equations are not so well turned; might save on wars and such. It would also louse up the football pools.

Once the soil strength factors are known, there are several ways to analyze. One is to consider soil under a foundation as being in a triaxial test, A. But in order for the soil to fail it must bulge, which means it must cause failure of the horizontally oriented sample at B. The confining pressure at A equals the axial load at B, and the confining pressure at B equals the weight of the overlying soil surcharge in depth D_s. If you work through all those equals it comes out



$$q = \gamma D_s\left(\frac{1 + \sin Ø}{1 - \sin Ø}\right)^2 \qquad (1)$$

for a Ø-soil, γ being the unit weight of the soil. For a c-soil it comes out

$$q = 4c \qquad (2)$$

For a Ø-c soil it comes out very long.

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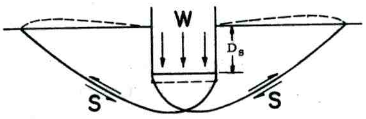
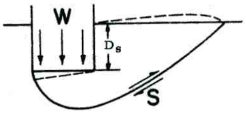
* Either this is a misprint or this is the only place that isn't. We don't believe in half-way jobs.

Return to Table of Contents





Plastic flow

Another way to look at it, probably closer to the facts, is to consider the shear plane or planes which form when a building sinks irretrievably into the ground. The shearing resistance S equals c plus a function of ϕ times the length of the shear arc. The exact solution depends on the assumed shape of the arc and a few other things, and some rather horrendous equations are available. When a chemist sees an horrendous equation he memorizes it; it's poetry. When an engineer sees one he draws a graph.

Graphical solutions take the form

$$q = \frac{\gamma b}{2}N + cN_c + \gamma D_s N_q \qquad (3)$$

where b is the footing width and the three N's depend on ϕ and are read from graphs.

Clay. In a c-soil the first and third terms practically drop out, and

$$q = 5.7c + \gamma D_s \qquad (4)$$

for a long footing, the second term depending on the depth below ground surface. For a square footing the first term is 7.4c.

Sand. In a ϕ-soil the middle term drops out:

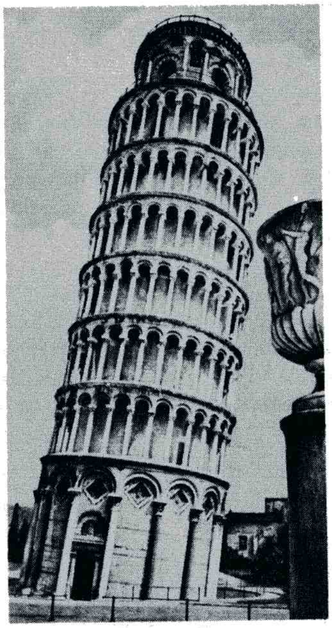
$$q = \gamma(\frac{b}{2}N_\gamma + D_s N_q) \qquad (5)$$

Bearing capacity is therefore a direct function of density γ, which means come high water there's hell. Buoyant effect reduces γ and friction as much as one-half, whether under a building or at the toe of a landslide, as in northern Italy. Soil engineers rank high in prevention of mass tragedy. Some feel such a responsible profession would bear licensing, as in the case of other branches of civil engineering, not to mention doctors, lawyers, druggists, barbers, and morticians.

A somewhat less acute factor in the equation is footing width b. A 2-foot square footing on sand will support up to twice as much as four 1-foot square footings with the same total area. No spike heels on the beach.

Unconfined compression

The unconfined compressive strength of undisturbed soil samples is often used as a basis for bearing pressure. In a clay with zero ϕ the fracture angle is 45°, and the unconfined strength q_u equals 2c. Substitution in equation (2) shows a built-in factor of safety of 2.0. By equation (4) it is 2.85 for long footings and 3.7 for square ones. Friction in a soil boosts this even higher, the limit being sand, which has a good bearing capacity but q_u equal to zero. Extra safe also means extra cost.



The Leaning Tower leans to the right despite objections from Italian leftists, illustrating the advantage of viewing a fact from all angles. The Tower is unique because unlike most medieval towers it is still standing. Doctors bury their mistakes; soil engineers go one better and let their mistakes bury themselves.

Lean of the tower has been attributed to shear failure of the underlying sand but is more likely due to consolidation of a clay some 30' down. Attempted remedy has been to grout the sand.

More to come

No discussion of foundation engineering would be complete without some mention of consolidation theory and settlement, field loading tests, and use of pile. We therefore would like to mention consolidation theory and settlement, field loading tests, and use of pile. A somewhat more complete account may be expected at some later date.

DEDICATION

This issue of "Screenings" is in memory of the late Dr. D. T. Davidson, under whose guidance the Iowa Engineering Experiment Station Soil Research Lab came to national prominence.

Following Dr. Davidson's untimely death a year ago Dr. R. L. Handy was named director, and work has been continuing at a rapid pace. All except for "Screenings." Some say the father ran off with some cute little Project to do some basic research, and desertion charges are pending. Meanwhile we expect the publication will be highly irregular.

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Return to Table of Contents