Building from the Ground Down

Thanks to the science of soil mechanics, what happens from the ground down is no longer a complete mystery

by Ronald Scott

The field of civil engineering is split up into three branches: structural engineering, dealing with the study of materials, forces, and stresses involved in the construction of buildings, dams, and bridges – in short, of those generally massive works of man which appear above the ground's surface; hydraulics, in which the flow of water in pipes, canals, rivers, estuaries, and harbors is studied; and foundation engineering or soil mechanics, whose studies concern themselves with the invisible aspect of structures – the part from the ground down.

All building rests ultimately on the ground, which thus becomes the foundation engineer's working material. Dust, earth, loam, peat, clay, sand, gravel – all are soil; a layered, stratified, inhomogeneous, variegated, and problematic material. It is hard to investigate, hard in many places to build things on, and hard to modify in useful quantities. Our field of study is all the earth's sediments in their numberless forms – not as chemical materials (although sometimes we have to force ourselves to look at such properties), and not as agricultural stuff (although agricultural terms and classifications have been used and adopted), but as a structural substance, a material whose deformational behavior in large masses we must learn to understand and to predict.

The pictures below show some soil stuff. The first is a piece of rock, familiar to everyone. Rock may occur in massive blocks or it may be jointed and fissured. We tunnel through it and build footings and foundations on it wherever possible. Usually it offers few problems.

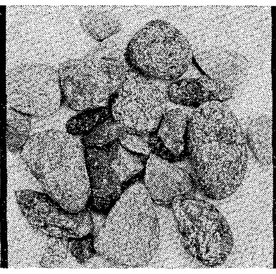
Rock is broken up by rain, heat, cold, freezing and thawing, and gravity, into fragments with a wide range of sizes. When the size is fairly large – an inch or two in diameter – we call the soil gravel. Some gravels are angular, indicating that they have only recently been formed from the parent rock. Others are rounded when a river or sea has extensively worked on them.

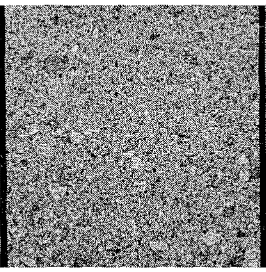
Progressive mechanical erosion results in smaller particles than gravel; these are sands. A sand is generally formed of a range of particle sizes, shapes, and colors. The different colors indicate derivation from different minerals in the parent rock, but the minerals do not greatly affect the mechanical properties of the soil in which we are interested. The size, range, and shape of the grains do influence the soil's strength, however, through different interlocking effects. We call sands those soils whose particle range extends down to the size at which our eyes can just distinguish individual particles.

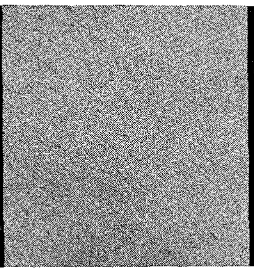
Still more grinding, reworking, and rubbing – all mechanical processes – result in finer materials called silts. Below this size, however, the soils formed are generally the result of chemical reactions. The last picture shows some lumps of clay.

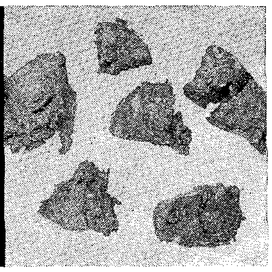
Between sands and clays there is a very obvious


Rock


Gravel


Sands


Silts


Clay

division, straddled by the silts; the clays exhibit cohesion – they stick together, wet or dry – and the sands do not. A heap of sand spreads out because the grains have no adhesion to each other, while a piece of clay will stand up because the particles cohere. Silts run somewhere in between, with less cohesion than clay and more than sand.

In the mass, each of these materials behaves differently under a building load, and many studies were made before the appropriate important properties of each material were recognized and methods found to measure them. This is particularly true of clays, whose cohesion is a very complex phenomenon.

Problems of a foundation engineer

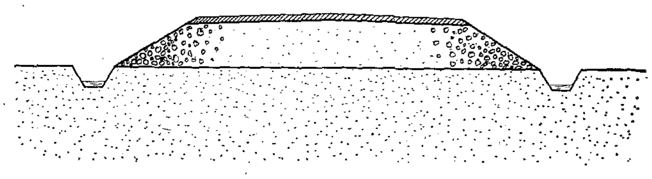
With what foundations does a foundation engineer concern himself? The pictures at the right illustrate some of our problems. Let us begin with what may seem the simplest – roads or airports. The upper drawing shows a cross-section through a typical highway. On top of the natural soil is placed a designed compacted fill material which may vary in thickness depending on the softness or stiffness (we term this "bearing capacity") of the natural soil and the loads and traffic the highway will have to bear. The wearing surface consists of concrete or asphalt, which carries the actual traffic while helping to spread the load on the underlying ground.

The next illustration shows two houses. Local building codes usually require that footings be placed a minimum distance below ground surface. The shaded zones below the footings of the left-hand house show how the stresses due to the weight of the building are spread out in the underlying soil. Usually we find that all of the significant stresses in a soil mass below a footing occur at depths less than one and one-half times the width of the footing, although the behavior of the foundation may be influenced by soft layers at greater depths.

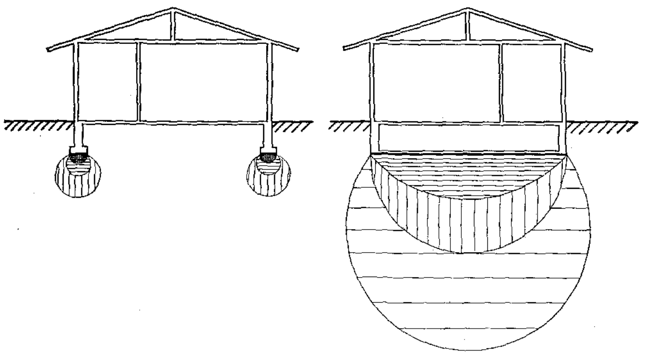
If the soil is not strong enough to bear the weight of the building, we can either reduce the pressure on the ground by using a so-called "raft" footing, as shown in the right-hand house, or we can drive piles to a firmer stratum underneath and build the house on the piles. In some cities, such as Boston, where compressible clays occur to depths of 100-120 feet, heavy buildings are sometimes "floated" by excavating a basement for the building, in which the weight of the soil removed from the excavation is equal to the total weight of the structure. The idea is that if excavation and erection are carried out quickly enough, the soil under the building will not know the difference between the weight of soil above and that of the building above!

Other areas which concern a foundation engineer are excavations, where it is necessary for him to estimate how high a face will stand unsupported – or, if a wall should be necessary, what soil pressure on the wall will be, so that the wall can be designed strong enough to support the soil behind it.

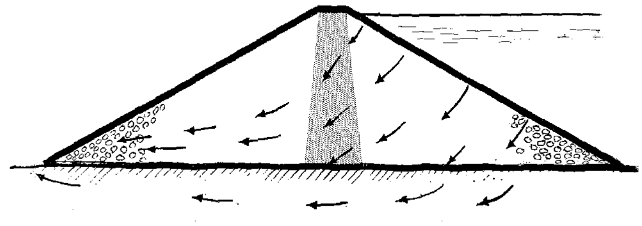
SOME TYPICAL PROBLEMS IN FOUNDATION ENGINEERING



Roads



Houses



Earth Dams

An area of growing interest in recent decades has been the construction of dams of earth. The last drawing shows a cross-section through a typical earth dam and we can use it to point out where soil mechanics problems arise. The most obvious function of a dam, even an earth one, is to retain water, and thus we must study the flow of water through the natural soil underlying the dam and through the artificially placed soil of which the dam is composed. The rate of flow must be ascertained to make sure that materials with small enough permeabilities are used. The water flowing through and under the dam exerts certain pressures on the dam's materials and these pressures must be calculated before, and checked during, construction. If they become too great, measures must be taken to reduce them.

Then, as the dam is built of reworked and remolded natural soil, the soil engineer must know the strength properties of the local material under differing conditions; he must determine how to compact the soil best so that it is, if possible, in its strongest and most impermeable state, and finally must be able to apply his calculations to the slopes of the dam to make sure that they will remain stable during and after construction under all conditions of reservoir heights, through storms, and through earthquakes.

Because of their heterogeneous, unpredictable nature, soils were long avoided as a subject of study and most of the early theories advanced regarding the behavior of soils under stress gave conflicting results in the field.

Civil engineers, of necessity, were hard, practical men, whose job consisted of utilizing the experience gained on previous works to predict the behavior and make designs for new situations. As theories didn't seem to apply to soils, few theoreticians wasted much time on the material — a situation which, to some extent, persists to the present day.

The hard-headed approach

A civil engineer, in general, is still a man who tests all materials by the hardness of his head, goes largely by past performances and is disinclined to trust theories — especially if they appear to contradict his own judgment or personal experience. A foundation engineer has a down-to-earth approach to his subject.

The experiences leading to the gradual growth of sound judgment in such engineers go generally uncommunicated to the rest of the workers in the field; this is the reason the science of soil mechanics has advanced so slowly through all the centuries of man's strivings to improve his environment.

For years it had been observed that many structures settled, without failing, through time. These structures continuously sank, and in many instances cracked. The successful investigation of this problem at last began the modern science of soil mechanics. It was shown that these gradual settlements were caused by the slow drainage of almost impermeable saturated clay layers underlying these settling structures. This process is describable mathematically and, while the variability of the properties of soil inevitably imposes limitations on its exact application, good predictions can now frequently be made of the amount of settlement to be expected.

The old question: "Are you planning to settle in these parts?" now brings from a foundation engineer a more precise answer: "Yes, about 3 to 4 inches."

Where soil conditions are bad and the analyses indicate that normal footings might settle too far or might possibly fail, piles are resorted to. Here is another field of study. How much energy is needed to drive a given pile? How far must we drive it? How much load can we put on it? How much will it settle under that load? Although in many cases these questions are still hard to answer, much information has been obtained. Pile driving, like the other divisions of soil mechanics, will never be precisely predictable.

So far I have indicated without emphasis the main difference between the foundation engineer and his fellow engineers and scientists. *He* must work with his materials as he finds them; he must try to find out about the properties of his working substance as it exists, and do what he can with it.

Other engineers are possibly more fortunate, but certainly less well-entertained men. The metallurgist, for example, makes his materials to the mechanical or structural engineer's specifications; the chemist or the physicist isolates or purifies his working substance to the state he desires and then causes it to operate according to his predictions. Heat, metals, chemicals, and electricity generally behave in a homogeneous, predictable manner. When they don't, a discovery is made, an invention is born.

The soil engineer has not, until very recently, been faced with this situation. The soil exists in its own sweet unconformity and he has had to do *what he* could with it. His science was a passive one, in which the design of the structure had to yield to the properties of the soil. With the expanding world of transportation, and the establishment of new cities and industries, water, power, highway and railroads were needed to feed them. A need arose for soil as a *construction* material to build bigger embankments, to be used under more highways, and for larger earth dams. It was at last necessary to investigate how the properties of soil could be modified — to find how we could make the soil behave according to our needs; how to make it stronger, less compressible, more impermeable.

Stabilization of soil

The stabilization of soil is the second, or active stage of the science. The first studies in this direction were towards compacting the soil. It was found that the highest soil densities could be obtained by ramming or vibrating the soil at an optimum water content for each soil. Since the highest density is generally associated with the greatest shear strength of a soil, it was obviously desirable to build embankments and earth dams using soil compacted at the *optimum* moisture content.

This was the first step in developing the potential of soil. In this way the strength and performance of the soil in embankments and highways could not only be *predicted*, it could be controlled!

In the studies of compaction methods, new ramming and compaction devices were invented. One of the most widely used is called a "sheep's foot roller." Not long ago I was reading a Scottish magazine, in which there was an article about the old crofts and crofters in the Highlands in that country. The author, with a fondness for the old way of life, had come across a description of the construction of these crofts. "The floor would be covered with a layer of mud and fine clay and trampled down by the men's feet. A flock of sheep was then driven in within the walls. The sheep were kept on the move for a whole day, and then let out. The result was a fine smooth floor, which needed nothing else but a good fire to dry it out and perhaps a goodly sprinkling of white sand from the shore. The surface was called a 'sheep's feet floor.' "

The investigations of the causes of the shearing strength of soil, and the discoveries about compaction began interest in a whole new field of soil studies, namely the study of changing the properties of soils by means of additives, usually chemicals.

The first main division and object of this field of study was the most obvious one of stabilizing the soil. Where we have a loose sand under a foundation, or when we want to build a structure or a road on a soft clay or peat bog, it would be pleasant if all we had to do was inject an appropriate chemical into the ground, whereupon the soil would harden sufficiently to take the applied loads.

Several chemicals have been discovered which can do this. Soil-cement and soil-lime mixtures have long been used in certain areas to build successful roads, and small quantities of other chemicals induce useful amounts of bond in otherwise soft or loose soils. However, to obtain the best, most desirable effects, the chemicals have to be thoroughly mixed with the soil under study. In sands and in silts it is possible to do a certain amount of this mixing merely by injecting the chemical into the soil. This method, of which there are several variations, has been successfully used in stopping loose soils from flowing into mine shafts and tunnels and has also been employed in stabilizing loose granular soils under existing foundations. It is not, however, possible to utilize injection procedures in fine-grained clays; the liquid simply will not percolate.

Mixing chemicals with soil

In the latter case, the chemical, liquid, or powder must be mixed with the soil. This immediately implies that the soil will be reworked, that its undisturbed in-place properties cannot be altered. That is a regrettable limitation, but reworked soils still offer a vast useful potential in highways, embankments, and dams.

The difficulty is in the mixing. In general, if large quantities of chemical are needed to stabilize a soil (say, one part chemical to 7-10 parts soil) then mixing need not be too efficient to achieve reasonable average results. If only small quantities (1 or 2 percent chemical) achieve a useful degree of stabilization, mixing must be thorough.

We immediately become involved in economics. How much do various chemicals cost per pound or ton, and in what proportions must they be used? How much does it cost to achieve adequate mixing of a given chemical? Is more mixing required than the soil gets during normal transportation and compaction? Can mixing be achieved more efficiently at less cost?

The sheep's foot roller — a widely-used compaction device — meets up with its natural inspiration.

The use of any of these chemicals depends on their cost which, in any world, depends on how much of a demand there is for them. In some cases useful chemicals could become much cheaper with better production if there were a greater demand for them — a demand which is strangled by the initial cost!

One such chemical is calcium acrylate. In quantities of 1 to 5 percent of the dry weight of soil it can usefully modify the strength and permeability properties of soil, but unfortunately it is at present produced in pilot-plant or laboratory quantities only and the cost at this time is $2 per pound. Since there are approximately 3,000 pounds of dry material in one cubic yard of soil, it would take 150 pounds of calcium acrylate to achieve stabilization, at a cost of $300 per cubic yard of stabilized soil. Since the normal cost of concrete is about $15 to $20 per cubic yard and the cost of earth placed in construction projects is about 70 or 80 cents per cubic yard, calcium acrylate is scarcely an economical substance to use as a stabilizing material. If, however, some other demand were to arise for it so that its price would drop the way the other acrylic resins have done since the war, it may yet be possible to use it for stabilizing purposes.

While this stage of the science is in its infancy, sufficiently promising results have been obtained with certain chemical additives to warrant the prediction of a bright future for such processes in the field of construction.

If I have done nothing else in this article I hope that I have indicated that there *is* a science of soil mechanics — and that what happens from the ground down is not a complete mystery to us any longer. It is possible to *design* foundations, piers, retaining walls and dams. There is no doubt whatever that our engineering abilities in this direction will continue to develop in the future.