the Water in the Soil – Part 1

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Introduction

Professor Alec Skempton of Imperial College was my external examiner at the provincial Irish university where I finished my masters in Soil Mechanics and Soil Physics in 1963. I remember being quite scared at the prospect of being questioned on my thesis by this British icon. But when it came down to it, he really only asked me one simple question: "What is the most important thing in Soil Mechanics?" My answer was equally to the point: "Water", I said, and couldn't think of anything else to add to make my response a bit longer. I remember him pondering there and really not bothering to examine me further. Now, after the forty plus years of geotechnical practice that has passed in the meantime I've not found a good reason to change my mind.

The thing that caught my attention time and time again during my working years was the power of water, not in the sense of generating electricity, but how water was almost always the cause of a slope failure, and how civil contractors used dewatering to make unnaturally steep excavation slopes below the water level. But in those intervening years I also came to realize that I was not at all sure that we engineers properly understood how water behaved in soils under deformation, not to mention during earthquake shaking. Neither was I convinced my engineering colleagues in academia knew any better. So slowly, as work allowed, I set about trying to figure it out for myself – from first principles.

Over the past two decades I've spent much of my spare time thinking about the real basics of pore water pressure in both saturated and unsaturated soils, doing so in the hope that I might eventually come up with a rational explanation for each of these soil conditions. In this series of articles I want to concentrate on pore pressure generation in saturated granular soils, leaving unsaturated soils and cohesive materials for another occasion.

Towards the end of the series I will propose the following equation for the generation of excess pore water pressure at any point within a saturated granular soil experiencing deformation:

$$K (24 \mu + \rho D v) L v / 2 D$$

I won't complicate things right now by explaining each of the terms, other than to say that the only unfamiliar terms are "K" and "L", and that these two will be fully developed in subsequent articles. Incidentally, nothing more than the early bits of Physics 101 will be needed to follow my line of argument.

Square One

In making a fresh start I had the luxury of deciding where to begin. And the easiest place for me to get going was liquefaction. Apart from being an attention grabber, I see liquefaction as a physical activity where it is easiest to grasp what's happening in the motion between the two phases (solid and liquid).

I do hope readers don't get too hung up on the term "liquefaction": This simple concept has been much abused over the years. So I suggest for those folk who believe dense sand, or a well graded granular fill can liquefy, you read instead something like "total collapse of a saturated soil-structure". In any event what I have in mind here is what happens when, in a fully saturated environment, a very loose mass of similarly sized sand grains falls into a denser arrangement due to some change in the stress system which had been keeping it in a precarious structure of mutual support.

The reason I think liquefaction is a good point of departure is this. As a consequence of collapse the soil-structure can no longer act as a rigid formwork for the discrete grains, and for some time thereafter they no longer interact or support each other. It is during this momentary separation of the two phases, as the two soil components merge into a composite fluid, that paradoxically, an opportunity is afforded to view the particles as acting independently and be apprehended in isolation as separate individuals.

To focus my attention on this particular phenomenon I dreamed up a cartoon of liquefaction in the simplest form I could imagine. I call this "thought-experiment" the three beaker question, and I will now described how it goes.

the Weight of Failure

Figure 1 shows three identical beakers containing particles submerged in water. In fact what I really have in mind is the same beaker at three different times. The number and size of the solid particles and the amount of water is exactly the same in each beaker. The beakers sit on weighing scales. The particle packing in the "before" beaker is as loose as can be and consequently is at the point of structural collapse. The "during" beaker has been subjected to a jolt which causes failure of the structure, so what is represented here is a soil being weighed during failure of the soil-structure. The "after" beaker is the situation prevailing shortly after failure when the new soil-structure has settled into a denser, more stable, packing arrangement.

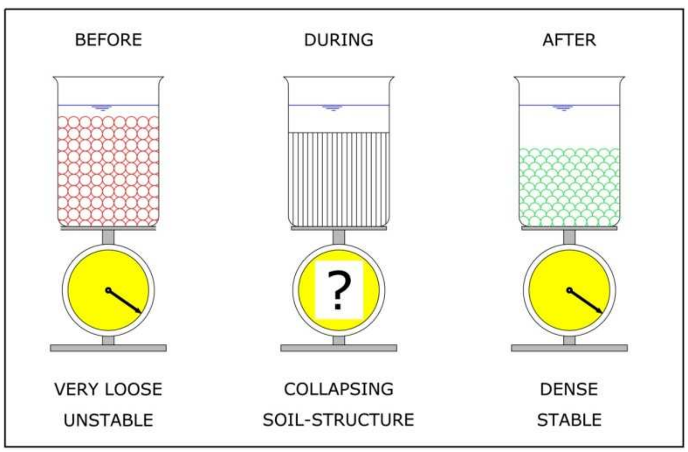

Figure 1: The three beaker question

The question is: Is there a difference in the weight between the three beakers ? More specifically, is the weight of the middle beaker different from that of the ones on either side.

I believe there are several "right" answers to that question, depending on particular details of particle size and the time at which the weight of the active beaker is recorded. My answer is that in most cases, most of the time, the weight of the active beaker is less than the other two – the other two (inactive) beakers being exactly the same in weight. My thinking goes along the following lines.

Since the two outside beakers (before and after failure) have the same mass of solids and water, and since they are static, just sitting there with nothing moving, there is no reason to justify a difference in weight. Using "g" for gravitational attraction, the weight of the first and third beakers is simply equal to m times g.

But things are different in the "during" beaker: There is movement, and that movement is downwards into the gravitational field. More than that, because the solids/particles were initially at rest and ended up at a lower elevation, the particles must at some stage have being accelerating downwards. That means they were experiencing some modification, let's call it "a", superimposed on the original gravitational field "g". They were in fact under the influence of a "g minus a" flux. Therefore, the weight of the beakers as measured by the scales should be:

Before	m g
During	m (g – a)
After	m g

And this quite definitely would prove the stable conditions were equal in weight and the "during" beaker lighter than both. Fortunately, however, things are not quite as simple as that: In what I've done so far I've been ignoring the water !

This introduces a few complications: The fact is that the solids moving down had to be accommodated by an equal volume of water moving up, and at some stage the water had to be accelerating too. Water density is only about 60% of buoyant grains and this argues in favour of the active beaker still being lighter. I simply don't know the ratio of the accelerations. To add to the murkiness of the situation, don't we all know failure is accompanied by an increase in pore water pressure when a contractive structure collapses ? So could water pressure on the base of the beaker make up the difference caused by the descending solids, and just add up to making everything turn out the same in the end ?

As we engineers know, thinking about problems only gets you so far, eventually you need to step into the real world of a site to get the answers to what really might be going on. Obviously it is now time for a reality check by a real life enactment of the "thought experiment". The problem here is that a laboratory test would be quite a difficult experiment to perform since it would involve some way of introducing a jolt enough to cause failure without the attendant commotion upsetting the vertical reading. Next best thing would be to reduce the test to its bare essentials and see if I could find a way of doing the measurement with what I could find around the house.

Kitchen Experiment

Looking at the "before" and "after" beakers it is apparent that mainly what changed was the position of the centre of gravity of the particles; it is lower after the collapse than before. So perhaps a very simple test involving just one solid particle would tell me something about what might be the range of possibilities in the "during" beaker. And this setup was so simple that I found in my kitchen enough for a "quick and dirty" version of such a test. Figure 2 shows all that's required. Setup to cleanup takes about half an hour.

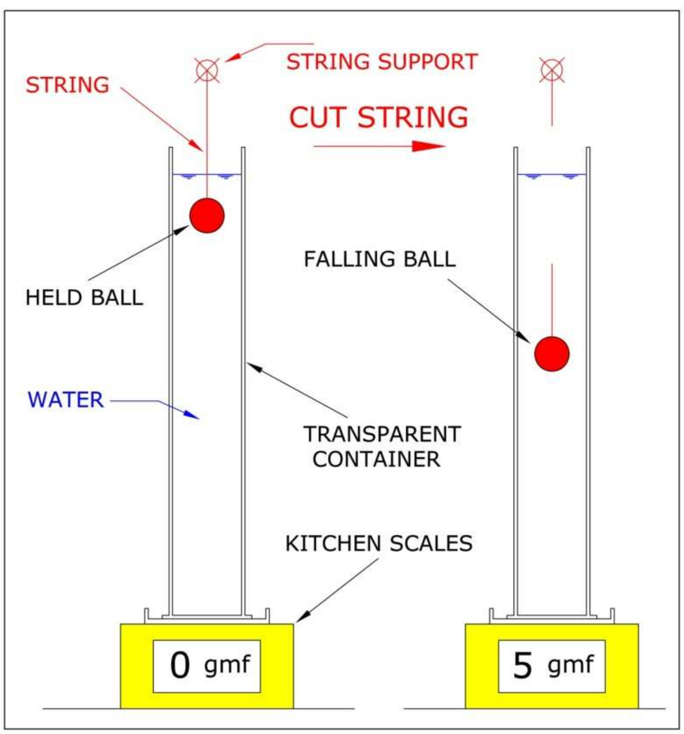

Figure 2: The kitchen experiment

To have enough time to see what was happening I needed to arrange to keep the action slow, and at the same time to produce a weight (buoyant) heavy enough to show up on my scales. After trying a few things which worked well enough, like a small potato and an egg (hard-boiled for obvious reasons), I settled on a golf ball.

The procedure was to hold the ball by a wire thread just below the water surface in a tall clear plastic container (spaghetti jar) . Then, after taring/zeroing the readout, let the ball fall while at the same time watching the reading on the scales. Right away I had what I was looking for. What I saw was that the scales showed nothing much until the golf ball had fallen about 10 cm – then it showed the full buoyant weight of the ball (~ 5 grams), and this appeared at a stage where and when the ball was still far above the bottom. This demonstrated quite clearly that the weight of the particle was felt when it had no hard physical contact with the scales. Two clear and undeniable conclusions are:

1) that the weight of the ball was transmitted to the scales by a column of pressurized water under the falling ball, and

2) that pressure transmission required some amount of movement by the ball through the water.

My reasoning from there went like this: Water pressure exerted on the base of the cylinder, and felt by the scales, was obviously a response to the weight of the falling ball above. But why the delay ? Why not the full weight right away ? There had to be another force involved temporarily, acting as a buffer. I couldn't think of anything to fit the bill other than viscous drag. And such a drag force is known to be generated between a solid and a fluid in relative motion. Fluid Mechanics had this all wrapped up generations ago so, as you'll see, it was just a matter of going to their comprehensive literature to work things out from there.

My scales was not sensitive enough, nor did it respond fast enough, to let me see what was happening between these two values. For this I needed to find a good laboratory in some university which would listen to a maverick with an odd notion about the genesis of pore water pressure.

UBC Test Setup & Prediction

Fortunately for me my good friend Yogi Vaid is Professor Emeritus at UBC and still had access to the fundamental soils laboratory at UBC which gained recognition as a world leader in triaxial testing during his tenure. Yogi, who was well used to listening to me ramble on about my abiding prejudice that pore water pressure had to come from relative motion between the phases, was happy to help. Here I got not only the better scales and a better readout device that I needed, but also the assistance of Scott Jackson and his experimental expertise.

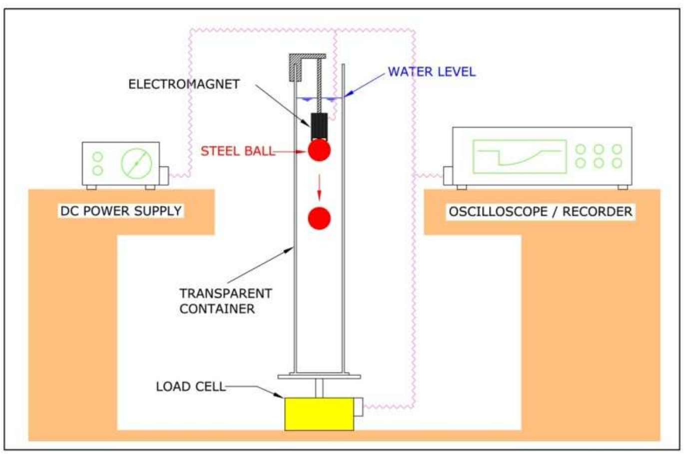

Figure 3: UBC laboratory test setup

For this opportunity I designed the apparatus shown in Figure 3. The design intent was to discover what was going on during the intermediate period between releasing the ball and the time its weight showed up on the scales. I decided the best thing to do was to record only one thing – the weight of the full system, that is, ball, water, and apparatus hardware. This involved some compromises. To get sensitivity in the readout the weight of the water had to be kept within reasonable limits and this meant using a cylinder which was a bit shorter and narrower than I'd have liked. Also the ball had to be quite heavy. I decided on a 2 inch ball bearing, using steel rather than ceramic because of its far greater buoyant mass density. Steel had the added advantage that it could be held in place by an electromagnet which could also drop it with a flick of the switch. The whole system, ball and all, sat on a load cell which was connected to an oscilloscope and a data recorder. All was necessary after things were setup was to power up the recorder and switch off the magnet.

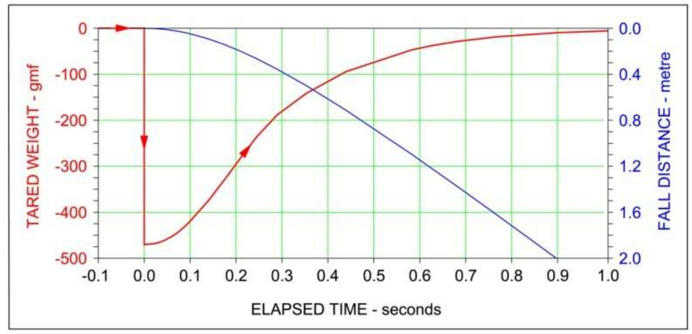

Figure 4: Prediction of UBC test results

In lab testing, as in site investigation sampling and construction instrumentation, you get much more out of it if you have already thought enough about what to expect to let you risk a prediction. With this in mind I calculated the weight history I anticipated on the basis of the hydrodynamics that I thought were going on. This prediction is shown on Figure 4. I wanted it to be a clear understanding that if the prediction was right then the hypothesis was justified, and if the prediction was wrong then it was time to forget the whole thing. Needless to say I wouldn't be writing this if it turned out all wrong.

in the Next Article

In the next of this series I'll give the results of the UBC test and compare them with the prediction made beforehand. And there I will also lay out the reasoning behind the predictive method and explain how the required calculations were made.