the Water in the Soil – Part 2

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This is the second in a series of articles in which I am proposing a way of calculating the pore water pressure that comes about within a saturated granular soil while it is undergoing deformation.

In the previous article I began the development and justification of this idea by showing that when a particle is falling through water there is a pressurized zone ahead of the particle, and suggested that the magnitude of this pressure front is somehow dependent on how far the particle had fallen through the water. Then I ended with a prediction of what would be the rate of generation of water pressure in front of a solid sphere in a test to be carried out in the research laboratory at UBC under the kind auspices of Professor Vaid.

Now here are those results and my interpretation of them. Afterwards I'll go on to suggest what these findings say about liquefaction of saturated soils.

Results of Test at UBC

In Figure 5 the ragged blue line is a trace of the digitized record of weight against time measured at UBC for the fall of a 2 inch ball bearing. The red curve is the weight predicted earlier. The x-axis shows time. The y-axis shows the system weight, and where the line approaching from the left is hovering around zero.

If you recall, the test setup that produced this trace (Part 1, Figure 3) has the ball suspended from an electromagnet below the water level in the cylinder; the load cell records the weight of all the hardware (cylinder, water, electromagnet and ball). So the trace in Figure 5 is the weight of all components measured before, and for about a half second after the power to the electromagnet is cut, resulting in the ball being abruptly dropped to let it "free-fall" through the water column.

Now, what the trace shows us is a sudden weight drop into negative values, and then, a subsequent

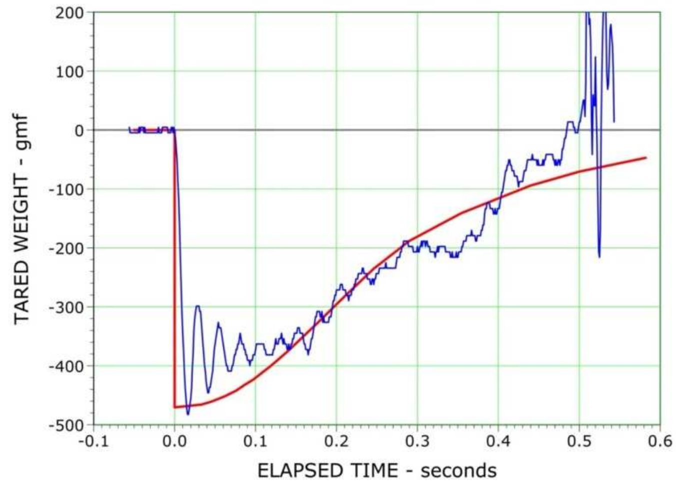

Figure 5 : Digital results of UBC test

gradual oscillating recovery of weight until, at the end of the trace, the readings go off-scale on both sides of zero. The mechanical explanation for the shape of the trace shape is as follows.

Immediately the ball is set loose the system records the complete loss of the buoyant weight of the steel ball. Now that it's weight is no longer attached to the side of the cylinder, the cylinder itself which up to that point has been carrying that load in axial compression, reacts like a spring and begins bouncing up and down. This vibration is seen as the cyclical waveforms superimposed on the record of the apparatus weight. Anyway, looking past the superimposed waves, it can be seen clearly enough that within a short time the weight of the system comes climbing back towards its pre-release weight. The excitement at the end of the trace is the crash when the ball runs into a sand buffer at the bottom of the cylinder. These impact readings show up as short lines alternating at either side of the oscilloscope weight range.

The waveforms due to system resonance are a bit of a nuisance and are a result of using a ball too big for the overall mass of the system. Basically, in hindsight, the cylinder was too small for the size of the ball. And also, apart from vibrations, I should think it likely there are boundary interference effects involved which contaminate the data. So what is being done at the moment to remove these undesirable attributes is to build a much longer and wider cylinder where the water pressure ahead of the ball is measured with an array of pressure transducers distributed about the base. Here, David Woeller of ConeTec has come to my aid by contracting Ron Dolling of Adara Systems to build this new apparatus, and most generously, donating it to this effort. So more and better data is on its way.

In any event, I believe there is already enough confirmation from the UBC results to answer the Three Beaker question, and to keep moving forward with this idea.

Interpretation of UBC results

As the load cell was set to read zero after all the objects contributing to the mass of the experimental setup were in place, any weight change subsequently showing up from this initial static condition would need to be explained in terms of a force arising out of the dynamic activity within the system. So as I see it, what went on inside the cylinder to explain the recorded trace may be understood as follows.

The instant the ball is released by the electromagnet its buoyant mass is set free in the gravitational field. In consequence, being instantaneously exposed only to gravitational attraction it begins to accelerate at a rate of "g" towards the centre of the earth. Therefore, since the ball is at this first instant in absolute free-fall there is no net acceleration acting on the mass to give it weight. This situation can be expressed as

$$\text{Weight} = m\,(\,g - g\,) = 0$$

This is why the load cell suddenly loses awareness, or fails to perceive, the ball's existence at the instant the electromagnet drops it. The next thing that happens – really it begins to happen simultaneously with the ball being set free - is that the ball starts to move downwards in response to gravity.

Once relative motion is initiated between the two phases, the water becomes aware of the ball's presence and tries to obstruct its further intrusion. This is because, as a viscous fluid, the water opposes the cavity expansion imposed on it by the progress of the ball through its domain. This opposing force we call hydraulic drag. Now, and this is the essential point: In order to support these drag forces it is then necessary that the water below the ball provide an equal and opposite reaction. It is this drag force reaction which shows up as increased weight on the load cell. The only way the water can convey this load is by compressive pressure. And I believe this is a clear example of the very same mechanism which accounts for excess pore water pressure in saturated soils.

If there is enough open water below the falling ball it then becomes a competition between gravity and drag, the one trying to increase the speed of fall, the other trying to slow it down. And the drag force, being proportional to the square of the ball's velocity, is bound to win in the end. With enough fall distance they come to a standoff when the speed of the ball reaches the point where the increasing drag forces rise to become equal to the buoyant weight of the ball. This familiar condition we know as Terminal Velocity [v_T].

Terminal Velocity & Liquefaction

In our line of business at present, we come across the concept of Terminal Velocity in the hydrometer test where Stokes' Law provides the relationship between small spheres and their v_T values, thereby allowing us to calculate the size distribution of silts. But now perhaps there is another more interesting use for it. And that is as a criterion for liquefaction.

I think that attaining relative velocities of v_T for particular sized particles is a necessary condition for saturated soils composed of those particles to liquefy. This is simply because at v_T the entire buoyant weight of the particle has been transferred to the water, thus rendering it effectively weightless. Weightless particles can have no frictional capacity because there is no normal force to impart to neighbouring particles. In essence, they have become dominated by the enveloping water, and functionally a part of the fluid. In a word, liquefied.

A consequence of this line of reasoning is that it is only uniformly graded soils that are prone to liquefaction. This seems to be so because if different sizes were involved in the mix it is hard to imagine how they all could attain v_T at the same time without moving past one another.

For some time past I've been hoping to establish an axiom of saturated soil behaviour that says: Increasing pore water pressure is not the *cause* of failure – it is the *result* of failure. In the particular case of the liquefaction-type failure discussed above that seems to be true. This is because the triggering event in the sequence is the failure of the soil-structure to prevent a particle from falling. It is only after the fall that water pressure begins to increase. Whether that argument can be sustained in the more general case of non-catastrophic soil-structure deformations I'll have to try and sort out as we go along.

Answer to the Three Beaker Question

This UBC lab test was designed to replicate the essential situation in the Three Beaker question, and that is, what weight would show up on the scales during collapse of the soil-structure?

After this effort it seems the answer is that at the moment of collapse the weight drops. It then gradually recovers. And I suppose, as the grains come to rest again, for an instant at least, the weight could even increase a bit.

How the Prediction was Made

Despite the fact that apparatus resonance and boundary conditions obscured what would otherwise have been a clearer picture, I was quite happy with the comparison between the history of load cell output and the prediction.

The prediction was made on the simple assumption that the weight shown on the scales would be equal to the resistance offered by the water to the falling ball.

In Fluid Mechanics a hydrodynamic force is known to act in resistance to solids moving through fluids. Our sister technology tells us how to determine the magnitude of that Drag Force [F_D] for any relative velocity between the two phases (solid and liquid). This force is calculated using their equation:

$$F_D = C_D \rho A v^2 / 2$$

where:

C_D Coefficient of Drag
P mass density of fluid (water)
A equatorial area of the solid (ball)
v relative velocity of fluid and solid.

Of these four variables "ρ" is virtually a constant (1000 N/m^3) over the range of temperatures we're interested in. We pick the value of "A", or rather, the diameter of the sphere we want to look at. The relative velocity is the independent variable we want to track.

For the moment I'll not show you the standard Fluid Mechanics way of presenting the range of values for C_D, and I'm withholding it for two reasons. First, it is such an ugly looking log-log plot related to that rather obscure hydraulic leveller, the Reynolds Number, that I'm afraid any interest the normal geotechnical reader might have in this idea would evaporate on the spot. Secondly, in the next article I will propose what I believe to be a better, more intuitively acceptable, way for us to view C_D. This "geotechnical" version of the Hunter Rouse relationship, while giving the same values as the original for the spherical solids I'm dealing with here, also opens a door to important insights into other hydrodynamic aspects of Soil Mechanics.

Using the above equation I wrote a simple computer program ("BALLFALL.exe") to determine the position of the ball, and the force acting on it at any time I wanted during its progress from stationary to Terminal Velocity. That's where the data for the red curve comes from. This program is freely available from Geotechnical News for anyone who wants it.

The conclusion I draw from the reasonable correspondence between the test readings and the calculated values is that the water in front of the moving solid carries a compressive force which is just about equal to the drag resistance offered by the water to the moving particle. Furthermore, I believe this reveals the actual physical mechanism of pore water generation within saturated soils experiencing deformation.

Pore pressure generation is simply a matter of hydrodynamics. And when you think about it, how could it be otherwise ?

What this Approach says about Liquefaction

The program BALLFALL does the calculations needed to construct the curve in Figure 6. This relationship is for a spherical particle of specific gravity 2.65 falling through 20° C water. The x-axis covers the range of diameters of interest to us. The y-axis gives the amount of fall required to transfer 99% of the particle's weight to the water; for convenience this value is shown in terms of the ratio of the fall distance to the particle diameter.

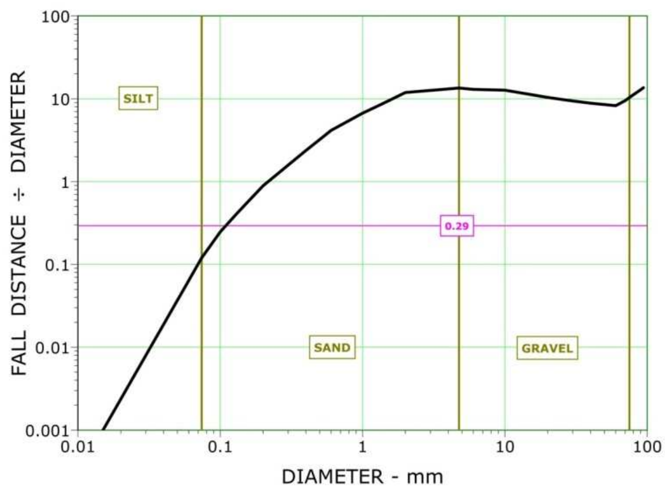

Figure 6 : Weight transfer for fall distance

The ratio 0.29 is highlighted because it is theoretically a readily achievable amount of fall. This is the amount of free drop which is available when the idealized loose packing of spheres contracts to the stable dense packing, involving a void ratio change from 0.91 to 0.35. And this geometric fact immediately suggests an interesting proposition: If this same density change were suddenly brought about in a saturated fine rounded sand by some triggering event, then the condition necessary for liquefaction of the mass would exist during the transformation.

Although I intend to limit myself to dealing with manageable geometric shapes I should say here that I think the more angular shapes of natural grains make them more vulnerable to this effect, and this is because of the larger voids that can exist between less rounded particles. So on this basis I don't have difficulty in thinking very loose sand-sized deposits, for instance, pro-glacial sands, or some dredged fills, could very easily liquefy once the saturated soil-structure gets a serious jolt, or more to the point, as I discuss in a later article, is exposed to a surface wave.

Looking further along the x-axis of Figure 6 to the coarse sand and gravel size range you can see that the ratio of fall-to-diameter is above 10. This implies that a gravel, of say 1 inch size, would need to find an open space of about 10 inches depth beneath it to fully shed its weight, and thereby, its frictional capacity. It is very difficult for me to imagine any geotechnical circumstances, whether natural or artificial, where almost a foot of open space could exist in a gravel deposit. This tells me that the idea of gravel size deposits liquefying is unreasonable. Of course in the case of a debris flow, that's quite another matter, and one which I hope to return to later in this series.

Along the same line of reasoning, how a well graded deposit of any type could liquefy I find quite unimaginable. Even if the finer particles found room to lose their weight these would entail only a small loss of the general frictional capacity, the loss being proportional to the relative volume they contributed to the overall soil mass. Within such an aggregate there is just nowhere the larger particles could drop unhindered.

Summary of Practical Implication

What the foregoing hydrodynamic line of reasoning says to me about liquefaction is that:

It is easy enough to understand how loose fine sands can liquefy.

It is difficult to imagine how gravel sizes could be brought to liquefaction either as a natural deposit, or as a construction fill, however poorly placed.

It is even more difficult to figure out how well graded materials of any density could manage to fail in this manner.

But a very interesting question arises and remains to be answered, and that is about silts. If this line of reasoning is valid, then: Why aren't silts even more prone to liquefy than sands? Figure 6 suggests they scarcely need to budge at all to reach their v_T.

In the Next Article

The next step in the development of this method of looking at the interaction of water and discrete solids is to show how C_D can be viewed as a geotechnical parameter. It is at this stage that an answer to the question of silt's apparently inexplicable behaviour will be first broached.

I will also provide values for the "L-factor" which is the first of two variables entering into the calculation of pore water pressure magnitude. The derivation of the L-factor is simple and straightforward. I will leave until a later article the more complicated development of what I call the "Crowding Factor". This K-factor is necessary to extend the implications of single discrete particle movements, presented so far in relation to liquefaction, into the much broader realm of real soils undergoing non-catastrophic deformations.