VIDEO-LESSON DEVELOPING
THE BIG IDEA OF SOIL MECHANICS “EFFECTIVE STRESS”
IN THREE PARTS + SUMMARY
BY ADDRESSING THE ESSENTIAL QUESTION
“WHAT HAPPENS WHEN SOIL COMPRESSES”

PART 3

1 Introduction

Congratulations for making it to the third from the three parts of the video-lesson.

2 Goal of video-lesson – Summary of Part 3

In this third lesson, we arrive to our goal, to how we predict the magnitude of settlement.

You see the contents in capital letters. WHEN SOIL COMPRESSES, EFFECTIVE STRESS INCREASES: EFFECTIVE STRESS IS THE STRESS CARRIED BY THE SOIL SKELETON. We have said that the soil skeleton is the assemblage of soil grains. Effective stress is a new concept we will discuss in this lesson. We need it because WITH EFFECTIVE STRESS WE CAN CALCULATE THE MAGNITUDE OF SETLLEMENT. Let’s get to know it.

3 Understanding the mechanism of compression due to loading – compression due to pumping: same or different?

So far we have seen two problems, with some common features, but also important differences. It is one thing to build a building, and quite another thing to pump water. We saw though that both result in settlements. Let’s study again the cause, as we try to understand their mechanism. We build a building, the load from the building compresses the soil. The soil compresses and expels water, like when we squeeze a sponge. I can think to relate the force with which I drain the sponge, how tight I choose to close my hand, to how much the sponge will be squeezed. We saw that the amount by which the soil compresses, like the amount by which the sponge compresses, is the same as the amount of water leaving.

But then, what about pumping? What is the force there? Nobody exerts a force. We simply pump water. Someone may suggest to relate the quantity of pumped water to the soil compression. It is not a bad idea. But, it is not safe for two reasons. First, because not all soils compress the same. So, if our calculation depends on water, how will I take into account the role of the soil? The second reason I cannot base my calculation on the amount of pumped water is that, as we said in the previous lesson, we pump from the sand, but the larger portion of the settlement is due to the neighboring clay layers. We must find something else. It was found in the 1920s.

4 Common mechanism of compression due to pumping or loading

The birth of Soil Mechanics as a distinct discipline of civil engineering is related to the realization that the compression of soil due to loading from buildings and due to pumping not only has the same result, but is caused by the same mechanism. Pumping is also a kind of loading, if we see the problem from the vantage point of the soil skeleton. This was a fundamental contribution of the father of Soil Mechanics, the Austrian Karl Terzaghi (1883 – 1963). Terzaghi conceived the quantity that describes the loading of the soil, not from our own vantage point, but from the vantage point of the soil skeleton. We saw that our own vantage point is expressed in terms of force, or force spread over surface, the quantity we named stress. Stress has units of pressure, force/surface. Internationally, civil engineers use for stress the Greek letter sigma.

5 From Mechanics (solid materials) to its offspring, Soil Mechanics (particulate material)

Mechanics is a branch of Physics that describes the behavior of solid materials when they are loaded.

We said that Soil Mechanics was born in the 1920s. It is an offspring of Mechanics, which is much older, it is Mechanics for the soil. In Mechanics we know how to relate the stresses exerted on a solid material to how much the material deforms, how much its shape changes.

We also know from our everyday experience that some materials deform with great difficulty, say steel, compared to others, say rubber.

Terzaghi thought of how to adapt existing knowledge and apply it to soil. Engineers do this often. We use a tool for a job and then we want to use it for a similar job, with suitable modifications, if necessary. This is what Terzaghi did. He took Mechanics, which applies to solid materials, and used it with fidelity in the study of soil, which is a particulate material. I cannot tell you how he conceived this idea, we do not know. But how his idea gave birth to Soil Mechanics you will be able to understand it in this lesson.

6 BIG IDEA of Soil Mechanics → distinguish two quantities: (1) stress applied by loads – (2) stress felt by the soil skeleton

Terzaghi thought of distinguishing the stress sigma (σ) we apply to soil when we construct buildings, by first giving it a name of its own. He called it **total stress**. In the case of the building, it is clear that we apply some total stress and the soil settles. On the contrary, in the case we pump, it is clear that we do not add any extra total stress, we do not apply any load. But the soil again settles. Hence, since the soil settles, Terzaghi may have thought, the stress felt by the soil skeleton increases. We may not have applied any additional load, but the soil skeleton was loaded. Hence, some other stress, not the total stress, describes the stress carried by the soil skeleton – THIS IS THE BIG IDEA OF SOIL MECHANICS. Terzaghi called this stress of the soil skeleton **effective stress**. Its symbol is sigma prime (σ′). This thought, that we have one stress for solid materials in Mechanics and another stress for particulate materials in Soil Mechanics, unifies the two problems of pumping and loading, it places them in a common frame and reveals that they have a common mechanism.

(1) We have started to understand why something happens. But the engineer wants to know how much of this something we have.

(2) Terzaghi did this too. He not only distinguished between total stress[1] and effective stress[2], he also found how they are related. You may have guessed by now that water has something to do with it. More precisely, the pressure of water, which in Soil Mechanics is symbolized by the letter u. Look how conveniently simple is the relationship found by Terzaghi:

$\sigma' = \sigma - u$

7 BIG IDEA of Soil Mechanics, continued → EFFECTIVE STRESS, the stress felt by the soil skeleton, describes the behavior of soil

$\sigma' = \sigma - u$

What does this relationship tell us? Let's read it. Effective stress sigma prime (σ') equals total stress sigma (σ) minus the pressure of water in the soil pores (u). Let's make a first attempt to give it some meaning. If we consider a large total stress to be a bad thing for soil, then we see that the water pressure relieves somewhat the soil skeleton, like buoyancy makes us feel our body lighter in water.

We said that the effective stress is the stress that tells us what the soil skeleton feels. Since it is total stress sigma minus pore water pressure u, effective stress increases (a) when total stress increases or (b) pore water pressure decreases. Let's think. Before I build a building, does the soil have some total stress or is it zero? Is there anything loading the soil or not?

To answer this question let's think of our body again. We always carry our weight. When we return from shopping we also carry the extra weight in the shopping bags. Same with soil. Its weight always applies a total stress and the soil skeleton feels a corresponding effective stress. How much packed, or compressed, a soil layer is depends on how deep it is, on how much soil has above it. The building is extra loading for the soil. "What does the water do?" you may ask. Many times water moves so slowly that it is almost as static. The corresponding water pressure we call it hydrostatic pressure. We know these things since grade school. We know since grade school that the hydrostatic pressure increases linearly[3] with depth.[4] The same linear

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[1] To distinguish in our mind the two stresses, we can think that effective stress σ is the physical quantity that results from the loads applied to soil.

[2] We can think of effective stress σ' as a concept, a quantity that is calculated as (σ - u), describes well the soil behavior and helps us understand the loading of the soil skeleton.

[3] Or, equivalently, the increase of the hydrostatic pressure is expressed by a straight line, as shown on slide 7.

[4] As an example that may help us understand better the difference between σ and σ', we imagine that we carry a cylindrical bucket full to the brim with saturated soil. The pressure of the pore water is hydrostatic and increases with bucket depth. The total stress σ and the effective stress σ' also increase with depth. The total stress σ describes the effect of the total load (the total weight of soil grains and pore water carried by our hand) on the bucket bottom. The effective stress σ', which describes the stress carried by the soil skeleton, is smaller than the total stress σ by u. We can again think of this relieving effect (stress decrease) for the soil skeleton provided by water as buoyancy.

increase often describes the pressure of water in the soil, as we saw in the previous lesson, and as we will see on the next two slides.

8 Construction of building increases load, increases effective stress, soil compresses
We now have all we need to understand what happens in the two problems. We start with the soil column in cartoon, loaded with its own weight W_1 before the building is built.

(1) BEFORE BUILDING CONSTRUCTION I use the subscript "before" for the stresses: $\sigma'_{before} = \sigma_{before} - u$

Then, the load of the building W_2 is added and total stress increases. What will the water do? What can poor water do? We do not expect it to carry any of the building load of course! Some part of water will escape, like when we drained the sponge[5]. We call this water "excess water". But, in some soils, water will take time to escape, in the clay soils we discussed. In these soils, the extra load from the building will affect both the total stress and the water pressure. At the beginning, both will increase. But the increase of the water pressure will not be permanent. When the settlement is completed, and the excess pore water has escaped, the water pressure will return to its initial value. On the soil column to the right we see that as water has left, soil pores are smaller and the soil has compressed. When all the excess water that wanted to leave has left, the soil skeleton carries all the extra loading from the building. Instead of words, I write this with symbols:

(2) AFTER SETTLEMENT DUE TO BUILDING CONSTRUCTION IS COMPLETE: $\sigma'_{after} = \sigma_{after} - u$

Subtracting the ~~second~~ first relationship from the ~~first~~ second, I get a third one:

(3) $\sigma'_{after} - \sigma'_{before} = \sigma_{after} - \sigma_{before}$

What does this relationship tell me? That when the water pressure returns to its initial value, the stress increase felt by the soil skeleton ($\sigma'_{after} - \sigma'_{before}$) equals the stress increase due to the construction of the building ($\sigma_{after} - \sigma_{before}$).

So that our students do not accuse me of cheating, I should tell you that the above holds for when the footprint of the building is very-very big, for example if I have a factory building spread out over an extended area. If my building is a block of flats, the above is an approximation or it is accurate at the center of the building and not near the building edges, where the soil carries less load.

END OF PART 3A – BEGINNING OF PART 3B

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[5] If we squeeze the sponge lightly (if we apply a small load) little water will escape, if we squeeze the sponge strongly (if we apply bigger load), more water will escape.

9 Pumping: decrease of pore water pressure increases effective stress, soil compresses

We are getting there, we arrived to pumping and we are almost done. What is happening during pumping? We see again Terzaghi's expression for sigma prime, which describes what the soil feels:

$\sigma' = \sigma - u$

I remind you that we pump from a certain depth[6], we see the ground surface subside and we conclude that the soil compresses[7]. What does compression mean to soil? Higher stress for the soil skeleton. But, when I pump, there is only the weight of the soil W_1, I did not add any extra weight. Since total stress does not increase, then, what changes during pumping?

Terzaghi's expression tells us that for the effective stress to increase under constant total stress, the pore water pressure u must decrease[8]. This decrease of water pressure can be confirmed by the Hydraulic Engineer. That's exactly what we want to achieve by pumping. We want to lower the pressure of water where we pump, so that water will flow into the pipes through which we pull water, in the same way orange juice flows up our straw when we suck. By subtracting, like on the previous slide, we find that the water pressure decrease corresponds to increase of effective stress at every point of the soil column[9], which results in soil compression.

10 Checking our understanding

One last check before our final goal, the quantitative prediction. Two soils have the same total stress and they experience the same decrease in water pressure due to pumping. So, they have the same effective stress. How much will each soil compress? What do we answer? The same amount of compression? Different?

It depends on how soft or hard they are, on how firmly their grains rest on each other. The denser the soil before pumping, the stronger the grains will support each other. This is the quantitative prediction the engineer must make. To achieve this, the engineer needs to do some tests in the laboratory. (1) First, we take a sample from the soil at some depth and then (2) we subject it to loading at the laboratory to see how much will the soil compress. That's how we find how the change in effective stress is related to compression for each soil. So our answer is that we expect the settlement to be different. Because our experiments tell us that for the same sigma prime, soil

[6] We remember the description in Part 2: we pump from a certain depth, that's why we show the arrow symbolizing the water we pump at the bottom of the soil column.

[7] The soil column to the right is denser, since the soil compressed while it remained saturated and the water level remained at the ground surface.

[8] The distribution of pore water pressure after pumping (u_{after}) describes in a simplified way the decrease of water pressure, in order to convey the main message: water pressure eventually decreases over the entire soil layer. In reality, this decrease evolves in time and in space. When pumping first starts on the slides of Part 2, the pressure decreases first on the interface between the sand and the overlying clay, and then gradually the pressure drops higher and higher in the clay layer. On slide 12 we will see a real distribution of this reduced water pressure at some point in time.

[9] Effective stress increases at every point of the soil column, since water pressure eventually decreases at every point of the soil column.

sample number two compressed less than soil sample number one. With this experimental information and the calculation of the effective stress increase, the engineer can predict how much will the soil settle.

11 Back to Venice

Let's go back to Venice. We arrived, with some effort, to a point where you could ask me: "wait a minute, didn't the engineers in Venice know that pumping reduces water pressure?" Of course they knew it. But they did not think of the effect of the reduced pressure on the soil skeleton. I remind you that pumping from deep aquifers does not mean that the soil empties from water, it does not mean that air occupies the pores and then soil compresses. So it is not unreasonable that they overlooked the impacts of the reduced water pressure, especially when Soil Mechanics was still a young discipline.

12 Back to Mexico City

Have a look at the figure depicting pumping at Mexico City. We pump from a permeable sand aquifer at significant depth. Water pressure drops within the aquifer, it also drops within the neighboring clay layers. We should worry about the drop in water pressure within these very soft clay layers, which have the tendency to compress a lot, these are the layers that create the trouble.

13 Holland: a little more complicated problem than Venice and Mexico City

If you want, take a little break here, hit pause, because I am going to add one last thing before we go to a brief summary with the main messages of this video lesson.

We said that we like to solve similar problems with the same tool. At the same time we avoid to use the same tool unless we are convinced that the mechanisms are the same, not only the results. It is even possible that the trigger is the same, the result is the same, but the mechanism is different.

Here's an example: Holland is a country that not only is very close to sea level (as its second name in most languages tells us), but already a large part of it is below sea level. Is pumping again the cause of subsidence? Yes, but through a different mechanism. The Dutch started pumping 1000 years ago, in order to dry the rich organic soil, peat is the proper name. Here they wanted to remove water from the surface soil so that they can cultivate it. Water was not pumped from deep layers, but from shallow, so the water level dropped. This was the desired result. But when peat is exposed to air, it reacts with oxygen (it oxidizes, we say), its consistency changes and, as a result, it shrinks and compresses. Due to the ground subsidence, the fields flooded easily again, and a further drop of water level was required. This was the job of the famous Dutch Mills – they were using wind power to pump water. But, more pumping causes more compression. It is a vicious circle, where every corrective move creates again the problem it corrects.

In other words, beware! In some pumping cases, we cannot explain land subsidence <u>only</u> with the increase of effective stress.

We have only two slides left, for those of you who would like to process better what you learned.

13 Homework

One of the best ways to learn something well is to explain it to someone else. For example, what may cause settlement in urban areas and why do we care.

14 Mexico City

Read at your own pace what happened to this monument (El Angel) in Mexico City. Although it is heavy, it behaves like the borehole pipe in the previous lesson: the monument remains at the same absolute elevation, while the ground around it subsides. How does the monument manage not to move? It is built on piles, which reach deep into strong soil layers.

Let’s move on to the last video to close the lesson with a brief summary.