What effect does pore water in soil have on shear strength?

Objective

In this lecture we will learn about the effect of pore water on the shear strength of a soil. In particular we will learn about the effect pore water has on silts and clays and we will learn about the new terms drained and undrained shear strength.

Introduction

So far in this subject you have learned that the shear strength of a soil comes from friction between the soil particles. You have also learned that we measure shear strength in a shear box and vertical movements of the lid tell us that dense soils dilate on shearing and loose soils compress, causing their strengths to change to a critical state value.

But so far, we have studied dry soils without pore water. We will learn the importance of effective stress when measuring the strength of soils with pore water. Also, the slow flow of water in silts and clays makes them behave differently to sands and gravels during shearing.

Effective normal stress $\sigma'$

The strength of a soil comes from friction between the soil particles. As you know, the greater the normal stress between the particles, the greater the friction and so the greater the shear stress $\tau$ that can be supported by the soil.

As we learned in Soil Mechanics I, when pore water is present in the pores (or voids) of a soil, the pore water pressure $u$ pushes the soil particles apart and reduces the stress between the particles (Figure 1).

\[ \text{Figure 1: Pore water pressure} \]

Friction between the soil particles only comes from normal stresses between the particles themselves. Therefore, soil strength depends on the effective normal stress $\sigma'$ and soil strength is denoted by the friction angle $\phi'$ with the symbol $'$ added to denote an effective friction angle. Wherever there is pore water in the soil, we must calculate the effective stresses at the start of any soil strength calculations.

Dilation and compression with pore water

You learned in the previous lecture that dense soils dilate (increase in volume) during shear and loose soil compress (decrease in volume) during shear.

If the voids of a soil are filled with pore water, this means that water must flow into the voids at the shear surface to allow dilation and flow away from the voids at the shear surface to allow compression (Figure 2).

\[ \text{Figure 2: Flow of pore water into and out of shear zones} \]

You may have noticed when you walk on wet sand at the beach that water disappears INTO the sand around your foot when you step on the wet sand. This is because the dense sand dilates under your foot and water flows INTO the sand. This seems strange until you learn soil mechanics because you would expect water to be squeezed OUT of the sand under the weight of your foot.

Shear strength of silts and clays

The flow of water into and out of shear zones in sands and gravels will happen quickly because these soils have high permeabilities. This means that dilation and compression of sands and gravels with pore water can happen immediately.

However, silts and clays have very low permeabilities and this means that the flow of water into and out of shear zones will happen very slowly. This phenomenon has a big effect on the shear behaviour of silts and clays.

Dense (stiff) silts and clays still have a high peak strength, but they take months or years to dilate and for their strength to reduce to the critical state. This means that dense (stiff) silts and clays have a high strength for periods of a few weeks or months. This is one reason why you can cut a vertical slope into a saturated clay and it does not fail. The clay seems stronger than gravel initially. But, months or years later, the slope will fail (Figure 3).
Figure 3: Short-term and long-term critical state shear strengths of stiff clay

Loose (soft) silts and clays still have a low shear strength, but they take months or years to compress and for the strength to increase to the critical state. This means that soft silts and clays are very difficult materials to work with as an engineering material. They normally require improvement by long-term pre-loading or cement-soil mixing.

Drained and undrained shear strengths

Clays and silts have a short-term undrained shear strength, the value of which depends on their in-situ density and effective normal stress. It is called undrained because water cannot flow into or out of the voids in the shear zone.

Clays and silts also have a long-term (perhaps years) drained shear strength, when water is allowed to flow into or out of the voids in the shear zone. In dense (stiff) silts and clays the drained shear strength is lower than the undrained shear strength because dilation has occurred. In loose (soft) silts and clays the drained shear strength is higher than the undrained shear strength because compression has occurred.

Shear strengths of sands and gravels are always drained shear strengths whether short-term or long-term because pore water always flows fast enough for volume changes to occur immediately.

Shear box tests on silts and clays

When you carry out shear box tests on silts and clays, the speed of the test makes a big difference on the result. A quick test (perhaps 30 minutes) would measure the undrained shear strength of the silt or clay because there was no time for dilation or compression to take place. This would be called an undrained test and you would obtain the graphs shown in Figure 4. A slow test (perhaps a whole day on a small sample) would measure the drained shear strength of the silt or clay because there is time for dilation or compression to take place. This would be a drained test and you obtain the graphs shown in Figure 5. These look the same as the graphs we obtain for tests on sand (which are of course drained tests as well) and if we change the normal force \( N \) and allow time for the effective stress \( \sigma' \) to change, we obtain different shear strengths and obtain a friction angle \( \phi' \) as shown in Figure 5.

In fact, if you carried out lots of undrained shear box tests with different normal forces \( N \) and plotted the shear strengths with normal force, you would obtain a horizontal line (Figure 4) which would give you the undrained shear strength \( c_u \) (kPa). The \( c_u \) is the same for all normal forces \( N \) because shear strength depends on the effective stress \( \sigma' \) in the silt or clay and this takes a long time to change in response to changes in normal force \( N \).