
How Negative Can Pore-Water Pressures Get?

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Introduction

Ever since the inception of modern soil mechanics, there has been a controversy regarding the magnitude of negative pore-water pressures. One viewpoint has been that the vapour pressure of water forms the lowest pressure (in an absolute sense) for the water in the pores of a soil. The vapour pressure of the water at 20°C is 2.3 kPa (absolute). This means that the pore-water could simply approach zero absolute pressure or one atmosphere negative. This concept has given rise to the term capillary zone, or capillary water where the pressures must be greater than zero absolute pressure. Water in the soil at drier conditions was referred to as hygroscopic water with little reference to the state of stress in the water. The convincing argument in favor of this concept is related to subjecting a container of water to one atmosphere of vacuum and watching it boil.

At the other extreme, it is possible to measure the relative humidity of a near air dried sample and compute a total suction approaching 10,000 atmospheres. Total suction is generally visu-

alized as being comprised of matric, ($u_a - u_w$) and osmotic components:

$$h = (u_a - u_w) + \pi \quad [1]$$

where:

u_a = pore-air pressure and

u_w = pore-water pressure.

In the case of a sandy soil where the osmotic component is negligible, the pore-water pressure can be visualized as being highly negative; as much as 10,000 atmospheres.

Therefore, as engineers, we are faced with one concept which limits pore-water pressures to one atmosphere negative and another concept which allows it to be as much as 10,000 atmospheres negative. This is an extremely wide range and surely questions regarding a carrier limit can be resolved; or can they?

In order to cast some light on this question, let us review some theory and then go through some "thought experiments". As a first "thought experiment", let us take a sample of relatively wet clayey soil and insert a tensiometer to measure the pore-water pressure. Let

us suppose that a measurement of 20 kPa gauge pressure is observed. Now the soil is allowed to dry and as it does the water content reduces to 35% as the pore-water pressure becomes -100 kPa. This is the limit for measurement using the tensiometer; however, the water content in the soil continues to digress as drying occurs. There is no evidence of the pore-water boiling and the question could be asked "What is the pore-water pressure as the soil becomes increasingly dry?" Is it lower than zero absolute? Or, is there some component of the pore-water potential which is not being realized? Or, does the pore-water totally change in its behaviour in the presence of a particular media, thus, allowing highly negative magnitudes to be realized? Where does the answer lie?

Physical Considerations

Probably the first question which should be asked is "What would be the meaning of a pore-water pressure less than 1 atmosphere negative?" By definition, liquids convert to vapour when subjected to their vapour pressure. Solids, on the other hand, can be subjected to large

tensile stresses. For example, metals can be subjected to many atmospheres of tensile stress before breaking. Does this, therefore, mean that the pore-water must be acting more like a solid once it is subjected to water than are atmospheres of tension?

Let us consider the physics related to the experiment illustrated in Fig. 1. There appears to be only two things which affect the vapour pressure adjacent to an air-water interface; namely, the radius of curvature of the meniscus and the presence of salts in the fluid.

The effect of the radius of curvatures on the meniscus is enforced from physics since it has been physically impossible to measure the vapour pressure about an air-water interface when the radius of curvature is extremely small. The effect of the radius of curvature is inferred from the Lord Kelvin type capillary model which in turn is related to the thermodynamic free energy of the soil water (Edlefsen and Anderson, 1943)

$$\Psi = \frac{-RT}{v_{w0}\omega_v} \ln \left(\frac{\bar{u}_v}{\bar{u}_{v0}} \right) \quad [2]$$

where:

Ψ = soil or total suction (kPa)

R = universal (molar) gas constant (i.e., 8.31432 J/(mol K))

T = absolute temperature (i.e., $T=(273.16 + t^\circ)$ (K))

t° = temperature ($^\circ\text{C}$)

v_{w0} = specific volume of water or the inverse of water density (i.e., $1/\rho_w$) (m^3/kg)

ρ_w = water density (i.e., 998 kg/m^3 at $t^\circ = 20^\circ\text{C}$)

ω_v = molecular mass of water vapour (i.e., 18.016 kg/kmol)

\bar{u}_v = partial pressure of pore-water vapour (kPa)

\bar{u}_{v0} = saturation pressure of pure water vapour over a flat surface of pure water at the same temperature (kPa)

This equation shows no limit of ap-

plication and measures combined effects of pore-water salts and the radius of curvatures. However, once again if a sandy soil is considered, the osmotic component can be taken as being negligible.

Equation [2] is based on thermody-

namic principles and exhibits a smooth transition from zero to thousands of atmospheres. It states that the potential in the pore-water can continually decrease without providing a microscopic illustration of the mechanisms involved. In other words, Lord Kelvin's equation

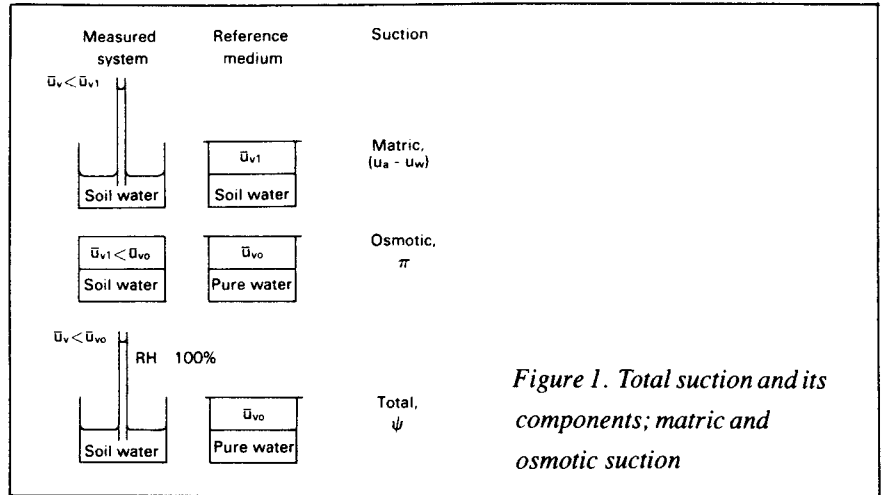


Figure 1. Total suction and its components; matric and osmotic suction

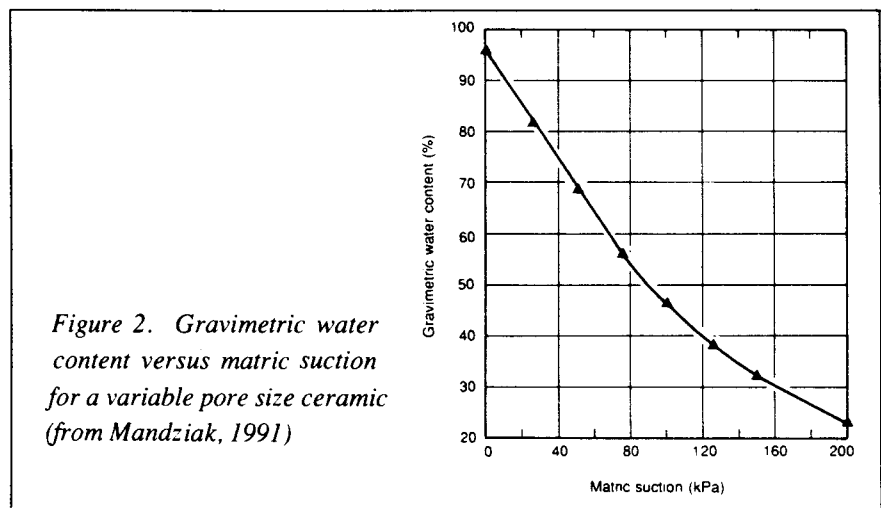


Figure 2. Gravimetric water content versus matric suction for a variable pore size ceramic (from Mandziak, 1991)

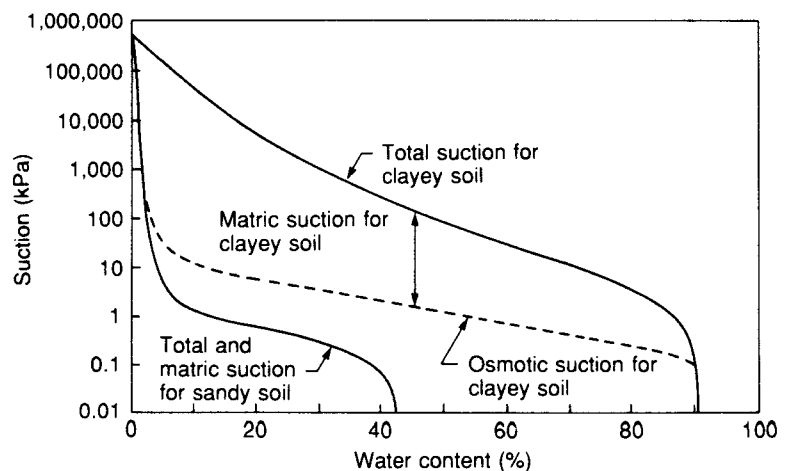


Figure 3. Water content versus the components of suction for a sandy and clayey soil

does not make clear whether the pore-water pressures are actually highly negative. Rather, there could be other mechanisms involved.

Before proceeding, let us clarify the role of osmotic suction in understanding pore-water pressures. The salts in the pore-water give rise to an osmotic suction component. Osmotic suction is present whether the soil is saturated or unsaturated. Simply put, saturated soils with positive pore-water pressures have osmotic suctions. However, their influence is not generally taken into account in the application of classical geotechnical mechanics. The question could be asked, "Why not?" Consideration of osmotic suction as an independent component of the stress state is avoided through the simulation of the component in the field and the laboratory testing. Therefore, any changes in osmotic suction in the field have also taken place in the laboratory when testing for soil parameters. The same rationale can be provided when studying the behaviour of unsaturated soils. Nothing appears to change with respect to the osmotic component as the pore-water pressure goes from positive to negative or so the soil becomes unsaturated. Therefore, once again we are left with the pore-water pressure as the primary component of interest. The exception is the situation where the osmotic component alone may be altered by adding salts to the soil.

Variable Pore Size Ceramic Experiment

Let us now conduct an experiment with a variable pore size, centered stone. Let us suppose that a specimen of soil is removed and backed within a kiln. The end result is a (e.g., 20 mm diameter and 40 mm long) ceramic stone with a variety of pore sizes. Next, a 3 mm diameter hole is drilled into the ceramic and a thermocouple is epoxied into the ceramic. This is essentially what is done in the manufacturing of thermal conductivity matric suction sensors.

The sensor can now be placed in pressure plate apparatus and calibrated against applied suctions. The pressure plate apparatus uses an axis-translation

techniques (i.e. the reference or atmospheric pressure is increased) in order to apply suctions greater than one atmosphere. In other words, various suctions applied to the ceramic will cause it to desaturate and gives different values for its thermal conductivity. It is also possible to weigh the ceramic and thereby determine the water content associated with each applied suction as shown in Fig. 2.

The ceramic is essentially a chemically inert incompressible soil. It can be calibrated over a suction range from 0 to several atmospheres (e.g., 400 kPa).

Several questions could be asked concerning the test results. Did the water content of the ceramic show a smooth and continuous change as suctions greater than one atmosphere were applied? The answer is, "Yes". Did the water in the chemically inert sensor boil? The answer is, "No". Since the osmotic component is of no significance, how can the behaviour of the water in the sensor be explained? Did capillary water end at zero absolute pressure, and did some other phenomenon take over past this point?

At this point, we could ask whether or not we are ready to develop a technology for unsaturated soil behaviour if there is not even agreement on our understanding of negative pore-water pressures. On the other hand, we could ask, "Does it matter what we are measuring as long as we measure a variable which is repeatable?" Now, this is probably a more intelligent question to ask!

Continuous Suction Components

Until the present time, there have been no components other than matric suction and osmotic suction suggested as existing in the description of the pore-water stress water. It would appear that we are left with one of two explanations for the behaviours we observe relative to negative pore-water pressures. Either there is another component (and associated mechanism) in the pore-water stress, or else the water changes its behaviour in the presence of a porous medium. In response to the above dilemma, I would prefer to go with the

latter possibility, but the most important realization is that it really doesn't matter. What matters is that variables being measured are continuous and reproducible.

So, what is the nature of the components of suction for an unsaturated soil such as a sand or a clay? Generalized distributions are shown in Fig. 3 for sand and clay respectively.

Observations that can be made are as follows:

The total suction of all soils goes towards approximately 10,000 atmospheres as the water content goes to zero (Ho, 1988). Next, the osmotic suction is negligible for a sand. All components of suction are continuous throughout the water content or stress range.

The matric suction can be viewed as the positive equivalent of the pore-water pressure. The pore-water pressure is, therefore, continuous throughout a wide range of pressures. These pressures extend well below zero absolute pressure. If water has to change from behaving as a liquid to behaving as a solid, so be it!

Before we become discouraged by our lack of understanding of micro-mechanisms, let us remember how far we've come without being able to understand the flow of electricity through a wire. Certainly, we are far ahead in understanding the flow of water, even in unsaturated soils.

References

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