



The Inadequacy of Conventional Pore Water Pressure Theory

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Terzaghi's conventional pore water pressure concept is a cornerstone in soil mechanics and has been almost universally applied to applications in geotechnical and geoenvironmental engineering. Conventional pore water pressure is an average pressure on a scale greater than millimeters. It's commonly measured by a piezometric head under saturated soil conditions, and a tensiometric head under unsaturated soil conditions (Figures 1a-c).

The underlying assumption for using this pore water pressure as a state variable is that soil's mechanical and hydrologic behaviors are adequately represented. But for many practical problems dealing with stress, fluid flow, and fluid-phase transition under saturated and unsaturated conditions, we contend that using the conventional pore water pressure is not adequate.

Capillarity and Adsorption

Soil-water interaction includes two distinct mechanisms: capillarity and adsorption,

which lead to two spatially and physically distinct forms of soil pore water, capillary water and adsorptive water (Figure 2a). In coarse-grained soils, capillary water dominates, except when gravimetric water content is less than about 1 percent. In fine-grained soils, and notably in high-surface-area or swelling soils like bentonite, adsorptive water can dominate even at a gravimetric water content as high as 40 percent. Both mechanisms lower the soil water potential or increase the corresponding matric suction. Capillary water mainly exists in large pores, and the associated increase in matric suction depends predominantly on the pore geometry and mineral surface characteristics by transforming mechanical energy (pressure) between curved air-liquid-solid interfaces. In contrast, adsorptive water exists near particle surfaces or within swelling clay mineral layers by transforming electromagnetic energy to mechanical energy (pressure) (Figure 2b). The conventional definition and measurable component of pore water pressure is limited to capillary

water. This pressure is generally compressive when soil is saturated, and tensile when soil is unsaturated. Water pressure due to adsorption is not measurable by piezometric or tensiometric devices, and is always compressive whether a soil is saturated or unsaturated, leading to significant changes in properties such as hydraulic conductivity, electric permittivity, and viscosity, and inter-particle stress such as effective stress.

Adsorptive pore water pressure is driven by electromagnetic forces originating in the soil solid, leading to highly localized pressure variation within a single pore (Figure 2b). The region of soil water experiencing locally elevated pore water pressure is the adsorptive water. The compressive pressure is very high near the particle surfaces and can be up to 800 MPa or even 1.6 GPa. This localized compressive pressure is due to the existence of soil sorptive potential, a synthesized electromagnetic potential that includes electrical double layer, van der Waals, surface hydration, and cation hydration components. The

extent of the zone influenced by these forces and the corresponding amount of adsorptive water has been shown to highly depend on the soil's specific surface area, cation exchange capacity, and pore-fluid chemistry.

Recently, both the adsorptive pore water pressure and the capillary pore water pressure can be linked by the unitary definition of matric suction, and derived through application of the local thermo-dynamic equilibrium principle. Matric suction of soil water can be expressed by summing the capillary suction and adsorptive suction. Capillary suction has been the conventionally used matric suction, and is often quantified as the difference between pore air and pore water pressure. Adsorptive suction quantifies the energy conversion between soil sorptive potential and local pore-water pressure. The adsorption-induced pore water pressure for any soil at any water content can be determined by measuring the soil-water retention curve or soil-water isotherm.

Under the influence of capillarity and adsorption, pore water pressure can vary locally from -10 MPa (tensile) in large pores to 1.6 GPa (compressive) near the particle surfaces (Figure 2c). Such high variability can significantly change fundamental soil properties in fine-grained soils. For example, soil water density can vary from 0.994 g/cm³ in large pores to 1.7 g/cm³ near particle surfaces, depending on soil water content and the location of water molecules with respect to particle surfaces (Figure 2d). The viscosity of soil pore water can vary from 1 mPa•s in large pores to orders of magnitude higher near soil particle surfaces (Figure 2e) where water is in a glassy state.

Like conventional pore water pressure, the adsorption-induced pore water pressure can control many macroscopic soil properties and engineering behaviors. Recent experimental data demonstrate, for example, that adsorptive water can cause the small-strain shear modulus to harden by as much as two orders of magnitude for soils transitioning from a saturated to dry state, can lower the soil water freezing point to as low as -22 °C,

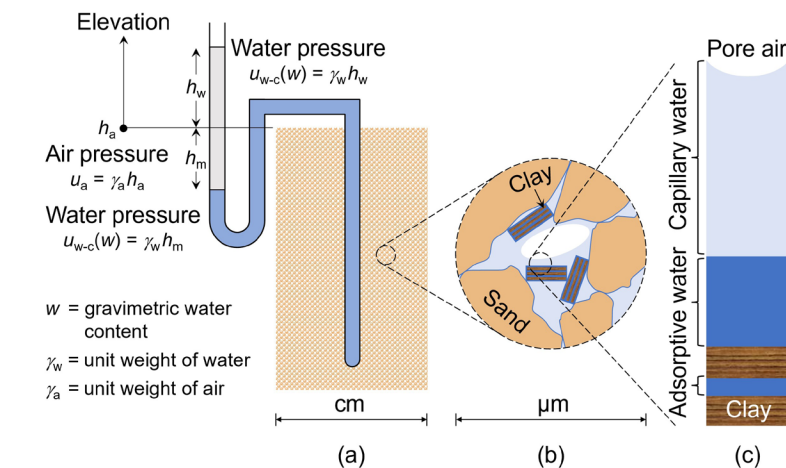


Figure 1. Illustrations of air and water pressure in unsaturated clay soil.

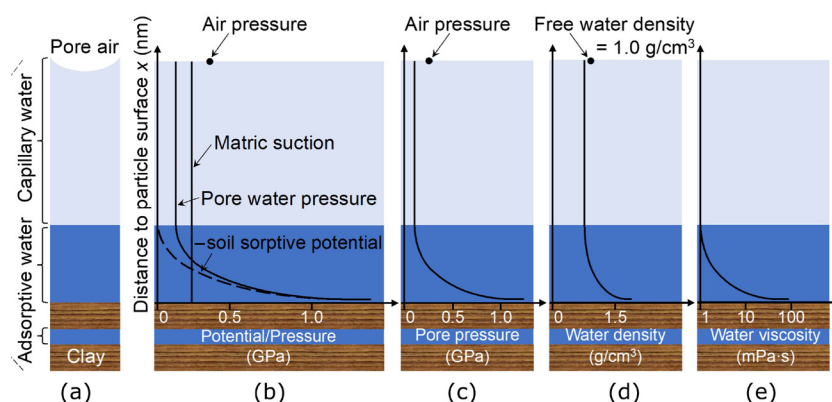


Figure 2. Illustrations of unitary definition of matric suction, pore water pressure variation in soil, and consequent variations in fundamental soil properties of water density and viscosity.

can cause elastic modulus hardening by as much as 5 MPa for clays, and can cause variations in a clay's thermal conductivity smaller than observed in sand.

The conventional definition of the pore water pressure is thus inadequate in describing many commonly encountered physical phenomena in soil, notably including water-phase transitions, coupled flows, effective stress, and deformation. A more general definition of the pore water pressure will help develop better theories and better engineering solutions for problems in geotechnical and geoenvironmental engineering. For example, hydraulic conductivity depends on soil water viscosity, so theories that explicitly consider the effect of local pore water pressure on viscosity will lead to better design and analysis of water transport problems in earthen infrastructure. 

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