Forum

Is the Conventional Pore Water Pressure Concept Adequate for Fine-Grained Soils in Geotechnical and Geoenvironmental Engineering?

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Introduction

> "[I]f there is one single thing that is mishandled and leads to problems, it's pore pressure."
>
> T. William Lambe, late professor, MIT, in a 2010 interview with graduate students from Virginia Tech when asked: "After investigating over 80 engineering failures, what advice can you share to help engineers avoid repeating these mistakes in the future?" (Geo-Strata 2010, p. 20).

Pore water pressure quantified as the product of the unit weight of water and piezometric or tensiometric pressure head has historically been used in virtually all analyses of geotechnical and geoenvironmental engineering problems. Is the conventional pore water pressure concept adequate? The authors contend that it is not and offer a general and adequate equation for soil pore water pressure under all saturation conditions.

Conventional Definition of Pore Water Pressure

The pore water pressure concept is a cornerstone of soil mechanics and a commonly used variable in geotechnical engineering practice. In his seminal book *Theoretical Soil Mechanics*, Terzaghi (1943, p. 12) noted "[pore water pressure] is equal to the product of the unit weight of the water γ_w and the height h_w to which the water rises in a piezometric tube at the point under consideration." Terzaghi further defined the corresponding equation as

$$u_w = h_w \gamma_w \quad (1)$$

He went on, stating, "The height represents h_w the piezometric head at the point of observation. It can be positive or negative. Hence u_w can also be positive or negative. If u_w is positive, it is usually called the pore-water pressure."

To date, this definition and description of pore water pressure, as illustrated in Fig. 1, has stood intact in nearly all soil mechanics analysis in geotechnical engineering practice. The piezometric head to which Terzaghi referred remains the standard way to measure pore water pressure.

In Terzaghi's view, pore water pressure u_w can be either positive or negative, implying that pore water can be under either compression or tension. In the latter case, the height h_m is called the *tensiometric head* and is some value lower than the reference atmospheric pressure head h_{atm} (Fig. 1). This situation can occur in the field under both saturated conditions (in the capillary fringe above the water table) and unsaturated conditions (above the capillary fringe). Terzaghi's mathematical definition of the pore water pressure Eq. (1) is thus applicable under all saturation conditions.

The pore water pressure is essential to define and quantify Terzaghi's effective stress, which forms the cornerstone for analysis of soil mechanical response. Theories for soil shear strength (e.g., limit equilibrium via Mohr-Coulomb failure criterion) and deformation (e.g., consolidation) based on the effective stress principle have been widely utilized for geotechnical design and analysis. Corresponding applications are wide ranging, including earth retaining structures, shallow foundations, deep foundations, slope stability, and many other historical applications.

Propounding Practical Questions

In the past century or so, many practical problems have emerged and challenged the adequacy of the conventional pore water pressure concept in characterizing some geotechnical engineering problems. Many such questions, including the three summarized subsequently, deal with fluid phase transition, fluid flow, and applicability of the effective stress principle under unsaturated soil conditions:

1. Can pore water pressure be used as a state variable for fluid phase transitions in soil such as solid–liquid or liquid–vapor transitions? Nearly one-third of the land surface of the Earth experiences freezing and thawing annually. All land surface experiences evaporation and condensation processes (e.g., Lehmann et al. 2019). Phase transitions for soil water, however, are remarkably different than for pure water. Soil pore water exists in very different physical forms of adsorptive water, primarily in relatively small pores, and capillary water, primarily

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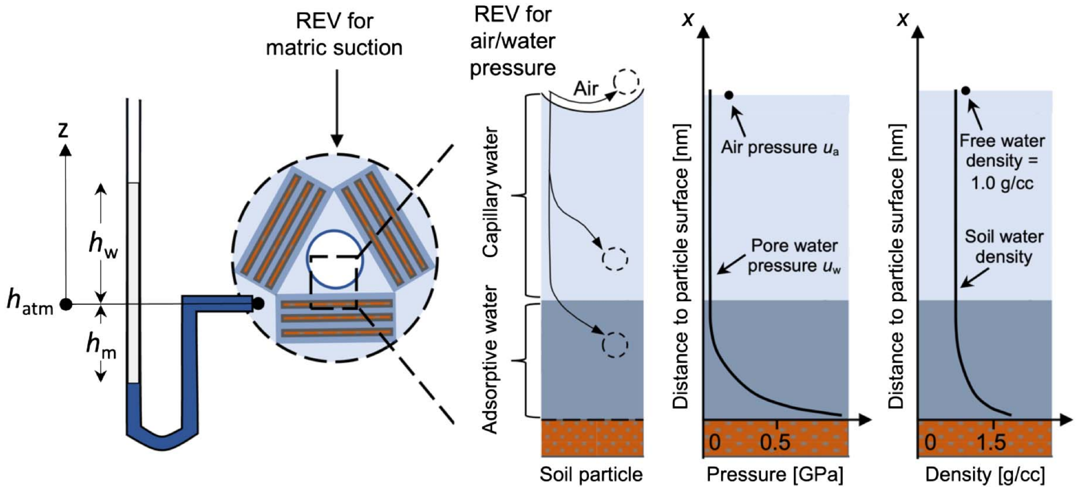

Fig. 1. Piezometer and tensiometer for measuring pore water pressure (positive or compressive) or capillary pressure (negative or tension). (Reprinted from Lu 2020, © ASCE.)

in relatively large pores (e.g., Frydman and Baker 2009). At locales near soil particle surfaces, the electromagnetic potential, or soil sorptive potential (SSP) (Lu and Zhang 2019), can be as low as a few negative gigapascals within a few nanometers of the particle surface. The SSP consists of van der Waals (Derjaguin et al. 1987), electrical double layer (van Olphen 1977), surface hydration (Butt and Kappl 2009), and cation hydration (Israelachvili 2011). Because water molecules are highly polarized, the intermolecular pressure (referred to as local pore water pressure hereafter) can be highly compressive with a magnitude up to a few gigapascals (Lu and Zhang 2019), as shown in Fig. 1. A prominent consequence is the abnormally high density of water adjacent to soil particle surface, as evidenced in measurements as much as $1.6\ \mathrm{g/cm^3}$ (Fig. 1) (e.g., Zhang and Lu 2018). The influence zone of adsorptive forces on pore water can be as much as 1,000 nm (0.001 mm) away from the particle surface, equivalent to approximately 300 molecular layers. A fundamental question arises because both piezometers and manometers (tensiometers) are limited to measuring pore water pressure in relatively large pores ($> \sim 1$ mm). Is it appropriate to use the pore water pressure defined using pressure head alone as a state variable for phase transition in soil?

2. Is Darcy's law quantified using pore pressure as a component of total head adequate for all fluid flow problems in geotechnical and geoenvironmental engineering? Fluid flow in soil under both saturated and unsaturated conditions involves movement of pore water, including water that exists as both capillary water and as adsorbed water (e.g., Bear and Nitao 1995; Nitao and Bear 1996). Both piezometers and tensiometers can only measure pore water pressure in relatively large pores (Fig. 1), which precludes their ability to measure local pore water pressure near soil particle surfaces or within interlamellar layers of expanding clay minerals. As such, the pressure state, which is the governing variable for fluid properties such as viscosity and density and fluid flow, cannot be gauged by either piezometer or tensiometer.
3. Can pore water pressure be a state variable for effective stress in soil under unsaturated conditions? Terzaghi's effective stress has been shown to be practically adequate for most geotechnical engineering problems under saturated conditions. For soil under unsaturated conditions, pore water pressure defined as capillary pressure has been extensively used in two competing schools of thought: Bishop's effective stress paradigm (Bishop 1959) and the independent stress state variable paradigm (Fredlund and Morgenstern 1977). Because capillary water and adsorptive water are governed by different physical mechanisms and possess different fluid properties, considerations of capillary water alone cannot adequately capture the role of adsorptive water in effective stress, and thus in the many practical problems involving soil strength and deformation.

Fundamental Challenges

Soil Water Phase Transitions

Water can exist in three phases under natural environmental conditions: liquid, vapor, and solid (ice). The governing state variables determining conditions for each phase are temperature and pressure. A corresponding phase diagram (Fig. 2) illustrates the bounds among the three possible phases. To determine the extent of water in a given phase within a soil's representative elementary volume

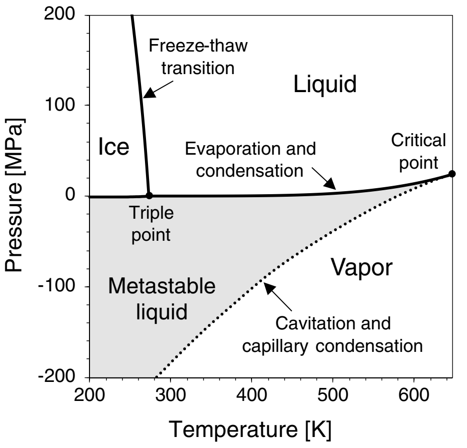

Fig. 2. Water phase diagram including metastable state where cavitation, evaporation, and condensation are the principal phase transition mechanisms in soil.

(REV) in Fig. 1, the temperature and pressure distributions within soil pores need to be quantifiable and quantified.

Temperature within an REV for a soil–water–air system can be reliably measured with commonly adopted temperature probes on the scale of the REV because temperature within an REV is a constant under local thermodynamic equilibrium condition (Edlefsen and Anderson 1943). Pore water pressure within a soil–water–air REV, on the other hand, can vary greatly at local equilibrium due to the presence of near-particle-surface electromagnetic fields and their consequent interactions with the water phase (e.g., Mitchell 1962). In saturated montmorillonite clay, for example, pore water pressure within the zone of adsorptive water near the particle surface can be compressive up to 800 MPa (Zhang and Lu 2018), whereas pore water pressure in the large pores of the REV (i.e., at the scale of a tensiometer or piezometer measurement) remains zero or at the ambient atmospheric pressure. The highly variable compressive pressure near the particle surface leads to variations in many fundamental soil properties that have commonly been treated as spatially invariable, including soil water density, soil water viscosity, and soil water freezing point. Thus, the conventional pore water pressure concept and currently available techniques for its measurement cannot adequately quantify the interwater molecular pressure in soil, which determines the soil water phase transition processes.

Evaporation and condensation occur at liquid–vapor or vapor–ice interfaces when water potentials between the two adjacent phases are different. For example, if the vapor pressure of air is greater than an adjacent liquid pressure, condensation will occur. The reverse is true for evaporation. Evaporation and condensation occur in soil, particularly near the ground surface. What is the pore water pressure when evaporation or condensation occurs? If a soil is under the saturated condition, liquid flow is the sole mode for water movement. If a soil is under the unsaturated condition, water movement can occur as liquid flow, vapor flow, and evaporation/condensation. Within 2–3 days after a heavy rainfall, for example, soil moisture is typically above the field capacity (defined as soil moisture content when soil suction or capillary pressure is ~33 kPa), so gravity will be the dominating factor driving liquid flow toward its field capacity. After reaching the field capacity, water movement in soil occurs mainly through two modes, as evaporation (including evapotranspiration)/condensation and vapor flow occurring under the driving forces of vapor pressure gradient or water potential gradient existing within soil or at the interface of atmosphere and soil on the ground (Nimmo and Landa 2005). As such, intermolecular pore water pressure becomes the governing variable controlling phase change most of the time during a typical year. When a soil is saturated or unsaturated with high water content, pore water pressure is the capillary pressure (tensiometer) and is negative or in tension. However, when a soil is in low water content or relative humidity less than ~40% (Lu and Likos 2004), pore water pressure is controlled by adsorptive water and is positive or in compression and varies highly with the water content. Cracking processes in most earthen structures such as clay liners, engineered and natural slopes, and retaining structure backfill are the results of evaporation (e.g., Vogel et al. 2005; Li and Zhang 2010). Analysis, design, remediation, and protection of these earthen structures demand knowledge of pore water pressure beyond the conventional pore water pressure.

Seepage

Seepage analysis in geotechnical and geoenvironmental engineering has been based on Darcy's law, including consolidation-induced settlement. Hydraulic conductivity is the key soil property controlling flow in soil and is inversely proportional to fluid viscosity. Fluid viscosity has been universally considered to be independent of pore water pressure, as in Darcy's law. For isothermal flow in soils with large pores and capillary water (Fig. 1), the assumption of a constant viscosity is mostly sufficient in quantifying fluid flow in soil and justifies the validity of Darcy's law (e.g., Olsen 1965). However, for flow in small soil pores (adsorptive water flow as shown next to particle surface in Fig. 1), this is unlikely to still be the case. Pore pressure in the adsorptive water can be very high, up to hundreds of megapascals due to the existence of strong soil sorptive potential. Studies have shown that viscosity is highly dependent on both temperature and pressure, more so in the latter case. For example, for water at 25°C, viscosity will increase more than 1,000 times or three orders of magnitude when fluid pressure increases from atmospheric pressure to 600 MPa (Schmelzer et al. 2005; Bair 2016). This implies that fluid flow as capillary water in large pores is quite different than as film flow for adsorptive water. Hydraulic conductivity in film flow would be orders of magnitude smaller, and thus Darcy's law may not be valid in clayey soil where the extent of adsorptive water is significant over a wide range of water content. Geoenvironmental problems such as chemical transport in clays, waste containment via clay-based barrier systems, and contaminant remediation in clayey soils thus necessitate a more general pore water pressure concept that can capture highly varying viscosity and its dependence on pressure.

Effective Stress

Continuous efforts have been made to extend Terzaghi's effective stress principle for soil under saturated conditions [Fig. 3(a)] to more general conditions, particularly unsaturated conditions [Figs. 3(b and c)]. These efforts remain for the most part differentiated by two philosophically different schools: direct extension of effective stress as a single-valued stress variable, and adoption of two independent stress state variables. To capture strength and deformation behavior of soil, for example, the well-known Bishop extension [Fig. 3(b)] uses a stress variable, $\chi(u_a – u_w)$ in lieu of pore water pressure u_w in Terzaghi's effective stress equation (e.g., Khalili and Khabbaz 1998; Khalili et al. 2004). Frameworks based on two independent stress state variables [Fig. 3(c)] employ capillary pressure $(u_a – u_w)$ and net total stress $(\sigma_t – u_a)$ in lieu of effective stress for capturing strength and deformation behaviors (Coleman 1962; Matyas and Radhakrishna 1968; Fredlund and Morgenstern 1977; Alonso et al. 1990).

At the REV level, Terzaghi's effective stress components (total stress and pore water pressure) qualify as stress quantities. Bishop's stress variable $\chi(u_a – u_w)$, like pore water pressure u_w, is a stress quantity, whereas the capillary pressure $(u_a – u_w)$ conceptualized in the two independent stress state variable framework is not a stress quantity (Lu 2008). Furthermore, both approaches use capillary pressure as the sole state variable to represent the unsaturated state of soil water, and thus are limited to the conventional pore water pressure measured by tensiometer or negative pore water pressure.

The fundamental problem with either of these approaches is that the proper physical state variable including both capillary pressure and pressure due to adsorption is missed. Both energy equilibrium and mechanical equilibrium are needed at the REV for soil because REV includes multiple phases. Using capillary pressure as the sole state variable assumes that energy equilibrium is completely governed by the capillary pressure. This is inadequate and fundamentally violates the energy equilibrium principle at the REV level. Capillary pressure is not the only mechanical energy stored in soil, and energy equilibrium requires equilibrium among soil matric

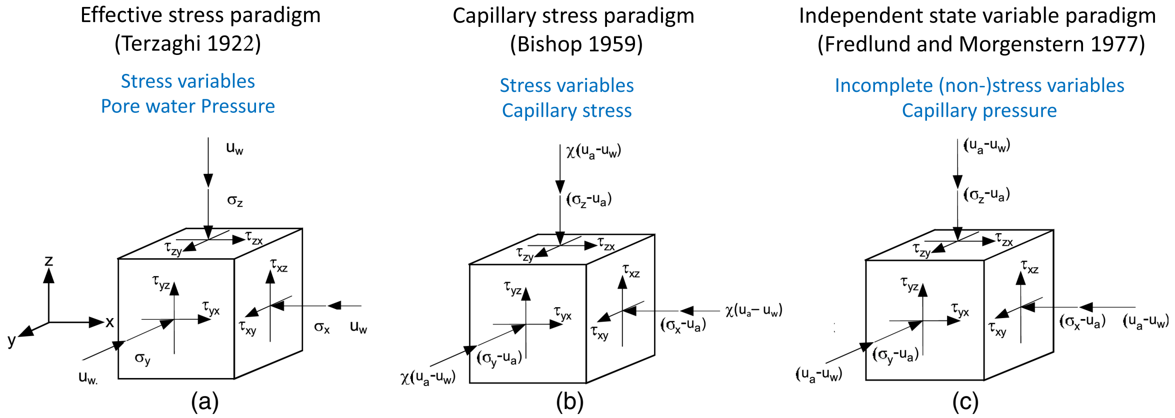

Fig. 3. Commonly used stress state representations at the representative elementary volume of soil–water or soil–water–air system: (a) Terzaghi's effective stress (Terzaghi 1922); (b) Bishop's effective stress (Bishop 1959); and (c) Fredlund and Morgenstern's two stress state variables (Fredlund and Morgenstern 1977). (Reprinted from Lu 2020, © ASCE.)

potential, capillary pressure, and soil sorptive potential (e.g., Iwata 2020; Lu and Zhang 2019).

Adequate Definition of Pore Water Pressure

A generalized equation for soil pore water pressure under all saturation conditions has emerged with a framework to experimentally determine all involved properties (Lu and Zhang 2019; Zhang and Lu 2019a, b). Pore water pressure $u_w(w,x)$ is defined not only as a function of soil water content w, but also a function of its location x with respect to the particle surface (Fig. 4). Pore water pressure consists of three components: matric potential $\psi_m(w)$, soil sorptive potential $\psi_{\mathrm{sorp}}(x)$, and ambient air pressure u_a, i.e., (Lu and Zhang 2019)

$$u_w(w,x) = \psi_m(w) - \psi_{\mathrm{sorp}}(x) + u_a \tag{2a}$$

If a soil is saturated, matric potential becomes zero, and pore air pressure is replaced by the conventional pore water pressure u_w, that is

$$u_w(x) = -\psi_{\mathrm{sorp}}(x) + u_w \tag{2b}$$

where the conventional pore water pressure u_w is a constant within an REV that can be probed by a piezometer, i.e., $u_w = h_w\gamma_w$. Soil sorptive potential completely results in local pore water pressure near the particle surface and can be experimentally determined from a soil water characteristic curve (SWCC) or water vapor sorption isotherm of the soil (Zhang and Lu 2020). Furthermore, if the conventional pore water pressure is zero, pore water pressure becomes a mirror image of the SSP, reflecting the complete conversion of the electromagnetic field of the soil particle into mechanically compressive pore water pressure, typically existing within 100 layers of water molecules or $x < \sim 30$ nm.

If a soil is unsaturated, matric potential $\psi_m(w)$ in Eq. (2a) is a function of soil water content as quantified by the SWCC. Matric potential $\psi_m(w)$ can be measured by tensiometer if soil matric potential is above cavitation pressure (Lu 2019) or can be measured by hygrometric probes if soil matric potential is less than cavitation pressure (e.g., Or and Tuller 2002; Duan et al. 2012).

Recent experimental and theoretical breakthroughs make it possible to accurately measure or quantify soil sorptive potential $\psi_{\mathrm{sorp}}(x)$ (Zhang and Lu 2020). The determination involves three steps. A vapor sorption analyzer (VSA) device is used to measure soil-water isotherm (SWI) with high resolution, as illustrated in Fig. 5 for Wyoming bentonite soil's specific surface area (SSA) (Zhang and Lu 2019a). A generalized SWCC model (Lu 2016)

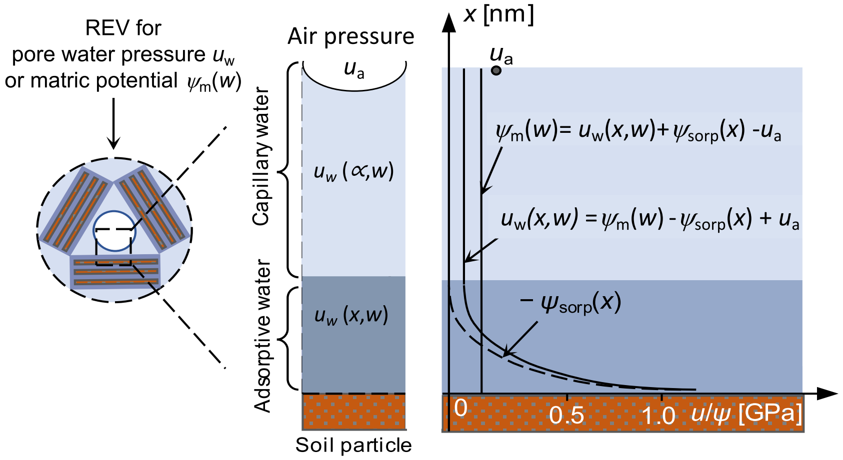

Fig. 4. Unified pore water pressure concept, and REV for pore water pressure and matric potential.

is used to separate adsorptive isotherm and capillary components of the isotherm (Fig. 5). The adsorptive isotherm is used to determine the SSP function needed in determining the pore water pressure Eq. (2*a*) with the aid of a simple scaling law linking the distance x, SSA, and the prevailing water content w (Tuller and Or 2005; Zhang and Lu 2020). Thus, with the three quantified constitutive functions—SWI, SSP, and $w(x)$—for a given soil, Eq. (2*a*) can be used to assess the local pore water pressure $u_w(w, x)$ under all saturation conditions.

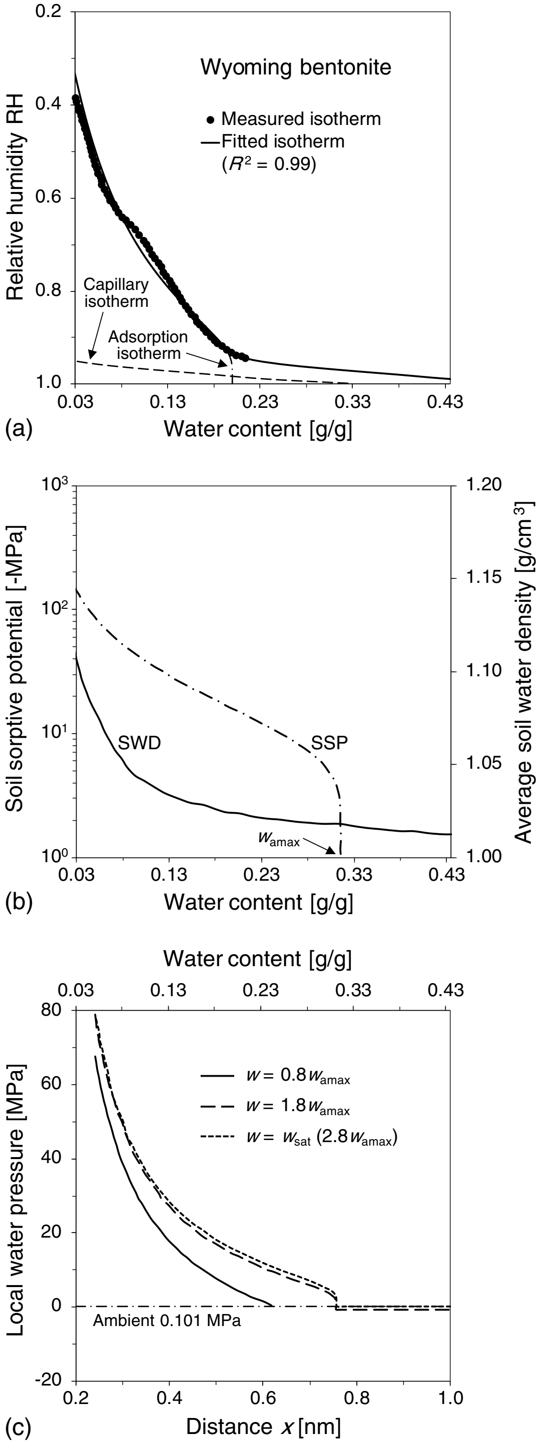

Fig. 5. (a) Measured soil water isotherm (data from Akin and Likos 2014) and its decomposition into capillary water isotherm and adsorptive water isotherm; (b) determination of soil water density function and soil sorptive potential function; and (c) local pore water pressure distributions under different environments (matric potentials) for a bentonite.

Implications in Soil Properties and Geotechnical Engineering Problems

Soil Water Density

Soil water density has been most commonly considered as unity ($1\ \mathrm{g/cm^3}$) over the range of state conditions encountered in geotechnical engineering practice. Given the existence of SSP and the prevalence of short-ranged soil–water interactions, however, water density can be as high as $1.6\ \mathrm{g/cm^3}$ near soil particle surfaces or within interlamellar layers of expandable clay minerals (e.g., Martin 1960; Zhang and Lu 2018). The presence of the SSP results in compressive pressure up to a few gigapascals and is responsible for the abnormally high soil water density. The impact of the SSP on soil water density becomes particularly significant when the SSA is high. Fig. 6(a), for example, exemplifies recent experimental results for soil water density as a function of water content for a clayey soil with SSA of $375\ \mathrm{m^2/g}$ (Dong et al. 2020). Soil water density is measured as high as $1.2\ \mathrm{g/cm^3}$ and the total adsorptive water content, inferred from the measured SWCC, is 0.16 g/g. The abnormally high density occurs right at the point of maximum adsorptive water [Fig. 6(b), Zhou and Lu 2021], indicating the controlling role of SSP in elevating the pore water pressure within the adsorptive water. Other experimental and theoretical studies indicate that soil water density can be as high as $1.6\ \mathrm{g/cm^3}$ for soil under atmospheric pressure conditions (e.g., Zhang and Lu 2018).

Deformation and Elastic Modulus

Shallow soil near the land surface is subject to seasonal cycles of wetting and drying and the elastic modulus experiences great

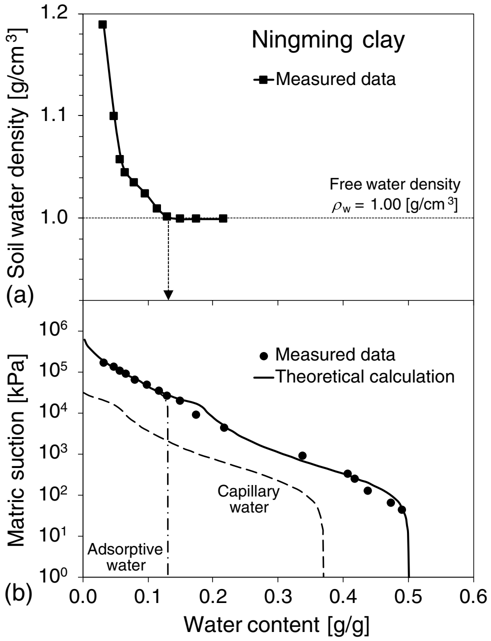

Fig. 6. Importance of the SSP and adsorptive water in high soil water density, thus the need for the local pore water pressure. [(a) data from Dong et al. 2020; (b) data from Zhou and Lu 2021.]

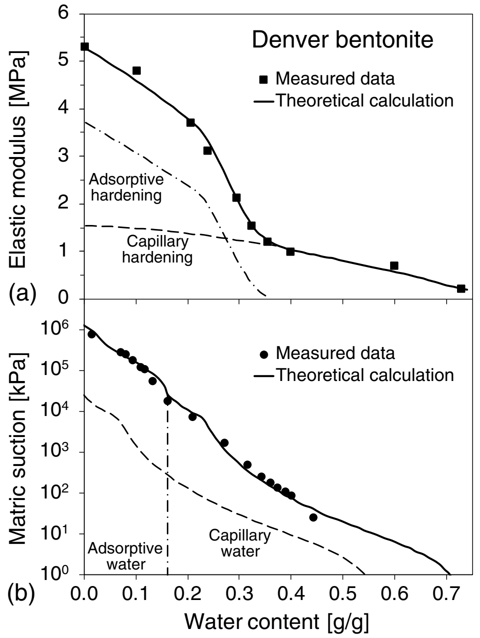

Fig. 7. (a) Hardening of elastic modulus due to capillarity and adsorption (data from Lu 2018); and (b) corresponding soil water retention due to capillarity and adsorption, thus the need for the local pore water pressure (data from Lu 2016).

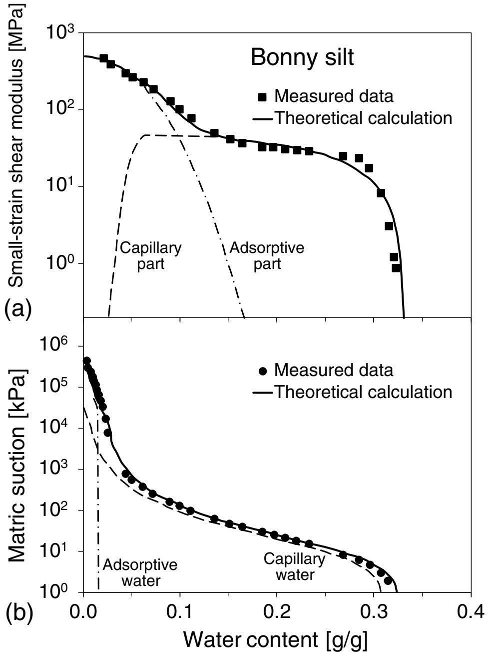

Fig. 8. (a) Importance of the adsorptive water in hardening of small-strain shear modulus; and (b) corresponding soil water retention mechanisms, thus the need for the local pore water pressure. (Data from Dong and Lu 2016.)

changes as soil water content varies. Experimental studies indicate that changes in modulus are negligible for uncemented sand, but can change much as 50 times ranging from the dry state to the saturated state for clayey soils (Lu and Kaya 2014). Transitions in soil water retention mechanisms between adsorption and capillarity also have distinguishable effects on modulus (Lu 2018). This is illustrated in Fig. 7(a), where experimental results (Lu 2018) show that the elastic modulus of a bentonite soil increases as water content decreases from its saturated state. Further hardening is evidenced when the soil becomes drier, and such behavior can be correlated to the soil water retention mechanisms of adsorption and capillarity [Fig. 7(b), Lu 2016]. The high increase in the local pore water pressure can lead to decreases in suction stress and a corresponding increase in effective stress, thus leading to higher elastic modulus as the soil approaches a completely dry state. A more general definition of pore water pressure using local pore water pressure that explicitly accounts for adsorptive and capillary water would more directly capture the dependence of the elastic modulus on soil water content and facilitate improved predictions of near-surface soil deformation resulted from changing environmental conditions.

Seismic Wave Propagation

The velocity of shear wave propagation in soil from natural seismic events or other human-made events depends directly on small-strain shear modulus $G_{\max}$. Small-strain shear modulus has been directly related to the effective stress (e.g., Cho and Santamarina 2001; Dong and Lu 2016). For soil under varying unsaturated conditions, the effective stress change is commonly attained through changes in suction stress, which can be quantified by adsorptive water and capillary water. Recent studies on the dependence of small-strain shear modulus on soil water retention mechanisms (e.g., Dong and Lu 2016; Dong et al. 2016, 2018) demonstrate the distinguishable contribution between adsorptive water and capillary water and highlight the role that local pore water pressure plays in suction stress. Figs. 8(a and b) illustrate the separable dependence of the small-strain modulus on soil water content and their retention mechanisms for a silty soil (Dong and Lu 2016), indicating the need to use more general pore water pressure for better description of the small-strain modulus in soil.

Soil Freezing and Thawing

The soil freezing curve (SFC) is a constitutive relationship between freezing temperature and liquid water content, as illustrated in Fig. 9 for Georgia kaolinite (Zhang and Lu, forthcoming). Until recently, the conventional pore water pressure or capillary pressure concept was widely used for developing theoretical models for the SFC. The fundamental control on the fusion of water, as illustrated in Fig. 2, however, is the local pore water pressure, although the mechanisms for changing pore water pressure could be osmotic, capillary, or adsorptive. In recent years, experimental data for the SFC of a wide range of soils show that the soil water content below which freezing temperature becomes pronounced is strongly correlated to the adsorbed water content, as illustrated in Fig. 9(a). The theoretical SFC using the local pore water pressure shows much improved prediction than that by the conventional pore water pressure (e.g., Hansson et al. 2004), again showing a need to use more general pore water pressure definitions for better description of soil freezing-thawing behavior.

Heat Conduction in Shallow Soil

Heat transfer in soil is primarily through conduction and convection. In many shallow soil environments where the soil water content is subject to seasonal variation, conduction is the main mechanism for heat transfer and thus the soil thermal conductivity is the key physical parameter. Fig. 10 illustrates measured thermal conductivity data for three representative types of soils: sandy, silty, and clayey soils. When soils are dry, their thermal conductivities

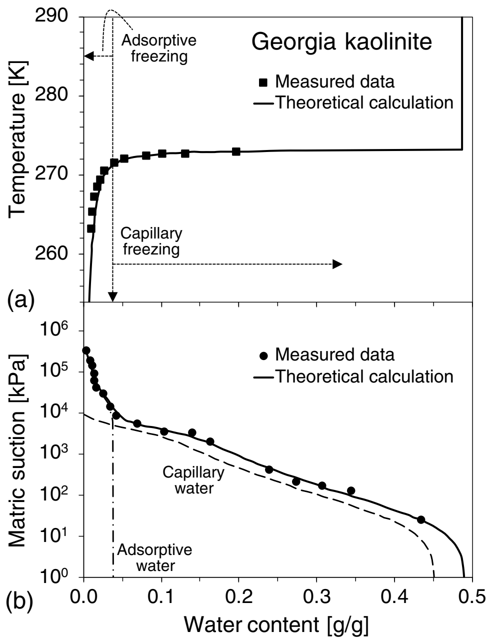

Fig. 9. (a) Importance of the adsorptive water in lowering of soil freezing temperature (data from Smith and Tice 1988); and (b) corresponding soil water retention mechanisms in SWCC, thus the need for the local pore water pressure (data from Likos and Lu 2003).

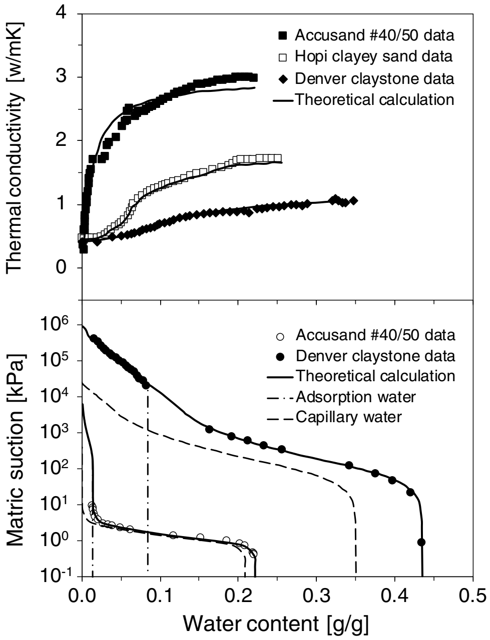

Fig. 10. (a) Importance of the adsorptive water in enhancing thermal conductivity; and (b) corresponding soil water retention mechanisms, thus the need for the local pore water pressure (data from Lu and Dong 2015).

are about the same, or ~0.25 W/mK. However, thermal conductivity varies in both magnitude and pattern when the water content increases. When the water content increases to 0.2 g/g, the sandy soil has the largest change of ~2.5 W/mK, the silty soil has a change of 1.4 W/mK, and the clayey soil has a change of only 0.75 W/mK [Fig. 10(a)]. The sandy soil has little adsorptive water content of ~2% and the rate of change in thermal conduction is the highest when the soil is dry, because all soil water is capillary water around the particle contacts where heat conduction is most effective. Therefore, the conventional pore water pressure is a sole state variable in controlling soil water content for the sandy soil, leading to a rate of change that decreases monotonically as the water content increases. On the other hand, the clayey soil has an adsorptive water content of 9% and a rate of change in thermal conductivity is the lowest when the soil is dry because adsorptive water mostly occurs on the particle surfaces instead of the particle contacts [Fig. 10(b)], such that the particle contact area does not change significantly in low water content. When adsorptive water content reaches its maximum of ~9%, capillary water starts to condense near the particle contact area, leading to a significant increase in the rate of change in thermal conductivity. The high correlation between the onset of increase of thermal conductivity and the onset of capillary condensation indicates that the maximum amount of adsorptive water controls the onset water content for capillarity, and the amount of capillary water controls the magnitude of thermal conductivity. This calls for further research in better understanding the roles of soil water retention mechanisms in thermal conductivity variation in soil.

Coupled Flows in Environmental Geotechnics

Coupled flows of water, heat, electricity, and chemicals are important phenomena in soils. The coupling is particularly significant in clays given the range of applications in an array of environmental geotechnics such as use of bentonite-rich soil for waste containment and application of remediation techniques for contaminant removal (e.g., Olsen 1969; Yeung and Mitchell 1993; Benson et al. 1999; Shackelford et al. 2019). The coupling material properties such as osmotic membrane efficiency, chemical diffusivity, and permeability are controlled by the pore water pressure in adsorptive water, not by the conventional pore water pressure. For example, in chemico-osmosis phenomena, clay membrane efficiency has long been experimentally demonstrated to be highly dependent on pore water solute concentration (Olsen 1969; Malusis and Shackelford 2002; Mitchell and Soga 2005). Membrane efficiency can be nearly 100% when there is no salt in pore water, but quickly reduces to much lower values when the salt concentration is high. Experimental evidence also shows that the membrane efficiency increases as porosity decreases, increasing to almost 100% when the mean pore size is on the same order of nanometers as that in fully consolidated claystone. These observations have been empirically attributed to the change in thickness of the electric double layer, which is the key parameter indicating the spatial extent of the local pore water pressure due to osmosis. For better understanding of the control of membrane efficiency in shales with small porosity, other electromagnetic potentials of cation and surface hydrations need to be considered in order to better describe the local pore water pressure (e.g., Revil and Linde 2006; Jougnot et al. 2010).

Summary and Conclusions

The 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 and is commonly measured by piezometric head under saturated soil conditions and tensiometric head under unsaturated soil conditions. The underlying assumption to use the pore water pressure as a state variable in both theoretical formulations and practical applications is that soil's hydrologic and mechanical properties, strength and deformation, and flow behavior are adequately represented. In reality, soil water consists of two spatially and physically distinct parts: capillary water and adsorptive water. The former mainly exists in large pores and the latter exists near the particle surface or within interlamellar mineral layers. The former is the conventional pore water pressure and is compressive when soil is saturated and tensile when soil is unsaturated. The latter is always compressive, whether a soil is saturated or unsaturated.

Soil water interactions in some soils are driven by electromagnetic forces originating in the soil solid, leading to highly localized pressure variation or interwater molecular pressure within a single pore. The soil water experiencing locally elevated pore water pressure is called adsorptive water. The local pore water pressure is invariably very high near the particle surface or within interlamellar layers, typically up to 800 MPa or even 1.6 GPa. This is the case whether a soil is in saturated or unsaturated state, or whether the soil is pure sand or bentonite clay. This is due to the existence of soil sorptive potential, a synthesized electromagnetic potential that includes van der Waals, electric double layer, surface hydration, and cation hydration components. However, the spatial extent of the influenced zone or the amount of adsorptive water is highly dependent on soil's specific surface area, cation exchange capacity, and pore fluid chemistry.

Like the conventional pore water pressure, the locally highly variable pore water pressure will control many macroscopic soil properties and engineering behaviors. Using some recent experimental data, the authors demonstrate that the local pore water pressure will determine soil water density, small-strain shear modulus, soil water freezing curve, elastic modulus, and thermal conductivity. Therefore, the conventional definition of the pore water pressure is inadequate in describing many commonly encountered physical phenomena in soil such as water phase transitions, coupled flows, and effective stress. To demonstrate the importance of the need for a more general pore water pressure definition, the authors highlight recent developments in a general pore water pressure definition to characterize soil properties of soil water characteristic curve, soil freezing curve, elastic modulus, and thermal conductivity function. The authors argue that the conventional pore water pressure is inadequate for describing many emerging challenges related to pore water pressure. It is imperative to develop and use a more general definition of the pore water pressure for developing better theories and seeking better engineering solutions to problems in geotechnical and geoenvironmental engineering.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

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