Unsaturated Soil Mechanics: Fundamental Challenges, Breakthroughs, and Opportunities

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Introduction

The author would like to use this forum article to express his views that: (1) current research and practice of unsaturated soil mechanics is in a vibrant and very healthy state, and (2) some outstanding fundamental challenges and recent breakthroughs will provide unparalleled opportunities for future research and practice. In the past half century, unsaturated soil mechanics has emerged as a flourishing expansion of classical soil mechanics in dealing with mechanics of soil under partially saturated conditions (Houston 2019). The field is broad because it includes all physical processes of water flow, heat transfer, electrical flow, chemical transport, and stress and deformation in the vast near-surface earth environment (Lu and Likos 2004). Unsaturated soil mechanics is at the intersection of several disciplines of engineering and science such as geotechnical engineering, geoenvironmental engineering, agricultural science, soil physics, and hydrology.

Driven by the practical problems in these disciplines, research activities in unsaturated soil mechanics are dynamic and continue to rapidly evolve. Current theoretical foundations for practical solutions are mostly from classical yet inadequate concepts of soil-water potential (e.g., Iwata 1972; Or et al. 2002), matric suction (e.g., Fredlund and Rahardjo 1993; Lu and Likos 2004), effective stress (Bishop 1959), and independent stress variables (e.g., Coleman 1962; Matyas and Radhakrishna 1968; Fredlund and Morgenstern 1977). The routine use of these state variables provides some basis for frameworks aimed to solve practical problems such as design and analysis of earth structures with expansive and collapsing soil (e.g., Fredlund and Houston 2009; Houston et al. 2018), shallow foundation design and analysis (e.g., Oh and Vanapalli 2011), energy foundations (e.g., Murphy et al. 2015), and slope stability under natural and engineered environments (e.g., Ching et al. 1984; Rahardjo et al. 2001). However, these state variables fail in explaining, describing, and predicting many phenomena occurring in the near-surface environment such as soil-water cavitation, expansive and collapsing soil behavior, and soil freezing and thawing behavior, among others. This is largely due to the omission of fundamental physical mechanisms of soil-water interaction in the basic concepts of matric suction, pore water pressure, effective stress, and independent stress variables.

Consequently, frameworks or solutions for practical geotechnical and geoenvironmental engineering problems based on the current concepts of matric suction, effective stress, and independent stress variables are not physically and mechanically sound; they are inadequate in their realistic physical representation of soil-water interaction. The history of geotechnical engineering, like many other disciplines, shows that engineering problems are best solved when the underlying fundamental variables are well defined, tested, and applied.

Outstanding Practical Challenges

Soil Suction Control and Measurement

Soil matric suction has been the cornerstone for all theories and design methodologies for unsaturated soil. Until recently, matric suction has been universally defined as the difference between pore air pressure \( u_a \) and water pressure \( u_w \), i.e., \( u_a - u_w \) (Fredlund and Rahardjo 1993; Lu and Likos 2004), as illustrated in Fig. 1. As such, the most widely used laboratory technique in controlling and measuring matric suction is the axis translation technique, in which both of these pressures are directly and externally controlled (Hilf 1956). The underlying assumption of axis translation is that by elevating pore air pressure while maintaining pore water pressure above the cavitation pressure, one can control the pressure difference \( u_a - u_w \). However, under natural conditions, water cavitation could be an effective water transport mechanism in soil (e.g., Or and Tuller 2002; Frydman and Baker 2009; Duan et al. 2012). Due to the existence of soil sorptive water, pore water pressure varies spatially in soil pores ranging from air-water interfaces to particle surfaces (Fig. 1), highly depending on the distance \( x \) from the particle or interlayer surface. Thus, the validity of treating matric suction as a capillary pressure, i.e., \( u_a - u_w \) is questionable (Lu and Zhang 2019; Zhang and Lu 2019b).

Soil Properties

Soil-water density has universally been treated as a constant equal to a unity, i.e., 1.0 g/cm\(^3\) for nearly all applications, e.g., soil phase diagram, specific gravity measurement, and volume change during consolidation and stress-strain testing. However, ample experimental and theoretical evidence shows that this is not the case in silty and clayey soil, where density as high as 1.6 g/cm\(^3\) in bentonite soil has been shown under low-water content conditions (Martin 1960; Mitchell and Soga 2005; Zhang and Lu 2018a). Recent studies (e.g., Zhang and Lu 2018a, b) conclude that two physical mechanisms are responsible for the existence of elevated soil-water density, all due to sorption of water: surface hydration and interlayer hydration. Both mechanisms result in high pore water pressure near the particle (Fig. 1) or lamellar sheet surface and...
can be reconciled by recognizing the existence of capillary and adsorptive water.

Water cavitates in soil under natural conditions. However, until recently, the exact thermodynamic condition under which it cavitates has been elusive and is not equivocally defined. It has been observed and speculated that different soils have different cavitation matric suction or capillary pressure. Cavitation pressure as high as 140 MPa has been experimentally demonstrated in quartz pores (Zheng and Durben 1991), although some recent work suggests that it is more likely to be around 400 kPa in soil (Frydman and Baker 2009). Recent work shows that matric suction or capillary pressure is not the fundamental variable to define water cavitation pressure in soil. Instead, intermolecular-scale pore water pressure, governed by soil sorptive potential, should be used (Lu and Zhang 2019).

The soil-water retention curve, also called soil-water characteristic curve, describes a soil’s constitutive relationship between matric suction and water content. It has been widely considered as the most fundamental constitutive function governing unsaturated soil’s hydrological and mechanical behavior. Yet, until recently, nearly all models (e.g., Brooks and Corey 1964; van Genuchten 1980; Fredlund and Xing 1994) focus on soil’s capillary water retention behavior, which lends applicability to model soil-water retention curve for matric suction less than 10 MPa. Because soil-water retention is significant for silty and clayey soil for matric suction greater than 10 MPa, developing validated models capable of modeling high matric suction due to soil sorptive potential is essential for using the soil-water retention curve as the theoretical basis for developing frameworks and protocols for design and analysis of earthen structures under unsaturated conditions.

The lowering of soil-water freezing temperature is a commonly observed natural phenomenon in silty and clayey soil. For a soil, the relationship between temperature and unfrozen water, the soil freezing curve, is a constitutive function needed for understanding and predicting soil freezing and thawing behavior. All the existing models for soil freezing curves (e.g., Hansson et al. 2004; Liu and Yu 2013), however, use matric suction or capillary pressure as the governing variable, thus overlooking the pore water pressure elevation due to the existence of soil sorptive potential. As such, these models do not predict soil freezing curve correctly, particularly for clayey soils (Zhang and Lu, forthcoming).

**Geotechnical Engineering Problems**

Expansive soil is widely spread around the world and causes significant damages to earthen structures due to cyclic variation of drying and wetting. The state of practice for mitigating the hazard caused by expansive soils relies on application of qualitative indexes such as swelling potential and quantitative indexes such as swelling pressure or potential swell (e.g., Holtz and Gibbs 1956; Seed et al. 1962; Chen 1975) to guide design and analysis (e.g., Likos et al. 2003). However, soil can have different swelling pressure or potential swell, depending on initial water content, initial void ratio, or confining conditions. While the source for swelling potential, swelling pressure, and potential swell are phenomenologically understood, i.e., due to crystalline swelling and osmotic swelling (e.g., Likos and Lu 2001; Likos et al. 2019), fundamental governing variable(s) based on soil sorptive potential for swelling behavior have yet to be identified and defined.

Clay is well known for its semimembrane behavior, i.e., being able to allow water to flow through but impeding the passage of solute (dissolved chemical matters) (e.g., Olsen 1969; Malusis and Shackelford 2002; Mitchell and Soga 2005). Assembled with textile materials, they form geosynthetic clay liners for a variety of geoenvironmental applications (e.g., Benson et al. 1999; Shackelford et al. 2019), and thus there is practical motivation to understand the phenomenon. The semimembrane behavior originates from the sorptive potential-electromagnetic field around clay particles and has been experimentally and theoretically shown to be highly sensitive to solute concentration, pore size distribution, and clay minerology. As such, membrane efficiency or ability to block solutes can dramatically reduce for permeant fluids with high ionic strength or clays with high porosity. While physical mechanisms responsible for membrane efficiency decrease have been well understood, physics-based quantitative predictive models are yet to be established.

Under a cyclic moisture fluctuation environment, clay-rich earthen materials are prone to developing desiccation. Desiccation alters soil’s hydrological and mechanical behavior, often leading to undesirable damage of waste barriers and earthen structures (e.g., Corte and Higashi 1960; Peron et al. 2009). Past research has been primarily focused on the characterization of desiccation development in terms of crack geometries, patterns, and mechanical analysis of cracking process. These analyses and characterization...
techniques are based on the paradigm of the traditional solid and soil mechanics, in which external loading is the driving force for crack development. However, recent studies indicate that the driving force for crack development is suction stress or internal stress (Lu and Likos 2006), which is a characteristic function of water content for a soil. As a clay dries, suction stress decreases (i.e., becomes more negative or tensile) everywhere in the soil, thus leading to a predominantly tensile stress field under certain restrained displacement boundary conditions. Cracking initiates when the tensile stress reaches the suction stress anywhere in soil. For clayey soil, suction stress due to sorptive potential could become a governing variable in cracking.

Outstanding Fundamental Challenges

The above-described practical challenges are rooted in the understanding and defining their common denominators, namely, matric suction, pore water pressure, effective stress, and independent stress variables. These common denominators form the basic building blocks and foundations for most frameworks built so far for geotechnical and geoenvironmental engineering problems, but are shown below to be physically or/and mechanically inadequate or/and incorrect.

Matric Suction and Pore Water Pressure Concepts

Soil-water interaction involves two categories of physically distinct mechanisms: capillarity and sorption (Edlefsen and Anderson 1943; Low 1951). Capillarity occurs at the interface of air and water (liquid), or air, water, and soil [Fig. 2(a)], where sorption occurs at or near the interface of soil and water [Fig. 2(b)]. Consequently, pore water pressure generally varies spatially with the distance of water away from the particle surface. Depending on pore size, water content, and soil sorptive potential, pore water pressure varies from its lowest near the air-capillary water interface, as governed by the Young-Laplace equation [Fig. 2(a)], to its highest at the particle-sorptive water interface, as governed by Kelvin’s equation [Fig. 2(b)].

In soil, the scale of the existence of capillary water varies from tens of nanometer (interwater molecular size) to millimeter (sand size), whereas sorptive water occurs mostly within hundreds of nanometer. Thus capillary water operates on the length scale up to 5 orders of magnitude higher than sorptive water. On the other hand, capillary water can only exist for pore water pressure greater than the prevailing saturated pressure at the cavitation vapor pressure. At a prevailing ambient temperature of 25°C and air pressure of 101.3 kPa, the saturated vapor pressure is ~3.2 kPa, resulting in capillary equal to 101.3–3.2 = 98.1 kPa or ~98.1 kPa with respect to the air pressure. In contrast, the pore water pressure near the particle surface due to sorption is compressive and can be on the order of GPA above the air pressure (Lu and Zhang 2019; Zhang and Lu 2019b). Furthermore, for sandy soil, the specific surface area (on the order of $10^{-2}$ m$^2$/g) is negligible in comparison to clayey soil (on the order of $10^{-2}$ m$^2$/g). Because of the disparities in the length and area scales and in pressure magnitude where capillary water and sorptive water vary and operate, pore water pressure in sandy soil is dominated by the capillary mechanism, but is dominated by the sorption mechanism in clay when water is close to particle surface (e.g., Bear and Nitao 1995; Nitao and Bear 1996).

When capillary water is present, air-water interfaces are curved and soil water potential is governed by the Young-Laplace equation [Fig. 2(a)], leading to pore water pressure lowering. However, when capillary water vanishes, soil water potential is purely sorptive and the air-water interfaces are flat [Fig. 2(b)], leading to no pressure drop crossing the interface. The soil water potential in the adsorptive regime is no longer governed by the Young-Laplace equation, but rather by Kelvin’s equation, which demands equilibrium of water potential in the pore air (vapor phase) and pore water. Thus, matric suction cannot be defined or measured by the classical definition of $(u_a - u_w)$. Two fundamental questions arise when only the sorptive water is present in soil: how is matric suction defined or measured? And what is the pore water pressure or pressure distribution in soil water?

Effective Stress Concept

Bishop’s effective stress $\sigma'$ is defined as:

\[ \sigma' = \sigma - u_a + \chi (u_a - u_w), \]

where $\chi$ is a scaling parameter, and $\sigma$ is the total stress. From a mechanics perspective, Bishop’s effective stress (Bishop 1959) is sound because it is a stress quantity or variable at the soil–water–air representative elementary volume (REV), as illustrated in Fig. 3(a). The validity of a stress quantity for Bishop’s effective stress is ensured by a dimensionless upscaling factor $\chi$ combined with capillary pressure $(u_a - u_w)$. A postulation of Bishop’s effective stress form is that it can be reduced to Terzaghi’s effective stress form, i.e., $\sigma' = \sigma - u_a$, by imposing $\chi = 1$ when soil is saturated and $\chi = 0$ when soil is dry. Nevertheless, Bishop did not propose a valid functional form for values of $\chi$ between dry and saturated conditions. In the past two decades, many research activities have sought specific forms of $\chi$ (e.g., Khalili and Khambaz 1998; Khalili et al. 2004; Lu et al. 2010).

In light of the challenge in defining matric suction and pore water pressure, from a physics perspective, Bishop’s effective stress form, no matter what the specific form of $\chi$ is, can only capture interparticle stress due to capillary water. Bishop’s effective stress form completely overlooks the interparticle stress due to sorption because sorption cannot be effectively cast in terms of capillary pressure $(u_a - u_w)$ (Lu and Zhang 2019; Zhang and Lu 2019b). To include the effect of sorptive water on effective stress, a general interparticle stress called suction stress is conceptualized (Lu and Likos 2004, 2006) and illustrated in Fig. 3(c).

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Alternative to the effective stress principle, a theory for independent stress state variables, i.e., $$\sigma - u_w$$ and $$(u_a - u_w)$$, has been formulated (Coleman 1962; Matyas and Radhakrishna 1968; Fredlund and Morgenstern 1977; Alonso et al. 1990) and postulated to describe strength and deformation for soil under unsaturated conditions, and to develop protocols for design and analysis of earthen structures with expansive and collapsing soil (e.g., Fredlund and Houston 2009). The cornerstone of the independent stress variables is illustrated in Fig. 3(b) for a soil-air-water REV. Clearly, the variable $$(u_a - u_w)$$ is considered as a stress quantity. Such treatment is mechanically and physically erroneous. Mechanically, variable $$(u_a - u_w)$$ is not a stress at the soil-water-air REV (Lu 2008). Because of this, theories developed for strength and deformation unavoidably created parameters without clear physical interpretation and they are hard to be characterized (Lu 2008).

Physically, the use of the variable $$(u_a - u_w)$$ as matric suction, although borrowed from the classical definition, is only representative of capillary pressure. When soil water is only sorptive water, which universally occurs in all soils under low water content or high matric suction ($$> \sim 10$$ MPa), the definition of matric suction as $$(u_a - u_w)$$ completely breaks down. Pore water pressure in the sorptive water retention regime is always equal to or greater than the ambient pore air pressure or compressive, and can be as high as on the order of GPa (Lu and Zhang 2019; Zhang and Lu 2019b).

This is the physical reason why under natural conditions soil water can remain in the liquid form. As such frameworks and protocols relying on the traditional definition of matric suction for design and analysis of earthen structures with expansive and collapsing soils inherently lack proper physical and mechanical representation of soil-water interaction.

Fundamental Breakthroughs

Water Potential Measurement

Under natural conditions, soil matric suction varies from 0 to 1,570 MPa ($$1.57$$ GPa) or relative humidity from 100% to 0.001%. Until recently, measurement or control matric suction has mainly relied on tensiometer ($$0 < $$ matric suction $$< 0.1$$ MPa), axis translation ($$0 < $$ matric suction $$< 1.5$$ MPa), filter paper (1 MPa $$<$$ matric suction $$< 500$$ MPa), and relative humidity measurement methods [4 MPa $$<$$ matric suction $$< 500$$ MPa (Lu and Likos 2004)]. In addition to the range limits for each of these methods, some of them can only measure, but not control, matric suction. All of them require long testing times to obtain soil-water retention curve, ranging typically weeks to months, if not longer.

A new technique called dynamic dew point (Likos et al. 2011) stemming from steady relative humidity measurement (Likos and Lu 2003) has emerged as a powerful way to obtain high resolution soil isotherms or soil-water retention curves under both wetting and drying for a matric suction range of 10–500 MPa. Fig. 4(a) shows a recent version of such a measurement device, and Fig. 4(b) shows typical measured soil-water isotherms. Because the approach employs a transient process and is fully computer automated, the entire soil-water retention curve for both wetting and drying can be measured in ~24 h with high resolution up to several hundreds of data points. This method has shown to yield high quality and high resolution data for understanding of sorptive behavior of soil, opening an unparalleled window probing into soil behavior in high matric suction range (e.g., Akin and Likos 2014; Khoshidi and Lu 2016; Khoshidi et al. 2017a). As such, it is possible to quantify soil’s specific surface area (SSA), cation exchange capacity (CEC), and cation species and quantities by using soil’s water isotherms (Khoshidi and Lu 2016; Khoshidi et al. 2017b). The standard methods for SSA and CEC do not use water as probing materials but instead use nitrogen gas, ethylene glycol monomethyl ether (EGME), and ammonia that may not interact with soil like water. With the water isotherm, it is also possible to quantitatively distinguish particle surface area, and interlayer surface area (Zhang and Lu 2019a), providing a first-hand evidence on flow behavior (the former) and expansive soil behavior (the latter).

Pore Water Pressure and Soil Sorptive Potential

Recent work (Lu and Zhang 2019) demonstrates that pore water pressure distribution in soil under both saturated and unsaturated conditions can be quantified by the consideration of soil sorptive potential. Soil sorptive potential is a synthesized concept of several well-established soil water potential theories in interface science, colloid chemistry, and soil physics. These potentials, namely, electrical double layer (e.g., van Olphen 1977), cation hydration (e.g., Israelachvili 2011), soil particle surface hydration (e.g., Butt and Kappl 2009), and van der Waals (e.g., Derjaguin et al. 1987) have been established individually in different disciplines in the past century or so. Recognizing the common ground among these potentials: the electromagnetic potential field around soil particles and all depending on the distance $$x$$ from the soil particle or interlayer surface, soil sorptive potential $$\psi_{sorp}(x)$$ generalizes matric...
suction concept by linking spatially the relationship with matric suction $u_m(w)$ and pore water pressure $u_w(x, w)$ (Fig. 5) (Lu and Zhang 2019):

$$u_m(w) = u_a - u_w(x, w) - \psi_{sorp}(x)$$

(1)

where $w$ = gravimetric water content; and $x$ = average distance from the particle or interlayer surface. Pore water pressure $u_w(x, w)$ can be further divided into capillary pressure component $u_{w-cap}(w)$ and sorptive pressure component $u_{w-sorp}(x)$, i.e.

$$u_w(x, w) = u_{w-cap}(w) + u_{w-sorp}(x, w)$$

(2)

Substituting the above into Eq. (1), the generalized matric suction becomes

$$u_m(w) = u_a - u_{w-cap}(w) - u_{w-sorp}(x, w) - \psi_{sorp}(x)$$

(3)

The first two terms on the right-hand side capture the classical matric suction or capillary pressure definition, which depends on soil-water content $w$, i.e., soil-water retention curve for capillary water, as illustrated in Fig. 5. The last two terms on the right-hand side represent the elevated pore water pressure due to soil sorptive, which is a function of both soil-water content $w$ and the distance $x$ from the particle surface. In general, soil sorptive potential vanishes for distance $x$ greater than 100 nanometers.

The above unitary definition of matric suction is valid for soil under both saturated and unsaturated conditions. When saturated, matric potential $u_m$ is zero, capillary pressure $[u_a - u_{w-cap}(w)]$ vanishes, and pore water pressure $u_{w-sorp}(x)$ is a function of the distance $x$, equal to negative soil sorptive potential, i.e., $-\psi_{sorp}(x)$, as predicted by Eq. (3). When unsaturated, matric suction $u_m(w)$ is a function of soil-water content $w$, and pore water pressure $u_w(x, w)$ is equal to capillary pressure $[u_a - u_{w-cap}(w)]$ in

Fig. 4. Illustration of high resolution water isotherm measurement: (a) a vapor adsorption analyzer (image by Ning Lu); and (b) water isotherms for various bentonite and kaolinite mixtures under wetting and drying.

Fig. 5. Illustration of generalized matric suction definition.
locations away from the particle surface, because \( u_{w,sorp}(x \to \infty) + \psi_{sorp}(x \to \infty) = 0 \), but becomes highly compressive near the particle surface, as predicted by Eq. (3) and depicted in Fig. 5. The latest works demonstrate that pore water pressure predicted by soil sorptive potential can reconcile the abnormally high soil-water density (Zhang and Lu 2020a), soil-water cavitation (Lu 2016), and freezing of soil water (Zhang and Lu, forthcoming).

### Soil-Water Retention Curve

Soil-water retention curve provides an indispensable bridge between the state variables of matrix suction and water content to engineering properties such as hydraulic conductivity function, soil classification indexes, resilient modulus, etc. The most popular soil-water retention models (e.g., van Genuchten 1980; Fredlund and Xing 1994) are based on the capillary pressure \((u_e - u_w)\) and are suitable for describing the functional relationship between capillary water and matric suction, which typically in matrix suction ranges less than 10 MPa.

Recently, generalized soil-water retention models (Revil and Lu 2013; Lu 2016) have been developed and validated for representing both capillary and sorptive water, as illustrated in Fig. 6(a). Using the van Genuchten’s (1980) model as the basis for capillarity water, sorptive water models are developed in lieu of the residual water content in the van Genuchten’s (1980) model. The total number of model parameters remains similar but each with a clear physical meaning or interpretation.

### Effective Stress

To go beyond Bishop’s capillary stress and to include the effect of sorptive water retention on interstitial stress, the suction stress characteristic curve (Lu and Likos 2004, 2006) was first conceptualized. Taking advantage of the closed-form equation for soil-water retention by van Genuchten (1980), a closed-form equation for suction stress characteristic curve was proposed (Lu and Likos 2004) and experimentally validated for matrix suction less than 15 MPa (Lu et al. 2010). Here for capillary water retention, suction stress can be intrinsically related to soil-water retention curve. Under the framework of suction stress \( \sigma' \), effective stress \( \sigma' \) for all saturation is unitarily expressed as \( \sigma' = \sigma - \sigma' \). Herein, Terzaghi’s effective stress becomes a special case when soil is in saturated state, i.e., \( \sigma' = u_w \). Under an unsaturated state, suction stress resumes the role of pore water pressure \( u_e \) in Terzaghi’s effective stress equation and can be completely determined by the parameters in soil-water retention curve. Shear strength parameters remain the same as in the saturated state, i.e., internal friction angle and drained cohesion. Thus the developed shear strength models accounting for unsaturated state are inconsistent with classic formulations in saturated soil mechanics. For capillary water, the closed-form equation has experimentally been shown to be valid for all types of soils for matrix suction less than 15 MPa. For sorptive water, suction stress is approximately represented by a constant corresponding to the residual water content.

Recently, suction stress characteristic curve models for better representations of both capillary and adsorption have been developed (Akin and Likos 2020; Zhang and Lu 2020b). With the advent of the generalized soil-water retention model and soil sorptive potential, a closed form equation for suction stress under both capillary and sorption conditions is developed and experimentally validated (Zhang and Lu 2020b), as conceptually illustrated in Fig. 6(b). This equation can be deduced to the closed-form equation by Lu et al. (2010) when sorptive water is treated as a constant, to Bishop’s effective stress form when only capillary water is considered, and to Terzaghi’s effective stress form when soil is in saturated state. Recent work (Zhang and Lu 2020b) also demonstrated that the unified effective equation can be used to predict soil shrinkage curve or deformation behavior.

### Future Opportunities

#### Measurement of Matric Potential at Both High and Low Suction Ranges

For low suction range, i.e., matrix suction <14,400 kPa (14.4 MPa or RH = 90%), currently, tensiometer is the only reliable and time-efficient technique to measure matrix suction but is limited to less than 100 kPa (RH > 99.93%). Although axis translation has been widely used to control matrix suction less than 1,500 kPa (RH > 98.9%), it is time consuming and is only capable of controlling capillary water. Furthermore, recent studies indicate that suppression of natural cavitation in silty and clayey soil can be significant, leading to errors in measuring soil-water retention curve. Thus, there is no reliable and time-efficient technique for routinely measuring or controlling matrix suction from 100 kPa to 14.4 MPa. Therefore, there is a great need in research and development in inventing reliable methods to measure and control matrix suction in the range from 100 to 14,400 kPa (14.4 MPa).

For matrix suction greater than 14 MPa (RH < 90%) and less than 440 MPa (RH > 4%), a vapor adsorption analyzer or other relative humidity methods (e.g., Likos and Lu 2003) are the most reliable and time-efficient techniques in controlling and measuring matrix suction. For matrix suction greater than 440 MPa and less
than 1,570 MPa (1.57 GPa or RH = 0.001%), which is the possible upper limit for soil matric suction, there is no reliable technique available for measuring or controlling matric suction. For any soil under the relative humidity less than 40% (matric suction > 125 MPa), soil and water interact only in sorptive mechanism (Zhang and Lu 2020a) and no capillary water can exist in soil. To fully understand soil’s hydrological and mechanical behavior in the sorptive water regime and to utilize these behavior as physical bases for developing methodologies and solutions for geotechnical engineering problems, reliable and routinely doable measuring and controlling high suction methods are imperative. While dynamic dew point emerges as a reliable method, it has an upper limit of 500 MPa or a low limit of ~2.5% relative humidity as now. The same or other new techniques (e.g., Dong and Lu, forthcoming) capable of measuring and controlling matric suction up to 1,500 MPa or relative humidity down to 0.001% would open unprecedented windows to the fundamental soil-water interaction behavior.

**Soil Property Measurement and Prediction**

Defining soil’s specific surface area, cation exchange capacity by soil-water interaction provides a most direct way to characterize soil’s basic physical properties. The breakthroughs in soil sorptive potential and soil-water sorption theory make it possible to develop standard protocols and procedures for testing and quantifying soil basic properties, including but not limited to thermal properties, soil water freezing properties, stiffness properties (finite strain modulus), and, dynamic properties (small-strain shear modulus and damping factor).

**Sample Geotechnical Engineering Problem**

Expansive and collapsing soil classification systems, using variables, instead of qualitative qualifiers are needed for the basis for developing effective and efficient protocols for the design and analysis of expansive soil foundations. Soil sorptive potential and generalized matric suction definition provide promising paths to develop variables such as swelling potential and collapsing potential, because these variables would be soil-water potential-based and capable of distinguishing soil-water interaction energies associated with specific behavior of swelling and collapsing.

**Sample Geoenvironmental Engineering Problem**

Flow in both saturated and unsaturated soil has been considered governed by Darcy’s law. Correspondingly, hydraulic conductivity function models are mostly based on pore size distribution, which is suitable for describing flow of capillary water. In fine-grained soil like clay, the flow of sorptive water or film water is important and models for hydraulic conductivity should include such an effect. The breakthrough in sorptive potential concept and its roles in pore water pressure distribution in low water content provide new opportunities to better describe flow behavior such as film flow, leading to better models for hydraulic conductivity function for clays. Engineering clay composites for optimum hydraulic conductivity and membrane efficiency for various application conditions remains a forefront research that can be best tackled by combining microscopic theoretical and macroscopic experimental and phenomenological approaches.

**Summary and Conclusions**

The very foundation of modern unsaturated soil mechanics has been built on classical soil mechanics and hydrology, and is not scientifically sound; the prevailing definitions of matric suction, pore water pressure, capillary effective stress, and independent stress variables fail to represent the important physical mechanism of sorption, which has been shown to be more and more prevalent in soil’s hydrological and mechanical behavior in the past half century. Practically feasible solutions for engineering problems should be simple but not simpler in the price of missing a major physical mechanism. As such, the author argues that soil sorption should be included in state variables for describing any soil-water interaction property and phenomenon, namely, thermal conductivity, solute diffusivity, hydraulic conductivity, membrane efficiency, stiffness, strength, soil-water retention, flows, stress, deformation, etc.

It has been demonstrated in recent fundamental conceptual breakthroughs that inclusion of soil sorption can better define matric suction, pore water pressure, and effective stress. These improved definitions can greatly guide and usher new opportunities in research and practice in seeking scientifically-sound and practically feasible solutions for many outstanding geotechnical engineering problems such as engineering soil classification systems, expansive and collapsing soil, soil freezing and thawing, and meltflow behavior, among many others.

Current research and practice of unsaturated soil mechanics is in a vibrant and very healthy state because they are being mutually stimulated, nurtured, propelled, and integrated. While it is always important and necessary to constantly inject the state-of-the-art understanding and methodologies into engineering practice, active research in problem-driven fundamental research is an indicator of a healthy field, and should not be viewed as a barrier or impendence for engineering practice in seeking better solutions for geotechnical engineering problems.

**Data Availability Statement**

All the experimental data reported are available from the corresponding author by request.

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