The Need for Unsaturated Soil Mechanics: A Brief Review

K. Ujwala Shenoy, K. S. Babu Narayan, and B. M. Sunil

Abstract Soils exhibit seasonal saturation and desiccation, often resulting in varying degrees of moisture content. In practice, soil is seldom fully saturated. When it is completely dry or wet, it behaves as a two-phase system. Otherwise, the moisture content within the interstices of soil vary, leading to partially saturated conditions. Unsaturated soil condition has significant influence on soil behaviour. This paper presents a brief review of the emergence of unsaturated soil mechanics and its applications.

Keywords Soil · Moisture content · Matric suction · Slope stability

1 Introduction

Soil, in general, is considered to be comprised of soil solids and pore spaces (filled with air and water). Yet, the analysis of geotechnical problems in day-to-day world is often based on a two-phase saturated soil model which assumes the soil to consist of soil solids and a water-filled pore space (saturated condition). In practice though, soil is seldom fully saturated. Seasonal saturation and desiccation, a commonly observed phenomena in soils all over the world, often results in soils that are in a state of varying degrees of saturation. The term 'unsaturated' has been adopted to distinguish soils whose behaviour is influenced by this variable degree of saturation. Since no completely dry or completely saturated soil exist permanently, soils which are partially saturated can be called as 'unsaturated soils' [3, 16, 21, 26].

Expansive soils, remoulded soils, compacted soils, collapsible soils, residual soils—all fall under the purview of unsaturated soils. Unsaturated soil behaviour is prominently seen in dry and arid climates around the world. The influence of highly unpredictable environmental factors has been one of the earliest deterrents to the lack of development of unsaturated soil mechanics on par with that of saturated soil mechanics.

K. Ujwala Shenoy (✉) · K. S. Babu Narayan · B. M. Sunil
Department of Civil Engineering, National Institute of Technology Karnataka, Surathkal, Mangaluru, Karnataka 575025, India
e-mail: ujwala.shenoy12@gmail.com

B. B. Das et al. (eds.), *Recent Trends in Civil Engineering*, Lecture Notes in Civil Engineering 105, https://doi.org/10.1007/978-981-15-8293-6_21

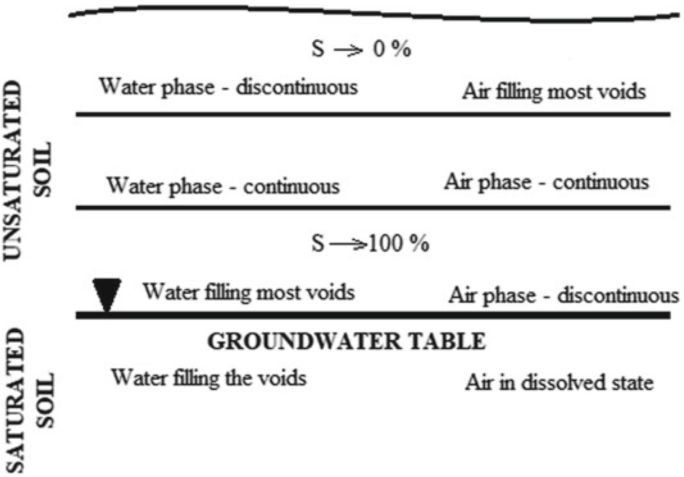


Fig. 1 Soil profile exhibiting varying degree of saturation [10]

The top-most part of the ground surface is often subject to changing environmental and climatic flux, as seen in Fig. 1. Since it is the region which has direct interaction with the surrounding environment, the soil pores are largely filled with air, leading to a discontinuous water phase. But with increasing depth below the ground, as the groundwater table is approached, the water phase tends to be continuous. The soil pores still consist of some air since the soil is above the groundwater table. In the vicinity of the groundwater table, the pores in the soil are filled with water due to capillary action while the pore air is discontinuous. All of these constitute an unsaturated soil, with varying degrees of saturation.

For a realistic description of the observed geotechnical phenomena and to obtain a result that is as close a solution to the problem at hand, it is important to take into account all the soil components. A thorough understanding of the behaviour of unsaturated soils would be highly beneficial in such a study.

2 Historical Developments in Unsaturated Soil Mechanics

Historical records of research on unsaturated soils obtained as conference proceedings and publications show the gradual emergence of the need to focus exclusively on unsaturated soils. The use of capillary theory in the 1950s to account for the behaviour of movement of water from the groundwater table towards the surface, although not successful, can be considered to be one of the earliest attempts made in the field of unsaturated soil research.

The applicability of independent state variables to describe the physical behaviour of any material has been relevant in soil mechanics right from its earliest conception stage. In the beginning, several effective stress equations were proposed for unsaturated soils (similar to that of saturated soils). However, researchers since then have come to the conclusion that the effective stress ($\sigma - u_{\mathrm{w}}$) alone is not sufficient to holistically describe the processes associated with unsaturated soil mechanics. Gens et al. [16] note that attempts to justify the observed phenomena in unsaturated soils by applying the concept of effective stress, as known in saturated soil study, were not entirely successful.

According to Fredlund [9], the acceptance of the presence of pore air in the voids and the recognition of the pressure this pore air exerts challenge the very concepts of soil mechanics that is often in practice. By the 1960s, the matric suction ($u_{\mathrm{a}} - u_{\mathrm{w}}$) was recognized as an important independent stress state variable that has to be considered to portray the behaviour of an unsaturated soil.

As a modification of Terzaghi's effective stress equation, Bishop [2] proposed the following equation for the effective stress of unsaturated soils, by introducing a parameter χ (related to the degree of saturation):

$$\sigma' = (\sigma - u_{\mathrm{a}}) + \chi (u_{\mathrm{a}} - u_{\mathrm{w}}) \tag{1}$$

in which σ' is the effective stress for unsaturated soils, u_{a} is the pore air pressure, u_{w} is the pore water pressure and χ is a function of the degree of saturation (S), with values ranging from 0 (when soil is dry) to 1 (when soil is saturated). However, it has been noted by researchers that the form of the function $\chi(S)$ has been difficult to determine, and Eq. (1) has often been questioned ever since [21].

The 1970s saw further development of the theoretical foundation for the establishment of stress state variables. The 1980s concentrated on solving problems in unsaturated soils by assuming suitable boundary values. The increasing advancements in the computational sciences in the form of computers with superior computational prowess during this period also smoothened the way for the transition of unsaturated soil mechanics from theoretical concepts to problem-solving methods. However, this did not translate into a practicing science, that is, application of unsaturated soil mechanics into practice did not pick up at a pace as expected by the pace of advancements in unsaturated soil science [10].

The 1990s saw the focus shift towards implementation into practice. The major obstructions here were the excessive time and cost involved in experimental determination of the unsaturated soil properties. The move to concentrate the research focus on unsaturated soils from the erstwhile broad spectrum of expansive soils began from 1992 onwards. Till then, soils with a negative pore water pressure (like residual soils and expansive soils) were grouped under expansive soils. Fredlund [9, 10] notes that this shift towards unsaturated soils has paved the way forward for a better understanding and theoretical conception to experimentation and subsequent push towards a practical implementation.

3 Soil–Water Characteristic Curve (SWCC)

Soil–water characteristic curve (SWCC) or soil–water retention curve (SWRC) is the plot of the volumetric water content or gravimetric water content against the matric suction. The SWCC exhibits hysteresis and has drying, wetting and scanning branches. A typical soil–water characteristic curve is presented in Fig. 2. The desorption curve is also known as the drying curve, and the adsorption curve is also known as the wetting curve. The hysteresis results in the adsorption and desorption curves not being a single, unique curve. The air entry value (AEV) of the soil is the matric suction at which air starts to enter the largest pores in the soil. The residual water content is that value of water content for the soil at which a large suction is needed to remove further water from the soil [11]. It mainly describes the interaction of soil air and soil water. SWCCs are useful in the study and analysis of the behaviour of an unsaturated soil. Properties such as shear strength, volume change and permeability are dependent on SWCC.

Rao and Singh [24] and Rostami et al. [25] based on their study concluded that SWCC can be used to determine hydraulic conductivity, shear strength, chemical diffusivity, chemical adsorption, volumetric water content, specific heat, thermal conductivity and volume change of soils. Fredlund [10] opines that it will not be wrong to conclude that the determination of the SWCC is the first and foremost requirement for a study on an unsaturated soil. SWCC is considered one the most important aspect of an unsaturated soil, which, when obtained, can further lead to the determination of many other unsaturated soil parameters.

To plot a SWCC, suction measurement is important. Filter paper, axis translation technique, vapor equilibrium method, osmotic method, pressure plate apparatus, tempe cell, tensiometer, pressure membrane extractor, dew-point potentiometer and so on are used to measure suction. The measurement techniques and procedures have

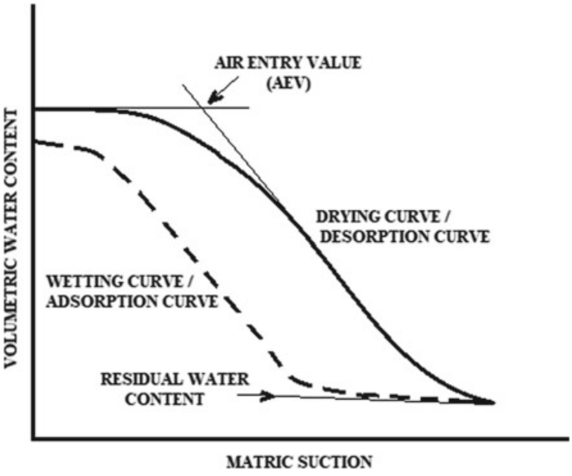


Fig. 2 Typical soil–water characteristic curve

their own limitations. The filter paper method is simple and affordable with its validity over a large suction range. However, its implementation needs extreme caution. The axis translation technique (ATT) also has some disadvantages—equilibration time required for soil with porous plate is lengthy, contact of soil with the plate has to be continuously ensured and the presence of occluded bubbles should be taken into consideration [4]. The insertion tensiometers, geotechnical centrifuges and pressure membrane extractors are valid for suctions between 80 and 1500 kPa while the dew-point potentiometer (WP4) is valid for suctions ranging from 1500 to 80000 kPa. Type of soil, size of soil specimen, applied air pressure and so on also influence the measurement time, as noted by Yang et al. [30]. Malaya and Sreedeep [20] reported that soil aging induces hydration which may in turn affect the SWCC through different suction measurement techniques and internal pore water redistributions over time.

The determination of SWCC by direct measurements is a time-intensive process and considering the economics involved, the search for alternative methods of obtaining an accurate and reliable SWCC in a cost and time-effective manner has been the focal point of many studies. The measurement of the complete SWCC is a difficult process with only a few data points actually measured on the desorption curve. The rest of the data points are plotted by using suitable curve-fitting equations to get the SWCC over the entire soil range. This has often led researchers to find alternative ways of obtaining or estimating the SWCC such as correlating the fitting parameters of SWCC with the plasticity as well as with the grain-size distribution curve. Since the shape of the SWCC resembles the grain-size distribution curve, many researchers have focused on establishing a relationship between these two so as to use the grain-size distribution curve parameters to estimate SWCC [9].

Table 1 gives a few well-known curve-fitting equations for SWCC (θ_w—volumetric water content, θ_s—saturated volumetric water content, θ_r—residual volumetric water content, a, b, c—parameters of the curve-fitting functions). Fredlund and Houston [13] have noted that the Fredlund and Xing [11] and van Genutchen [27] equations yield an accurate SWCC and hence are considered a best fit up to residual soil suction.

Table 1 Soil–water characteristic curve functions

Author	Equation	Remarks
Gardner [14]	$\theta_\mathrm{w} = \theta_\mathrm{r} + \frac{\theta_\mathrm{s} - \theta_\mathrm{r}}{1 + \left(\frac{\psi}{a}\right)^b}$	Three-parameter equation, Unknowns: θ_r, a, b
Brooks and Corey [5]	$\theta_\mathrm{w} = \theta_\mathrm{r} + (\theta_\mathrm{s} - \theta_\mathrm{r})\left(\frac{a}{\psi}\right)^b$	Three-parameter equation, Unknowns: θ_r, a, b
van Genutchen [27]	$\theta_\mathrm{w} = \theta_\mathrm{r} + \frac{\theta_\mathrm{s} - \theta_\mathrm{r}}{\left[1 + \left(\frac{\psi}{a}\right)^b\right]^c}$	Four-parameter equation, Unknowns: $\theta_\mathrm{r}, a, b, c$
Fredlund and Xing [11]	$\theta_\mathrm{w} = \left[1 - \frac{\ln\left(1 + \frac{\psi}{\psi_\mathrm{r}}\right)}{\ln\left(1 + \frac{1,000,000}{\psi_\mathrm{r}}\right)}\right] \frac{\theta_\mathrm{s}}{\left\{\ln\left[e + \left(\frac{\psi}{a}\right)^b\right]\right\}^c}$	Four-parameter equation, Unknowns: ψ_r, a, b, c

Although the various methods of indirect measurement of SWCC give an estimation, they can never replace an SWCC obtained by actual measurements. The prediction/estimation of soil suction directly from the SWCC is not encouraged as the hysteretic behaviour of SWCC results in a range of soil suction values rather than a single suction value. The errors involved in the measurement of SWCC may also show up as cumulative and lead to erroneous predicted suction values. Limitations such as these show that the soil suction estimation from SWCC is a potential area for future research.

4 Utility of Unsaturated Soil Mechanics in Prediction–Protection–Prevention of Landslides

The concepts of unsaturated soils can be effectively implemented in addressing a large variety of soil-related problems, especially in a country like India, which has a predominant tropical climate. With a booming population, the strain on our resources is at an all-time high. In such scenarios, the pressure or burden on soils is also heavy. Some of the areas where unsaturated soil mechanics can be successfully applied are in slope stability cases (subject to rainfall), landfill liner systems (mining, natural resources and waste management), nuclear waste disposal through clay barriers, water recharge through deep wells and bore holes, foundations, pavements, retaining walls, buried structures and so on. Issues related to expansive soils such as damage to foundations of buildings, infrastructure like roads and bridges can also be addressed by employing the concept of unsaturated soil mechanics [19].

Slope stability has been a significant issue in the field of soil engineering. From an economic point of view, the losses incurred as a result of slope failures in a variety of domains from road and railway embankments to natural slopes are huge. Hence, the study of stability of slopes is of great economic importance.

It is well known that the stability of a slope is largely due to the shear strength of the soil comprising it, which in turn is dependent on numerous factors. The angle of inclination of the slope, the soil density, surcharge acting on the slope are also influential in the stability. Some of the factors affecting shear strength of unsaturated soils are rate of strain, matric suction, initial water content and so on [28]. The extended Mohr–Coulomb failure envelope, as shown in Fig. 3 (which is a modification of the Mohr-Coulomb failure envelope for saturated soils), is considered for unsaturated soils. The additional cohesion provided by the matric suction contributes to the shear strength of an unsaturated soil. Hence, when the matric suction decreases, the associated cohesion also decreases and the shear strength reduces.

The shear strength of a saturated soil is given by the equation proposed by Terzaghi:

$$\tau = c' + (\sigma - u_{\mathrm{w}}) \tan \phi' \tag{2}$$

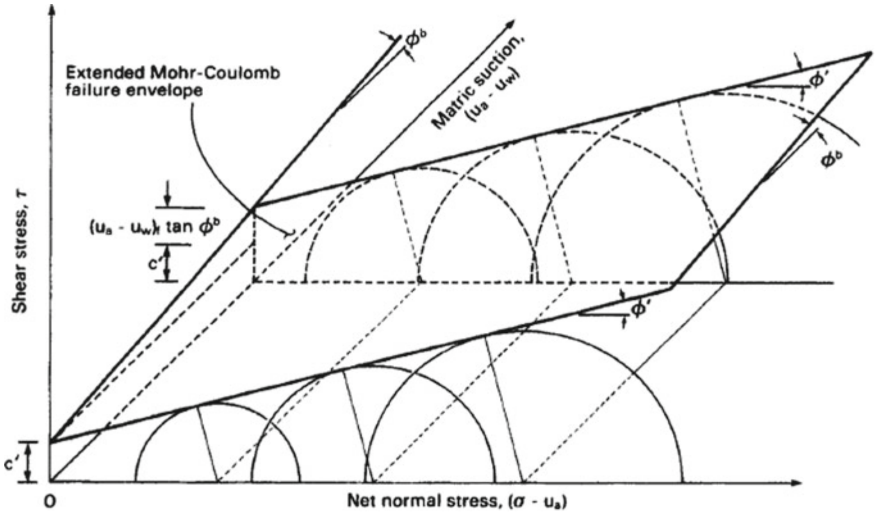


Fig. 3 Mohr–Coulomb failure envelope for an unsaturated soil [12]

where

τ	shear stress at failure
c'	intercept on the shear stress axis for a zero effective normal stress
$(\sigma - u_w)$	effective normal stress at failure
ϕ'	effective angle of internal friction.

To account for the pore air pressure and its effects in an unsaturated soil, the above shear strength equation has been modified as [12]:

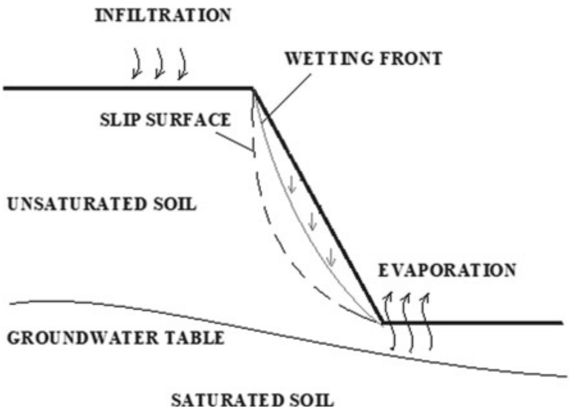
$$\tau = c' + (\sigma - u_a) \tan \phi' + (u_a - u_w) \tan \phi^b \tag{3}$$

where

c'	intercept on the shear stress axis of the extended Mohr–Coulomb failure envelope when the net normal stress and the matric suction are equal to zero
$(\sigma - u_a)$	net normal stress at failure
ϕ'	angle of internal friction identified with net normal stress state
$(u_a - u_w)$	matric suction at failure
ϕ^b	angle signifying the rate of increase in shear strength relative to the matric suction.

Similar to the determination of SWCC, the experimental procedures to determine unsaturated shear strength are most often slow and expensive. Alternative procedures for estimating the unsaturated shear strength using various tools like the soil–water characteristic curve, relationship between the air entry value and confining pressure

Fig. 4 Slope failure due to rainfall-infiltration [23]



have been reported. The lack of a universal, unique equation that can satisfactorily predict the shear strength of all unsaturated soils has been noted by Garven and Vanapalli [15]. Most of the proposed equations deal with the drying shear strength of the unsaturated soil and do not address wetting shear strength [17]. There is a need for further research to provide more improved and reliable techniques for the estimation of shear strength of soils. More experimental studies are required to be conducted following standard testing procedures to achieve this.

Studies on stability of slopes have been the focal point of many researches worldwide, especially in the areas subjected to rainfall. A typical slope failure due to rainfall-infiltration is exhibited in Fig. 4. Many instances of slopes being stable with a factor of safety less than one (as computed by using saturated concepts) is proof enough that there is a necessity to widen our horizons and look beyond the theories of saturated soils. The inclusion of unsaturated soil properties in a slope stability analysis is important, particularly for slopes in tropical areas where the residual soils are often partially saturated and are highly susceptible to failure under rainwater infiltration [7, 12, 18].

According to Cho [8], the infiltrating rainwater displaces the air from the pores in the soil, causing an increase in the air pressure which results in a delay in the advancement of the wetting front. As the water starts filling the soil pores, the bulk weight (γ) of the soil increases, altering the shear stress distribution along the slope depth. The critical failure surface for a slope under infiltration conditions is not constant and is influenced by the interactions between the air and the infiltrating water. For an accurate slope stability analysis, the influence of hydraulic hysteresis has to be suitably considered to avoid underestimating the safety factor associated with slope stability. Air entrapment is an important factor that has a considerable influence on the suction stress profile and correspondingly on the factor of safety. Thus, the concept of unsaturated soils can also be effectively applied as a slope protection measure [6, 29].

Landslides in tropical regions are often caused due to water seeping into the soil. The introduction of any form of drainage system to expel the excess pore water pressure makes the negative pore water pressure a permanent fixture, which has to suitably accounted during the modelling and analysis of stability of a slope [1]. Providing surface and sub-surface drainage is important as a preventive action to increase the stability of the landslide-prone slope. Use of unsaturated concepts has also been proven beneficial in cover systems designed to protect slopes. These act as a retaining wall and help to maintain suction values, thereby preserving the shear strength of the slopes [22].

5 Summary and Conclusion

A developing country like India, pushing for a massive overhaul in the infrastructure sector, necessitates the focus to be on the development and maintenance of these infrastructures on a low cost-maximum benefit basis. With natural disasters such as floods and droughts ravaging large parts of the country, a transition towards reliable, robust technologies and monitoring systems for the maintenance of these infrastructures is the need of the hour.

The need for considering multi-phase aspect of soil behaviour for a better engineering judgment is significant for any type of geotechnical problem encountered in the field. These issues can be realistically described by considering soil as a multiphase material where the presence of pore air influences the behaviour of the soil. A deviation from the two-phase saturated soil behaviour increases the complexity of soil mechanics with the introduction of the suction component. With more and more 'problematic soils' being encountered in the field, the need to understand unsaturated soils has never been as acute and important as in the present.

As interest in unsaturated soil mechanics is gaining momentum and with people realizing that the adoption of unsaturated soil concepts can, in fact, produce better results which are closer to reality, implementation is gaining traction, albeit at a slow pace. It is often opined that a major hindrance to the successful implementation of the principles of unsaturated soil mechanics in routine geotechnical applications is a lack of sufficient technical knowledge in engineers together with the high cost expected in the measurement of unsaturated soil properties such as SWCC.

The estimation and indirect determination methods and techniques become significant as laboratory determination of parameters of unsaturated soils is still considered complex and is not as popular as its saturated counterparts. The search for cost-effective alternatives for the expensive testing procedures is a prime area for research. The theoretical knowledge on unsaturated soils has been developed over the decades into a robust science and the versatility of the applications of unsaturated soil mechanics has opened up a wide range of possibilities for future research.

The ultimate goal of any theoretical formulation or research is a sound practical implementation. The technological advancements in the form of superior instrumentation and computational tools has resulted in further enrichment of our knowledge and comprehension of the behaviour of unsaturated soils. It is high time we apply this theoretical knowledge to solve and optimize the solutions to a variety of situations often faced in civil engineering practice.

References

1. Batali L, Andreea C (2016) Slope stability analysis using the unsaturated stress analysis. Case study. Proc Eng 143:284–291
2. Bishop AW (1959) The principle of effective stress. Teknisk ukeblad 39, 859–863
3. Blight GE (2013) Unsaturated soil mechanics in geotechnical practice. CRC Press
4. Bonder BH, Miguel MG (2010) Soil-water characteristic curves obtained through the wetting paths for a tropical soil profile. In: Fifth international conference on unsaturated soils, Barcelona. Taylor & Francis Group, London, vol 1, pp 441–446
5. Brooks R, Corey T (1964) Hydraulic properties of porous media. Hydrol Papers, Colorado State Univ 24:37
6. Chen P et al (2017) Effect of hydraulic hysteresis on stability of infinite slopes under steady infiltration. J Geotechn Geoenviron Eng 143(9):04017041
7. Ching RK et al (1984) Increase in factor of safety due to soil suction for two Hong Kong slopes. Proc 4th Int Symp Landslides 617–623
8. Cho SE (2016) Stability analysis of unsaturated soil slopes considering water-air flow caused by rainfall infiltration. Eng Geol 211:184–197
9. Fredlund DG (2000a) Historical developments and milestones in unsaturated soil mechanics. In: Proceedings of the 1st Asian conference on unsaturated soils (UNSAT-ASIA 2000), Singapore, pp 18–19
10. Fredlund DG (2000) The 1999 RM Hardy lecture: the implementation of unsaturated soil mechanics into geotechnical engineering. Can Geotech J 37(5):963–986
11. Fredlund DG, Xing A (1994) Equations for the soil-water characteristic curve. Can Geotech J 31(4):521–532
12. Fredlund DG, Rahardjo H (1993) Soil mechanics for unsaturated soils. Wiley
13. Fredlund DG, Houston SL (2009) Protocol for the assessment of unsaturated soil properties in geotechnical engineering practice. Can Geotech J 46(6):694–707
14. Gardner WR (1958) Some steady-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Sci 85(4):228–232
15. Garven EA, Vanapalli SK (2006) Evaluation of empirical procedures for predicting the shear strength of unsaturated soils. Unsaturated Soils 2006:2570–2592
16. Gens A et al (2006) On constitutive modelling of unsaturated soils. Acta Geotechnica 1(3):137
17. Guan GS et al (2009) Shear strength equations for unsaturated soil under drying and wetting. J Geotechn Geoenviron Eng 136(4):594–606
18. Ip SCY et al (2020) Three-dimensional slope stability analysis incorporating unsaturated soil properties in Singapore. Georisk: Assess Manag Risk Eng Syst Geohazards 1–15
19. Likos WJ et al (2019) Fundamental challenges in unsaturated soil mechanics. In: Geotechnical fundamentals for addressing new world challenges. Springer, Cham, pp 209–236
20. Malaya C, Sreedeep S (2012) Critical review on the parameters influencing soil-water characteristic curve. J Irrig Drainage Eng 138(1):55–62
21. Pande GN, Pietruszczak S (2015) On unsaturated soil mechanics–personal views on current research. Stud Geotechn Mech 37(3):73–84
22. Rahardjo H et al (2017) Numerical analyses for assessment of geobarrier system performance. PanAm Unsaturated Soils 2017:132–148
23. Rahardjo H et al (2019) Role of unsaturated soil mechanics in geotechnical engineering. Int J Geo-Eng 10(1):8
24. Rao BH, Singh DN (2009) Establishing soil-water characteristic curve of a fine-grained soil from electrical measurements. J Geotechn Geoenviron Eng 136(5):751–754

25. Rostami A et al (2013) Pore network investigation on hysteresis phenomena and influence of stress state on the SWRC. Int J Geomech 15(5):04014072
26. Sheng D (2011) Review of fundamental principles in modelling unsaturated soil behaviour. Comput Geotech 38(6):757–776
27. van Genuchten MTh (1980) A closed-form equation for predicting the hydraulic conductivity of unsaturated soils 1. Soil Sci Soc Am J 44(5):892–898
28. Vanapalli SK (2009) Shear strength of unsaturated soils and its applications in geotechnical engineering practice. In: Keynote Address. Proceeding of 4th Asia-Pacific Conferennce on Unsaturated Soils. New Castle, Australia, pp 579–598
29. Xie W et al (2020) Influence of the features of the unsaturated zone on the air injection method in a slope. Proc Inst Civil Eng-Geotechn Eng 173(2):115–124
30. Yang H et al (2004) Factors affecting drying and wetting soil-water characteristic curves of sandy soils. Can Geotechn J 41(5):908–920