Study on Unsaturated Soils's Influence on Stability of Geotechnical Engineering

Le T.B.T.

Department of Civil Engineering, National Central University, No.300, Zhongda Rd., Zhongli District, Taoyuan City, Taiwan 320317 (R.O.C.).

Email: 112382603@cc.ncu.edu.tw

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ABSTRACT

The behavior of unsaturated soils significantly influences the stability of geotechnical engineering structures. Unsaturated soils, often known as partly saturated or compacted soils, are soils in which the voids contain both air and water. Unsaturated soils have negative pore water pressure due to the attraction of water molecules to soil particles. Suction affects the soil's strength and volume-change behavior. Moisture content, which represents the amount of water present in the soil, also plays a vital role in determining soil properties. The shear strength of unsaturated soils differs from that of saturated soils due to the presence of suction. Unsaturated ground can withstand volumetric alterations in response to modifications in humidity content or stress conditions. These volume changes can lead to soil collapse, settlement, or heave, affecting the stability of engineered structures. Proper characterization of volume change behavior is essential for designing foundations and assessing the long-term performance of geotechnical systems. Overall, this topic highlights the significance of considering unsaturated soil mechanics for planning and analyzing geotechnical engineering structures to ensure their safe and reliable performance.

Keywords: *Unsaturated, saturated, soil, geotechnical engineering, pore water pressure*

1. INTRODUCTION

Soil mechanics combines engineering mechanics, soil behavior, and soil characteristics. This depiction includes a variety of soil categories. These earths could be saturated with liquid or other solutions in the voids. The evolution of conventional soil mechanics has resulted in a focus on certain types of soil. Normal soil classifications include saturated sands, silts and clays, and dry sands.

Manifold soil constituents running into engineering applications exhibit behavior that is inconsistent with the fundamentals and concepts of traditional saturated soil mechanics. The existence of many fluid phases, for example, causes stuff behavior that is difficult to engineer in practice. Unsaturated soils (those with water and air in the gaps) are the most common soil kinds that doesn't behave according to conventional saturated soil mechanics.

Soil mechanics can be separated into two subfields: saturated soils and unsaturated soils. The distinction between saturated and unsaturated soils is required due to fundamental variations in matter composition and engineering processes.

Many geotechnical and geo-environmental difficulties exist around the world, and unsaturated soils play an important role in a numerous geotechnical and environmental engineering challenges. Historically, engineering analyses have concentrated on saturated soils or fully dry circumstances. However, the behavior of compacted soils has been challenging to anticipate using classical soil mechanics.

Unsaturated soil mechanics must be considered when dealing with issues such as landslides, dam construction and maintenance, landfills, shallow foundations, and sand pavements located in areas with problematic soils such as shrink-swell clay, collapsible loess, and expansive clays. Furthermore, the comprehesion of unsaturated soil mechanics basis has been applied to a expansive range of geotechnical issues connected with earths above the groundwater level, including vadose zones, compressed soils, and more complex behavior than saturated soils. An unsaturated soil consists of more than two phases, with pore-water pressure being negative in comparison to pore-air pressure. When the water table is below ground, any soil close to the surface may encounter negative pore-water pressures and a probable decrease in saturation. As a result, the assumption that soils are either entirely saturated or completely dry may not truly represent or be acceptable for solving such problems, especially in geotechnical and environmental engineering.

The utilization of the saturated soil mechanic theory might be insufficient to solve these problems. Therefore, the application of unsaturated soil mechanics theory is necessary for the comprehensive analysis and understanding of various related problems, including seepage behavior, shear force, and volumetric transition.

2. OVERVIEW OF UNSATURATED SOILS

2.1. Causes induce unsaturated soil

Both natural and man-made soils are likely to be unsaturated. Natural unsaturated soils are abundant in arid or semi-arid regions where the water table is often many metres deep. Arid or semi-arid regions cover roughly one-third of the earth's surface, where possible vaporization exceeding precipitation. Nevertheless, any soil near the ground surface in a reasonably waterless condition is likely to get a negative pore water pressure, resulting in desaturation or air arrival into the pore cavities. Although the ground may be saturated for some distance above the phreatic surface, if the pore water pressure falls adequately, air will penetrate the porous spaces. Fig. 1 shows the transition from positive pore water pressure beneath the groundwater level to negative pore water pressure above it. Compacted fills, such as those used in earth dams, road subgrades, and embankments, are typically unsaturated due to the inability to completely crush and close all air holes.

Climate is critical to the creation of unsaturated soils, as evaporation in warmer weather dries out the ground, causing fine-grained soils to shrink. Subsequent watering after rain causes swelling and fracture closure but does not necessarily eliminate suction-induced soil structure completely. The subsequent behavioral features of tiny particles are affected by their aggregation after drying. Future climate change caused by global warming has the potential to create considerable mutations in soil moisture regimes and, consequently, soil conditions throughout tremendous regions in the world. Plants can also cause considerable ground desaturation because of evapotranspiration, but vegetation subtraction can result in later re-saturation, most notably slope instability owing to deforestation. Where unsaturated soils contain highly flexible clays, massive swelling and shrinkage phenomena can occur due to water uptake or a decrease in humidity content, resulting in ground motions adapted to inflicting serious structural destruction.

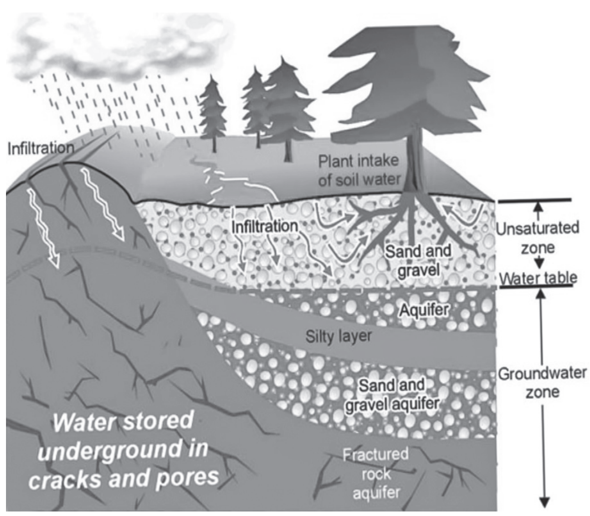


Figure 1. *Unsaturated soils in the ground [1]*

2.2. Unsaturated soil in the hydrological cycle

Fig. 2 illustrates the unsaturated soil environment and its involvement in the inherent hydrological cycle. The equilibrium position of the phreatic surface is determined by the system's overall geomorphology, soil qualities, and the steadiness of the ecological systems that add or withdraw liquid to or from the subsurface. The range of the associated water cycle could be local or regional, ranging from a single engineering-employed place to the continental or world scale.

Globally, the unsaturated sphere in the middle of the phreatic surface and the ground surface contain less than 0.01% of the total water participating in the hydrological cycle [2]. The unsaturated zone, which connects the atmosphere to deeper groundwater aquifers, plays a crucial role in the water cycle.

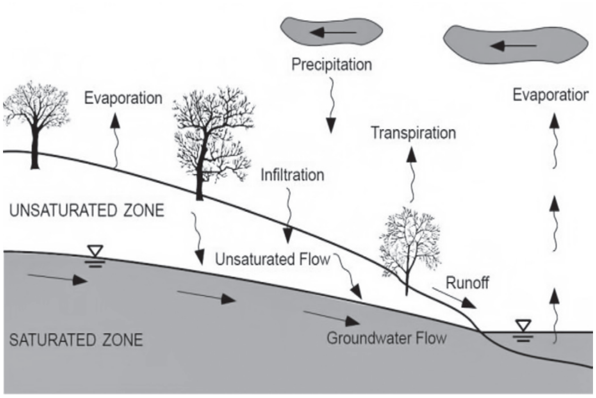


Figure 2. *The function of the unsaturated zone in the inherent hydrological cycle [2]*

2.3. Basic unsaturated soil mechanics concepts

Soils fluctuate in their water content both temporally and spatially. During precipitation, water can enter the soil, causing a downward flow and finally saturation. The water table is the depth to which the earth becomes completely saturated with liquid. Water can be lost from the soil through dissipation and/or evapotranspiration progresses, which cause an upward movement of water, causing the material to gradually dry and crack. Groundwater is frequently extracted for agricultural, municipal, and industrial reasons via extraction wells. Given that climate variation regulates the groundwater table, Figure 3 depicts the distinction between saturated and unsaturated zones in natural soils.

The unsaturated zone is located in the middle the ground surface and the regional phreatic surface. It contains the capillary edge. The capillary edge is the soil cover where aquifer level rises from a groundwater level due to capillary pressure. The pores near the place of the capillary fringe are totally full of liquid. Nevertheless, because pore sizes vary, the saturated section of the capillary edge is smaller than the overall capillary increment. As a result, soils with tiny and homogeneous pore sizes could be entirely saturated by liquid several feet above the aquifer level. When the pores are large, the soaked section will only reach a few inches above the phreatic surface. As a result, capillary behavior promotes a fringe zone above the saturated zone, in which moisture declines with range above the phreatic surface. In the unsaturated soil zone, the pressure of pore water may reach from zero at the phreatic surface to a ultimate tension of around 1,000,000 kPa under moistureless conditions [1]. The unsaturated zone varies with the saturated zone in that the pores are totally filled with liquid and the water pressure exceeds atmospheric pressure.

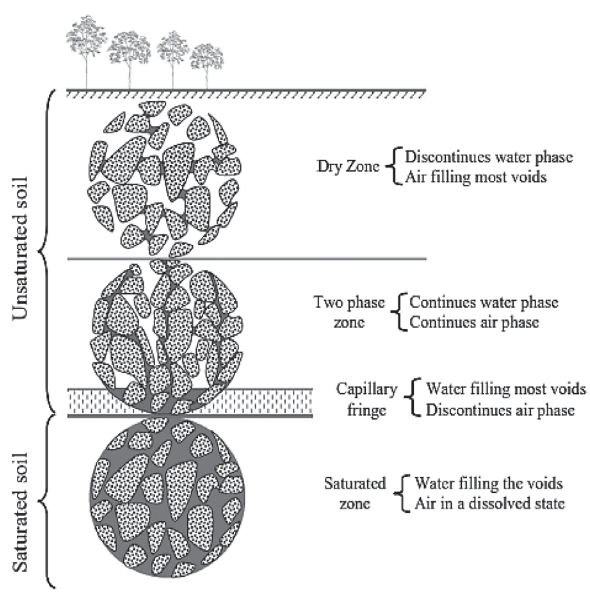


Figure 3. *Soil classification according to the level of saturation [1]*

2.3.1. Soil suction

Permeable materials feature an inherent capacity to draw and hold liquid. It is commonly known as suction. During drought circumstances, if the liquid in a ground's gaps were affected to gravity, the earth over the water table would be entirely dehydrated. Soil suction is caused by the soil's attraction to liquid, and it manifests as tensile hydrostatic stress in a saturated piezometer with a permeable filter in close interaction with the fluids in the soil. Weak intermolecular electromagnetic appeals are triggered by short-range or motivated dipole-dipole reactions. These are typically known as van der Waals forces [1]. Attractive forces are smaller than ionic forces but greater than van der Waals forces. As a result, the compound of hydrogen bonds and van der Waals forces can produce a range of high contact between liquid and soil grains. Fig. 4 depicts the area where water atoms are highly adsorbed by a dotted line that surrounds each soil particle. In addition, water molecules have a strong attraction to each other due to the force of surface tension. This surface tension acts like an elastic film, pulling the water molecules together and minimizing the water's surface area. As a result, the water forms a curved structure, usually called a meniscus.

Water is held around the contact point of two particles because of the capillary force generated by the tension on the surface regarding liquid and air. Water remains trapped by either strong adsorbing forces at the soil grain's surface or via capillary actions at the soil grain's interface. The size of the voids determines the extent to which soil above the phreatic surface attracts water, just as the diameter of a narrow bore glass tube limits the height to which liquid rises inside the tube when dipped in liquid. Water is harder to remove from a smaller void. The soil suction, ψ, is indicated as a positive quantity and described as the total of matric suction, $(u_a - u_w)$, and osmotic suction, π.

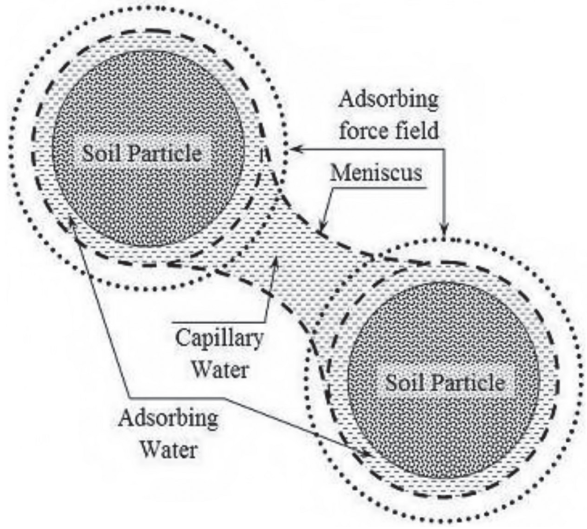


Figure 4. *Schematic diagram of water soil interaction [1]*

2.3.2. Osmotic suction

The pore water is replaced by the amount of soluble salts that will cause osmotic suction (π), which is pressure-independent. It may be calculated as the distinction in partial pressure of water vapor in balance with pure water against that in balance with underground water. Though the osmotic influence is associated with unsaturated soils rather than saturated soils, salt in pore water can be found in both saturated and unsaturated soils. As a result, osmotic suction works similarly well on saturated and unsaturated soils. The osmotic impact occurs when the concentration of soluble salts in pore water varies with that of externally accessible water. As a result, changing the salt content of a soil will cause a alteration in its entire volume and shear force. Swelling might happen in the specimen if the external fluid involves less soluble salts than the porewater. When compared to the effect of matric suction, the osmotic suction is thought to have a minor impact. As a result, assuming the salt concentration remains constant, osmotic suction should have no impact on soil behavior. As a result, a deviation in total soil suction, ψ, is roughly comparable to an adjustment in matric suction, $(u_a - u_w)$.

2.3.3. Matric suction

The matric suction (u_a - u_w), is connected to capillary tension in pore water and the water adsorption strengths of soil grains, both of which are affected by the geometrical arrangement of the soil structure. Matric suction is the difference between pore-air pressure (u_a) and pore-water pressure (u_w). As shown in Fig. 5, dry and rainy seasons create fluctuations in the suction characteristics, especially near the top layer of ground. Matric suction also influences the height of the phreatic surface.

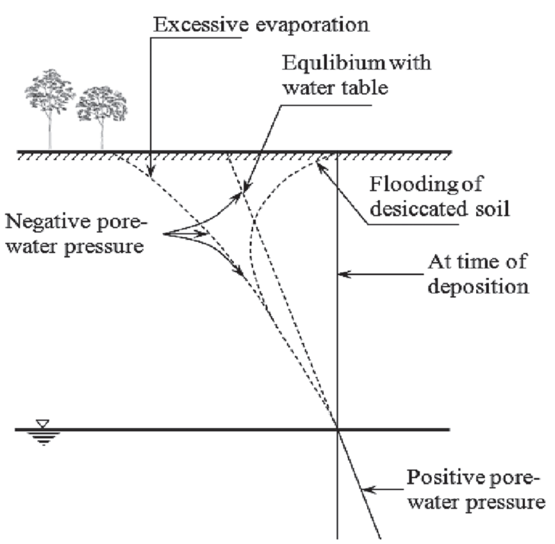


Figure 5. Typical pore-water pressure profile [3]

As a result, deeper groundwater levels are expected to have higher matric suction. Ground surface vegetation, otherwise, can impose a pore-water tension of 1 to 2 MPa by evapotranspiration.

Therefore, evapotranspiration may produce an increase in matrix suction. Water has a simple molecular structure, with two hydrogen atoms linked covalently to one oxygen atom by a common pair of electrons. Because oxygen captures electrons much stronger than hydrogen, hydrogen atoms have a net positive electrical charge while oxygen atoms exhibit a net negative charge. Finally, the electrical charge drew the water molecules closer together, making separation more difficult. This attracting force lends water its cohesive and sticky qualities.

2.4. Nature of unsaturated soil

The soil terminology, as used in geotechnical technology, refers to a variety of particle elements. Soil mechanics can be divided into two categories: saturated and unsaturated soils, as shown in Fig. 6. In a saturated condition, all void spaces between particles are made full with liquid, whereas in an unsaturated condition, a portion of the blank cavities is become full with air. The large variety of particle dimensions and native variability in soils result in behavioral features that are difficult to rigorously analyze. Geotechnical solutions sometimes require simplifications and generalizations to account for particle shape, stress history, and time-dependent properties.

A soil mass consists of three phases: hard grains, liquid, and air. Historically, scholars have made significant advances towards understanding the behavior of saturated, finer soils and dry, coarse soils. However, improving our comprehension of unsaturated soil behavior, in particular those with high fines, proved problematic. This is mostly owing to the existence of an additional fluid phase of air or other gases in the voids, which confuses the crucial assignment of managing stress regimes. When analyzing unsaturated soil behavior, it is vital to take into account changes in air and water pressures, phase compressibility, and their contacts, as well as chemical influences. The connections include a shrinkage skin among the fluid phases, which causes a surface tension effect that is especially important in forming the characteristic aggregated structure of fine-grained soils.

Unsaturated soils have a unique behavior due to the presence of the shrinkage skin or air-water interface, which acts as a fourth phase in addition to the solid, air, and liquid phases. The shrinkage skin performs like a thin membrane throughout the gaps, separating air and water phases; therefore, its existence fundamentally influences the mechanical response of unsaturated soils. However, changes in the stress state of the contractile skin can induce variations in the soil's water content, volume, and shear strength. The contractile skin governs the degree of saturation by controlling the ratio of air to water within the voids. In conclusion, it is particularly important to view an unsaturated soil as a four-phase mixture when considering the stress state of unsaturated soils, as shown in Fig. 6.

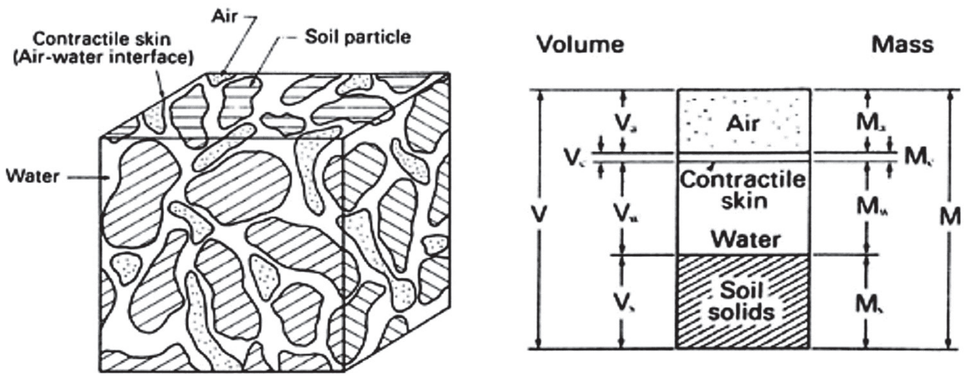


Figure 6. *Phase diagram for unsaturated soil [4]*

Unlike conventional soil mechanics, which assumes that soils are either fully saturated or dry, unsaturated soil mechanics considers the effects of partial saturation, such as suction, hysteresis, and volumetric alternation, on the strength, stiffness, and permeability of soils. These effects are important for many engineering applications, such as slope stability, retaining walls, foundations, pavements, dams, and landfill liners. Therefore, unsaturated soil mechanics also poses many challenges for geotechnical engineering practice, such as the complexity of the theoretical models, the difficulty of the experimental methods, and the uncertainty of the field conditions.

2.5. Soil-Water Characteristic Curves (SWCC) for unsaturated soils

The SWCCs play a vital role in determining the properties of unsaturated soils. SWCC provides a conceptual knowledge of the relationship between the water volume in the ground and its energy state in liquid phase. The SWCC has proven to be an interpretive model that employs the simple capillary model to provide insight into the propagation of liquid in the gaps. As shown in Fig. 7, the SWCC chart is typically drawn as the volumetric moisture versus the logarithm of soil suction. It demonstrates the relationship between how much water a soil holds and particles, leading to the force required to extract that water. Nonetheless, SWCC has an S-shaped curve with two important points: the air-entry value (when water starts to be removed) and residual conditions (when most water is gone).

In addition, the curves of SWCC are not only a single line but also behave as hysteresis. It responds similarly when changing from greater moisture content to lower humidity values (the desorption path) as well as altering from lower humidity contents to higher humidity values (the adsorption path). This indicates similar behavior in how tightly water is held in that dry state for both drying and wetting processes. Nevertheless, the soil holds onto water more tightly during drying than when being wetted from a dry state, resulting in a loop on the graph. Nonetheless, the determination of unsaturated soil property functions to obtain SWCC functions can be done using approaches as shown in Fig. 8.

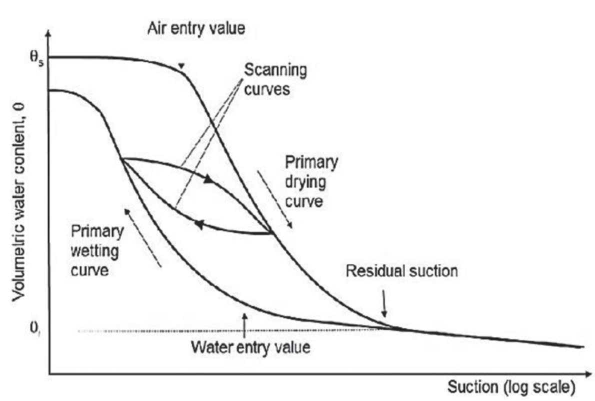


Figure 7. *Typical Soil Water Characteristic Curve [5]*

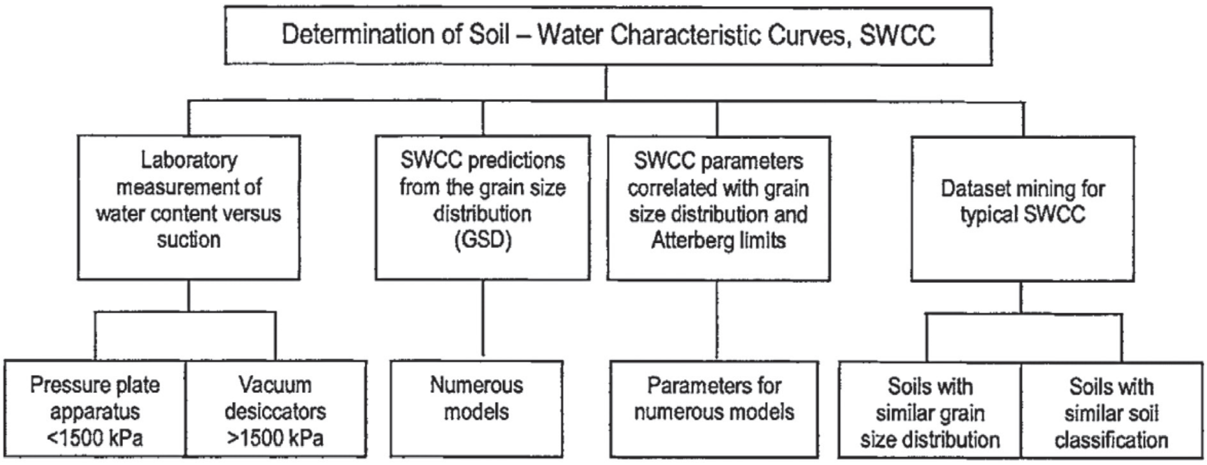


Figure 8. *Approaches that can be used to obtain SWCC [5]*

SWCC plays a vital role in understanding and determining the behavior of unsaturated soils. As shown in Fig. 9, there is a relationship between SWCC for these 3 types of soil. Curves demonstrate the correlation between the water content (mass or volume) of a soil and the matric suction or energy state of the liquid phase at equilibrium conditions. Granular soils like sandy soil will yield less matrix suction than silty soil and clayey soil, respectively. Especially, indeed, at the same moisture content, clay exhibits much more suction than sand. For that reason, this creates a larger total surface area for clay particles to interact with water molecules. Hence, the smaller pores in clay exert a stronger attraction on water molecules, requiring more suction to remove them. Sand particles have a bigger diameter compared to clay, resulting in larger pores between them. These larger pores hold water less tightly due to weaker adhesive forces.

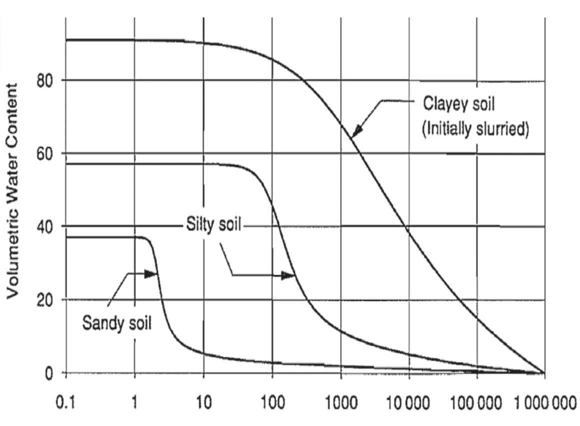


Figure 9. *Typical features for SWCC of different type of soils [6]*

2.6. Permeability function for unsaturated soils

Generally, the permeability (hydraulic conductivity) of saturated soils usually assumes water fills the pores, creating a continuous pathway for laminar flow. In unsaturated soil, air occupies some of the pores, disrupting this continuity. Therefore, water flow will become more complex, with water needing capillary force around air bubbles. This significantly reduces the overall ease of flow compared to a fully saturated scenario.

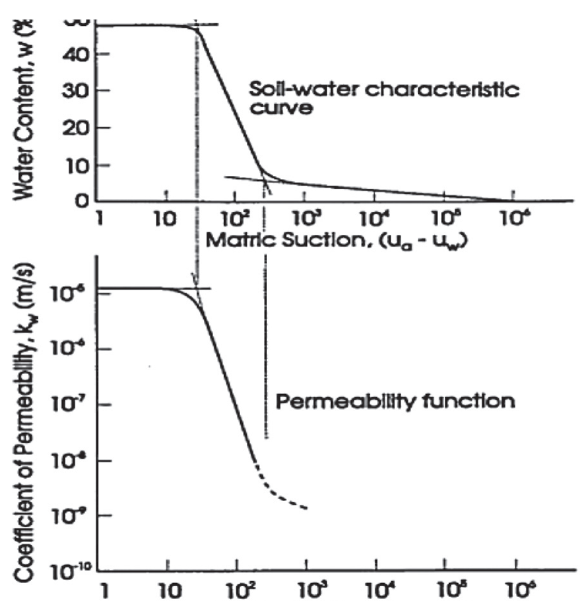


Figure 10. *Relationship of Permeability function that related to SWCC [7]*

In other words, water flow through unsaturated soils isn't only dependent on the soil when it's completely saturated with water. The SWCC provided a tool to consider the amount of water, the degree of saturation, and the forces holding it within the soil. Hence, the permeability will moderate with the amount of water (volumetric water content). It can be called “the permeability function” of unsaturated soils. The permeability function purports to explain the hydraulic head flow of water via unsaturated soil where the water content exceeds the remaining water level. Usually, it is possible for a coarse-grained material to have a lower permeable coefficient than a fine-grained material. Besides, the permeability function can be estimated from the saturated permeable coefficient and the SWCC through the use of an integration process, as shown in the relationship in Fig. 10.

3. UNSATURATED SOILS'S INFLUENCE ON STABILITY OF GEOTECHNICAL ENGINEERING

3.1. Some challenges of unsaturated soil

3.1.1. Theoretical Models

Perhaps the most difficult tasks in unsaturated soil mechanics is developing and validating theoretical models that effectively reflect unsaturated soils' complicated behavior and interconnections. Unsaturated soils, unlike saturated soils, require two stress factors to characterize their state: net stress and suction. Furthermore, unsaturated soils respond to stress and suction changes in a nonlinear and hysteretic manner, implying that their behavior is determined by their loading history and path. As a result, unsaturated soil mechanics necessitates more advanced constitutive models, such as elastoplastic, viscoplastic, or damage models, capable of accounting for the effects of suction, hysteresis, and volume change on unsaturated soil stress-strain relationships.

3.1.2. Experimental Methods

Another problem in unsaturated soil mechanics is developing and applying experimental methods for measuring and controlling the important parameters and variables of unsaturated soils. Unlike saturated soils, which may be examined with standard laboratory equipment such as triaxial or direct shear devices, unsaturated soils necessitate the use of specific devices, such as suction-controlled or osmotic devices, to create and maintain a desired suction level on the soil specimen. Furthermore, unsaturated soils necessitate more advanced measurement tools, such as tensiometers, psychrometers, or dielectric sensors, which can monitor soil suction and moisture content while testing. As a result, unsaturated soil mechanics necessitates increasingly complex and expensive laboratory facilities, techniques, and instruments capable of producing trustworthy and precise data on unsaturated soil properties and behavior.

3.1.3. Field Conditions

Unsaturated soil mechanics faces a third challenge: estimating and predicting field conditions that affect geotechnical construction performance and safety. Unlike saturated soils, which are assumed to have uniform and constant moisture content and suction, unsaturated soils have spatial and temporal variations in moisture content and suction caused by natural or artificial factors such as rainfall, evaporation, irrigation, drainage, or vegetation. As a result, unsaturated soil mechanics necessitate more comprehensive and frequent field studies, such as boreholes, sampling, or in situ testing, to determine the soil's initial and boundary conditions. Furthermore, unsaturated soil mechanics necessitates increasingly advanced numerical models, such as finite element or finite difference models, that can predict the coupled hydromechanical behavior of unsaturated soils under a variety of loads and environmental conditions.

3.2. Applications and some cases of unsaturated soil's influences on stability of geotechnical engineering

3.2.1. Slope stability

One of the most prevalent uses of unsaturated soil mechanics is slope analysis and design, particularly in unsaturated zones where rainfall and evaporation can produce considerable changes in soil moisture content and suction—that is, the negative pressure in pore water caused by the presence of air—and it can improve the shear strength and stiffness of unsaturated soils. As a result, slope stability is determined by not just soil weight, cohesiveness, and friction angle but also suction distribution and variance. In the case of soil slopes during heavy rains, as shown in Figure 11, many slope failures arise on steep residual soil slopes with a deep underground water. Rainwater penetration into soil hillsides is the primary source of rainfall-induced landslides. In other words, rainwater infiltration into the slope surface helps to raise the aquifer level, called the wetting front, while diminishing matric suction. Reducing matrix suction in unsaturated soils leads to a reduction in shear strength along the slip surface until it reaches failure mode.

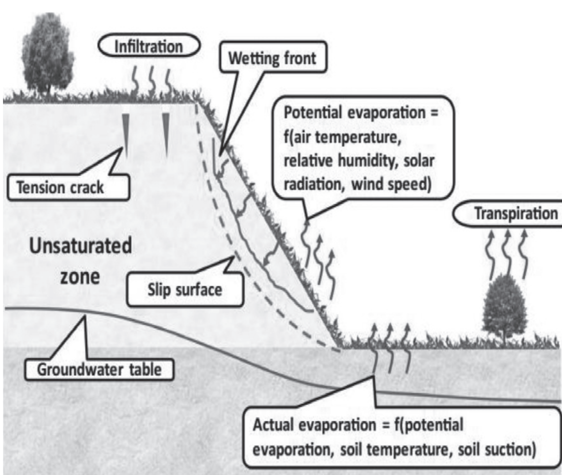


***Figure** 11. Mechanism of rainfall-induced slope failure [8]*

One of the main applications of unsaturated soil mechanics to slope stabilization is the design and installation of a capillary barrier system (CBS) as a slope cover to reduce rain infiltration into slopes, as shown in Fig. 12. However, CBS runs as the concepts of unsaturated soil mechanics. CBS includes two layers of non-cohesive fine-grained and coarse-grained soils.

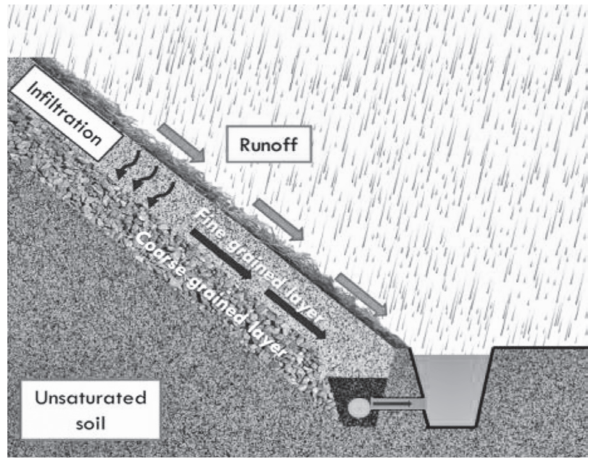


Figure 12. *Mechanism of capillary barrier system [8]*

For this case, using a numerical model of ground slope - SEEP/W software - to analyze seepage. The slope of a 4-meter height with an inclination angle of 45° was modeled as a typical slope in Singapore. In conclusion, results of numerical analysis show that the slope with CBS cover had an initial FS of 1.64, which was somewhat higher than the previous slope's 1.61 due to CBS cover reinforcement. The original slope had a greater rate of drop in FS over time than the covered slope. At the end of the rainy event, the FS for the original slope reached 1.0, whereas the FS for the slope with CBS cover reached 1.36, as shown in Figure 13. As expected, the CBS has a significant effect on slope stability in transient situations.

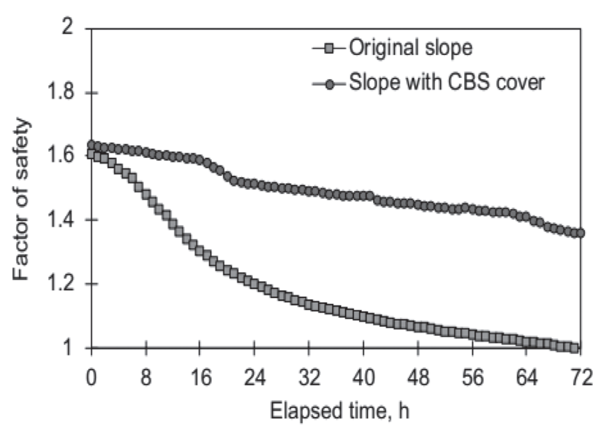
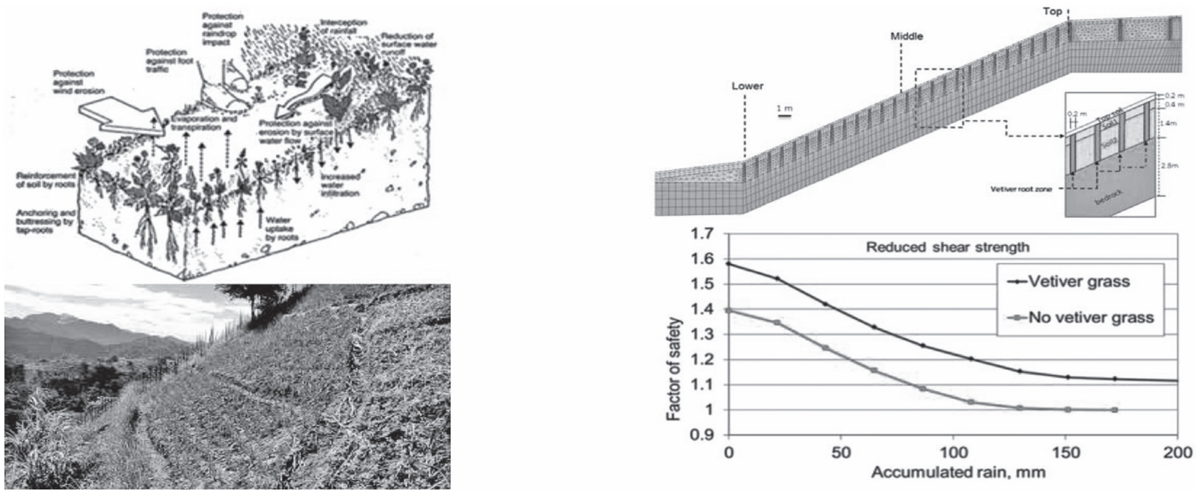


***Figure** 13. Variations in factor of safety for the original slope and the slope with CBS [8]*

Additionally, the root-reinforced soil method, such as the use of a vertiver glass for slope protection, can be used to address landslides, slope failures, and erosion issues based on unsaturated soil mechanics. This method is expected to be greater in strength and permeability, which would help to minimize runoff by allowing for more infiltration, enhancing the soil, conserving water, and strengthening the safe factor during heavy rainfall, as shown in Fig. 14.



a) Effects of vegetation on slopes   b) Profile of slope with vertiver and comparison of FS

***Figure** 14. The use of soil slope with vetiver grass to protect the slope [8]*

3.2.2. Retaining Walls

Unsaturated soil mechanics can also be utilized to design and build retaining walls, which are structures that maintain vertical or near-vertical incisions in the ground. Retaining walls are subject to lateral earth pressures from backfill dirt, which vary depending on soil parameters and wall deformation. In unsaturated soils, suction can reduce or increase lateral earth pressure depending on the direction of wall movement. Geotechnical engineers can use unsaturated soil mechanics to identify the suitable wall type, size, and reinforcing, taking into account the effects of suction and variations caused by wetting and drying cycles or seepage.

3.2.3. Foundations

Unsaturated soil mechanics is used in the design and construction of foundations, which are structures that transfer load from a superstructure to the underlying soil. Settlement, or vertical movement of soil caused by an applied load, occurs in foundations. Suction also affects settlement in unsaturated soils, causing shrinkage or swelling depending on moisture content and stress level. Unsaturated soil mechanics can assist geotechnical engineers in evaluating bearing capacity and foundation settlement, taking into account the effects of suction and changes caused by loading and unloading or environmental conditions.

For bearing capacity, shallow foundations typically have shallowly distributed footings (Fig. 15). The bearing capacity of underlying soils is frequently calculated using the soil's unconfined compressive strength. When the water table is lower than the footings' elevation, shallow footings are simple to build. In many cases, the water table is at a significant depth, and the soil beneath the spread footings has low pore-water pressure. Undisturbed samples, held together by negative pore-water pressures, are frequently examined in the laboratory to determine the soil's shear strength. The assumption is commonly made that the pore-water pressure conditions in the field will remain relatively constant over time, and hence the unconfined compressive strength will remain virtually unaltered. The soil's carrying capacity is calculated using this assumption and a reasonably high design factor for safety.

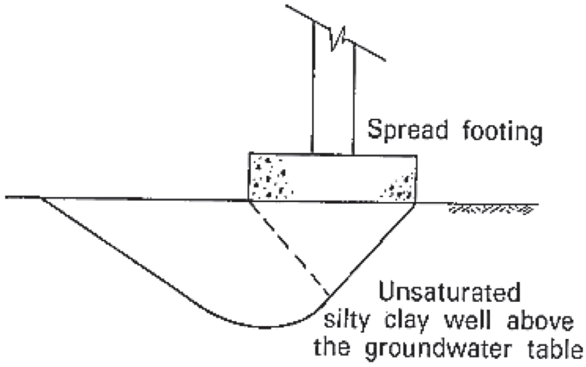


Figure 15. *Analysis of bearing capacity for lightly loaded structure placed on unsaturated soil with negative pore-water pressures [9]*

4. CONCLUSION

Over the last few decades the research on unsaturated soil has been growing exponentially. Many researchers engaged in this area is likely to be larger than that in all remaining branches of Soil Mechanics. Generally, the influence of unsaturated soils on the stability of geotechnical engineering structures cannot be overstated. By incorporating the principles of unsaturated soil mechanics into design and analysis processes, engineers can ensure the safe and reliable performance of infrastructure projects in a wide range of environmental conditions.

The main conclusions emerging from this report relating to unsaturated soils are as follows:

- Any soil near the ground surface in a reasonably dry environment is likely to have a negative pore water pressure, resulting in de-saturation or air entry into the pore spaces. Besides climate is critical in the creation of unsaturated soils.

- The unsaturated zone, which connects the atmosphere to deeper groundwater aquifers, plays a crucial role in the water cycle.

- pore-water pressure can reach from zero at the phreatic surface to a maximum tension of around 1,000,000 kPa under waterless conditions. The unsaturated zone varies from the saturated zone in that the pores are totally filled with liquid, and the water pressure exceeds atmospheric pressure.

- Unsaturated soils have a unique behavior due to the presence of the contractile skin or air-water interface, which acts as a fourth phase in addition to the solid, air, and water phases. It is particularly important to view an unsaturated soil as a four-phase mixture when considering the stress state of unsaturated soils.

- The SWCCs have an important role in the determination of unsaturated soil properties, functions and behaviors.

- The permeability will be changed regarding to the change of amount of water (volumetric water content). It can be called "the permeability function" of unsaturated soils. The permeability function appears to describe the hydraulic head flow of water through an unsaturated soil as long as the water content is greater than the residual water content.

- Early research recognized the role of capillary forces (water surface tension) in unsaturated soil behavior. When soil is fully saturated and water pressure is compressive (pushing inwards), it acts to reduce the overall stress on the soil particles.

- Some challenges of unsaturated soil such as developing and validating theoretical models that effectively reflect unsaturated soils' complicated behavior and interconnections; developing and applying experimental methods for measuring and controlling the important parameters and variables of unsaturated soils; estimating and predicting field conditions that affect geotechnical construction performance and safety.

- Applications and some cases of unsaturated soil's influences on stability of geotechnical engineering such as slope stability; retaining walls; foundations.

Continued research and innovation in this field will further enhance our understanding and ability to address the challenges posed by unsaturated soils in geotechnical engineering practice.

REFERENCES

[1] Ali Murtaza Rasool, (2014). *Mechanical behavior of unsaturated soils in isotropic loading-unloading, monotonic and cyclic load sequence.* A Master thesis - the Department of Civil and Environmental Engineering Saitama University, Japan.

[2] Lu, N. and Likos, W. J. (2004). *Unsaturated soil mechanics*, J. Wiley Hoboken, NJ.

[3] D. Pérez-Ruiz. 2012. A Refined True Triaxial Apparatus For Testing Unsaturated Soils Under Suction-controlled Stress Paths. *International Journal of Geomechanics.* DOI:10.1061/(ASCE)GM.1943-5622.0000138

[4] Fredlund, D. G., Rahardjo, H. and Fredlund, M. D. (2012). *Unsaturated Soil Mechanics in Engineering Practice*. John Wiley & Sons, Inc.

[5] Fredlund, D. G. (2006). Unsaturated soil mechanics in engineering practice. *Journal of geotechnical environmental engineering* **132**(3): 286-321.

[6] Fredlund, D., Xing, A. and Huang, S. (1994). Predicting the permeability function for unsaturated soils using the soil-water characteristic curve. *Canadian Geotechnical Journal* **31**(4): 533-546.

[7] Fredlund, M., D., Wilson G., W., and Fredlund, D., G., 1997. Indirect procedures to determine unsaturated soil propertyfunctions. *Proceedings of the 50th Canadian Geotechnical Conference*, Ottawa, Ontario, Canada, October 20-22, 1997

[8] Rahardjo, H., Kim, Y., and Satyanaga, A. (2019). Role of unsaturated soil mechanics in geotechnical engineering. *International Journal of Geo-Engineering* **Vol.10**, pp.1-23

[9] Fredlund, D. G. (2015), Use of Unsaturated Soil Mechanics for Environmental Protection and Sustainability, *International Conference on Multiphysical Interactions and Environment Vinh Long*, Vietnam: pp.1-22