



Al-Rafidain Journal of Engineering Sciences

Journal homepage <https://rjes.iq/index.php/rjes>

ISSN 3005-3153 (Online)



Shear Strength Behaviour of Unsaturated Soils: A Review

Baidaa A. Abdullah¹, Yasir Mawla Al-Badran²

^{1,2}Department of civil Engineering, Mustansiriyah University, Baghdad, Iraq.

ARTICLE INFO

Article history:

Received 23 October 2024

Revised 24 October 2024

Accepted 17 November 2024

Available online 17 November 2024

Keywords:

unsaturated soils

shear strength

Triaxial test

Matric suction

SWCC

ABSTRACT

Soil in which the voids contain both water and air is typically referred to as unsaturated soil. In recent times, the attention in both research and practical applications regarding the investigation of shear strength in unsaturated soil has been a growing. For the safe geotechnical design of structures such as embankment slopes, foundations, and retaining walls, precise assessment of the shear strength of soil is essential. The review identifies gaps in the current understanding of unsaturated shear strength behavior, particularly in relation to specific soil types and environmental conditions. It emphasizes the need for more extensive research and the development of more accurate predictive models. The study concludes by outlining potential future directions in the study of unsaturated shear strength behavior, with the aim of enhancing the safety and efficiency of geotechnical structures.

1. Introduction

An unsaturated soil is normally defined in the literature by means of soil where the voids are filled with water and air. Under the definition provided [1], unsaturated soil is characterized by a negative pressure in its pore water.[2] proposed the existence of a fourth stage known as the contractile skin, which is analogous to the water-air contact. The water-air interface can be likened to a flexible membrane that is intricately woven into the empty spaces of the soil, establishing a barrier between liquid phases and the gaseous [3]. The air-water interface is theoretically regarded as a fourth phase due to its influence on volume and shear

strength change. Due to the direct connection between the air-water interface and the air, water, and solid phases, unsaturated soil can be most accurately described as a three-phase assemblage.

In order to ensure the safety of the design of geotechnical structures such embankment slopes, retaining walls, and foundations, it is necessary to conduct an accurate assessment of the shear strength of the soil[4]. Therefore, soil is either entirely saturated or completely dry, according to the conventional theory of soil mechanics. However, large numbers of the issues that are encountered in engineering are caused by unsaturated soil zones. These zones

* Corresponding author E-mail address: baedaa@uomustansiriyah.edu.iq

<https://doi.org/10.61268/sje51356>

This work is an open-access article distributed under a CC BY license (Creative Commons Attribution 4.0 International) under

<https://creativecommons.org/licenses/by-nc-sa/4.0/>



are characterized by the presence of a mixture of air and water that fills the gaps that are normally vacant between the soil particles. When it comes to practical matters, these zones are frequently ignored, and it is assumed that the soil is either completely saturated or completely dry.[5].

2. Overview of the Stress State in Unsaturated Soils

Previous research has been undertaken to determine the effective stress parameter for unsaturated soils. Bishop (1959) introduced a stress equation that demonstrates efficacy in the context of unsaturated soils, and posited its potential utility in the interpretation of shear strength in such soils [6].

Applying a similar theoretical framework as Terzaghi (1943)[7], the present study seeks to analyse the shear strength of saturated soil.

$$\tau = c + [(\sigma_n - u_a) + \chi(u_a - u_w)] \tan \phi \quad (1)$$

The following definitions apply to the variables in this particular equation: τ characterizes the shear strength of unsaturated soil, c characterizes the effective cohesion, ϕ represents the effective internal frictional angle, $(\sigma_n - u_a)$ represents the nett normal stress, $(u_a - u_w)$ represents the matric suction, and χ represents a parameter that depends on the degree of saturation, ranging between 0 and 1. In their study,[8] established a distinct correlation between the parameter χ and the soil's suction and air entry value. Jennings and Burland (1962) argue that Eq. (1) fails to accurately depict the correlation between volume alteration and effective stress in the majority of soils, especially those that are below a crucial level of saturation [9]. Coleman 1962 proposed the utilisation of three stress factors, namely $(\sigma_1 - u_a)$, $(\sigma_3 - u_a)$, and $(u_w - u_a)$,

to accurately represent, pore-water pressures and the axial, confining when analyzing triaxial test data[10]. In 1963, Bishop and Blight reassessed their previously suggested equation for effective stress in unsaturated soils and discovered that altering the matric suction $(u_a - u_w)$ did not provide the same influence on soil behavior as modifying the net normal stress $(\sigma - u_a)$. [11]

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \quad (2)$$

Over the past thirty years, there has been a growing inclination to utilize two distinct stress factors to characterize the behavioral properties of unsaturated soils [11]–[13]

Additional research conducted by [2] shown that the stress state of a four-phase soil can be characterized by any two of the three independent stress variables: $(\sigma - u_a)$, $(\sigma - u_w)$, and $(u_a - u_w)$. The primary independent stress state variables commonly observed are nett stress $(\sigma - u_a)$ and matric suction $(u_a - u_w)$ [14]. This methodology formed the foundation for progress in simulating the constitutive behaviour of unsaturated soil. The application of two distinct stress variables, rather than a singular effective stress variable, has yielded more significant and coherent explanations of unsaturated soil behaviour, which has had a substantial influence. This collection of models possesses a variety of compelling attributes as it consistently clarifies the processes of shear failure and collapse induced by wetness. [15], [16]. It is impractical to consider the influence of saturation level on mechanical behaviour using only these two stress state variables. This phenomenon is a result of hysteresis in the water retention curve that occurs throughout the processes of drying and wetting. Therefore, if one sample of soil is drying and another sample is being wetted, even if they are exposed to the identical suction values, their

saturation levels can differ significantly. The inter-particle forces produced by the water in the meniscus, the water in the bulk, and the air show distinct qualitative variations [17]. Even if two samples have identical net stresses, suction, and void ratio, they can still display different mechanical behavior when subjected

to different levels of saturation. This can result in a change in the inter-particle forces transmitted by the soil skeleton. The practical effectiveness of the technique that employs two distinct stress state variables has been constrained due to several factors, as highlighted by [8], [18]

3. The concept of soil suction

Porous materials possess an inherent capacity to draw and hold water, as a general characteristic. The existence of this crucial attribute in soils is referred to as suction in the engineering literature, which indicates the negative tension generated by pore water [13]. The combination of matric suction and osmotic suction is referred to as total suction. It was primarily within the framework of soil-water plant systems that the notion of suction was developed. Soil suction, which consists of two components: matric suction (s) and osmotic suction (π), plays an important role in the behaviour of unsaturated soils [1], [13], [19] defines total suction ψ as:

$$\Psi = s + \pi \quad (3)$$

Matric suction is a result of the interaction of capillarity, soil texture, and surface adsorptive forces. According to [13],[20], osmotic suction is caused by the presence of dissolved salts in soil water. The capillary effect caused by water surface tension as the controlling factor for matric suction in unsaturated soils. Osmotic suction refers to the disparity in salt concentrations between the pore water within the investigated system and the surrounding water. This phenomenon is quantified in terms of pressure, as described by [21].

4. Soil-Water Characteristic Curve (SWCC)

Soil suction and volumetric water content are related as SWCC and it is crucial in the subject of unsaturated soil mechanics [22]. The term used to describe this is the soil water characteristics curve (SWCC) or soil water retention curve (SWRC) [23]. The Soil-Water Characteristic Curve (SWCC) describes the precise correlation between the moisture content and the suction force in soil. The water content is represented by three variables: gravimetric water content, volumetric water content, and degree of saturation [24, 25] SWCCs play a critical role in defining the characteristics of unsaturated soils and are extensively utilised in engineering applications related to unsaturated soils. This phenomena is associated with both fluid dynamics and the properties of shear strength and compressibility [26,27] The SWCC is conventionally measured using the pressure plate technique and vapour pressure technique in low suction and high suction ranges respectively [13]. The SWCC is divided into three distinct stages of unsaturation, the boundary effect zone, the transition zone, and the residual zone of unsaturation, as shown in Figure. 1.

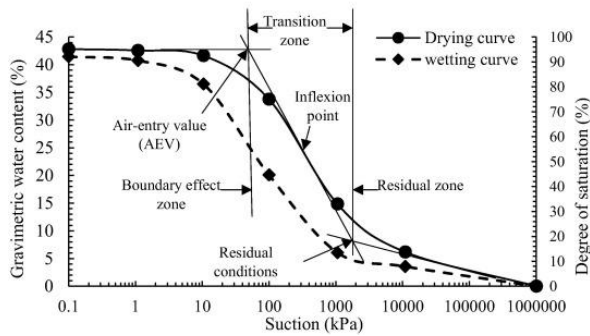


Figure 1. Typical characteristic curve of a soil[28]

SWCC is categorised into two distinct types: drying and wetting. The drying curve is determined by calculating the moisture content of a soil sample during drying, whereas the wetting curve is formed by measuring the moisture content during soaking. Diverse initial conditions for the drying and wetting processes provide distinct curves. These curves are typically referred to as scanning curves. The hysteresis of soil pertains to the phenomena linked to the distinct curves of the drying and wetting processes[29– 31]

5. Previous study

5.1 Previous study on Shear strength of unsaturated coarse grained soil

J. Abdullah conducted a Plane-strain (biaxial) test in 2010 [32], utilizing two materials and a novel double-wall biaxial apparatus. The influence of fine content on soil water characteristic curves was analyzed through the use of combinations of Hostun sand and Spergauer kaolin. The investigation employed mixtures of Spergauer kaolin at concentrations of 5%, 10%, and 30%. Two methodologies, the axis translation technique (ATT) and the vapour equilibrium technique (VET), were utilized to determine the relationship between suction and the degree of saturation of the studied soil. The laboratory program involves the examination of the mechanical properties, specifically

shear strength and volumetric change behavior, of dry, saturated, and unsaturated Hostun sand using the innovative double-wall biaxial apparatus. Every single one of the biaxial investigations required the specimens to be sheared under draining circumstances after they had been consolidated. In order to investigate the impact that the initial void ratio has on behavior, the sand was put through a series of tests under two distinct beginning conditions: a loose specimen with $e_0 = 0.89$ and a dense specimen with $e_0 = 0.66$. We conducted biaxial drained compression experiments on both saturated and unsaturated dense sand ($e_0 = 0.66$). The results of these tests were consistent. There were three different test sets carried out: B10, B50, and B100. For each set, the net confining pressure ($\sigma_3 - u_a$) was maintained at a constant value, while the matric suction ($u_a - u_w$) was changed. This was done in order to evaluate the impact of the matric suction on the shear strength and volumetric change behavior of the vessels that were not saturated as in Figure 2.

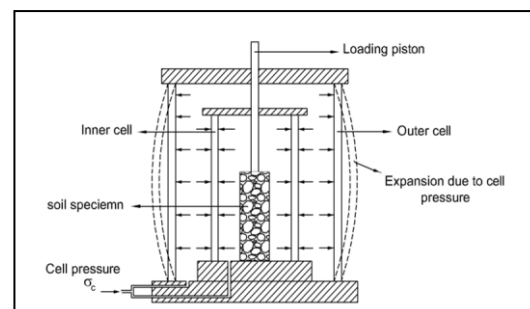


Figure 2. The concept of double-wall cell[32]

The maximum deviator stress, $\Delta\sigma_{\max}$, increases with higher matric suction, as shown in Figure 3. The maximum deviator stress is associated with a matric suction value of 2 kPa. Surpassing this matric suction value leads to a decrease in shear strength until it reaches the minimum shear strength at higher matric suction levels. Biaxial studies on

unsaturated dense Huston sand indicate that shear strength increases with density. Additionally, matric suction in the transition zone ranges from fully saturated to 2 kPa, slightly surpassing the sand's air entry

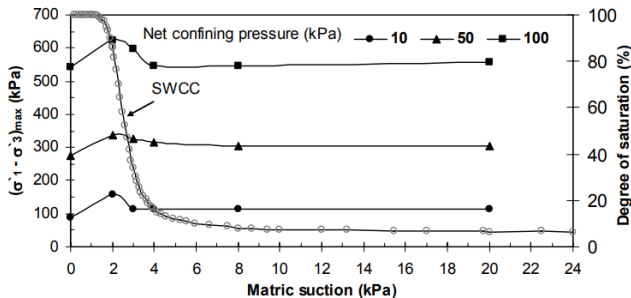


Figure 3.Effect of the matric suction on the maximum deviator stress[32]

H. W. Al Rofa (2011)[33] examined the characteristics of unsaturated soils containing gypsum. Soil samples were collected from four different places: Tikrit city, Alalam, Baiji, and Samara city. These samples had varying gypsum content, ranging from 10% to 65%. Tests were conducted on these samples to estimate the soil water characteristic curve (SWCC) and suction. Through a series of classification tests the soils properties were identified. The testing encompassed physical and chemical analyses, along with engineering assessments such as the direct shear test and compressibility test. The schematic of typical direct shear testing setup used in the study shown in Figure 4. The results indicate a nonlinear relationship between water content and angle of internal friction, ranging from 27 to 35 degrees, with many peaks. Those with water content below 10% exhibit a higher peak than those with water content over 10%. The correlation between matric suction and shear strength is not linear. In general, an increase in matric suction results in a corresponding rise in shear strength.

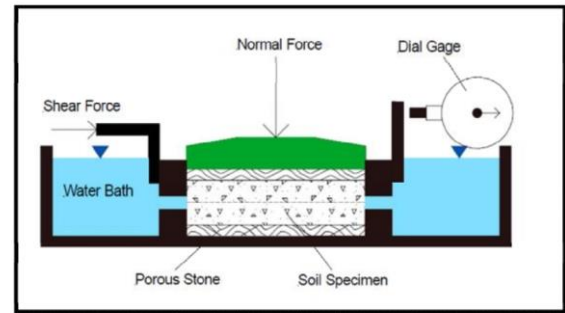


Figure 4. Schematic of typical direct shear testing setup.[33]

(Pujiastuti et al, 2018)[34] A series of laboratory experiments was done to examine the effect of matric suction on the shear strength characteristics of sandy clay. The contact filter paper method was applied to measure matric suction, while the SoilVision knowledge-based system was employed to forecast the comprehensive soil water characteristic curve (SWCC). A series of unconsolidated undrained (UU) triaxial tests were performed to examine the shear strength of the unsaturated sandy clay. Experimental investigations were performed on soil samples under matric suction circumstances ranging from 40 to 600 kPa. The experiment demonstrated a substantial enhancement in the soil's shear strength attributable to inter-particle stress generated by negative pore water pressure. In conditions of considerable matric suction, a consistent relationship between matric suction and shear strength is detected. This phenomenon occurs because the low water content impedes the effective transfer of matric suction to the interface among soil particles. The results demonstrate a clear relationship between the soil's ability to endure shearing stresses and the level of matric suction. Prior observations indicate that when matric suction is below the air entry value (AEV), the shear strength of the soil increases proportionately with the rise in matric suction. The linear relationship arises

from the soil being in a suitably saturated state.

In a study conducted by (I. A. Abd, et al. 2020 [35], the focus was on understanding shear strength characteristics of unsaturated sandy clay soils under changing matric suction levels. The sample was collected from the site of the Technical College of Kirkuk in Kirkuk city, located in northern Iraq. To carry out this study, a customized triaxial test apparatus was utilized. The matric suction ranged from 0 to 100 kPa, incrementing by 10 kPa each time. The study's findings revealed a distinct relationship between shear strength and matric suction, consisting of two distinct phases. The initial phase exhibited a linear relationship, while the subsequent phase was non-linear. The point at which these two phases intersected denoted the reversal stress point, often referred to as the peak stress point. Notably, as matric suction increased, so did the soil's elasticity and all associated stress factors, This results in an increase in the angle of internal friction between the particles of the soil. Additionally, the highest shear stress was recorded at greater matric suction levels when confining pressure was enhanced as shown in Figure 5.

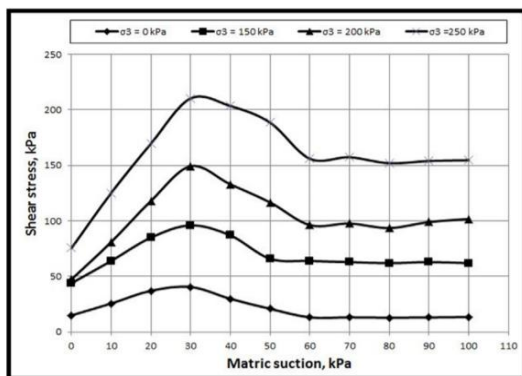


Figure 5 Relationship between shear stress and matric suction under different values of confining pressure.[35]

A. S. Abood et. al. 2023 [36]determined the appropriateness of unsaturated gypseous soil obtained from Tikrit, Salah Al-Dean government as a subgrade layer for carrying fundamentals the testing program included investigation behavior and the geotechnical characteristics of unsaturated gypseous soil and using static triaxial compression (CU-test) to determine the shear strength parameter of the soil. The value of gypsum content determined (44, 70). The samples were generated with 70% relative density of gypseous soil in natural condition. Experimental investigations are carried out on gypseous soil with different levels of saturation (30%, 60%, and 80%), encompassing both unaltered, unsaturated soil and fully saturated soil, to examine the characteristics of the gypseous soil. At all saturation levels, A rise in the moisture content of the gypseous soil leads to a reduction in the angle of internal friction for both the total and effective stresses (γ' and ϕ). On the other hand, it was discovered that the soil's ability to stick together, known as cohesion, representation as the gypseous soil moisture content increased up to saturation (60%). This increase in cohesion resulted in a higher resistance to shearing forces in the soil.

5.2 Previous study on Shear strength of unsaturated fine grained soil

R. Laureano R. Hoyos et al. 2005 [37]created a revolutionary true triaxial equipment as shown in Figure 6 for testing unsaturated soils under multiaxial stress conditions. A novel true triaxial apparatus has been created to evaluate 3-inch cubic specimens of unsaturated soil under controlled suction

conditions throughout a broad spectrum of stress routes unattainable in a typical cylindrical apparatus. The device was created for cubical soil specimens and was able to simulate real-world stress conditions more closely than typical cylinder testing methods. They employed air and water pressure modulation to regulate matric suction and stress. The soils investigated included fine-grained soils, with an emphasis on how suction affected shear strength and deformation. The efficacy of the axis-translation method in the anew designed apparatus was empirically confirmed through two constant-suction (drained) tests on two uniformly arranged samples of silty sand. The tests were conducted at a constant matric suction of 200 kPa and a loading rate of 10 kPa/hr. As a result of the findings, it was concluded that the newly designed equipment is appropriate for the evaluation of soils. using the axis-translation technique under conditions where suction control is present. Future improvements will include the ability to control the temperature of pore fluids, which include both air and water.

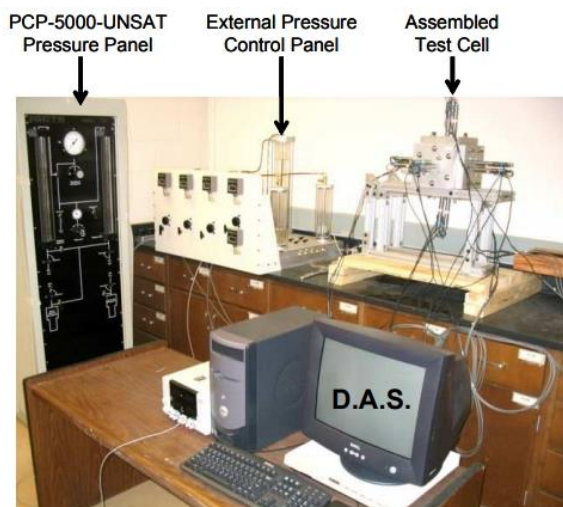


Figure 6. Photograph of entire cubical test setup[37]

T. B. Hamid and G. A. Miller 2009 [38] Direct shear experiments were carried out on fine-grained soil with low plasticity in order to explore the impact that shearing pressures had on the behavior of unsaturated soil surfaces when they were exposed to the pressures. The findings exhibited that the matric suction significantly influences the maximum shear strength of unsaturated surfaces of a material, although the shear strength after reaching the maximum remains reasonably consistent. According to the findings of the study, variations in the net normal stress have an effect on both the maximum and subsequent shear strength. An examination of failure envelopes based on the characteristic curve of the soil and water interaction. Accurately represented the non-linear impact of matric suction on both soil and interface shear strength. According to Hamid and Miller (2009), the shear strength of unsaturated lean clay soil interfaces can be determined by doing direct shear experiments shown in Figure 7 at the interfaces using the linear strength theoretical framework. Their findings revealed that the soil exhibited the highest angle of friction with regard to matric suction. The mentioned phenomena can be elucidated by the disparities in matric suction and soil structure at the interface, together with the modifications in local matric suction during shearing caused by the disturbance of air.

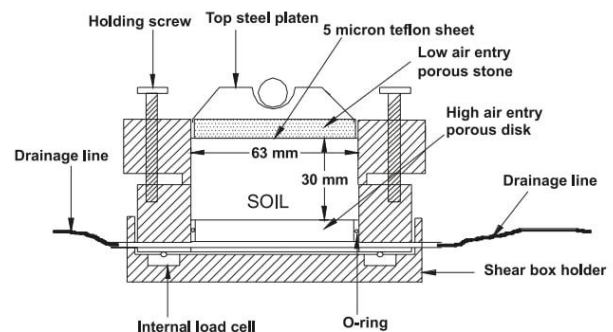


Figure 7. A view of the soil shear box obtained from a cutaway cross-section (raising screws are not displayed).

The study conducted by **Maleki, M., & Bayat, M. (2012)**[5] investigated the mechanical characteristics of silty sand in unsaturated condition while maintaining a constant water content. This paper reported the results of a sequence of triaxial experiments conducted on samples of unsaturated silty sand. An axis translation method was employed to quantify the suction of the soil matrix, while triaxial cell of double-wall was utilized to evaluate the variation in pore air volume. To examine the impact of matric suction, initial density, and net confining pressure on soil behavior, two sets of triaxial tests were conducted. The experiments were carried out under both unsaturated and saturated operating situations. The experimental findings suggest that there exists a non-linear correlation between shear strength and matric suction. The relationship between net confining pressure and shear strength is linear, regardless of whether the circumstances are saturated or unsaturated. The volumetric properties of soil are influenced significantly by the suction of the matric material and the net compression pressure. The water menisci develop along the failure plane. See Figure 8.

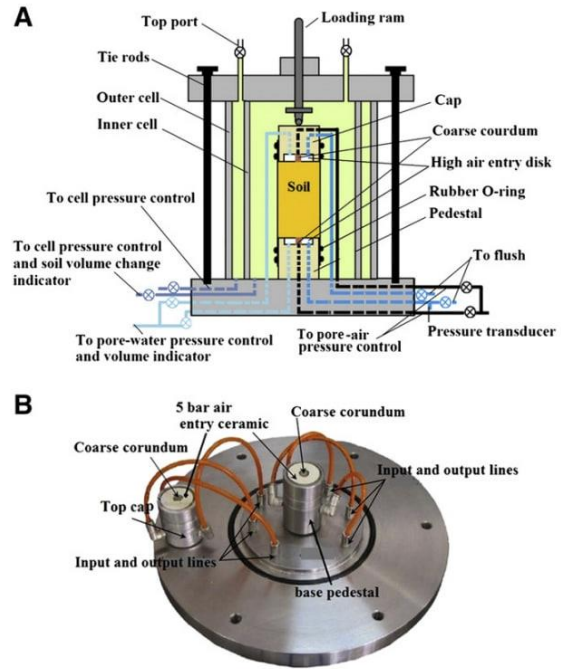


Figure 8.(A) used triaxial cell for testing unsaturated soils; (B) base plate of unsaturated triaxial test apparatus.[5]

The test results indicate a non-linear relationship between shear strength and matric suction as shown in Figure 9.

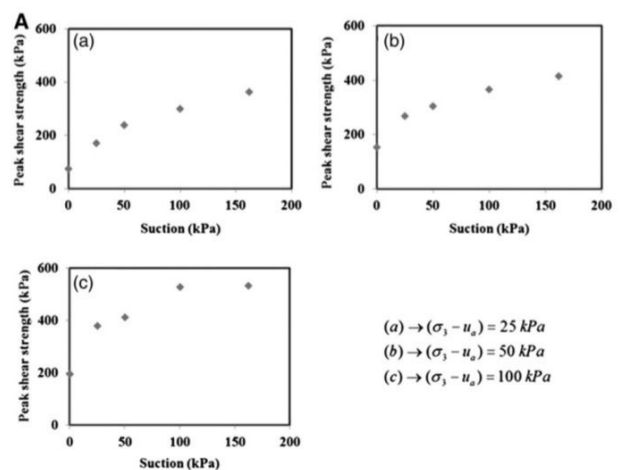


Figure 9. Relationship between initial matric suction and peak shear strength [5]

The study conducted by **Khaboushan et al. (2018)**[39] investigated the relationship between soil properties and unsaturated shear strength metrics, aiming to establish a predictive method for parameters such as effective cohesion (c'), angle of effective

internal friction (ϕ'), and angle of internal friction associated with matric suction (ϕ^b), through multiple-linear regression (MLR). Fine (clay), medium (silt loam, loam, silty clay loam, and clay loam), and coarse (sandy loam) textures were found in the soils that were analyzed. The soils revealed a wide range of particle size distribution, which encompassed a variety of soil textural classifications. The shear strength properties of 14 soils were assessed using direct shear tests done at different combinations of three normal stresses (25, 50, and 100 kPa) and four matric suctions (0, 10, 30, and 50 kPa). A total of 12 tests were conducted for each soil sample. Substantial inverse correlations were detected between c' and ϕ' . The c' demonstrated a robust positive connection with the clay concentration. A significant negative correlation was identified between the variables c' and sand fractions, as well as the geometric mean diameter (d_g). A robust positive correlation was identified between ϕ' and the proportions of sand, along with, d_g . The ϕ' is contrariwise associated with fine silt content and the clay. The ϕ^b showed no significant association with soil parameters, suggesting that ϕ^b is mainly affected by matric suction and not influenced by properties of soil.

(Banerjee et al, 2020)[40] In order to determine the properties of clayey silty soil that had been strongly compacted, a series of suction-controlled multistage triaxial experiments were carried out. Each test was carried out on the same soil sample, with the suction level being maintained at a constant level while the net confining pressures were adjusted. All of the tests were carried out under drained circumstances. In order to determine the endpoint of the shearing phase, either the stiffness or the volume change in the monotonically sheared specimen was

selected. This decision was made based on which of these two factors is more likely to prevent the specimen from failing prematurely. During the course of this research, the influence of errors resulting from multistage triaxial testing on the predictions of shear strength in unsaturated soil was investigated. With the use of a well-known equation, the approach involved the production of a three-dimensional failure envelope in p - s - τ space. This was then followed by a comparison with the findings obtained from single-stage triaxial testing. Furthermore, it was noted that the utilization of multistage testing in order to determine the shear strength properties of soil resulted in a reduction of the testing period to fifty percent of what was required for single-stage triaxial testing. Unsaturated soil testing is becoming increasingly appealing to experts as a result of the reduction in testing durations, which in turn leads to a large decrease in testing prices.

A. E.-H. Refai Kassab et. al (2021) [41] performed a series of direct shear tests on a box to examine the shear strength of unsaturated clay, specifically the clay found in the Middle Delta Nile region of Egypt. Various water content (WC) levels were used to test the samples. Matric suction was tested at different water content levels using the filter paper technique. The experiments on the behavior of unsaturated shear strength appear to demonstrate a relationship as non-linear with matric suction. Two linear segments approximate the failure envelope of Mohr-Coulomb for data points located between the unsaturated matric suction and shear strength. The point of inflection for the two linear segments occurred about at the matric suction value corresponding to the plastic limit. The study shown that the rate of growth of unsaturated clay shear strength (ϕ^b_1) varies with an

average rate of 2.630 within zone (I), which begins at the water content of the clay equal to the liquid limit and extends to the plastic limit state of the clay. In zone II, the unsaturated clay shear strength increases at an average rate (ϕ^b_2) of 0.280, which is lower than the rate of change in zone I. Zone II starts at the water content of clay equal to the plastic limit state and continues until the shrinkage limit state.

6. Conclusion

Based on a previous studies on testing shear strength of soil, the following conclusions are presented:

1. Using conventional triaxial , modified triaxial and direct shear, apparatuses is effective to estimate unsaturated soil 's shear strength.
2. There is a clear difference in the behavior of unsaturated and saturated soils. Water content and matric suction are two important key variables that greatly affect shear strength.
3. Research has revealed that increasing matric suction, which is caused by soil-air-water tension forces, increases shear strength instantaneously.
4. A nonlinear correlation exists between suction and the soil shear strength.
5. For sandy soils in unsaturated conditions, the suction in sand is relatively low because of its larger pore spaces, which allow water to move more freely. This results in less capillary action and lower matric suction.
6. Clay exhibits lower shear strength compared to sand and higher suction in unsaturated conditions due to its fine particles and small pore spaces. This leads to significant capillary action and higher matric suction, This can augment the shear strength to a specific threshold.

References

[1] D. G. Fredlund and H. Rahardjo, "An overview of unsaturated soil behaviour," *Geotech. Spec. Publ.*, p.

- 1, 1993.
- [2] D. G. Fredlund and N. R. Morgenstern, "Stress state variables for unsaturated soils," *J. Geotech. Eng. Div.*, vol. 103, no. 5, pp. 447–466, 1977.
- [3] D. G. Fredlund, H. Rahardjo, and M. D. Fredlund, *Unsaturated Soil Mechanics in Engineering Practice*. 2012. doi: 10.1002/9781118280492.
- [4] W. Ahmad, U. Taro, and M. Umar, "Comparison of the shear strength of unsaturated sandy soils at optimal and residual moisture contents," *GEOMATE J.*, vol. 24, no. 101, pp. 43–51, 2023.
- [5] M. Maleki and M. Bayat, "Experimental evaluation of mechanical behavior of unsaturated silty sand under constant water content condition," *Eng. Geol.*, vol. 141, pp. 45–56, 2012.
- [6] A. W. Bishop, "The principal of effective stress," *Tek. Ukebl.*, vol. 39, pp. 859–863, 1959.
- [7] K. Terzaghi, *Theoretical soil mechanics*. 1943.
- [8] N. Khalili and M. H. Khabbaz, "A unique relationship for χ for the determination of the shear strength of unsaturated soils," *Geotechnique*, vol. 48, no. 5, pp. 681–687, 1998.
- [9] J. E. B. Jennings and J. B. Burland, "Limitations to the use of effective stresses in partly saturated soils," *Géotechnique*, vol. 12, no. 2, pp. 125–144, 1962.
- [10] J. D. Coleman, "Stress strain relations for partly saturated soil," *Coresp. to Geotech.*, vol. 12, no. 4, pp. 348–350, 1962.
- [11] A. W. Bishop and G. E. Blight, "Some aspects of effective stress in saturated and partly saturated soils," *Geotechnique*, vol. 13, no. 3, pp. 177–197, 1963.
- [12] J. B. Burland, "Some aspects of the mechanical behaviour of party saturated soils," *Moisture equilibria moisture Chang. soils beneath Cover. areas*, pp. 270–278, 1965.
- [13] D. G. Fredlund and H. Rahardjo, *Soil mechanics for unsaturated soils*. John Wiley & Sons, 1993.
- [14] S. J. Wheeler and D. Karube, "Constitutive modelling," 1996.
- [15] E. E. Alonso, A. Gens, and A. Josa, "A constitutive model for partially saturated soils," *Géotechnique*, vol. 40, no. 3, pp. 405–430, 1990.
- [16] D. Gallipoli, A. Gens, R. Sharma, and J. Vaunat, "An elasto-plastic model for unsaturated soil incorporating the effects of suction and degree of saturation on mechanical behaviour," *Géotechnique*, vol. 53, no. 1, pp. 123–135, 2003.
- [17] S. J. Wheeler, R. S. Sharma, and M. S. R. Buisson, "Coupling of hydraulic hysteresis and stress-strain behaviour in unsaturated soils," *Géotechnique*, vol. 53, no. 1, pp. 41–54, 2003.

- [18] M. Nuth and L. Laloui, "Advances in modelling hysteretic water retention curve in deformable soils," *Comput. Geotech.*, vol. 35, no. 6, pp. 835–844, 2008.
- [19] G. D. Aitchison, "Soil properties, shear strength and consolidation," *Proc. Sixth Int. Conf. Soil Mech. Found. Eng.*, pp. 318–321, 1965, [Online]. Available: https://www.issmge.org/uploads/publications/1/40/1961_01_0004.pdf
- [20] E.-C. Leong and H. Abuel-Naga, "Contribution of osmotic suction to shear strength of unsaturated high plasticity silty soil," *Geomech. Energy Environ.*, vol. 15, pp. 65–73, 2018.
- [21] D. G. Fredlund and H. Rahardjo, "Chapter 4, Measurement of Soil Suction, Soil Mechanics for Un-saturated Soils, A Wiley-Interscience Publication." JOHN WILEY & SONS, INC, 1993.
- [22] C. P. K. Gallage and T. Uchimura, "Effects of dry density and grain size distribution on soil-water characteristic curves of sandy soils," *Soils Found.*, vol. 50, no. 1, pp. 161–172, 2010.
- [23] B. Shwan, "Experimental and numerical study of the shear strength of unsaturated sand." University of Sheffield, 2015.
- [24] J. Williams, R. E. Prebble, W. T. Williams, and C. T. Hignett, "The influence of texture, structure and clay mineralogy on the soil moisture characteristic," *Soil Res.*, vol. 21, no. 1, pp. 15–32, 1983.
- [25] X. Ren, J. Kang, J. Ren, X. Chen, and M. Zhang, "A method for estimating soil water characteristic curve with limited experimental data," *Geoderma*, vol. 360, p. 114013, 2020.
- [26] Y.-S. Song, "Suction stress in unsaturated sand at different relative densities," *Eng. Geol.*, vol. 176, pp. 1–10, 2014.
- [27] P. D. G. Orlando and F. A. M. Marinho, "Influence of matric suction on the shear strength of a cohesive soil-geosynthetic strap interface," in *PanAm Unsaturated Soils 2017*, 2018, pp. 320–329.
- [28] J. Musso and G. Suazo, "Determinación de la curva de retención de agua para relaves multimetálicos de la industria minera de Chile," *Obras y Proy.*, no. 25, pp. 22–29, 2019.
- [29] H. Q. Pham, D. G. Fredlund, and S. L. Barbour, "A study of hysteresis models for soil-water characteristic curves," *Can. Geotech. J.*, vol. 42, no. 6, pp. 1548–1568, 2005.
- [30] A. Tarantino, "A water retention model for deformable soils," *Géotechnique*, vol. 59, no. 9, pp. 751–762, 2009.
- [31] D. Gallipoli, A. W. Bruno, F. D'onza, and C. Mancuso, "A bounding surface hysteretic water retention model for deformable soils," *Géotechnique*, vol. 65, no. 10, pp. 793–804, 2015.
- [32] J. Alabdullah, "Testing unsaturated soil for plane strain conditions: a new double-wall biaxial device," 2010.
- [33] H. W. Al Rofa, "STUDY OF STRENGTH PARAMETERS OF UNSATURATED GYPSEOUS SOILS." Ministry of Higher Education, 2011.
- [34] H. Pujiastuti, A. Rifa, A. D. Adi, and T. F. Fathani, "The effect of matric suction on the shear strength of unsaturated sandy clay," *GEOMATE J.*, vol. 14, no. 42, pp. 112–119, 2018.
- [35] I. A. Abd, M. Y. Fattah, and H. Mekkiyah, "Relationship between the matric suction and the shear strength in unsaturated soil," *Case Stud. Constr. Mater.*, vol. 13, p. e00441, 2020.
- [36] A. S. Abood, M. Y. Fattah, and A. S. Al-Adili, "Studying characteristics and strength of the unsaturated gypseous soil with various saturation degrees," *Eng Technol J*, vol. 41, no. 11, pp. 1309–1324, 2023.
- [37] L. R. Hoyos, A. Laikram, and A. J. Puppala, "A novel true triaxial apparatus for testing unsaturated soils under suction-controlled multi-axial stress states," *Proc. 16th Int. Conf. Soil Mech. Geotech. Eng. Geotechnol. Harmon. with Glob. Environ.*, vol. 2, pp. 387–390, 2005, doi: 10.3233/978-1-61499-656-9-387.
- [38] T. B. Hamid and G. A. Miller, "Shear strength of unsaturated soil interfaces," *Can. Geotech. J.*, vol. 46, no. 5, pp. 595–606, 2009.
- [39] E. A. Khaboushan, H. Emami, M. R. Mosaddeghi, and A. R. Astaraci, "Estimation of unsaturated shear strength parameters using easily-available soil properties," *Soil Tillage Res.*, vol. 184, pp. 118–127, 2018.
- [40] A. Banerjee, A. J. Puppala, and L. R. Hoyos, "Suction-controlled multistage triaxial testing on clayey silty soil," *Eng. Geol.*, vol. 265, p. 105409, 2020.
- [41] A. E.-H. Refai Kassab, A. H. Moubark, W. H. Elkamash, and K. M. Hafez Ismail, "Shear Strength of Unsaturated Soils with Different Plasticity," *J. Univ. Shanghai Sci. Technol.*, vol. 23, no. 11, pp. 197–217, 2021, doi: 10.51201/jusst/21/11887.