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Shear Strength Behaviour of Unsaturated Soils: A Review

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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 the 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 characterised by a negative pressure in its pore water. The existence of a fourth stage known as the contractile skin, which is analogous to the water-air contact [2]. 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 the gaseous and liquid phases [3]. The air-water interface is theoretically regarded as a fourth phase due to its influence on shear strength and volume 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.

For the safe geotechnical structures design such as embankment slopes, retaining walls and foundations, , precise assessment of the shear strength of soil is essential[4]. The conventional theory of soil mechanics models soil as either completely saturated or dry. Nevertheless, a significant proportion of engineering challenges arise from the existence of unsaturated soil zones within which the empty spaces between the soil particles are occupied by a combination of air and water. Practically, these zones are often disregarded

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and the soil is presumed to be either fully soaked or entirely 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.

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

In this context, The variables in the equation are defined as follows: τ represents the shear strength of unsaturated soil, c represents 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 analysing 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 behaviour as modifying the nett 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 utilise two distinct stress factors to characterise the behavioural 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 nett stresses, suction, and void ratio, they can still display

different mechanical behaviour 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].Total suction is the sum of both matric and osmotic suction. The concept of suction evolved predominantly within the context of soil-water plant systems. 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)

The relationship between soil suction and volumetric water content termed to 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 the soil. The water content is represented by three variables: gravimetric water content, volumetric water content, and degree of saturation [24, 25] SWCCs play a crucial role in determining 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.

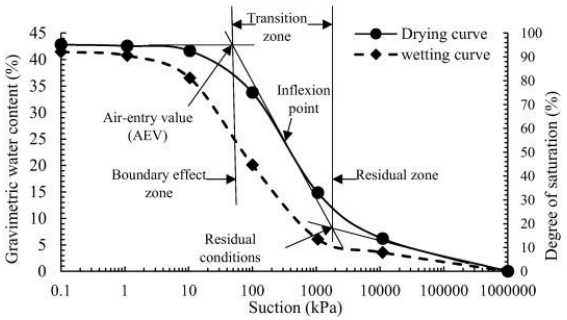

Figure 1. Typical characteristic curve of a soil[28]

SWCC is categorized into two distinct types: drying and wetting. The drying curve is determined by measuring 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 wetting and drying 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] ,this investigation utilized two materials using novel double-wall biaxial apparatus figure 2. The impact of fine content on soil water characteristic curves was examined using combinations of Hostun sand and Spergauer kaolin. Mixtures utilised in the investigation include Spergauer kaolin at concentrations of 5%, 10%, and 30%. Two methodologies, namely the axis translation technique (ATT) and the vapour equilibrium technique (VET), were employed to ascertain the relationship between the degree of saturation and suction of the examined soil. The laboratory programme entails examining the mechanical properties (shear strength and volumetric change behavior) of dry, saturated, and unsaturated Hostun sand utilising the novel double-wall biaxial apparatus. In all biaxial experiments, the specimens were sheared under drained conditions following consolidation. The impact of the initial void ratio on behaviour was examined by testing the sand under two distinct initial conditions (loose specimen e_0 = 0.89 and dense specimen e_0 = 0.66). Biaxial drained compression measurements conducted on both saturated and unsaturated dense sand (e_0 = 0.66). Three test sets were conducted: B10, B50, and B100. In each set, the net confining pressure (σ_3-u_a) was maintained constant while the matric suction (u_a-u_w) was varied to examine its influence on the shear strength and volumetric change behaviour of the unsaturated specimens.

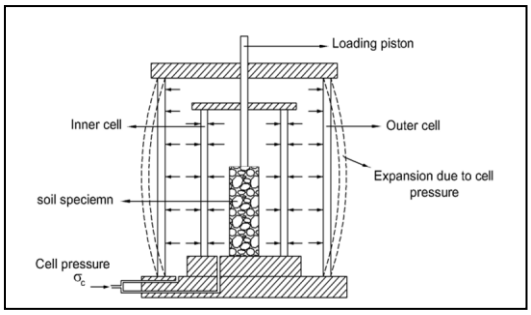

Figure 2. The concept of double-wall cell[32]

The maximum deviator stress, $\Delta\sigma_{max}$, rises with an increase in matric suction, as illustrated in Figure 3. The highest deviator stress corresponds to a matric suction value of 2 kPa. Exceeding this matric suction value results in a decline in shear strength until it attains the minimum shear strength at elevated matric suction levels. Biaxial studies on unsaturated dense Huston sand demonstrate an increase in shear strength with rising density, while matric suction in the transition zone varies from fully saturated to 2 kPa, marginally exceeding the sand's air entry value (AEV = 1.7 kPa). Shear strength decreases when matric suction beyond a specific level. The minimum shear strength corresponds to the fully saturated specimen.

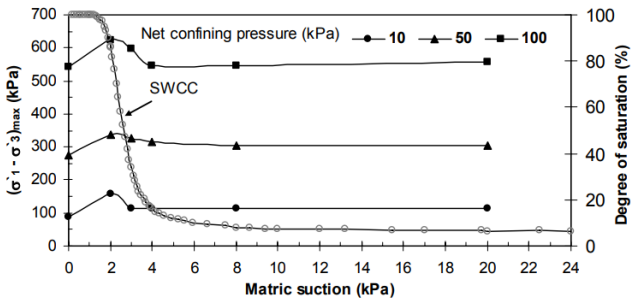

Figure 3.Effect of the matric suction on the maximum deviator stress[32]

H. W. Al Rofa (2011)[33] examined the characteristics of unsaturated soils containing gypsum. Soil samples were collected from four locations: 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

determine the soil water characteristic curve (SWCC) and suction. The properties of these soils were identified through a series of classification tests. 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 Figure4. 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.

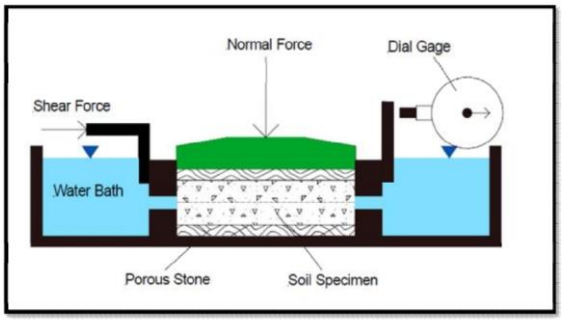

Figure 4. Schematic of typical direct shear testing setup.[33]

(Pujiastuti et al, 2018)[34] A series of laboratory experiments was done to examine the influence 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 shear strength and matric suction is observed. 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 determining the shear strength characteristics of unsaturated sandy clay soils under different matric suction levels. The sample was taken from the Technical College of Kirkuk, which is located in Kirkuk, northern Iraq. A unique triaxial test apparatus was used to conduct this investigation. The matric suction varied from 0 to 100 kPa, with 10 kPa increments between each. The study's findings indicated a specific link between shear strength and matric suction, which is divided into two stages. The first phase showed a linear connection, but the second phase was non-linear. The reversal stress point, also known as the peak stress point, is where the two phases overlap. Notably, as matric suction increased, so did the soil's elasticity and its related stress components, resulting in a rise in the internal friction angle among soil particles. Furthermore, the maximum shear stress was seen at greater matric suction levels when confining pressure was increased, as illustrated in Figure 5.

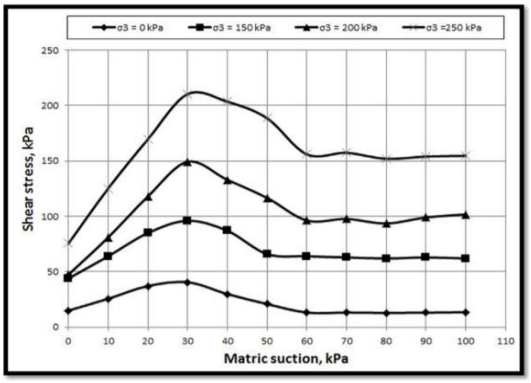

Figure. 5 Relationship between matric suction and shear stress under different values of confining pressure.[35]

A. S. Abood et. al. 2023 [36]determined the appropriateness of unsaturated gypseous soil soil obtained from Tikrit, Salah Al-Dean government as a subgrade layer for carrying foundations the testing program included investigation the geotechnical characteristics and behavior 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 a relative density of 70% using the natural gypseous soil. Experimental investigations are carried out on gypseous soil with different levels of saturation (30%, 60%, and 80%), encompassing both unaltered, unsaturated soil and completely saturated soil, to examine the characteristics of the gypseous soil.At all saturation levels, An increase 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, rose as the moisture content of the gypseous soil increased up to saturation (60%). This increase in cohesion resulted in a higher resistance to shearing forces in the soil.

4.2 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 newly designed apparatus was empirically confirmed through two constant-suction (drained) tests on two uniformly prepared specimens of silty sand. The tests were conducted at a constant matric suction of 200 kPa and a loading rate of 10 kPa/hr. The findings indicated that the newly devised equipment is appropriate for evaluating soils under suction-controlled circumstances utilising the axis-translation method. Upcoming enhancements will involve regulating the temperature of pore fluids (air and water).

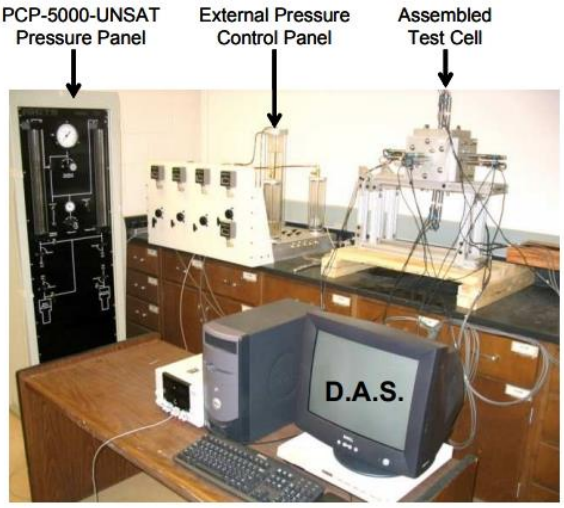

Figure 6. Photograph of entire cubical test setup[37]

T. B. Hamid and G. A. Miller 2009 [38] conducted direct shear tests on low-plasticity fine-grained soil to examine the behaviour of unsaturated soil surfaces when subjected to shearing forces. The findings showed that the matric suction greatly influences the maximum shear strength of unsaturated surfaces of a material, although the shear strength after reaching the maximum remains reasonably consistent. The study additionally discovered that fluctuations in nett normal stress impact both the maximum and subsequent shear strength. An analysis of failure envelopes based on the soil-water characteristic curve.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 as 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.

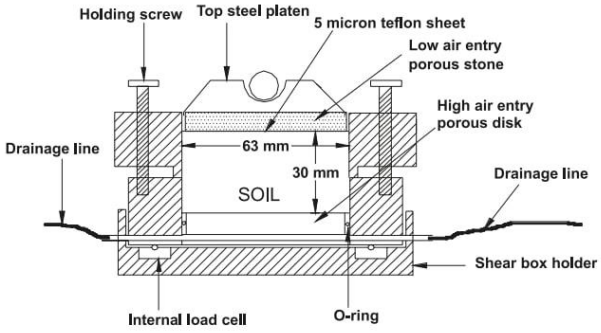

Figure 7.Cutaway cross-section view of the soil shear box (raising screws not shown)

The study conducted by **Maleki, M., & Bayat, M. (2012)**[5] investigated the mechanical characteristics of unsaturated silty sand 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 a double-walled triaxial cell was utilised to evaluate the variation in pore air volume. To examine the impact of initial density, matric suction, and nett confining pressure on soil behaviour, two sets of triaxial tests were conducted. The experiments were carried out under both saturated and unsaturated operating conditions. The experimental findings suggest that there exists a non-linear correlation between shear strength and matric suction. The relationship between shear strength and nett confining pressure is linear, regardless of whether the circumstances are saturated or unsaturated. The volumetric properties of soil are significantly influenced by the suction of the matric material and the net compression pressure. The water menisci develop along the failure plane.

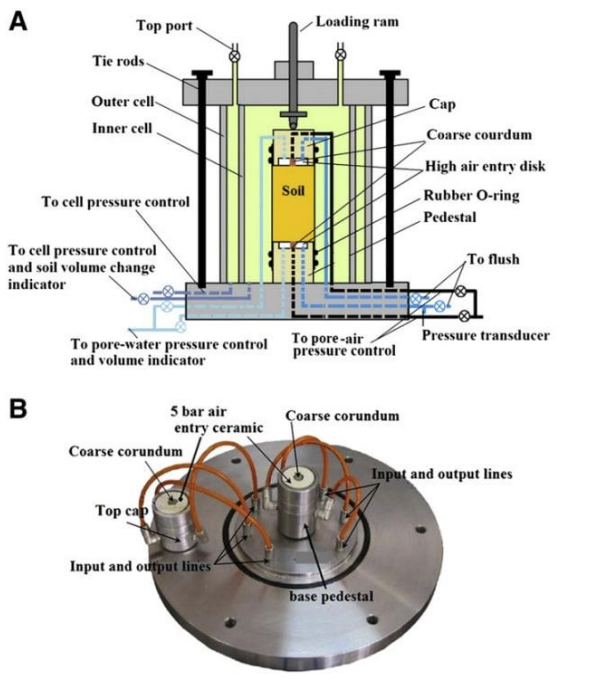

Figure 8.(A) used triaxial cell for testing unsaturated soils; (B) base plate of unsaturated triaxial test apparatus.[5]

The test results indicate a non-liner relationship between shear strength and matric suction as shown in Figure 8.

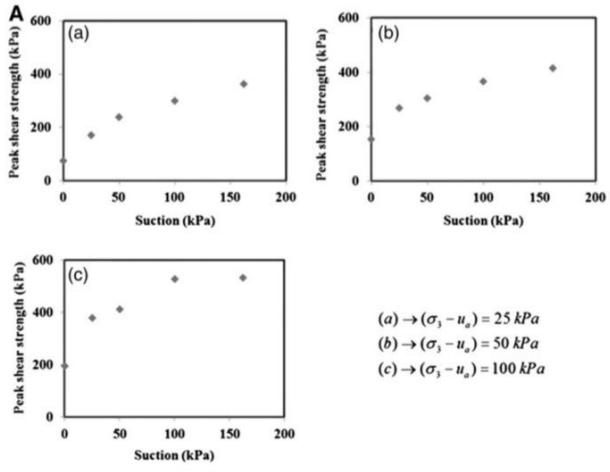

Figure 9. Relationship between peak shear strength and initial matric suction [5]

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). The analysed soils exhibited a broad spectrum of particle size distribution, encompassing diverse soil textural classes: fine (clay), medium (silt loam, loam, silty clay loam, and clay loam), and coarse (sandy loam) textures. The shear strength parameters of 14 soils were evaluated using direct shear tests done at varied 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 substantial inverse relationship was found between the variables c', sand fractions, and geometric mean dimension (dg). A strong positive association was found between ϕ' and sand proportions, including dg. In contrast, ϕ' is related with clay and fine silt concentration. The ϕ^b showed no significant association with soil parameters, suggesting that ϕ^b is not influenced by soil properties and is primarily affected by matric suction.

(Banerjee et al, 2020)[40] conducted a series of suction-controlled multistage triaxial tests on tightly compacted samples of clayey silty soil. Each test was performed on the same soil sample, keeping a consistent suction level while adjusting the nett confining pressures, all under drained conditions. The endpoint of the shearing phase was established by choosing either the stiffness or the volume change in the monotonically sheared specimen, based on which factor mitigates premature failure of the specimen. This study assessed the impact of inaccuracies from multistage triaxial testing on predictions of shear strength in unsaturated soil. The procedure entailed the creation of a

three-dimensional failure envelope in p-s-τ space utilising a recognised equation, followed by a comparison with results obtained from single-stage triaxial tests. Furthermore, it was observed that employing multistage testing to evaluate the shear strength properties of soil reduced the testing duration to fifty percent of that needed for single-stage triaxial testing. The reduction in testing durations leads to a significant decrease in testing expenses, hence enhancing the attractiveness of unsaturated soil testing for professionals.

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 tests on the behaviour of unsaturated shear strength seem to exhibit a non-linear relationship with matric suction. The Mohr-Coulomb failure envelope for data points lying between the unsaturated shear strength and matric suction is approximated by two linear segments. 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 shear strength of unsaturated clay ($\phi b1$) 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 shear strength of unsaturated clay increases at an average rate ($\phi b2$) of 0.28o, 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.

5. Conclusion

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

1. Using direct shear, conventional and modified triaxial apparatuses is effective to evaluate shear strength of unsaturated soils.

2. There is a clear difference in the behaviour of saturated and unsaturated soils. Matrix suction and water content are two important key variables that greatly affect shear strength.

3. Research has shown that the shear strength can be immediately increased by increasing the matric suction, which is a result of the tension forces generated by the soil's air-water interaction.

4. A nonlinear relationship exists between suction and the shear strength of a soil. Suction values that are low

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 soils exhibit lower shear strength compared to sand higher suction in unsaturated conditions due to its fine particles and small pore spaces. This leads to significant capillary action and higher matric suction, which can enhance the shear strength up to a certain point.

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