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Unsaturated Soil Behavior: Soil Water Characteristic Curve (SWCC) Review Study

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ABSTRACT

The basic correlation that determines the mechanical and hydraulic characteristics of unsaturated soils is the Soil Water Characteristic Curve (SWCC). Critical synthesis the present review brings forth the latest developments in SWCC modeling, measurement and application, with a more specific interest in determining the factors that question the financial forecasting properties of current simple models, especially with dynamic environmental circumstances. In our analysis, we have found that current empirical models are frequently ineffective because they lack the explicit ability to integrate the complex/coupled nature of microstructural properties (e.g., fractal geometry and nano-porosity) and compositional differences (e.g., organic matter). More so, the synthesis shows that there is a fundamental conflict in modeling, whereas the more intricate a conventional empirical model gets, the less accurate it becomes, whereas sophisticated data-driven methods such as Deep Learning are much more effective at making predictions. As a consequence, this review confirms that one of the main future research needs should be the creation of coherent constitutive models that will combine mechanistic controls (fractal theory) and advanced AI prediction. Most importantly, the implications in practice reveal that the neglect of such coupled considerations directly compromises the validity of long-term geotechnical performance forecasts, that is, in relation to slope stability and foundation resilience to moisture changes caused by climate change. The review gives the conclusion by recommending that laboratory results should be immediately validated at a field scale to bring together the gap between theory and engineering design.

1. Introduction

Unsaturated soil is a soil that contains more than two physical phases, where water, air, are present in the pores between solids. In this soil, some of the pores are filled with air while others contain water. It differs from saturated soil, in which all pores are filled with water. Unsaturated soil is typically found

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below the ground surface in the upper layers where water does not completely fill the pores, resulting in negative pore water pressure (Ramirez, 2013). Unsaturated soils are found primarily in arid or semi-arid regions, where evaporation rates are higher than precipitation. In these areas, unsaturated soils develop due to a lack of moisture in the ground. Areas where unsaturated soils are found include; deserts, dry plains, and some mountainous regions with harsh climates, they may also occur in areas where the environment has been modified such as; construction sites or agricultural areas subject to artificial drainage [1].

The formation of this type of soils is controlled by several environmental and natural factors. The level of groundwater in arid areas or even arid lands that have a long time of drought becomes low and the pores are occupied with air. The evaporation and aeration of the soil occur through natural procedures which lead to water and air exchange within the pores hence, unsaturated soil. The moisture balance in the soil can be shifted to unsaturated soils as a result of the human activities like; excavation, compaction and rearrangement [2]. Such soils are quite essential in geotechnical engineering since their properties influences the stability of buildings, drainage of groundwater and the capability of the soil to sustain numerous loads. As an example, in regions that are facing soil shrinkage and swellings as a result of variation of moisture, these can result in cracking of roads and other buildings along the course and this could demand serious engineering mechanisms to curb the impact of the same phenomenon.

The difficulties of unsaturated soil behavior are due to the extreme non-linearity, as well as, spatial variability of the matric suction relationship, which is summarized by the Soil Water Characteristic Curve (SWCC). This connection determines the influencing power of water content on the most important geotechnical characteristics such as shear strength, volume change, and permeability. This means that proper forecasting of the SWCC is critical to the engineering practice, especially to ones which are vulnerable to environmental forces. Nevertheless, there are still difficulties with moving laboratory measurements into large-scale design parameters that can be trusted. Moreover, the consistent modeling of these effects especially with dynamic loads such as earthquakes, traffic, and intense rainfall depends more and more on the technique of numerical modeling (Finite Element or Finite Difference methods) in order to follow the flow of fluids and stress variations accurately, thus enhancing the design and resistance of long-term engineering structures. The existing simple empirical modeling may fail to be accurate when used in these complex, real-world loading conditions which drives the development of the more sophisticated synthesis-based modelling [3,4].

Further, their water holding capacity and hydraulic conductivity determine the behavior of unsaturated soils. In such soils, the movement of water by drainage is not that of the saturated soils because, the air in the pores suppresses the movement of water. On top of that they could be subjected to earthquakes in which they could lose certain mechanical properties as an abrupt decrease in suction pressure in the pores, which could result in a subsidence of the soil or an escalation of the cracks on the surface. It may make buildings and roads unstable especially where there is high seismic activity. Traffic can also vibrate and hence result in changes in distribution of water in soil due to changes in its characteristics in the long run.

On the other hand, climate change and increased droughts in many regions increase the prevalence of unsaturated soils, impacting water resources and infrastructure. Studies indicate that rising temperatures and increased evaporation rates can lead to permanent changes in soil moisture balance, impacting the sustainability of agricultural land and groundwater distribution. To effectively manage unsaturated soils, advanced engineering techniques are required, such as; improved drainage techniques to prevent water accumulation, the use of stabilizing materials like lime and cement to enhance their stability, and the development of sustainable irrigation systems tailored to their water-holding capacity. Modern numerical modeling has also become an effective tool for studying the behavior of these soils under various environmental and hydraulic conditions, helping to improve the design of engineering structures and infrastructure.

1.1 Unsaturated Soil Properties

Unsaturated soil has several unique properties, regarding the porous structure, unsaturated soil contains a mixture of water and air in the pores. Air constitutes the major phase in the pores, being present between soil particles, while water occupies a portion of the pores at low (negative) pressure. The size of the pore and water to air ratio in the pores are dynamic and rely on moisture content of soil. Unsaturated soil has very varied porosity which depends on the soil type and can include a sandy soil, clayey soil or a mixture of them [3]. Even though, negative pressure (negative hydraulic pressure of the water filling the pores) is discussed as one of the most salient features of the unsaturated soil. Here, the water pressure will be lower than the air pressure that is present in the pores, so, water becomes trapped in the soil under negative pressure, and it, too, is subjective of the moisture level and the water air status of the soil. This negative pressure may lead to expending or contracting the soil under the impact of changes in the environment, which is moisture and temperature [4,5] Also, soils with low percentages of saturation (unsaturated soils) undergo the process of Volume changes (shrinkage and swelling) when subjected to changes in moisture. When unsaturated soils are wet, they can swell i.e. they can expand making the pores capture the water molecules. This is mainly intense in clayed soils having minor porosities. They Affect or Adversely Impact the ShfE soils on the other hand when soils lose water due to drying out, they may shrink resulting to a reduction in the volume of soil and in some cases the soil may crack particularly in the surface sandy or clayey soils. Change in volume is one of fundamental problems in the design of foundations and roads [4]. The mechanical properties possessed by unsaturated soil differ with the saturated soil. When moisture level changes, it is more prone to volume change, which is shrinkage and swelling. When the dry soil is wetted, water may enter the pores so that the soil particles can expand and compact [2].ccur due to water absorption into the pores [2].

Lastly, unsaturated soil has low Hydraulic conductivity also known as permeability compared to saturated soils because air does not allow passage of water in the soil pores easily. However, permeability can increase in unsaturated soils when they contain a higher water content or when the pores are larger, such as in sandy soils. This property plays an important role in the infiltration and retention of water in the soil, significantly affecting the behavior of the soil under drying or wetting conditions [6].

1.2 Unsaturated Soils Behavior

The behavior of unsaturated soils differs significantly from that of saturated soils due to the presence of more than one phase (water and air) in the pores. This behavior is affected by various factors include; moisture content, changes in pressure, and temperature. Unsaturated soils exhibit a characteristic volumetric behavior, undergoing volume changes due to moisture fluctuations where shrinkage occurs when the soil loses water, while swelling occurs when the soil absorbs moisture. The magnitude of the change is determined by the soil type (sandy, clayey, or a combination of both) [7,8].

Accordingly, when moisture content decreases, soil particles begin to shrink due to water loss from the pores, in clay soils in particular, water loss leads to cracks, affecting soil stability and increasing engineering risks such as; collapse or cracking in foundations. Sandy soils may also exhibit shrinkage, but to a lesser extent than clay soils. While, when moisture content increases, soil particles begin to absorb water, causing the soil to expand in volume, this phenomenon is more pronounced in clay soils, which contain fine particles and a high surface area. Swelling leads to significant changes in soil volume that can affect the stability of foundations and engineering structures. [9].

For the case of unsaturated soils, water in the pores is under negative pressure, which is less than atmospheric pressure, which creates a pressure difference between the water in the pores and the surrounding air. This negative pressure can cause the soil to expand as water is absorbed, increasing shrinkage or swelling. In sandy soils, the effect may be less pronounced, but in clayey soils, which are characterized by narrow pores, this behavior becomes more pronounced [7].

Moreover, seepage property in unsaturated soil occurs when water mixes with air in the pores. However, due to the presence of air, the hydraulic conductivity is lower than that in saturated soil. Water movement in unsaturated soil is affected by many factors like moisture content and pore size, and soil type. As water passes through the soil, this can lead to water retention in some areas, altering its mechanical and hydraulic behavior. For sandy soils, water may pass easily between pores because the pore size is larger, while, in clayey soils, water encounters greater resistance due to the small pores that contain negative pressure ([10].

On the other hand, unsaturated soil behavior underloading can be significantly affected by the changes in moisture content. When a load is placed on unsaturated soil, it can change in volume due to the changes in moisture content resulting in altering its mechanical properties. Due to the large pores in sandy soils, their behavior under loading is less susceptible to volumetric changes, but significant effects may occur when water is added. Clay soils react more strongly to changes in moisture content under loading, it may swell as moisture increases, resulting in volume changes and increased pressure on foundations.

From another perspective, shrinkage and collapse caused by changes in moisture levels can cause collapses in unsaturated soils, posing a significant challenge to engineering structures where unsaturated soils can lose strength, leading to foundation cracking or a reduction in soil bearing capacity [9].

Additionally, unsaturated soil exhibits low permeability comparing to saturated soils, which limits the ability of water to move through the soil under the influence of water pressure. The permeability however can become higher when the moisture content of the soil is higher or when the soil already contains large pores such as in the case of sandy soil as compared to clay soils.

Based on all that was listed above, it could be concluded that the way in which unsaturated soils behave is greatly dictated by the environmental circumstances such as the humidity and temperature. Such aspects result in volume changes and the differences in behavior mechanically, and in the long run humidity or water pressure can change the soil and cause it to alter structurally, resulting to damage of foundations [11,12].

Against this background, the main goal of the review is to critically synthesize the latest developments (2020-2024) on the topic of the SWCC and its use in unsaturated soil mechanics. Particularly, this report will seek to harmonize divergent results of SWCC modelling, devise a more generalized model of the effectiveness of microstructural and compositional constraints and state precisely the implications of the results on the practical improvement of geotechnical resilience in the discipline.

The rest of this paper is organised in the following way: Section 2 is a critical analysis of the factors affecting SWCC based on synthesis of the existing literature into organised themes of material, environmental and advanced modelling controls. Section 3 gives a revised and a more comprehensive description of the laboratory and numerical techniques of calculating the SWCC. Section 4 contains the final conclusions and the overview of the main synthesized findings. Lastly, the Future Research Needs and Recommendations are given in Section 5 which gives a definite direction to future researchers and practitioners in the field.

2. Soil water characteristic curve in unsaturated soil (SWCC)

The key constitutive relationship of shear strength, volume change, and fluid flow of unsaturated soils is the Soil Water Characteristic Curve (SWCC or SWRC). Although previous studies have already worked out many empirical frameworks, the recent literature (2020-2024) proves that there is an essential change towards reconciling complex variables and construct more reliable prediction models. In this section, critical evaluation of these advances is done in 3 major thematic areas.

2.1. Critical Evaluation of methodological Comparability

The diversity appears in the methods that are used to measure SWCC data: the filter-suction technique used by Karim et al. [10] (medium suction range) and vapor absorption technology used by Wang (2022) [13] (medium to high matric potential). The Soil Water Balance Curve (SWI) developed by Wang using the vapor sorption model was very effective in terms of both the ability to differentiate between external surface and interstitial absorption, with a very higher level of success (R^2= +0.99). Comparability Challenge: It may be assumed that the results of studies that are carried out in separate domains of suction, e.g. capillary forces (low-to-medium suction) and adsorption forces (high suction) are not comparable. It is a methodological scale-dependence that usually restricts the possibility of making direct, quantitative conclusions at the entire spectrum of soils and conditions.

2.2. Reconciling Advanced Modeling Approach: Comlexity and Prediction

The recent literature has a major controversy on the ideal complexity of SWCC predictive models, with the need to balance the interpretability with the uncooked predictive ability. The Conflict of Complexity, a notable contradiction exists between the results of Du (2020) [14] and Li et al. (2023) [3].

The comparative analysis of 22 models on 94 soil samples by Du showed that, the more complex or more parameters a model has the less accurate it is in the conventional empirical formulas (as with Brooks and Corey and Van Genuchten). Conciliation Conversely, Li et al. [3] proved that high-complexity, non-linear architecture, brought in by high-data-powered models (Deep Neural Networks, DNNs) outperforms limitation witnessed by over-parameterized empirical traditional models. Synthesis and Reconciliation, this tension is resolved by the acknowledgement that data-driven models (AI) of high complexity and non-linearity outperform shortcomings of simple empirical models. What AI can do those simple empirical equations alone can not, non-linear high-dimensional space the assumption that the SWCC can be rationalized by simple empirical equations is not applicable, and AI is much competitive in that case. The Role of Mechanistic Models, complementary to AI is the fractal theory of fractal theory (Yang, 2023) [15], which connects the SWCC to measurable parameters, i.e. physical quantities. Yang discovered a strong relationship that existed between fractal dimensions and soil clay content. One future research (to be performed in parallel) should be to consider an opposite solution: to incorporate the physical bounded parameters based on the fractal theory into high-level AI models in order to get physically plausible and massively accurate predictions.

2.3. Framework of Microstructural and Compositional Control

The effect of controlling factors can be generalized into a framework which separates between physical alteration (microstructural) and chemical/material alteration (compositional), each of which is a successful strategy to improve water retention.

Microstructural Controls, As reported by Zhang et al. (2021) [16], the study involved the use of nano-porosity in sandy soils. Their results revealed that water-holding capacity at low suction increased significantly by 23% with increasing nano-porosity by 15% at low suction. The physically based mechanism is confirmation that the pore geometry manipulation is an effective method of increasing capillary forces.

Rattan (2020) [17] examined how the addition of organic matter impacts agricultural soils. When the percentage of organic matter was added to 5, the water retention was enhanced by 22% to 33 kPa suction. This modification of composition adds hydrophilic elements which increase the ability of the soil to absorb water.

Generalization, Microstructural modification (nanopores) and compositional modification (organic matter) can both be considered viable and generalized applications to the engineering of the SWCC; and in both studies, coarse-textured (sandy) soils tend to be most benefiting of such alteration, which is a fundamental technique to counter droughts.

2.4. Geotechnical Performance and Environmental Implication

The final merit of SWCC studies is that the research findings have implications on the large-scale geotechnical performance of long-term geotechnical performance under varying environmental loads.

Karim et al. (2022) [10] evaluated the effect of climate change on clayey soils directly. They discovered that an increase in temperature of $20 o C decreased water-holding capacity by 12 to 50 kPa suction, which supported the direct impact of climate on SWCC. Implication on a Field Scale: This reduction in matric suction directly corresponds to a diminished shear strength in the field, more likely to cause landslides and slope instability in wet areas and contribute to foundation problems.

On the other hand, Torres et al. (2024) [18] showed that geotechnical materials and ground coverings enhanced the water-holding capacity of soil by 25 regime of the soil at suction. Field-Scale Implication: This implies that the effective stress can be observed to be more stable with the strategic application of engineered materials which can perceivably diminish the seasonal variation of the effective matric suction and as such heighten foundation resilience and reduce soil instability in construction programmes.

The review conducted by Onyelowe (2022) [19] (403 studies) proves that matric suction is the only most powerful indicator in geotechnical operations (e.g., slope stability, bearing capacity, and settlement). It is important to mention, however, that the conclusions made here concerning the stability in the field are grounded more on the findings made in labs of use on a large scale (R1, P8). The difficulty of applying these small-scale, fine-grained insights to the complex and non-uniform behaviour of the field is the big bottleneck in the practical use of the SWCC.

Table (1) presents comparative information from previous studies on soil water retention curves (SWRC), methods used, and results obtained.

Table 1 Analysis of soil water retention curves based on previous studies

Study	Year	Objective	Methodology	Main results	Recommendations
Torres et al. [18]	2024	Effect of ground covering and geotechnical materials on SWRC curves	15 types of geotechnical materials and 30 soil samples, displacement pressure analysis	The soil's water holding capacity increased by 25% at 100 kPa suction	Using geotechnical improvements to reduce drought problems
Yang [15]	2023	Analysis of SWCC curves using fractal theory	UNSODA2.0 database, 12 soil types	Clay soil holds more water, and the fractal dimension is related to the clay content	Using the fractal SWCC model to describe soil properties
Li et al. [3]	2023	Developing a SWRC prediction model using artificial intelligence	Deep Neural Network (DNN), 500 samples	Predictive accuracy R^2 = 0.985 compared to 0.912 for traditional models	Adopting artificial intelligence to improve forecasting accuracy
Onyelowe [19]	2022	Review of SWRC applications in geotechnical engineering	Analysis of 403 previous studies	Matric suction is the most influential factor	Developing artificial intelligence techniques to solve engineering problems
Wang [13]	2022	Soil Water Balance Curve (SWI)	Analysis of 21 soil types using vapor absorption technology	SWI model accuracy > 0.99 in soil properties analysis	Use of the model in geotechnical engineering
Karim et al. [10]	2022	Impact of climate change on SWRC	25 samples, filter suction technique	Soil water retention capacity decreases by 12% when temperatures rise	Study of the impact of climate change on soil stability
Zhang et al. [16]	2021	Effect of nanoporosity on SWRC	SEM analysis and nitrogen adsorption	Increasing nanoporosity by 15% increases the soil's water retention capacity.	Improving SWRC models to include the effect of porosity
Du [14]	2020	SWRC Model Evaluation	Analysis of 94 soil samples, comparison of 22 samples	EG model is the best performing, BC and VG are the least accurate.	Use complementary models to improve representation.
Rattan [17]	2020	Effect of organic matter on SWRC	40 samples, van Genuchten-Mualem analysis	Water retention increases by 22% when 5% organic matter is added.	Enhancing the sustainability of agricultural soil by adding organic matter

As can be infer for the table recent studies on soil water retention curves (SWRCs) used different techniques. Many studies have relied on advanced mathematical techniques, such as artificial intelligence and fractal theory, to analyze the influence of various factors on soil water retention capacity. Studies have also shown that fine-textured soils retain more water than coarse-textured soils, and that geotechnical techniques such as geotextiles can significantly improve soil water retention capacity.

3. Methods for determining the SWCC curve

There are several laboratory and numerical methods for determining the SWCC curve, including:

3.1. Laboratory methods

Pressure Plate Method: This involves placing the soil in a sealed device, applying different pressures to draw out water, and measuring the relationship between suction and water content. It is suitable for measuring high suction values (>1000 kPa).
Filter Paper Method: It relies on the balance of suction between the soil and the filter paper, where the moisture content of the paper is measured after reaching equilibrium. It is used to measure suction in the medium range (10-1500 kPa).

Tensiometer and Ceramic Matrix Method: Uses sensors that measure suction directly within the soil. Effective in low suction ranges (<80 kPa).

3.2. Numerical and experimental methods

Van Genuchten Model: Uses empirical equations to describe SWCC, with coefficients adjustable depending on soil type.

Brooks and Corey Model: Relies on determining the inlet air pressure and critical saturation values to estimate the relationship between suction and water content. [20].

Figure (1) shows the relationship between the volumetric water content (%) and the capillary tension (suction) in kilopascals, where the continuous lines represent the drying path, while the dashed lines represent the wetting path. This diagram reflects the effect of capillary hysteresis on the water retention curves in the soil, which is a phenomenon that occurs as a result of the difference in water distribution in the soil pores during the drying and wetting processes.

It can be seen that at the beginning of the curve, when the soil is fully saturated, the volumetric water content is high and remains so until the soil reaches the air entry value, the point at which air begins to penetrate the larger pore spaces, resulting in a rapid decrease in water content as capillary tension increases. During the drying process, the water content continues to gradually decrease until the soil reaches residual suction, the point at which water loss becomes limited, as the remaining water is trapped in the micropores by adhesion forces.

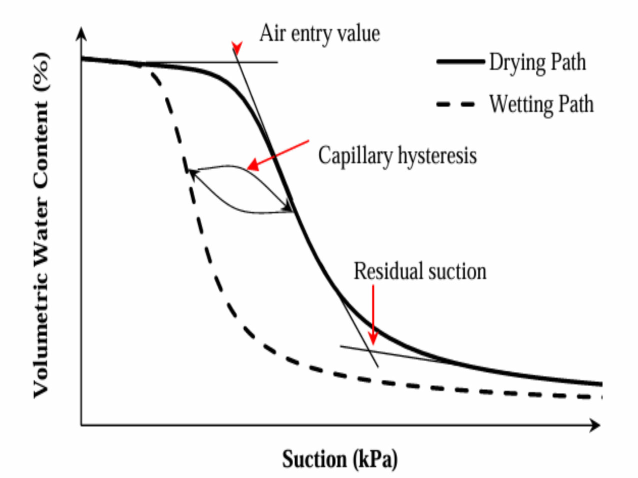

Figure 1 Typical soil water retention curve (SWRC) showing the effect of capillary hysteresis. [21]

On the other hand, the wetting path exhibits a different behavior due to capillary hysteresis, requiring less tension to re-saturate the soil compared to the tension required during drying. This behavior results from the different geometric distribution of pores between the drying and wetting processes. Larger pores are responsible for draining first during drying, while re-saturating them requires less tension due to the presence of residual water in the micropores, resulting in a mismatch between the two paths.

From an engineering perspective, the presence of residual tension indicates that soils may not lose all of their water content even at high capillary tension, making some soils more drought-resistant than others. Understanding the effect of hysteresis is also important in the design of underground drainage systems, as it can be used to improve water resource management strategies and prevent undesirable saturation of infrastructure. Table (2) shows some of the methods that are used to determine the SWCC.

Table 2 Summary of studies on determining the water retention curve in soil and the effect of soil type on the results

Study	Year	Soil type	Used method	Conclusions
Torres et al. [16]	2024	clay, sand, mixed soil	Displacement pressure analysis, volumetric suction techniques	Ground covering increased water retention by 25% at 100 kPa suction. Permeable membranes reduced desiccation by 18%.
Yang [15]	2023	clayey soil, loamy clay, sandy loam, silty loam, sand	Fractal analysis using UNSODA2.0 data	Fine soil holds more water than coarse soil.
Li et al. [3]	2023	Various types of soil	Deep learning using deep neural networks (DNN)	AI improved the accuracy of SWRC curve prediction, with an error rate of less than 3% at 100 kPa suction.
Onyelowe [19]	2022	Unsaturated soil of different types	alysis of 403 previous studies, predictive models	Matrix suction is the most influential factor in soil behavior, and predictive models have improved the accuracy of geotechnical forecasts.
Wang [13]	2022	Unsaturated soil with a wide range of plasticity index (4-132 PI)	Vapor absorption technology, SWI curve	The SWI curve is based on surface absorption and interfacial voids, with an accuracy of $R^2 > 0.99$.
Karim et al. [10]	2022	Clayey soil	Filter suction technique, Fredlund-Xing model	Increasing the temperature from 15°C to 35°C reduced water retention by 12% at 50 kPa suction.
Zhang et al. [16]	2021	Sandy soil	SEM analysis, nitrogen adsorption, modified van Genuchten model	increasing nanoporosity by 15% increased the retained moisture by 23% at 10 kPa suction.
Du [14]	2020	Different types of soil	Analysis of 22 models using data from 94 soils	The EG model was the most accurate, while VG and BC were the least accurate, and the effect of soil texture was the largest.
Silva et al.	2020	Agricultural soil, sand, clay	van Genuchten-Mualem equation	Adding 5% organic matter increased water retention at 33 kPa suction by 22%.

Both methods have certain benefits and drawbacks that affect the precision of the SWCC. Although the pressure plate extractor is consistent with high suction, long equilibrium intervals are necessary and it can underestimate suction of highly plastic clays. Filter paper method is also sensitive to changes in temperature and calibration differences, and hence the variation between laboratories. Tensiometers give direct and true values and are limited to suction of less than 80 kPa by cavitation limits.

Simple numerical models like the van Genuchten and Brooks-Corey are popular because of their simplicity but they cannot capture hysteresis and microstructure. More complex models demand quality data, and necessary parameter optimization.

The main problem is that every laboratory technique involves a distinct range of suction and cross-comparison of the studies is hard. Capillarity-dominated mechanisms are reflected in low-suction methods, whereas adsorption forces are determined in high-suction methods. This mismatch is another cause of inconsistencies in SWCC datasets.

4.Conclusions

1. The Value of Soil Water Retention Curves Analysis: Water-soil characteristic curves play a critical role in the investigation of how the soils become when they are subjected to the presence of water. This knowledge assists in the optimization of engineering and farming constructions depending on the conduct of soil in unsaturated regimes. Furthermore, the curves offer grounds to research the influence of either seismic loads or vehicle traffic on unsaturated soils.
2. Influences of quantities on soil-water characteristic curves: The behaviour of the soil-water characteristic curves are influenced by several factors which include the type of soil, mineral content, water content and pressure exerted on the soil. Such influences also result into substantial alterations in the hydraulics of the unsaturated soils and this means that it is crucial to take these factors into consideration when in assessing soil response under diverse loads.
3. Numerical Modeling: This is a major method of representing the seismic or use of the traffic on uncured soils. The impact of these loads may be accurately evaluated with the help of the techniques like finite element modeling (FEM) and finite element modeling (FDM) and the effects of them on the soil water characteristics may be investigated. This is useful in the design of projects to bring about soil stability due to changing conditions.
4. Applications: The soil-water property curves can be applied in permeability analysis, volumetric change, and resistivity among others. By appreciating these properties, it is possible to come up with new engineering solutions to challenges like water accumulation, ground degradation and engineering response to seismic loads.

Most of the studies analyzed are based on laboratory-based measurements of the Soil Water Characteristic Curve (SWCC), however, it is worth mentioning that laboratory outcomes do not usually reflect the field-scale hydrological and geotechnical behavior. Under actual field conditions, soil layering, macro-pores, root channels, climatic variations, wetting drying cycles, and natural stress paths can also have a significant effect on the shape and parameters of the SWCC. Thus, laboratory curves can either exaggerate or be inaccurate in the water retention of large scale such as slopes, foundations and embankments. Additional field-based measurements and long-term monitoring schemes are necessary to confirm laboratory results and to come up with scale-modulated SWCC models in order to explain natural heterogeneity and boundary effects.

5. Recommendation and Future Works

According to the critical analysis of recently available literature, the following research objectives are suggested to fill the gap between laboratory results and the geotechnical practice to contribute to the accuracy of soil behavior prediction in the unsaturated conditions:

Future studies should aim at coming up with unified SWCC models, which effectively capture key controlling factors observed in the present review. It involves going beyond the models that have typically used two or three parameters (e.g. Van Genuchten) to models that explicitly consider the microstructural parameters (e.g. fractal dimension) as well as the compositional parameters (e.g. organic matter content) in different soil textures. Although AI and Deep Learning (Li, 2023) [3] show better predictive accuracy, there is usually no way to interpret their usage physically. Future research would be to consider complementary methods that would incorporate the data-driven power of AI with the mechanistic information of theories like fractal geometry (Yang, 2023) [15] to formulate more robust and physically justifiable SWCC predictors.

A majority of the existing research is laboratory-oriented; consequently, the future research should focus on large field experimentation and long-term investigation. This involves the calibration of numerical models (FEM) with data collected by in-situ observations to determine geotechnical performance (i.e. slope stability and foundation resilience) in the real-world dynamic and environmental conditions (i.e. climate change induced moisture variations).

More fundamental modeling of the multifaceted phenomena of hysteresis and the SWCC during dynamic loading (e.g., traffic vibration, earthquake loading) is required. This is crucial in the knowledge of transient unsaturated flow and stress paths in vital geotechnical structures such as roadways, railway embankments, and earth dams.

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Conflicts of Interest

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