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Advances in unsaturated soils mechanics and technology in Brazil

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Review Article

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Abstract

Unsaturated soils mechanics (USM) and unsaturated soils technology (UST) have been the subject of great interest to Brazilian researchers and practitioners since the inception of the Brazilian Association for Soil Mechanics and Geotechnical Engineering (ABMS). This is in great part due to the geotechnical challenges involving swelling and collapsible soils commonly found in the country and issues related to landslide risk assessment and management. Progressively, problems associated with civil infrastructure, transportation geotechnics, environmental geotechnics, and engineered mine tailings disposal systems have also drawn the attention of professionals dealing with unsaturated soils. This paper celebrates the 75th anniversary of ABMS by presenting a summary of some of the main advances produced by Brazilian academia and geotechnical practitioners, in the field of USM and UST. Fundamentals of unsaturated soil are discussed, in the context of some typical Brazilian soils, including issues regarding soil microstructure, soil-water retention, and unsaturated shear strength. Brazilian developments in terms of swelling and collapsible soil identification, testing, and modeling are explored. Finally, geotechnical and geoenvironmental applications are discussed, focusing on the main issues investigated in the past four decades.

1. Introduction

The concepts of unsaturated soil mechanics (USM) have become essential for the understanding and design of geotechnical structures in contexts where soils exhibit a degree of saturation below 100% or undergo significant seasonal variations in this parameter. Accounting for the hydraulic and mechanical properties of unsaturated soils often enables a more accurate assessment of stability, deformability, flow behavior, and the overall performance of soils and porous materials in general (Fredlund et al., 2012).

Despite the solid conceptual foundation and the advancement of experimental and numerical tools related to unsaturated soils, there remains a certain reluctance within the professional community, both abroad and in Brazil, to systematically incorporate the principles of USM into geotechnical analyses and design. This hesitancy partly stems from the additional complexity involved in characterizing the hydraulic and mechanical parameters of unsaturated soils. However, this perspective is gradually shifting. Increasingly, the concepts of USM are proving to be useful, and, in many cases, indispensable for solving practical problems in projects exposed to variable climatic and environmental conditions. The growing frequency of extreme weather events has further intensified the need to understand geotechnical behavior from the perspective of unsaturated soils, reinforcing the

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importance of integrating these concepts into the toolkit of modern geotechnical engineering.

Unsaturated soil mechanics has been a subject of great interest to Brazilian researchers and practitioners. Evidence of such awareness can be observed since the early years of the Brazilian Association for Soil Mechanics and Geotechnical Engineering. For example, a series of symposiums on unsaturated soils has been organized by ABMS (Figure 1), with the first edition taking place in 1991, in Brasília, Central-West region of Brazil. Recently, a summary of Brazilian advances in USM and unsaturated soils technology (UST) was presented in the book organized by Camapum de Carvalho et al. (2023b). In addition, numerous papers have been published by Soils and Rocks on the general field of unsaturated soils geotechnics and its applications. Two special issues of Soils and Rocks have been dedicated to unsaturated soils behavior, the first in 2016 and the second in 2021. The next several paragraphs will present an overview of some papers published by Soil and Rocks, offering a glimpse of research done in Brazil on the topics of USM and UST.

The first paper published by Soils and Rocks on USM appeared in 1984, when the journal was still being published under the title *Solos e Rochas*. In that first publication, Kochen (1984) presented an overview of current theories of that time for unsaturated soil consolidation analysis. Those concepts were applied to the simulation of shallow foundations and clay core rockfill dams. Nonlinear elastic analyses using the Finite Element Method were combined with the state surface concept (Figure 2a), using the independent stress state variables, namely: matric suction and net total stress.

Multiple geotechnical engineering problems were motivating Brazilian researchers to study unsaturated soils, as shown in subsequent publications also appearing in Soils and Rocks. The study by Dias (1987) focused on the fundamentals of the behavior of lateritic unsaturated soils. She presented an investigation that included direct shear tests under both flooded and natural water content conditions. Unfortunately, matric suction was not measured or controlled. Later, Campos (1992) presented the use of tensiometers as a tool for determining negative pore-water pressures on compacted soils. Additional advances in the monitoring of unsaturated soil states (e.g., water content, negative pore-water pressure, total suction) were presented in Conciani et al. (1996), Mahler et al. (2005), Vieira et al. (2005) and Soto & Vilar (2006), among many others.

Figure 1. Proceedings of the Brazilian symposiums on unsaturated soils.

Shear strength behavior, often in the context of landslides in Brazil, were also a significant factor motivating early studies on unsaturated soils. In a paper published by Soils and Rocks, Abramento & Pinto (1993) discussed the behavior of a Brazilian colluvium from Serra do Mar and presented the use of suction-controlled triaxial tests to investigate its shear strength. The results were interpreted using both the effective stress concept and the independent stress state variables. The authors observed a nonlinear relationship between suction and apparent cohesion (Figure 2b) that a few years later would be brought up by several other researchers around the world. Later, Machado & Vilar (1998) and Vilar (2007) applied a hyperbolic function to model the nonlinear apparent cohesion.

The presence of collapsible soils in several regions of Brazil also motivated developments in the field of USM which appeared in several papers published in Soil and Rocks. Ferreira & Lacerda (1993) presented the use of field load tests that allow the determination of surface displacements of soil profiles subjected to flooding. Meticulous comparisons with double-oedometer tests were presented (Figure 2c). Mendonça et al. (1993) also presented investigations involving collapsible soils and using double-oedometer tests, including an evaluation of correlations between collapse and basic physical properties. Agnelli & Albiero (1997) investigated the microstructure and volume change of a collapsible soil and the influence of its stability when in contact with pore-fluids of various chemical compositions. Very important lessons are presented by the authors regarding the impact of soil contamination on collapse and the understanding of physicochemical processes involved in microstructural stability. Later, international trends involving the use of critical state concepts and elastoplastic models with isotropic hardening to model soil collapse (Figure 2d) also influenced research in Brazil, as show in Oliveira et al. (1999). Curiously, not much has been published by Soils and Rocks in terms of swelling soil behavior, even though substantial research has been done in Brazil in that field, as will be shown later in this paper.

The soil-water retention curve (SWRC), also commonly referred to as the soil-water characteristic curve (SWCC), was the subject of several papers published in Soils and

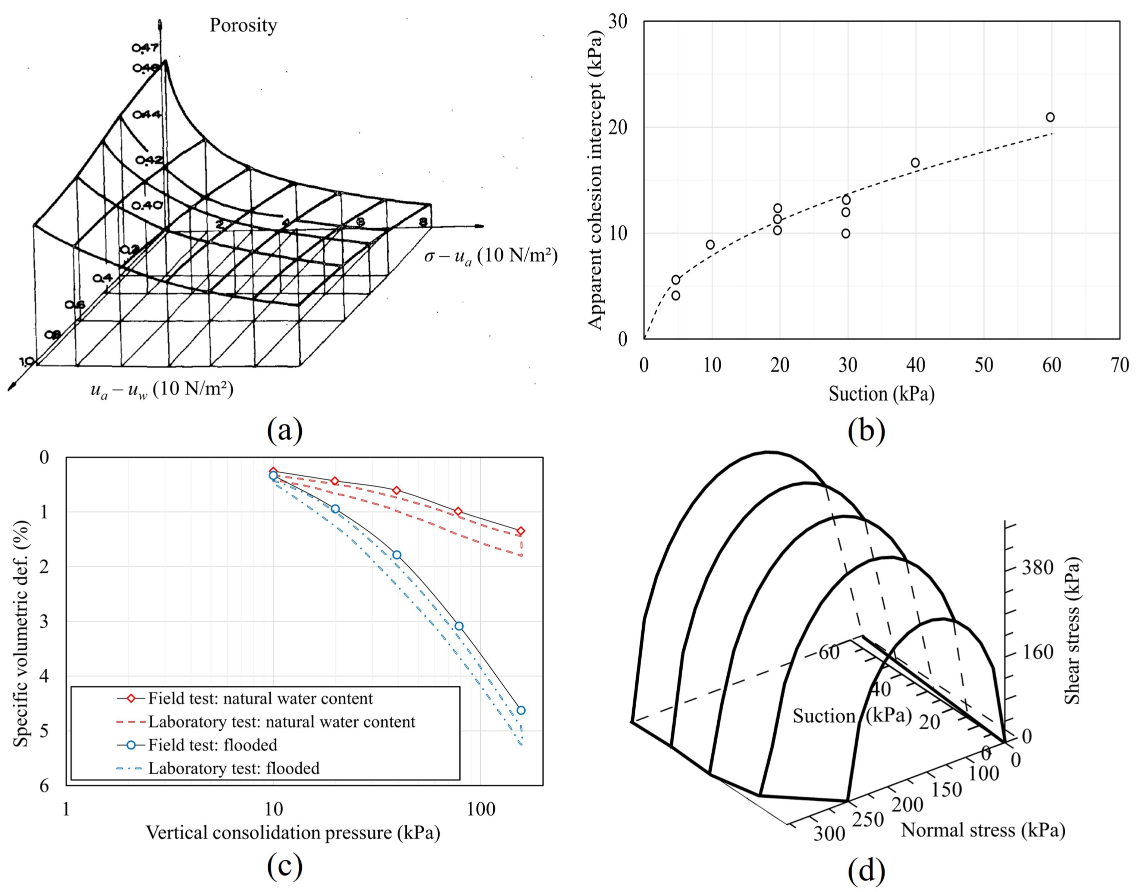


Figure 2. Some studies on unsaturated soils in Brazil: (a) void ratio state surface (modified from Kochen, 1984); (b) apparent cohesion of a colluvium from Serra do Mar (modified from Abramento & Pinto, 1993); (c) collapse behavior of a sandy soil from Petrolandia, PE (modified from Ferreira & Lacerda, 1993); (d) yield surface of a collapsible soil from Porto Alegre, RS (modified from Oliveira et al., 1999).

Rocks, some of which will be referred to herein. The role of the SWRC in the implementation of USM in geotechnical engineering practice gradually emerged in Brazil during the early 2000s. Lima et al. (2000) presented SWRCs of a soil profile from Manaus, Brazil, and its relationship with other basic soil properties. Machado et al. (2003) presented a method for estimating the unsaturated hydraulic conductivity function using water content monitoring in the field and the SWRC. The retention properties were a key aspect of the investigation presented by Marinho et al. (2003) on the pore-water pressures developed during embankment construction. Camapum de Carvalho & Leroueil (2004) examined and modeled the influence of void ratio on the SWRC. Gerscovich et al. (2004) utilized genetic algorithms to predict the SWRC of some Brazilian soils. Marinho & Teixeira (2009) demonstrated the use of high capacity tensiometers in the determination of the SWRC. Gitirana Junior & Fredlund (2016) presented a statistical analysis of typical SWRC parameters, allowing the incorporation of water retention uncertainty in geotechnical analysis. More recent studies have been focusing on bimodal SWRC behavior (Oliveira et al., 2022) and on the role of the SWRC as a key parameter controlling tropical soil behavior (Camapum de Carvalho & Gitirana Junior, 2021).

The role of unsaturated soil geotechnics in environmental problems has also stood out as a main subject of concern, as shown in several papers published in Soils and Rocks. For example, Sousa et al. (2011) demonstrated the use of tensiometers to determine the storage characteristics of soils contaminated with non-aqueous phase liquids. Several papers presented investigations of soil-atmosphere interaction problems (e.g., Bicalho et al., 2015; Sestrem et al., 2015). USM has also been applied in Brazil in the context of analysis and design of municipal landfills (Jucá et al., 2021).

This brief overview of papers published in Soils and Rocks dealing with unsaturated soil geotechnics demonstrates the breadth of research on USM developed in Brazil. Relevant progress can be observed in both basic research and applied geotechnics. Most of those advances focus on issues that Brazilian engineering faces when dealing with collapsible soils, swelling soils, and soil-atmosphere interaction, including landslides. In addition, unsaturated soils behavior has been considered a relevant subject in the process of educating society regarding sustainable and safe land use (Camapum de Carvalho et al., 2023b). Knowledge of unsaturated soils concepts is, as will be shown herein, essential for geotechnical engineering practice, making the design and execution of works safer and better optimized. Given the wide scope of applications and developments in Brazil, the task of summarizing these advances becomes quite challenging. Yet, this paper presents an extensive but not exhaustive overview of some relevant developments and contributions of Brazilian engineering to unsaturated soils geotechnics.

2. Fundamentals of unsaturated soils behavior

2.1 Chemical composition, mineralogy, and structure of tropical soils

In tropical climate countries, like Brazil, it is common for soils to present weathering profiles with a chemical, mineralogical and structural composition that varies markedly along their depth. The most altered soils are commonly found in the near-ground surface layers. An example of a weathering profile typical of tropical regions is presented by Camapum de Carvalho and Gitirana Junior (2021). In the case of tropical soils, there are numerous relevant Brazilian contributions to the interpretation of the relationship between unsaturated soil behavior and soil chemical composition, mineralogy, and structure (Camapum de Carvalho et al., 2023a). Some important lessons learned are presented in the next sections.

2.1.1 Soil chemical and mineralogical composition

When analyzing the properties and hydromechanical behavior of unsaturated soils, it is important to consider their chemical composition. Many soils found in Brazil present fine-particle aggregations forming inter-aggregate macropores and intra-aggregate micropores. These aggregations present exchangeable ions and chemical compounds such as iron and aluminum oxyhydroxides that act as cementing agents. The stability of these aggregations plays an important role in the behavior of these soils.

The cementing agents found in many Brazilian soils may be solubilized and leached by chemical attack and suction gradients. This situation is often observed when chemical stabilizers are used or when the soil is faced with chemical-biological contamination. In this case, it is necessary to consider the variations and distribution of osmotic suction in the soil. The chemicals introduced in the soil can, due to the osmotic suction imbalance, migrate to the interior of the aggregates, affecting the mechanical stability conferred by cementing agents (Silva et al., 2008; Ayala, 2020; Cardona Pérez, 2022).

Regarding soil mineralogy, three aspects have been of great relevance when analyzing the properties and behavior of tropical unsaturated soils typically found in Brazil: a) the alterability and degree of evolution of the minerals; b) the structural and mineralogical expansibility; and c) the chemical composition of the soil. It is important to note that many of the minerals present in the soil are often not directly involved in the soil's behavior, as exemplified in electron microscopy images presented by Camapum de Carvalho & Gitirana Junior (2021). It is also worth noting the method proposed by Queiroz de Carvalho (1976) for quantifying the components contained in the clay fraction of lateritic soils.

The alterability and evolutionary stage of minerals influence the shape of pores and adsorption forces, affecting the relationship between moisture, matric potential, and osmotic suction (Thyagaraj & Salini, 2015; Paranthaman & Azam, 2024). Thus, for example, thermal variations affect viscosity and the water-mineral interactive forces themselves and have an influence on the SWRC (Pérez Collantes, 2022). Minerals considered to be chemically stable, such as kaolinite, can be altered by the chemical actions of contaminants, as shown by Silva (2024). It should be noted that, in the case of aggregated soils, the main effect of the minerals that make up aggregations concerns their stability and the effects of this stability on the behavior of the soil.

Structural and mineralogical expansibilities, which are strongly dependent on suction, have different impacts on hydromechanical behavior. The structural expansion and contraction of soil minerals tends to be directly related to the variation in the void ratio, thus maintaining a more direct relationship with the soil's behavior (Camapum de Carvalho, 1985). In mineralogically expansive soils, swelling will also be affected by the variation in the volume of the particles themselves (Camapum de Carvalho et al., 2019). Hydromechanical behavior and suction will be more closely related only to the change in void volume, which needs to be distinguished from the overall volume change (i.e., void volume changes plus structural expansion of particles).

2.1.2 Soil structure

In the classic models for analyzing the properties and hydromechanical behavior of soils, the structure is seen as the result of the interaction between independent particles, being classified at the extremes as oriented or flocculated. However, studies carried out involving aggregated soils have shown that different analyses of structural characteristics such as pore-size distribution and its relationship with unsaturated conditions are necessary (Camapum de Carvalho, 1985; Camapum de Carvalho et al., 2002; Camapum de Carvalho & Pereira, 2002; Camapum de Carvalho & Gitirana Junior, 2021).

In this context, Pereira et al. (2024) and Alves et al. (2025) have demonstrated that the aggregated and disaggregated grain-size distributions (GSDs) may be used to infer microstructure and to evaluate how it affects the pore-size distributions. This is done by quantifying the degree of aggregation, considered to be proportional to the difference between both GSDs. The degree of aggregation has been found to be strongly related, for example, to the air-entry value of macropores.

Brazilian contributions to the study of the structural evolution of soils have often involved highly weathered materials. In these cases, it has been shown that increase in stresses and level of compaction can cause aggregates to break down, intervening more directly in the suction and hydromechanical behavior of the soil (Delgado, 2002).

2.2 Soil-water retention curve

The soil-water retention curve (SWRC) is one of the most important unsaturated properties because it allows the interpretation of multiple aspects of soil behavior. In this context, Brazilian geotechnical engineering has made significant efforts in terms of SWRC testing and modeling. Unsaturated soil testing usually requires some modifications of equipment and special procedures to allow the measurement or control of matric suction.

Capillarity, adsorption, and osmosis decrease water energy, making the interstitial water pressure lower than atmospheric and limiting, for most devices, the range of suction which can be directly measured to about 70 kPa without cavitation. Therefore, porous stones with high air-entry value (HAEV) in association with the use of the axis translation technique are often employed to allow suctions above 70 kPa to be applied or measured. In addition, vapor equilibrium and osmotic techniques have gained wider adoption in recent years (Delage et al., 1992; Blatz et al., 2008).

The suction range required to define the SWRC varies not only with the type of soil, but also with the engineering application. While certain seepage or retention analyses may only require low suctions, others, such as those involving collapse potential, strength, or long-term behavior under climatic variations, demand characterization across a much broader suction spectrum.

For low-suction ranges, up to approximately 30 kPa, the suction plate is commonly used, particularly for sands and silts. However, for finer soils, such as clays or some residual soils, higher suctions become relevant. In such cases, techniques like the Richards' pressure plate extractor (0–1,500 kPa), vapor equilibrium, osmotic methods, and filter paper testing are often adopted (Marinho et al., 2023; Mendes & Marinho, 2020; Vilar, 2021).

Among all methods mentioned, the filter paper technique stands out for its simplicity, cost-effectiveness, and wide measurement range, from about 20 kPa to beyond 30 MPa. Although the method's systematic use was established earlier (Chandler et al., 1992), its application to Brazilian soils and subsequent methodological refinements have been implemented by Marinho (1994). Many other contributions have improved calibration procedures and expanded the technique's applicability (Marinho & Oliveira, 2006; Marinho & Silva Gomes, 2012; Marinho et al., 2023; Zanin et al., 2024).

Some contributions from Brazilian researchers towards the improvement of SWRC testing can be found in literature. For example, Machado & Dourado (2001) presented a modification, based on the work of Fourie et al. (1995), to accelerate tests using the Richards' chamber. The technique is based on the interruption of the drainage of specimens' water before equilibrium, while keeping the water and air pressures monitored. Vaz et al. (2021) present a detailed study of the equilibrium process of suction and pressure plate tests, including the utilization of the Machado &

Dourado (2001) approach. They quantified the influence of the HAEV interface, soil characteristics, initial matric suction, and matric suction increment magnitude. According to the researchers, decreasing the HAEV interface thickness or using thin membranes is highly beneficial in reducing the equilibrium time, mainly for low matric suctions and relatively permeable soils. The testing approach proposed by Machado & Dourado (2001) proved to be an efficient and adequate procedure for reducing the total testing time.

2.2.1 Interpretation of SWRC behavior for some Brazilian soils

Figure 3 presents representative soil-water retention curves for typical soils found in Brazilian tropical weathering profiles. In this diagram, suction is expressed as pF, the base-10 logarithm of suction expressed in centimeters of water column. Although suction is shown here as a function of degree of saturation (*S*), SWRCs may also be plotted against gravimetric (*w*) or volumetric water content (θ).

Deeply weathered soils, such as lateritic soils, commonly exhibit a bimodal pore-size distribution, with distinct macro- and micropore domains. This leads to SWRCs with two inflection zones separated by intermediate pores. In some cases, more complex or simple pore arrangements may result in multimodal or unimodal behavior, respectively. The bimodal response is associated with aggregated microstructures (Alves et al., 2025). Fine-particle aggregation, although very common in Brazilian tropical soils, are often absent in quartz-rich soils, even when deeply weathered. These tropical soils generally lack expansive clay minerals. Instead, they contain iron and aluminum oxides, which may dissolve under specific pH conditions. Consequently, osmotic suction can become relevant, particularly when the soil undergoes chemical treatment or contamination (Silva, 2024).

In contrast, poorly weathered soils tend to exhibit unimodal curves. For non-expansive materials, the steepness of the SWRC reflects pore-size uniformity, similar to what is observed in sandy soils from temperate and cold climates. Expansive Brazilian soils, in turn, show water retention behavior comparable to that of similar soils in other regions of the world.

Saprolitic and sandy soils often share similar SWRCs, typically characterized by a single linear segment between the air-entry value and the residual suction. The slope of the main drainage branch is controlled by the pore-size distribution of the material.

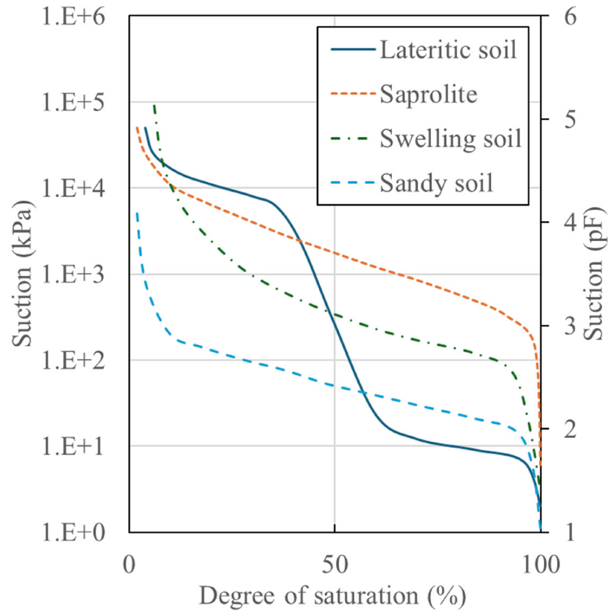


Figure 3. Typical soil-water retention curves (drying path) of some Brazilian soils.

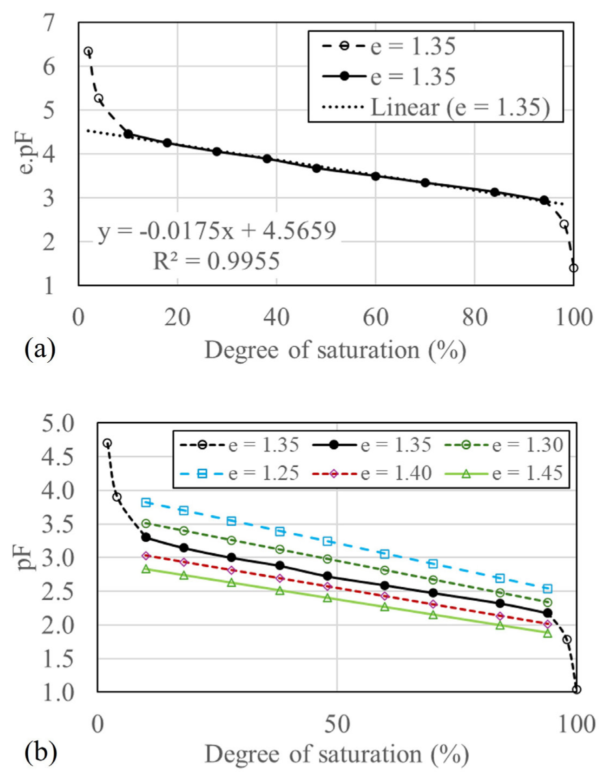


Figure 4. Alternative ways to interpret SWRCs and the effect of void ratio: (a) *e.pF* vs. *S*; (b) *pF* vs. *S*.

2.2.2 Effect of void ratio on SWRCs of tropical soils

Camapum de Carvalho & Leroueil (2004) proposed a semi-empirical method to combine SWRCs obtained for different void ratios into a unique curve where suction (in pF) is transformed by the void ratio (*e.pF*) and represented as a function of the degree of saturation (*S*). Figure 4 shows an illustration of the method. Figure 4a shows the *e.pF* vs. *S* curve and Figure 4b shows the *pF vs. S* curves obtained from the correlation equation obtained in Figure 4a. The dashed sections are not part of the correlation, since before the air-entry value the suction has not produced desaturation and because for high suctions soil water storage is mainly due to adsorptive forces and suffers little influence from porosity.

This technique is highly relevant for pavement structures and embankment projects, where variations in porosity are inherent to the variability of constructive processes. In addition, these projects do not work with soils that are close to saturation or at very low water contents, which means that the exclusion of boundary-effect and residual regions, as indicated, is not detrimental to the proposed technique.

2.3 Shear strength behavior

Shear strength was studied since the early stages of unsaturated soil research (Bishop et al., 1960). Brazilian soils have been investigated by Abramento & Pinto (1993), de Campos & Carrillo (1995) and Röhm & Vilar (1995), among many other researchers. To illustrated some features of unsaturated shear strength of Brazilian soils, Figure 5a shows stress-strain results from triaxial compression tests performed on an undisturbed colluvial lateritic soil (γ = 16.5 kN/m^3; S = 50% and e = 1.0) and Figure 5b shows stress-displacement results from direct shear tests performed on a highly-weathered residual soil (γ = 16.1 kN/m^3; w = 17% and e = 0.95 – average values). Both tests are consolidated drained and use the axis translation technique to impose and control matric suction.

Shear strength and stiffness increases with suction in all tests shown in Figure 5. Shear strength envelopes considering Bishop (1960) effective stresses results in the shear strength equation presented as follows:

$$\tau_f = c' + \sigma' \tan\phi' \tag{1}$$

where: τ_f is the shear strength; c' is the effective cohesion; ϕ' is the effective friction angle; and σ' is the effective normal stress.

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \tag{2}$$

where: σ' is the effective normal stress; σ is the total normal stress; u_a is the pore-air pressure; u_w is the pore-water pressure; and χ is Bishop's effective stress parameter. In the context of shear strength, the χ parameter must vary between 0 and 1 and is considered to be a function of the degree of saturation, although not a simple relationship is available.

Another possibility is to adopt the independent state stress variables proposed by Fredlund & Morgenstern (1977):

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

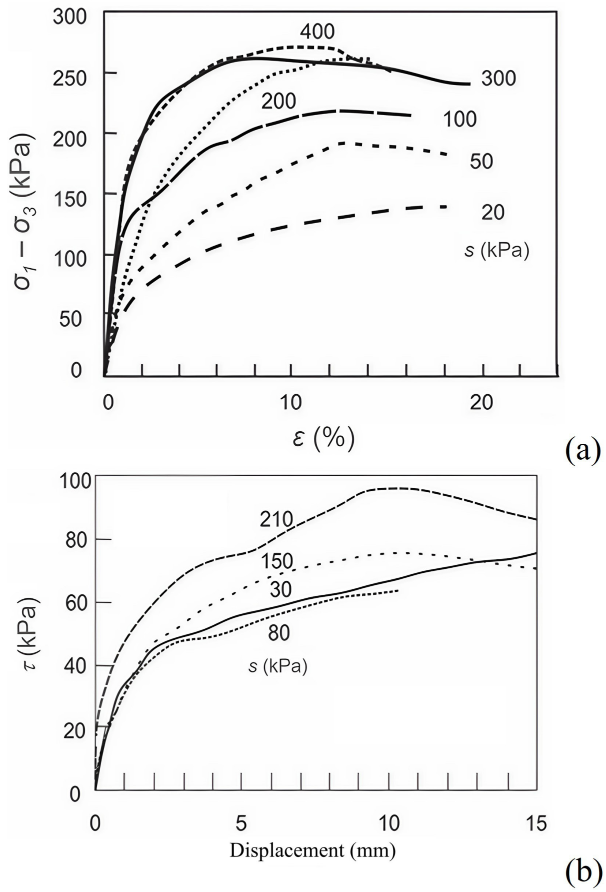


Figure 5. Stress-strain results from Brazilian soils: (a) triaxial tests on a lateritic soil, $\sigma_3 - u_a$ = 50 kPa (modified from Rohm, 1992); (b) direct shear tests on a mature residual soil, $\sigma_n - u_a$ = 50 kPa (modified from Campos & Carrillo, 1995).

In this regard, experimental test results indicate that soil suction seems not to influence the effective friction angle, although some variation has been measured and that a practically linear relationship arises in envelopes in (τ, σ - u_a) plane for constant suction.

Since direct methods are complex and time-consuming, many methods were developed for indirect determination of soil properties, especially for permeability and shear strength, as summarized in Table 1.

Figure 6 shows test results of a tropical lateritic sandy soil (Machado & Vilar, 1998) and the performance of several unsaturated shear strength models using the methods included in Table 1. This figure underscores the fact that approximate indirect methods must be used with caution, particularly when the prediction is applied to soils different from those used during model development. For instance, in the case of Figure 6 the lateritic soil presents an air-entry value (AEV) close to 1 kPa and the Khalili & Khabbaz (1998) method would only perform well, assuming an unrealistic AEV of 13 kPa. In addition, the microstructure of the tropical lateritic

Table 1. Some equations to predict the shear strength of unsaturated soils.

Shear strength due to matric suction effects	χ	Reference
$\Delta\tau_s = S(u_a - u_w)\tan\phi'$	S	Öberg & Sällfors (1995)
$\Delta\tau_s = (u_a - u_w)(\Theta^{\kappa} \cdot \tan\phi')$	Θ, κ	Fredlund et al. (1996)
$\Delta\tau_s = \left[\frac{(u_a - u_w)}{(u_a - u_w)_b}\right]^{-0.55} (u_a - u_w)\tan\phi'$	$\left[\frac{(u_a - u_w)}{(u_a - u_w)_b}\right]^{-0.55}$	Khalili & Khabbaz (1998)
$\Delta\tau_s = \frac{u_a - u_w}{a + b(u_a - u_w)}$	$\frac{(c_m - c')}{(c_m - c') + (u_a - u_w)\tan\phi'}$	Vilar (2007)

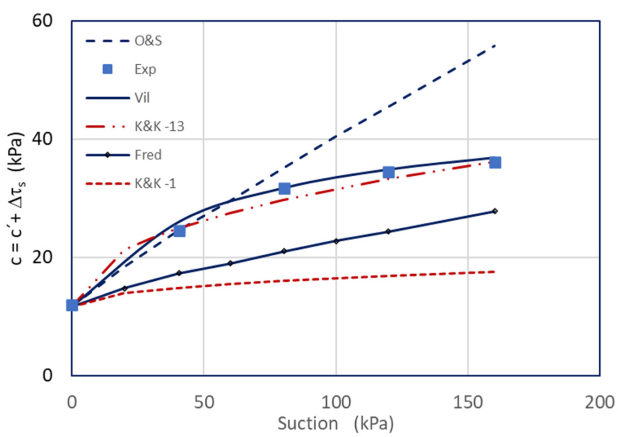


Figure 6. Data fitting of a tropical lateritic soil. O&S – Öberg & Sällfors (1995); Exp – experimental results; Vil – Vilar (2007): a = 1.633; b = 0.0029; K&K-13 – Khalili & Khabbaz (1998), AEV = 13 kPa; Fred – Fredlund et al. (1996), κ = 2.254; K&K-1 – Khalili & Khabbaz (1998), AEV = 1 kPa.

soil makes the consistency limits less useful for predicting soil properties and this may be the reason why the estimation using κ values based on plasticity index performs poorly.

Legend: $\Delta\tau_s$ is the increment in shear strength due to matric suction; S is the degree of saturation; u_a is the pore-air pressure; u_w is the pore-water pressure; ϕ' is the effective friction angle; Θ is the normalized volumetric water content; κ is a soil parameter dependent upon the soil type, $\kappa = 1 + 0.0975 \times PI - 0.0016 \times PI$; PI is the plasticity index; $a = 1/\tan\phi'$; $b = 1/(c_m - c')$; c' is the effective cohesion; c_m is the cohesion measured for specimens air dried until the target maximum suction in a test without suction control.

Bishop's effective stress equation has been criticized for its limitations in dealing with volume change of collapsible soils upon effective stress reduction (Jennings & Burland, 1962). Additional difficulties are observed when predicting shear strength, indicating the need to introduce a fitting parameter, A, that could account for the soil type and/or soil pore-size distribution and microstructure:

$$\Delta\tau_s = A \cdot f(u_a - u_w)\tan\phi' \quad (4)$$

where: $\Delta\tau_s$ is the increment in shear strength due to suction; A is a fitting parameter; and f indicates a function representing the effect of matric suction. If such a relationship could be found, this would provide a smooth transition between saturated and unsaturated soil mechanics, avoiding the use of two variables to control the mechanical behavior of unsaturated soils.

3. Problematic soils

3.1 General concepts

Some typical unsaturated soils from Brazil present substantial volume change caused by variations in water content and suction. Unsaturated soils that present high volume change can cause damage to structures and, for that reason, are often called "problematic soils". In Brazil, high volume change is frequently observed during the expansion and contraction of swelling clays, through the collapse of colluvial soils, and also during the collapse of soils presenting natural cementation and porous structure (Ferreira, 1995).

Problems associated with high volume change are more common in climates with alternating rainy and dry seasons, which are also typical of many regions in Brazil. Various studies carried out in Brazil show that the climate has a strong influence on the matric suction profile and on the process of volume change. The top layer of soil suffering significant variations in water content and suction is called the active zone. Figure 7a and 7b show suction profiles of swelling soils during the dry and wet seasons. These field

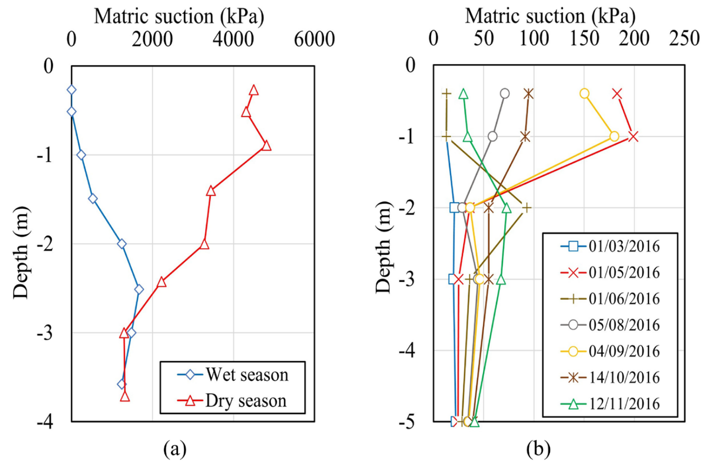


Figure 7. Matric suction profiles from: (a) Paulista, PE (modified from Silva et al., 2004); and (b) Bauru, SP (modified from Saab, 2016).

measurements indicate that the active layer is limited to a depth of around 2.0 to 2.5 m in these locations.

3.2 Collapsible soils

3.2.1 Collapsible soil identification and typical test results

Collapsible soils have long been recognized as posing significant engineering challenges worldwide (Gibbs & Bara, 1962; Vargas, 1973). The early studies dealt with empirical criteria for collapsible soil identification (e.g., Vilar & Ferreira, 2015). Vilar & Rodrigues (2015) indicated that the available collapsible soil identification criteria were indirectly linked to low dry unit weights. To address this limitation, they proposed a chart (Figure 8) that introduces the use of relative compaction, $RC_n = \rho_d/\rho_{dmax}$, where ρ_{dmax} is the maximum dry density at optimum moisture content (w_{opt}) obtained in Standard Proctor test and ρ_d is the in situ soil dry density. In addition, the water content deviation (w-w_{opt}) is also used, where w is in situ soil moisture content. To avoid confusion, it is important to emphasize that optimum compaction conditions are being used in Figure 8 to identify undisturbed collapsible soils.

Some typical experimental data demonstrating the influence of soil suction on soil compression and collapse of Brazilian soils is presented herein. Figure 9a shows compressibility curves of a sandy lateritic soil (SC; γ = 19.2 kN/m^3; w = 16.7%; e = 0.65; and S = 70%). Pre–consolidation or yield stress and compression indexes (C_c) increases with suction. The increase in C_c is typical and the relationship between yield stress and suction gives rise to the "Load-Collapse" yield curve of Barcelona Basic Model, BBM (Alonso et al., 1990). Figure 9b shows the effect of suction on the yield stress and a fitted curve based on the model by Balmaceda et al. (1992). The model considers the convergence of compressibility curves at different suctions when net normal stresses are sufficiently high.

Figure 10 shows the development of collapse strains of an undisturbed sandy soil (SC; ρ_d = 1.44 g/cm^3; w = 7.2%) during suction decrease and suction cycling. In the first step of suction reduction, from 60 to 50 kPa, strains are negligible. For suctions lower than 50 kPa, there are significant increases in strains that reach a maximum at zero suction. Strains increase with load but reach a maximum and then decrease as one can observe by comparing the curves for 400 and 200 kPa of net load. Another interesting observation is that cycling of suction does not introduce additional strains, until new low levels of suction are reached.

3.2.2 Collapse modeling

The analysis of collapse near the Três Irmãos Dam reservoir is an interesting example of comprehensive collapse modeling done by Brazilian researchers. Três Irmãos Dam was built in the outskirts of the City of Pereira Barreto, SP, Brazil. The resulting rise of local groundwater table (GWT) affected many buildings due to soil collapse. Rodrigues (2007) summarized various previously executed field and laboratory tests, along with the monitoring of GWT and settlements. These investigations were complemented by field and laboratory tests to determine the SWRC and the hydraulic conductivity function, together with suction-controlled tests to measure shear strength and compressibility. The typical local soil is a fine to medium sand, with around 20% of fines (SC; ρ_d = 1.44 g/cm^3; w = 7.2%; e = 0.845 and S = 22.4%). Both initial measurements and unsaturated soil parameters were used to model settlement data using CODEBRIGHT (Olivella et al., 1994), along with the BBM model.

Amongst the several buildings monitored, PB-2 was in an area considered to be the most critical in terms of predicted soil collapse. Six settlement marks installed in the building were monitored since June of 1990. Figure 11 shows the time evolution of settlements that varied from 74.41 mm to 126.20 mm and caused structural damage and breaking of the

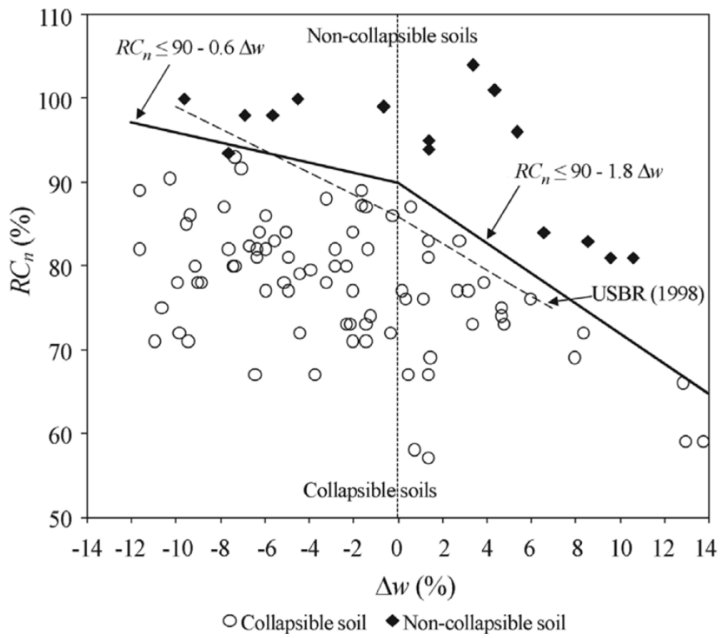


Figure 8. Expedite criterion for collapsible soil identification (modified from Vilar & Rodrigues, 2015).

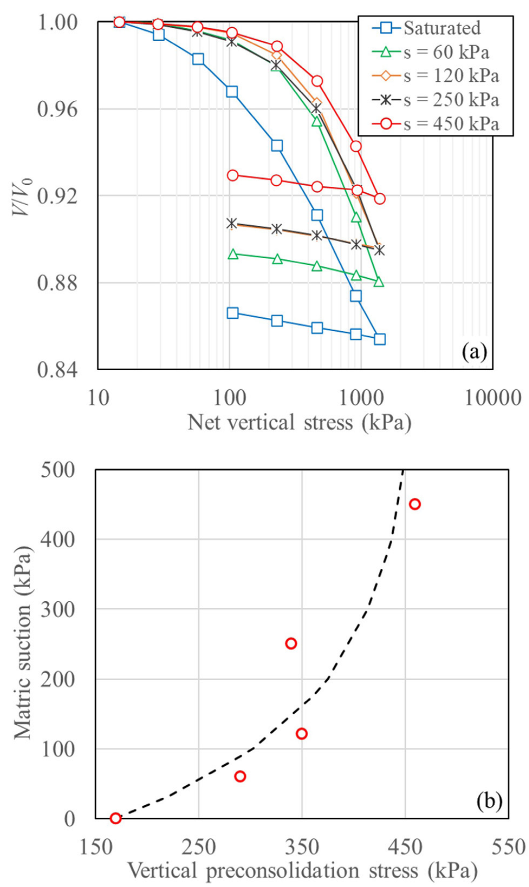


Figure 9. Typical collapse behavior: (a) compression curves under various soil suctions (s); (b) experimental and fitted Load Collapse curve from BBM (modified from Machado, 1998).

wastewater pipe. This building was demolished for security reasons and reconstructed in the same location.

The settlement marks stayed stable until the 8th of April 1991, when the GWT rose from 318.2 m to 323.4 m. By January 1991, GWT was rising but was still contained within the sandstone and no collapse strains were registered. By May 1991, the GWT reached the collapsible layer and remained approximately constant at the elevation of 326.5 m. At this time, collapse increased progressively until GWT stabilization, after which no further significant deformations were observed. However, as dam filling progressed later in July 1993, GWT rose once again and collapse further increased.

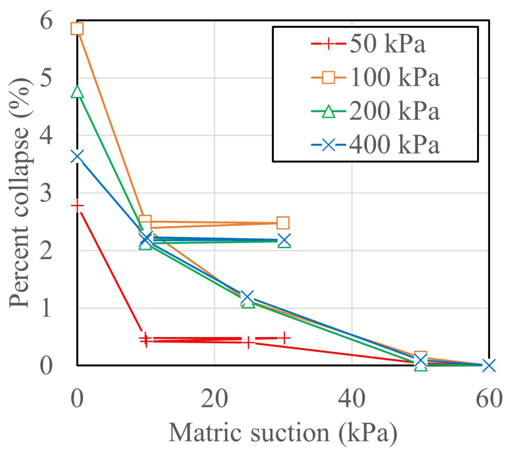


Figure 10. Percent collapse during matric suction reduction from 60 to 0 kPa for various vertical net load (from 50 to 400 kPa) and cycling of suction (modified from Rodrigues, 2007).

Figure 12 shows the collapse strain modeling of Mark S-5, chosen for its proximity to the points of investigation at the PB-2 location. The base of the strip footing was 0.25 m in width, placed at 0.45 m in depth and under an applied load of 85 kPa. Despite the complexity of the scenario and the required simplifying assumptions, such as the initial suction profile based on historic data, the results of the modeling effort agreed reasonably with the measured collapse strains.

3.3 Swelling soils

In Brazil, swelling soils are often derived from igneous rocks such as basalt, diabase, gabbro, pyroxene, and feldspar. Sedimentary rocks with the clay mineral montmorillonite such as shales, marls and limestones can also be associated with expansive soils (Ferreira et al., 2013). As a result, swelling soils are very common and may be found in all regions of Brazil. In the state of Pernambuco, Brazil, the first studies on swelling soils date back to 1983 (Jucá & Lins, 1991). In the state of Ceará, swelling soils have been found in various locations, including the soil from Cariri, studied by the Geotechnical Research Group of the Federal University of Cariri. In the state of Ceará, swelling soils were also found in the municipalities of Juazeiro do Norte, Crato, Barbalha, Missão Velha, Santana do Cariri, Iguatu, Penaforte and Brejo Santo. Bandeira et al. (2015) and Batista et al. (2024) are examples of research works on swelling soils carried out in Ceará state.

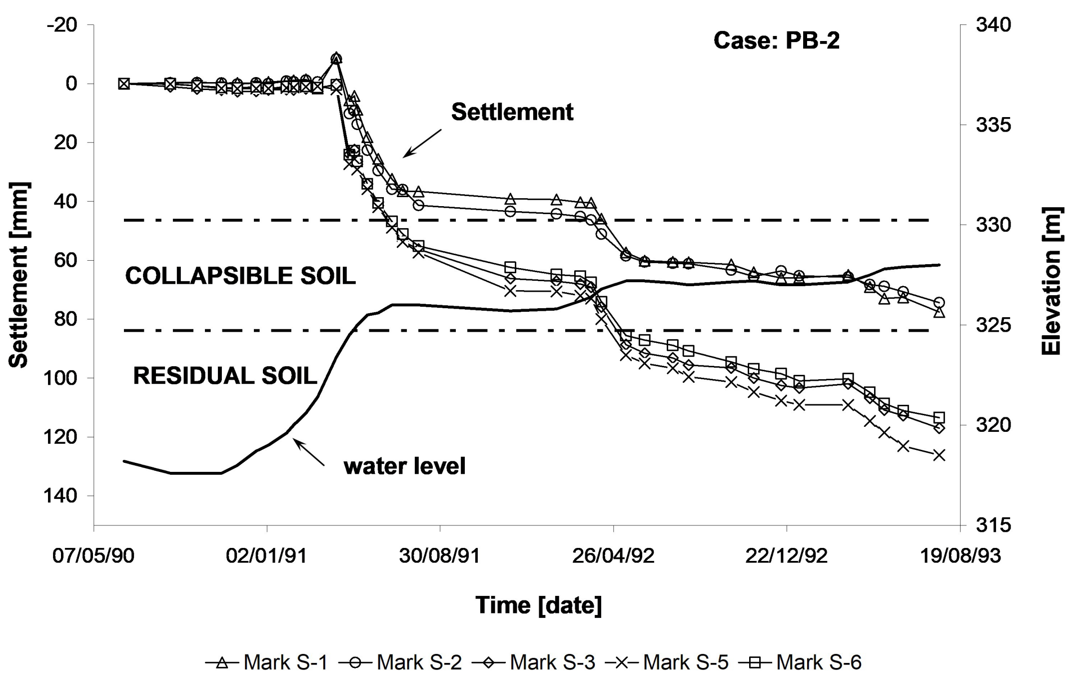


Figure 11. Soil profile, groundwater rising with time and settlement measured in the settlement marks installed in the building for Case PB-2 (modified from Rodrigues, 2007).

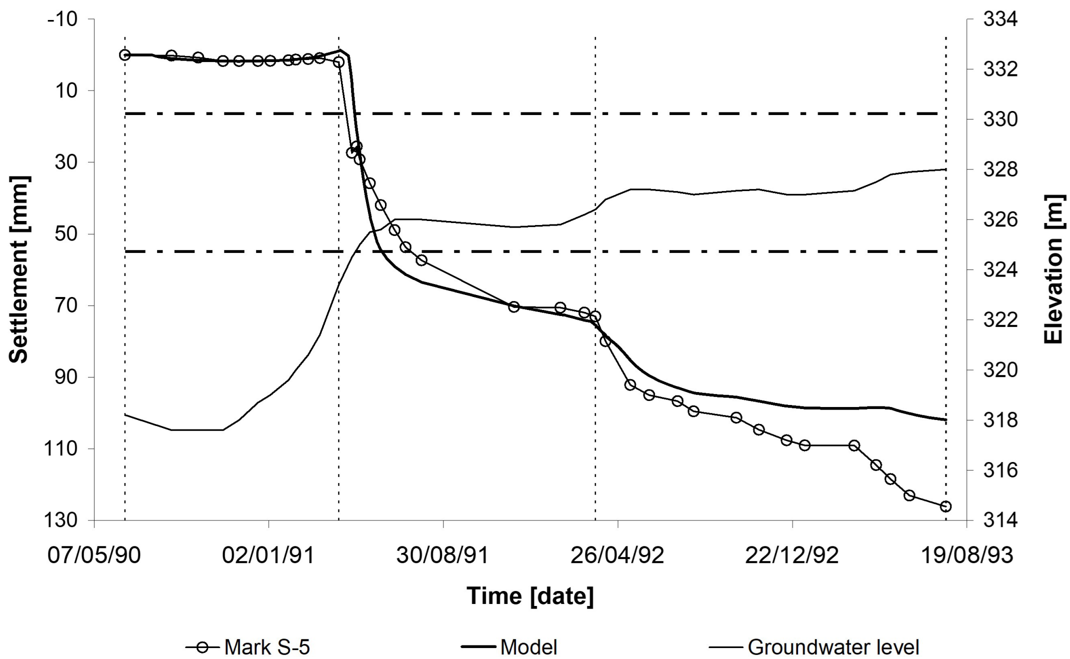


Figure 12. Comparison of measured and modeled settlements for Case PB-2 (modified from Rodrigues, 2007).

3.3.1 Swelling pressure and swell potential testing

Volume change testing using apparatuses that allow suction-control are sometimes used for the analysis of swelling soils. In Bahia, northeastern Brazil, studies involving suction date back to the 1980s (Pousada Presa, 1982). These publications presented important contributions to advancing the knowledge related to earth works in Brazil dealing with swelling soils.

The most cited methods in the literature for identifying swelling soils and determining swelling parameters can be classified into two categories: indirect and direct methods. Indirect methods are based on the mineralogical identification, physical indices, consistency limits, and soil texture (Jucá et al., 1997). Direct methods are based on the results of tests carried out in oedometer cells, in which the free swell potential and the swelling pressure are determined after flooding (Jucá & Lins, 1991). The free swell is determined as a percentage after stabilizing the deformations of the specimen, as follows:

$$SP(\%) = \frac{\Delta H}{H_i} \times 100\% \tag{5}$$

where: SP is the expansion potential; ΔH is the variation in the height of the specimen due to flooding; H_i is the height of the specimen before flooding.

Soil volume change depends on the vertical total stress. Depending on the vertical total stress, the soil can present expansion or collapse during flooding. The swelling potential depends also on the initial water content and pre-consolidation stress (Silva & Ferreira, 2007). Some soils investigated in Pernambuco, for example, showed swelling behavior when subjected to a vertical total stress of 160 kPa, with initial water contents below 18%. When the initial water contents were higher than 20%, collapse was observed for the same total vertical stress, as shown in Figure 13.

It is important to note that stress history and soil sampling also play a significant role in the determination of the swelling characteristics of a soil. Sampling, for example, may reduce the swelling potential and the swelling pressure. Therefore, free-swell curves could be compared to compressibility curves determined under constant water contents (i.e., using the double oedometer test procedure), to cancel out sampling disturbance and hysteresis effects.

Numerous direct testing methodologies are used to obtain the swelling pressure, as shown in Figure 14. Methods 1 and 3 are the most widely used in Brazil. The methods used to study the swelling pressure differ in terms of the stress paths, resulting in different values. The works by Justo et al. (1984) and Vargas et al. (1989) provide extensive discussions on the differences between different testing methodologies. It should be noted that a wide variety of equipment is used in Brazilian laboratories for studying the volumetric variation of unsaturated soils, both with and without suction control. Among the most widely used are conventional and suction-controlled oedometers. In oedometer tests with controlled suction, various stress and suction paths can be reproduced, improving the interpretation of results and helping to understand the behavior of unsaturated soils.

In 1987, the Technical Committee TC6 (Expansive Soils) of the International Society for Soil Mechanics and Foundation Engineering (ISSMFE) proposed a standardization of test procedures for swelling soils. The free swell was defined as the increase in volume corresponding to a token load of 1.0 kPa. The swelling pressure was defined as the stress applied to the soil that prevents it from changing volume. As for the initial moisture content in undisturbed samples, it was proposed that the initial moisture of the specimens should correspond to that of the driest season of the site studied. In the case of compacted soils, the initial moisture should be that corresponding to the shrinkage limit.

The need for standardization was presented once again in 1991, in Brasilia, Brazil, where several researchers met to discuss definitions, nomenclatures and testing methodologies for unsaturated soils. Unfortunately, to this date there is still no standard for identifying and classifying swelling soils in Brazil.

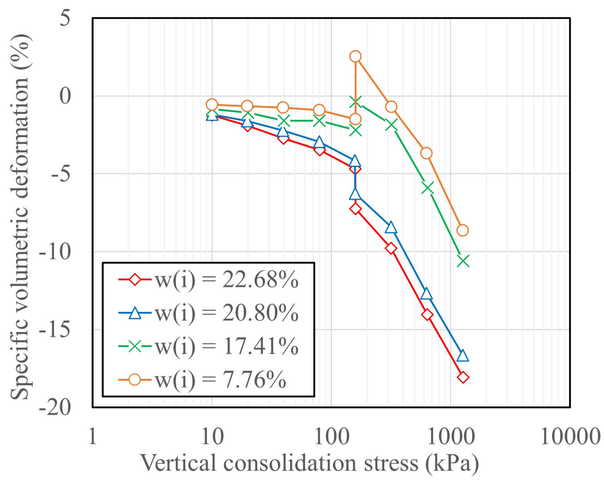


Figure 13. Volumetric deformation for several initial gravimetric water contents w(i) after flooding under a vertical stress of 160 kPa (modified from Ferreira & Ferreira, 2009).

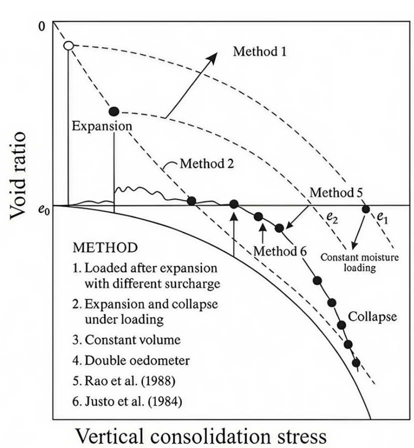


Figure 14. Methods for determining the swelling pressure, modified from Ferreira & Ferreira (2009).

3.3.2 Influence of wetting and drying cycles on soil swelling characteristics

Pousada Presa (1982) made an important contribution to the behavior of swelling soils subjected to wetting and drying cycles. Several complex factors may influence the soil volume change. For example, during wetting and drying cycles, the micropores may be converted into macropores due to loss of both fine and water-soluble cementing particles. Expansive soils may also present higher free swelling and swelling pressure values after the second wetting and drying cycles. However, some soils may suffer fatigue with each cycle and this process results in lower free swelling and swelling pressure values.

Oliveira & Cavalcante (2024) studied the effects of wetting and drying cycles on the swelling pressure and free swell of expansive soil from Aracaju city, Brazil, using oedometric tests. The specimens were subjected to eight wetting and drying cycles. The highest free swelling reduction rate was observed from the first to the second cycle. In the last cycle a free swelling reduction of approximately 62% was observed. In the second cycle the swelling pressure reduction rate observed was 72%. Afterwards, the specimen maintained the swelling pressure values observed in the other cycles, ranging from 100 kPa to 138.33 kPa. The authors concluded that the wetting and drying cycles have a remarkable influence on the swelling properties.

In shale soils or rocks, wetting-drying cycles can destroy cementations and digenetic bonds, increasing the soil's expansion potential (Skempton, 1953). However, cycles can also generate bonds (e.g., aluminum oxide bonds) and recrystallizations (e.g., iron oxide deposits) at different stages, which can decrease the soil's swelling characteristics (Allam & Sridharan, 1981). Further research is needed to understand this behavior in the wetting and drying cycles in Brazilian soils.

3.3.3 Swelling pressure and swell potential of some Brazilian soils

Table 2 summarizes the data on free swell and swelling pressure values of several Brazilian soils from the Northeast region. Most studies used Method 1, "loading after expansion", with different vertical consolidation stresses. The studies carried out on the swelling soils of Pernambuco between 1989 and 2001 showed that the clay fractions ranged from 24 to 74%, the silt fractions from 7% to 32% and the sand fractions from 3% to 63%. The void ratios of the soils studied ranged from 0.46 to 0.80. Suction varied between 5 MPa to 6 MPa during the region's dry season. The free swell potential, obtained with a token load of 5 kPa, varied from 1.6% to 33.3%. The swelling pressure was as high as 500 kPa, with higher values observed for the soils located

Table 2. Free swell and swelling pressure values of some Brazilian soils from the Northeast region.

Reference	State	Municipality	Soil type	Free swell (%)	Swelling pressure (kPa)
Silva & Ferreira (2007)	Pernambuco	Pesqueira	N/A	---	168
Ferreira & Ferreira (2009)		Petrolândia	silty clay	---	333
Paiva e Ferreira (2011)		Cabrobó	silty clay sand	---	90
Ataíde & Ferreira (2016)		Ipojuca	N/A	30	383
Paiva et al. (2015)		Paulista	highly compressible clay	10.5	300
Alves et al. (2015)	Sergipe	Aracaju	silty clay	27	300
Santana et al. (2022)		Nossa Senhora do Socorro	highly compressible clay	66	975
Bandeira et al. (2015)	Ceará	Juazeiro do Norte	highly compressible silt	18.5	377
Alexandre et al. (2022)		Juazeiro do Norte	silty clay	8.0-11.7	200-310
Batista et al. (2024)		Santana do Cariri	highly compressible clay	39	1700

in the metropolitan region of Recife. More information can be found in Ferreira (2007).

In Sergipe, clayey soils presented free swell of around 34% and swelling pressures of around 300 kPa. The void rations varied between 0.45 and 0.49 and the suction was approximately 10 MPa during the region's dry season (Cavalcante et al., 2007).

In the south of Ceará, studies were carried out in the municipalities of Santana do Cariri and Juazeiro do Norte stand out. In Santana do Cariri, the highly compressible clay soil, originating from shales and marls, showed a high expansion potential of 39% and swelling pressures around 1700 kPa (Batista et al., 2024). In Juazeiro do Norte, swelling potentials varying between 8% and 18.5% and swelling pressures between 200 kPa and 377 kPa were observed (Alexandre et al., 2022; Bandeira et al., 2015).

4. Geotechnical applications

Modeling and analyzing geotechnical problems involving unsaturated soils require careful attention to nonlinear soil properties and boundary conditions, as these govern the relevant hydraulic and mechanical processes. In certain cases, the problem may be primarily hydraulic, such as infiltration and water redistribution; in others, mechanical aspects related to suction variation, deformations, and stress conditions require a coupled hydro-mechanical analysis or a simple combination of flow analysis e limit equilibrium. Unsaturated soils are subject to both transient and steady flows, strongly influenced by local climatic and hydraulic conditions. Therefore, the practical application of USM is largely based on the soil water retention curve (SWRC).

The geometry of the problem plays a decisive role in the spatial distribution of suction, and consequently in flow patterns and shear strength. Atmospheric processes, such as seasonal variation of evaporation and precipitation, have a direct impact on the behavior of unsaturated soils. The soil's hydraulic and mechanical response to suction changes, whether due to drying or wetting, results from the interaction among stratigraphic, geometric, and climatic factors, and is strongly affected by surface drainage conditions and anthropogenic influences such as buried utilities and subsurface structures.

The following sections present real-world applications of USM concepts in various design and construction scenarios. The objective is not to provide guidance on how to apply these concepts, but rather to highlight their use in both routine and less common engineering cases.

4.1 Shallow foundations

Shallow foundations are particularly sensitive to the hydro-mechanical behavior of unsaturated soils, as they are typically embedded within the upper layers of the ground, commonly within the active zone, where variations in suction, degree of saturation and water content are most pronounced due to climatic effects (Sestrem et al., 2015; Bicalho et al., 2015). In such systems, seasonal conditions influence the apparent cohesion and stiffness of the soil. These changes can significantly alter the bearing capacity, potentially leading to differential settlements, loss of support, or variability in load test performance. Collapsible and swelling soils may introduce additional challenges related to high volume changes (Ferreira et al., 2013; Vilar & Rodrigues, 2015).

The fluctuation of suction and corresponding change in degree of saturation directly affects bearing capacity (Cintra et al., 2005). During the rainy season, a reduction in pile load capacity is commonly observed, associated with an increase in the degree of saturation and a consequent reduction in matric suction in the active zone and sometimes due to a rising water table. To account for unsaturated soil behavior, designers must: a) define the soil-water retention curve (SWRC) and hydraulic conductivity function; b) quantify seasonal suction variations through numerical modeling or field monitoring; c) ensure that load tests or quality control measures reflect representative conditions (e.g., dry vs. wet season scenarios); and d) adopt conservative design margins if seasonal moisture variations are not explicitly modeled. This approach ensures more robust and resilient performance of shallow foundations, especially in semi-arid or tropical regions where unsaturated conditions dominate the shallow subsurface. As a result, the design of this type of foundation will be affected by the foundation depth, applied loads, climatic regime, and depth of the active zone.

Seasonal effects have implications not only for the long-term performance of the structure but also for load tests conducted during construction. Such load tests can yield misleading results if variations in suction within the active zone are not properly considered. Therefore, these variations should be accounted for when performing load testing, to ensure proper assessment of foundation performance. When load tests are specified for shallow foundations, they are typically conducted under two distinct conditions: a) "natural", based on the soil condition at the time of testing. This "natural" condition must be interpreted carefully; b) "saturated", following the application of a predefined quantity of water, intended to simulate a critical condition.

The saturation process does not always achieve the intended outcome, namely, the reduction of suction to zero. Analytical studies show that the commonly used saturation method by surface flooding often fails to induce full saturation, and when effective, it typically impacts only the top 30 cm of soil after 2 hours or up to 80 cm after 7 days. This depth may not be sufficient to influence the foundation behavior significantly. In contrast, natural infiltration caused by climatic events can lead to deeper and more pronounced wetting fronts. Simple numerical analyses can be used to evaluate the influence of different moisture conditions on soil behavior, indicating that real rainy season conditions may result in more critical saturation states than artificial wetting procedures (Machado et al., 2003).

As a practical example of USM principles, consider short piles subjected to pullout loads, a common scenario in solar panel foundation systems. A simplified evaluation can be performed using the following equation, from Hamid & Miller (2009), which incorporates the effect of suction on pullout resistance:

$$\tau_f = c_a' + (\sigma_{nf} - u_{af})\tan\delta' + (u_{af} - u_{wf})\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)\tan\delta' \tag{6}$$

where: τ_f is the shear strength; $(\sigma_{nf} - u_{af})$ is the net normal stress on the failure plane at failure; $(u_{af} - u_{wf})$ is the matric suction on the failure plane at failure; c_a' is the effective adhesion intercept for the interface; δ' is the interface friction angle with respect to net normal stress; θ is the current volumetric water content, θ_r is the residual volumetric water content, and θ_s is the saturated volumetric water content.

The analysis begins by defining suction profiles over the desired time period, which can be obtained using public-domain software such as Hydrus 1D. Once suction profiles are established (Figure 15a), the pullout resistance can be estimated over time and along the profile depth (Figure 15b). This straightforward analysis demonstrates that pullout capacity is highly influenced by the degree of saturation. It also underscores the critical importance of considering seasonal climatic effects in both the design and quality control of shallow foundations. More comprehensive seepage modeling may also allow the consideration of the land use characteristics (e.g., vegetation cover changes, pipe leaks).

4.2 Slope stability

The stability of natural slopes is often characterized by relatively low factors of safety (FS) when analyzed under the conventional framework of saturated soil mechanics. This apparent "low FS" results from the fact that such analyses disregard the contribution of matric suction present in unsaturated soils, which, in practice, acts as an additional stabilizing mechanism. When planning any anthropogenic intervention, such as cuts, embankments, or retaining structures, a minimum FS is required, based on normative and conservative criteria, which often leads to the adoption

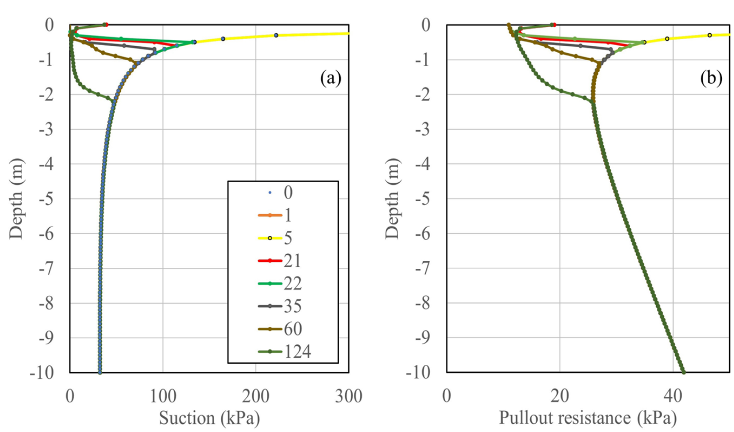


Figure 15. Effect of weather conditions on short piles: (a) suction profiles; and (b) pullout resistance profiles.

of complex and costly structural solutions. While technically prudent, this approach frequently results in the overestimation of the necessary stabilization measures, especially when the role of suction is neglected.

This scenario gives rise to a fundamental dilemma: can the persistent presence of suction be trusted as a stability factor? The answer is not trivial, as suction is not a constant variable; it depends directly on the soil moisture conditions, which vary according to precipitation patterns, vegetation cover, geomorphology, surface drainage, and other environmental factors. To address this issue, USM offers a theoretical and practical framework that enables the quantification of suction's role in soil shear strength, in a way that is consistent with the temporal and spatial variations in moisture content. Through coupled analyses of transient flow and limit equilibrium stability, it becomes possible to simulate how infiltration resulting from rainfall events affects suction profiles over time and, consequently, the factors of safety.

This approach allows for: a) realistically capturing the contribution of suction during dry periods, avoiding overdesign; b) assessing the risk of suction loss during critical rainfall events, identifying the most vulnerable periods; and c) establishing more refined design and monitoring criteria, based on the hydraulic and mechanical behavior of the soil in its natural condition. Therefore, the use of USM does not imply neglecting safety but rather addressing it with greater technical rigor and alignment with the reality of natural slopes, cuts, and fills. It simultaneously serves as a tool for both resource optimization and risk management, provided it is grounded in adequate flow models, realistic infiltration assumptions, and parameters obtained through specific testing and addressing filed conditions.

Each step of the analysis must be carefully designed, starting from a representative geometric model, which applies to both natural slopes and those that have undergone human intervention. The analysis should begin with the definition of a conceptual model that adequately represents the slope geometry, the involved stratigraphy, and any containment or reinforcement elements. The model should include all relevant soil layers, potential rock interfaces, structures such as soil-cement bags or nails, and representative hydraulic boundary conditions based on field conditions.

Shear strength parameters should be determined through specific laboratory tests. Whenever possible, triaxial tests under varying suction states are recommended, allowing for the direct definition of the unsaturated strength envelope. Alternatively, unconfined compression or direct shear tests under controlled moisture conditions can be used, with subsequent calibration of the parameters for models such as Vilar (2007). Hydraulic parameters should be obtained through laboratory testing or model-based estimation based on the SWRC and the saturated hydraulic conductivity.

Numerical analysis should be performed using software capable of coupling unsaturated water flow with limit equilibrium stability analysis. The modeling must account for both spatial and temporal variations in suction, integrating these results into the shear strength evaluation over time. Transient flow modeling, which remains uncommon in practice, should be carried out, using at least one of the following approaches:

- Imposed infiltration: a constant infiltration flux is imposed, equivalent to the saturated hydraulic conductivity of the soil (K_s), for a defined period, simulating extreme events. It is emphasized that soil cannot accommodate infiltration rates greater than K_s for extended periods of time. However, in the initial stages, hydraulic gradients can be very high due to the presence of suction at the soil surface. The infiltration duration should be chosen carefully, considering the climatic conditions of the study site;
- Realistic climatic regime: a historical series of local precipitation is used, along with evapotranspiration data, allowing for the simulation of wetting and drying cycles. In this case, hydrological data must be critically evaluated to determine whether daily records or monthly averages are more appropriate, depending on the level of detail required.

Boundary conditions must be carefully defined to represent surface drainage systems, impermeable layers, and free-drainage edges, in accordance with field observations. A critical aspect is the definition of the initial suction condition. To avoid overestimating this initial condition, it is recommended that simulations span a sufficiently long period (multiple years), thereby minimizing the influence of uncertain starting values.

With the suction profiles generated by the flow analysis, stability verification is carried out using the limit equilibrium method. Shear strength is updated at each time step, considering the effect of suction on apparent cohesion. The critical failure surface may vary over time, reflecting changes in the soil's hydraulic state.

The factors of safety obtained should be evaluated based on their minimum values throughout the simulated period and compared to the applicable design standards. This approach allows for identifying critical periods of suction loss, informing the planning of drainage works, and guiding more effective strategies for slope monitoring and maintenance.

4.3 Filtered tailings stacks

USM is essential for assessing the hydraulic and mechanical behavior of filtered tailings stacks over time. Understanding the mechanisms associated with moisture and suction variation, particularly its relationship with shear strength, supports not only the design and operation of these structures, but also long-term monitoring actions and closure strategies. A key aspect to be considered is the SWRC. Based on this curve, it is possible to realistically estimate the behavior of the stack under varying climatic and operational conditions. Capillary rise can contribute to the increase in degree of saturation, including regions near slopes, which may lead to suction loss and a corresponding reduction in shear strength.

Moreover, infiltration induced by precipitation events or failures in surface drainage systems can lead to partial or even full saturation of the structure. This condition is especially critical when considering the liquefaction potential of the tailings. Even when the material has been compacted according to safe state parameters, such as a void ratio below the critical state and controlled density, eventual full saturation may place the system in a condition of potential instability, whether due to dynamic loading or unexpected increases in static loads.

Filtered tailings stack design should be based on transient infiltration analyses under representative climatic series. This approach would allow the identification of zones susceptible to suction loss and potential transition to saturation. The active zone, i.e., the portion of the stack subject to significant variations in moisture and suction, should be treated as a key element in the design, operation, and placement of monitoring instrumentation. Finally, fully saturated scenarios must also be considered in stability assessments and in the planning of preventive measures. The use of surface covers, efficient drainage systems, and continuous monitoring of moisture and suction are fundamental strategies to prevent water accumulation from driving the material into critical conditions of saturation and strength loss, with a consequent risk of liquefaction.

4.4 Pavement structures

Subgrade soils are generally situated above the water table level, exhibiting unsaturated behavior. Climate-environmental conditions, such as rainfall, temperature, vegetation, and wind, as well as drainage conditions, result in changes in water content and matric suction. Such changes impact both elastic and plastic deformations of pavements, thus representing important factors to consider in the long-term behavior. Therefore, the matric suction constitutes an essential variable for the understanding of pavement behavior in response to climate-environmental factors. The earliest studies on the influence of unsaturated soil behavior in pavement structures were presented by Gerrard et al. (1975), Fredlund et al. (1975), Jin et al. (1994) and Phillip (1994).

Gerrard et al. (1975) observed a nonlinear relationship between the resilient modulus (M_R) and matric suction. Fredlund et al. (1975) showed that the resilient behavior of road subgrade soils is dependent on three stress-state variables: deviator stress (σ_d), confining stress (σ_3 - u_a), and matric suction (u_a - u_w). Jin et al. (1994) proposed an M_R model for swelling subgrade soils which considers changes in stress states, water content, and pavement temperature. Phillip (1994) highlighted the importance of accurately determining the changes in water content in the field to predict the M_R of subgrade soils.

In Brazil, a pioneering study was presented by Gehling et al. (1998), wherein the influence of soil suction on the resilient behavior of compacted lateritic soils in road pavement subgrades was investigated. The study was carried out through laboratory and field tests. In the laboratory, the relationship between M_R and matric suction was determined through dynamic triaxial tests with measurement of matric suction using a pressure transducer. The authors have shown that an increase in matric suction results in an increase in M_R up to a certain maximum value. Thereafter, M_R decreases or remains constant for any level of σ_d, as shown in Figure 16.

Gehling et al. (1998) also investigated the effects of matric suction on the resilient behavior of pavements in the field. The subgrade matric suction of test tracks was monitored over two years using jet-fill tensiometers. The matric suction was measured before, during, and after the application of load by a traffic simulator. Data from deflection basins measured on the pavement surface were used to back-calculate the in-situ M_R. The matric suction was relatively low in this case, ranging from 0 to 14 kPa. However, the effect on the subgrade back-calculated M_R was significant, as shown in Figure 17.

Soil suction values of the same order of magnitude were found by Castro et al. (2021) in a study of the influence of water content and suction changes on the hydro-mechanical behavior of railroad subgrades. In this study, field monitoring of soil suction was performed using five sensors installed at different depths in the subgrade of a test track section. Subsequently, field suction data were compared with numerical simulation results. The authors observed that the subgrade soil tends to reach a state of equilibrium influenced by local climatic conditions and does not return to its original compaction condition. In this case, following a period of 150 days (5 months), the hydraulic behavior of the soil began to be controlled by the local climatic conditions. Soil suction values were observed to range from 0 kPa during the wet season to 20 kPa during the dry season. The authors also observed

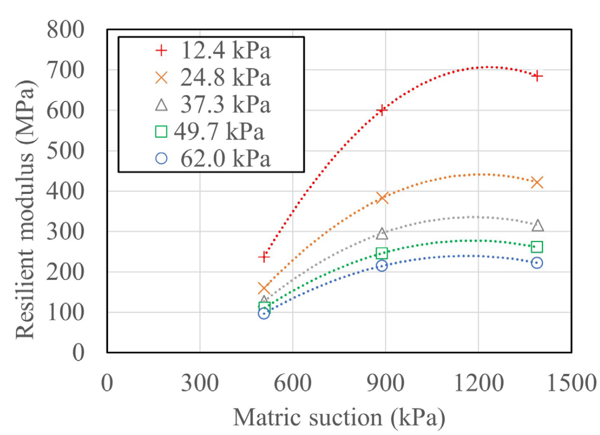


Figure 16. Relationship between M_R and matric suction, for values of deviator stress ranging from 12.4 kPa to 62.0 kPa (modified from Gehling et al., 1998).

that the changes in soil suction are more pronounced in the zones subjected to atmospheric action than in those situated beneath the ballast and sub-ballast layers. This finding shows the important contribution of evaporation in increasing soil suction in zones near the subgrade surface.

Ceratti et al. (2004) evaluated the effects of compaction methods and water content on the resilient deformations of lateritic soils. The results are shown in Table 3. Ceratti et al. (2004) observed that the M_R of specimens compacted in the wet branch (w_{opt} + 2%) was not significantly affected by the compaction method. However, the compaction method did affect the M_R of specimens compacted at w_{opt}. In this case, the M_R values of the specimens compacted by the static method were found to be 140% higher than those of the specimens compacted by the dynamic method, and 220% higher than those obtained by kneading. The specimens compacted in the dry branch (w_{opt} - 2%) exhibited a similar trend. In general, the specimens compacted by kneading exhibited lower M_R values than the other methods. It is important to consider this aspect, as in the field, lateritic soils are typically compacted with sheep-foot rollers, which reproduce compaction similar to the kneading method. Therefore, specimens compacted by the static method in a laboratory setting may yield higher M_R values than those obtained effectively in the field.

Similar findings were reported by Camapum de Carvalho et al. (1987) in a study on the influence of semi-static, vibro-static, and dynamic compaction methods on the mechanical behavior of soils. In this case, the authors studied the compressive strength of a cohesive soil. The authors observed that the soil compacted using the semi-static method exhibited greater resistance than the material compacted in the field.

Freitas et al. (2020) investigated the unsaturated resilient behavior of lateritic and non-lateritic soils. The authors showed that the relationship between M_R and stress-state variables depends on the degree of laterization. In this sense, it was observed that the M_R of the lateritic soil was more sensitive to changes in water content and matric suction than the non-lateritic soil, considering a comparable range of water content deviation from optimum condition (w-w_{opt}). In this case, given a matric suction range of 51 kPa (between 69 and 120 kPa), the M_R values of the non-lateritic soil varied between 135 MPa and 160 MPa. In the case of the lateritic soil, a wider variation of M_R was observed, with values ranging from 279 MPa to 768 MPa for a matric suction range of 69 kPa (between 5.9 kPa and 71 kPa). Although the mechanical behavior of the lateritic soil was superior to that of the non-lateritic soil, these results highlight the importance of accounting for changes in water content and matric suction to predict M_R.

Another research topic of interest has been the influence of seasonal variations on the unsaturated resilient behavior of tropical soils in pavement structures. In recent years, studies were presented by Ceratti et al. (2004) and Weber et al. (2014). Ceratti et al. (2004) investigated the influence of seasonal variations on the M_R of compacted lateritic soils

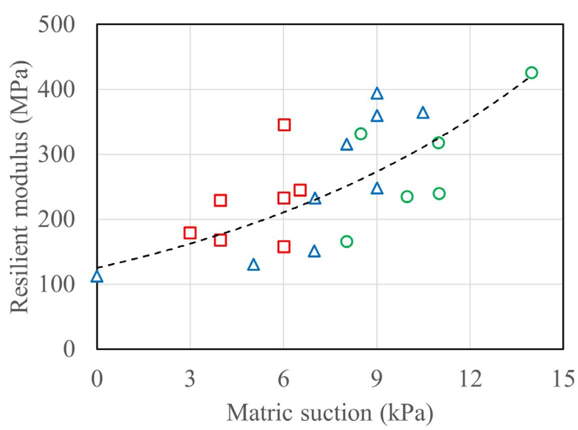


Figure 17. Influence of matric suction on soil back-calculated M_R (modified from Gehling et al., 1998).

Table 3. Effects of compaction methods and water content (w) on soil resilient modulus (Ceratti et al., 2004).

Compaction Method	w (%)	k_1 (MPa)	k_2	r^2 (%)	M_R (MPa) range (*)
Static	w_{opt} + 2%	116	-0.64	91	133 - 181
Dynamic	w_{opt} + 2%	147	-0.01	2	147 -147
Kneading	w_{opt} + 2%	134	-0.32	78	143 - 167
Static	w_{opt}	746	0.01	1	741 - 744
Dynamic	w_{opt}	293	-0.11	62	300 - 316
Kneading	w_{opt}	216	-0.16	77	224 - 242
Static	w_{opt} - 2%	788	-0.09	40	804 - 839
Dynamic	w_{opt} - 2%	610	-0.15	50	630 - 676
Kneading	w_{opt} - 2%	430	-0.03	8	433 - 439

(*) Corresponding to deviator stresses (σ_d) varying from 50 kPa to 80 kPa and theoretically acting 30 cm below granular bases of the sections constructed in the Pavement Testing Facility. Legend: w is the water content; M_R is the resilient modulus, $M_R = k_1 \left(\sigma_d / 100\right)^{k_2}$; σ_d is the deviator stress in kPa; k_1 and k_2 are the model regression constants; w_{opt} is the optimum water content.

of road subgrades. The authors showed that the wetting and drying paths remarkably affect the M_R. Figure 18 shows the variation of M_R as a function of σ_d of specimens compacted at optimum water content (w_{opt} = 21%) that were subsequently subjected to drying (w = 19%) and wetting (w = 23%) paths. The authors observed that the M_R values of specimens subjected to the drying path increased slightly. Conversely, the increase in water content of the specimens subjected to the wetting path leads to a significant decrease in the M_R values. Additionally, it was observed that the M_R tends to be independent of the stress state for σ_d levels higher than 60 kPa, thereby characterizing a state of linear elastic behavior.

Weber et al. (2014) studied the resilient behavior of tropical soils subjected to wetting and drying paths. The authors observed that the M_R values of specimens compacted in the dry branch or subjected to drying paths increased with the increase in σ_d, in contrast to the behavior expected for cohesive soils. Conversely, the M_R values of the specimens compacted in the wet branch or subjected to wetting paths decreased significantly with the increase in σ_d. In this case, the M_R values of the specimens subjected to a wetting path were remarkably lower than those of the specimens compacted in the wet branch.

The soil resilient modulus is an important property on mechanistic-empirical pavement design methods. However, classic models do not consider properties related to changes in water content and/or matric suction. In Brazil, prediction models have been proposed by Ceratti et al. (2004), Freitas et al. (2020) and Gonçalves (1999).

Ceratti et al. (2004) proposed a straightforward equation based on field data monitoring. In this study, the M_R of a compacted lateritic subgrade soil was determined by back-analysis based on deflection basins measured on the pavement surface of a test track. Soil suction was measured during the tests using jet-fill tensiometers. The measured soil suction values did not exceed 14 kPa and therefore the proposed model is valid for low matric suction levels. The proposed model is as follows:

$$M_R = 142 + 16.9(u_a - u_w) \quad (7)$$

where: M_R is the resilient modulus in MPa; (u_a - u_w) is the matric suction in kPa.

Gonçalves (1999) proposed a prediction model that considers M_R as a function of σ_d and matric suction, as expressed in Equation 8:

$$M_R = k_1 {\sigma_d}^{k_2} {\psi_m}^{k_3} \quad (8)$$

where: M_R is the resilient modulus in MPa; σ_d is the deviator stress; ψ_m is the matric suction in kPa; k_1, k_2, and k_3 are the model regression constants.

Freitas et al. (2020) proposed a model based on statistical analysis of seven equations from the literature. The model was validated using M_R data from different soil types collected from the literature. The model is also proven applicable to both lateritic and non-lateritic tropical soils. Equation 9 presents the proposed model, which includes two independent stress-state variables, and a third state variable that accounts for the water content deviation from the optimum conditions:

$$M_R = e^{k_1 - k_2 (w - w_{opt})} {\psi_m}^{k_3} \Delta^{k_4} \quad (9)$$

where: M_R is the resilient modulus in MPa, (w-w_{opt}) is the water content deviation from the optimum water content, ψ_m is the matric suction in kPa, Δ is the total stress state variable that has the highest correlation with M_R, and k_1, k_2, k_3, and k_4 are the model regression constants.

Although several studies on the unsaturated behavior of tropical soils in pavements have been published in recent decades, little attention has been paid to the effects of water content and soil suction on permanent deformation. In Brazil, studies were presented by Núñez et al. (2011) and Santos et al. (2024).

Núñez et al. (2011) showed the important role of soil suction on the permanent deformation of tropical soils in low-volume roads. The authors evaluated the permanent deformation of a saprolitic soil compacted at different water contents (w_{opt} and w_{opt} + 2%), and dry unit weights (γ_{dmax} and 0.90 x γ_{dmax}). As shown in Figure 19, the accumulated permanent deformation of the specimen compacted at w_{opt} and γ_{dmax} was close to 4%, whereas the deformation of the specimen compacted at w_{opt} + 2% and γ_{dmax} continuously increased up to failure. In this case, the difference in soil suction was an important factor in the observed behavior.

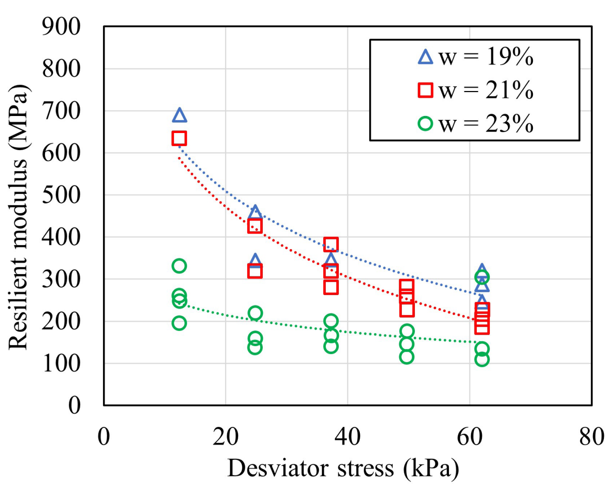


Figure 18. M_R of specimens submitted to drying or wetting paths (modified from Ceratti et al., 2004).

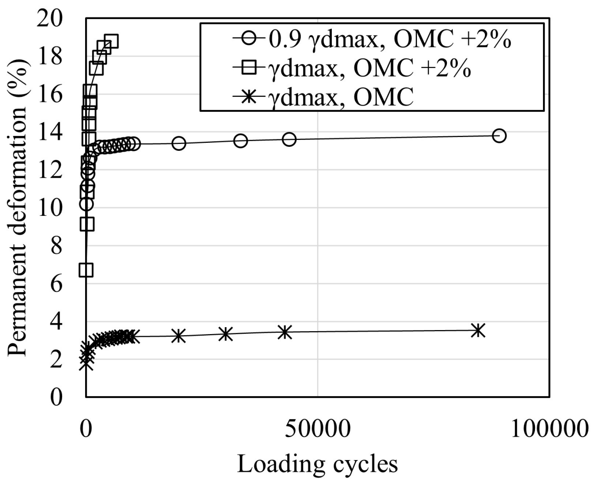


Figure 19. Permanent deformation evolution in specimens with different compaction degrees and water contents, where OMC is the optimum water content (Núñez et al., 2011).

The specimen compacted at w_{opt} and γ_{dmax} achieved a degree of saturation of 76%, corresponding to a matric suction of 10 kPa. In contrast, the specimen compacted at w_{opt} + 2% and γ_{dmax} achieved a degree of saturation of 83%, corresponding to a matric suction of 50% lower (5 kPa). Although it may seem negligible, this variation in soil suction was important to the soil's permanent deformation behavior.

Figure 19 shows that the specimen compacted at w_{opt} + 2% and a lower dry specific weight (0.90 x γ_{dmax}) did not fail despite the extremely high initial deformations. In this instance, the soil suction was once more a significant factor influencing the observed behavior, given that the degree of saturation was lower (S = 66%), corresponding to a higher matric suction level than that of the specimen compacted at w_{opt} + 2% and γ_{dmax}. Based on this, Núñez et al. (2011) argue that paving standards should specify the degree of saturation to control compaction moisture deviations instead of water content, as it consists of a parameter that combines water content and void ratio.

Santos et al. (2024) presented a study on the effects of water content and soil suction on the permanent deformation of three tropical soils with different geological-geotechnical characteristics. It was observed that due to the microstructural changes caused by the compaction process, the specimens compacted in the wet branch had greater water storage capacity and increased permanent deformation. Furthermore, the authors highlighted the importance of matric suction in representing the effects of water content variations on the plastic deformation of soils subjected to cyclic loading.

In this sense, Santos et al. (2024) proposed a permanent deformation prediction model that considers the influence of matric suction. The proposed model, expressed in Equation 10, considers permanent deformation as a function of the deviator stress, confining stress, the number of cyclic load applications, matric suction, and water content deviation from the optimum water content.

$$\varepsilon_p(\%) = \left(\frac{\sigma_3}{\rho_0}\right)^{\psi_1}\left(\frac{\sigma_d}{\rho_0}\right)^{\psi_2} (N)^{\psi_3}\left(e^{\psi_4-\psi_5\cdot(w-w_{ii})}\right)\left(\frac{\psi_m}{\rho_0}\right)^{\psi_6} \tag{10}$$

where: ε_p (%) is the specific permanent deformation, σ_3 is the confining stress, σ_d is the deviator stress, N is the number of loading cycles, ρ_0 is the atmospheric pressure (0.1 MPa or 100 kPa, depending on the stress unit), (w-w_{opt}) is the water content deviation from the optimum water content, ψ_m is the matric suction, and ψ_1, ψ_2, ψ_3, ψ_4, ψ_5 and ψ_6 are the parameters of the model.

5. Geoenvironmental applications

5.1 Contaminant effects on the hydraulic behavior of unsaturated soil

Soil contamination may affect the behavior of unsaturated soils. When a second non aqueous phase (NAPL) is present in the soil's interstitial voids, the wettability order dictates the fluids' distribution among small and larger pores and a second HAEV is necessary to measure the pressures in the phases air, NAPL and water. Some Brazilian researchers have investigated these effects, considering several practical applications.

Cardoso (2011) developed a modified Richards' chamber for SWRC determination in multiphase systems with air, water, and a non-aqueous phase liquid (NAPL) as interstitial fluids. Two HAEV porous stones are used, one of them having its surface modified by the silanization technique (Lenhard & Parker, 1988). The silanization process is used in chromatography to modify silicon and metallic oxide surfaces (Sousa et al., 2011), giving them stiffness, thermal stability, and, mainly, hydrophobic characteristics. At the end of the process, a thin hydrophobic layer is created, changing the wettability order of the three liquid phases from water-NAPL-air in standard porous stones to NAPL-water-air in silanized ones. Having two HAEV porous stones is fundamental in monitoring multiphase flow to separate suction measurements in water and NAPL phases (e.g., using hydrophilic and hydrophobic tensiometers) (Sousa, 2012; Sousa et al., 2011, 2019) or when determining experimentally multiphase soil liquid retention curves (Cardoso, 2011). Figure 20 illustrates the development of suction registered by two tensiometers during a water evaporation followed by diesel saturation experiment performed in a dune sand (Sousa et al., 2011). In Figure 20a, both tensiometers have a standard tip; one is filled with water, and the other with diesel. As observed, the oil and water tensiometers measured similar suctions during water evaporation. After pouring diesel over the sample, the suction values in the oil tensiometer dropped immediately, while the suction recorded in the water tensiometer presented a decrease over time. This behavior contrasts with Figure 20b, where the oil tensiometer has a silanized tip. In this case, the oil tensiometer is almost insensitive to water suction as the water evaporation progresses.

After the diesel injection, the suction in the silanized tensiometer was reduced immediately to zero. In contrast, the water suction was reduced from 47.2 kPa to 7 kPa, reflecting

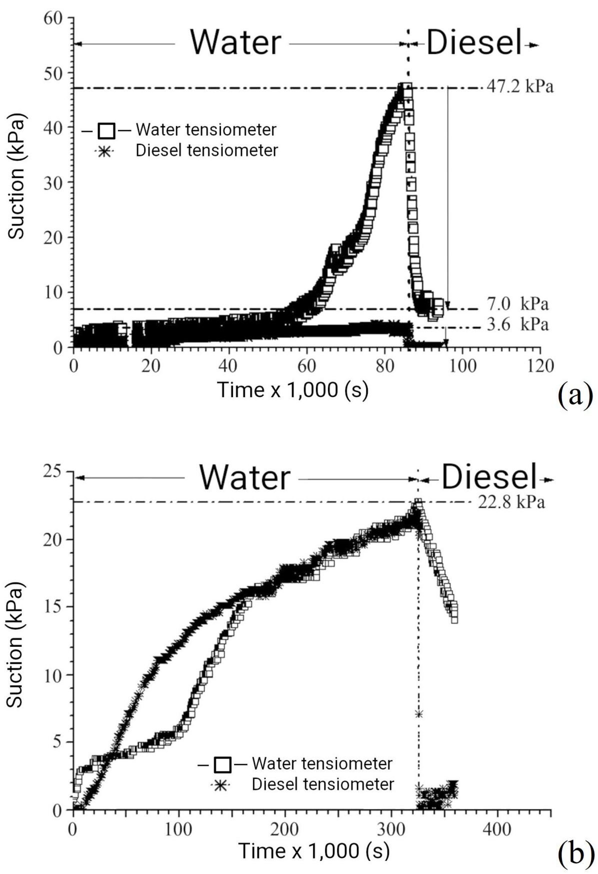


Figure 20. Performance of the tensiometers with: (a) standard porous tip; and (b) the silanized tip (Sousa et al., 2011).

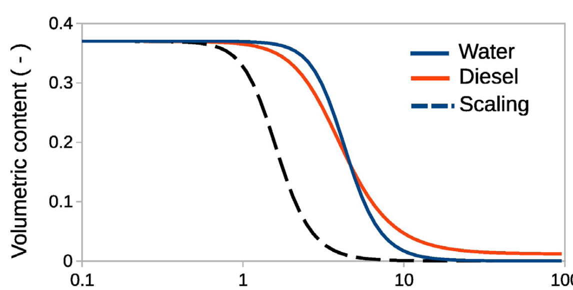


Figure 21. Fitted soil-liquid retention curves and soil-Diesel capillary scaling curve.

the menisci formation in the diesel/water interface. Figure 21 illustrates the soil-liquid characteristic curves (SLRC) obtained for diesel and water in a dune sand specimen. The experimental results are compared with those predicted by capillary scaling; a technique largely used in multiphase flow modeling to estimate the SLRC from the SWRC. As observed, capillary scaling for this specific case is not acceptable, leading to curves that disagree with experimental data.

The developed hydrophilic and hydrophobic tensiometers were used successfully by Sousa (2012) and Sousa et al. (2019) in an instrumented channel to perform two-dimensional infiltration experiments with diesel and water as the permeate liquids.

5.2 Contaminant effects on the shear strength of unsaturated soil

Not only are the hydraulic properties of the soil affected by the presence of a third fluid in the interstitial voids. The NAPLs, besides having an intermediate wettability (wettability order in most nor organic soils: water - NAPL – air) and superficial tension (20-30 mN/m for most NAPL and 70.75 mN/m for water at 20 °C), have often a low polarity and, as a consequence, a low relative dielectric constant ($\varepsilon_r \sim 2$) compared to water, which has ε_r around 80. In a micro scale, a variety of mechanisms control the soil-fluid interactions, and the double layer theory is a fundamental concept to address these interactions. The presence of NAPL reduces the diffuse layer thickness, approaching the solid particles. According to Coulomb's law, a decrease in ε will increase the attraction/repulsion intensity of the forces between the particles, changing the balance of forces around the clay particles (Machado et al., 2023).

Almeida (2019) and Almeida et al. (2020) studied the shear strength behavior of soil specimens with different saturations of water, ethanol, and diesel, besides completely dried (of fully saturated by air) specimens. The authors developed an empirical model to predict the soil shear strength as a function of the difference between the relative dielectric constant of the water (ε_{rw}) and the interstitial fluid (ε_{rf}), which presented a good adherence between experimental and predicted results. More recently in Machado et al. (2023), the same dataset was used to extend the expedite procedure proposed by Vilar (2007) to estimate the unsaturated soil's shear strength for other fluids than water. In the model by Vilar (2007), a hyperbolic relationship predicts the soil shear strength gains with suction - see Equation 11 and Equation 12. Figure 22 illustrates the expansion proposed by the authors. The dried samples (interstitial fluid with $\varepsilon_r \approx 1$) still render the ultimate shear strength. However, if fluids with different relative dielectric constants are used, the initial saturated shear strength must be modified accordingly. The saturated specimens increase their shear strength as ε_r decreases. Specimens with diesel as interstitial fluid, which has an $\varepsilon_r \approx 2.13$, have a saturated shear strength that is already close to the values obtained by dried samples, which have air as interstitial fluid ($\varepsilon_r \approx 1.0$). Therefore, the shear strength gain

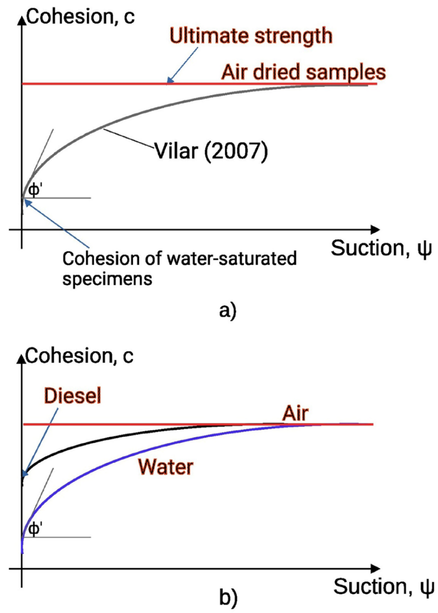


Figure 22. Modeling the effect of contaminants on the unsaturated shear strength: (a) original Vilar (2007) model; and (b) model extension for different fluids (modified from Machado et al., 2023).

by suction in the drying process is limited compared to water, which presents a value of $\varepsilon_r \approx 80$.

Furthermore, the authors (Machado et al., 2023), using Bishop's equation (Bishop, 1960) developed an equation for SLRC that ensures the shear strength converges to the values predicted by Vilar (2007) for $\psi \to \infty$. This is done by equaling the shear strength gains by suction in both equations:

$$\frac{\psi}{\tan(\phi)^{-1} + \dfrac{\psi}{c_{ult} - c'}} = \chi \psi \tan(\phi) = (S)^{\alpha} \psi \tan(\phi) \tag{11}$$

where: ψ is the suction; ϕ is the angle of shear strength; c_{ult} is the shear strength ultimate or unsaturated residual value; c' is the effective cohesion; χ is the Bishop's parameter of effective stress; S is the degree of saturation; α is a soil parameter.

Rearranging the terms results in Equation 11 results:

$$S = \left[1 + \frac{\psi \tan(\phi)}{c_{ult} - c'}\right]^{-1/\alpha} \tag{12}$$

where: S is the degree of saturation; ϕ is the angle of shear strength; c_{ult} is the shear strength ultimate or unsaturated residual value; c' is the effective cohesion; χ is the Bishop's parameter of effective stress; α is a soil parameter.

The adoption of $\chi = S^{\alpha}$ is based on the study by Alonso et al. (2010) concerning the applicability of effective stress equations for unsaturated soils based on stiffness and shear strength experimental data. According to the authors, defining effective stress for unsaturated soils requires the definition of a single stress variable that encompasses total stress, suction, and sometimes the degree of saturation. The main concern in the case of assuming $\chi = S$ is its evolution as suction increases. To preserve physical feasibility, the product $\chi\psi$ cannot tend to infinite values when imposing drying paths because it would imply an indefinite soil compression. The authors used different SWRC equations to analyze the behavior of $\chi\psi$. They concluded that to prevent $\chi\psi$ from tending to infinite values, χ must tend to zero more rapidly than S when suction increases. Still, according to the authors, assuming that:

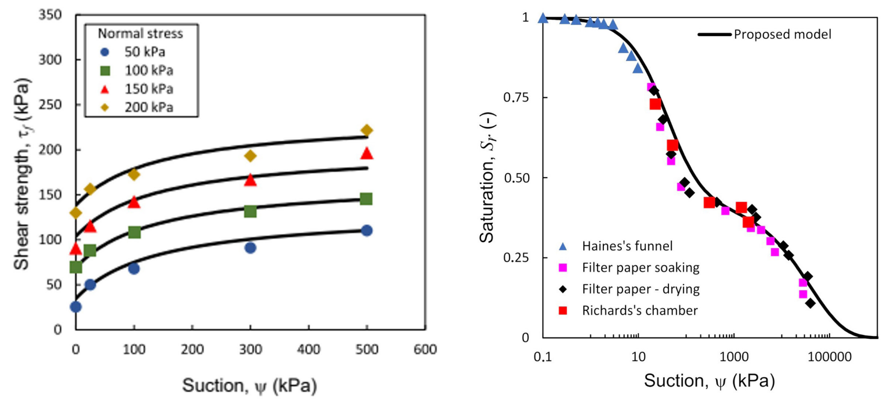
$$\chi = S^{\alpha} \cdot \alpha \geq 1 \tag{13}$$

can satisfy this requirement, where α is a soil parameter that helps better to represent the suction influence on the effective stress. In their work, α values varied from 2 to 6.5 for different soils and SWRC equations. Coupling $S^{\alpha}\psi$ (Machado et al., 2023) with shear strength parameters ensures the convergence in the soil shear strength for high suction values. According to the authors, the use of a constant α is enough for continuous SLRC and soils having a high air entry value. However, for more general retention curves, including those with bimodal behavior, the following equation can be used:

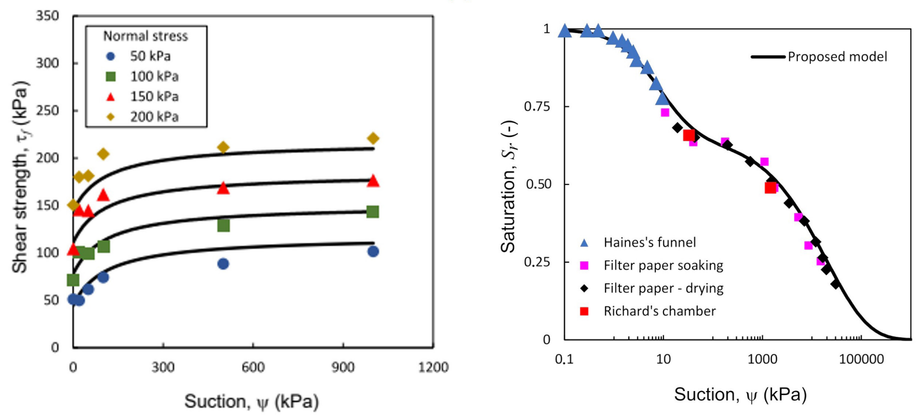
$$-\frac{1}{\alpha} = \left[\frac{\ln(S_r)}{1 + \dfrac{(\aleph + \quad {}_{in})\tan(\quad)}{c_{ul} - c'}}\right] - \left(\frac{\psi}{1 \cdot 10^{6}}\right)^{\alpha_p} \left[\frac{\ln(0.001)}{1 + \dfrac{10^{6}\tan(\phi)}{c_{ul} - c'}}\right] \tag{14}$$

where: α is a soil parameter; S_r is the residual degree of saturation; ψ is the suction; ψ_{in} is the suction corresponding to the inflection point of SLRC; ϕ is the angle of shear strength; c_{ult} is the ultimate shear strength or unsaturated residual value; c' is the effective cohesion; α_p is the size of the transition between micro and macro pores.

Three parameters are required: S_r and ψ_{in}, the suction corresponding to the inflection point of SLRC. As the obtained SLRC are roughly symmetric to ψ_{in} in a semi-log plot, ψ_{in} is located at a mid-distance between the SLRC air entry value and the first residual suction, which corresponds to the beginning of the nearly horizontal plateau in the SLRC, meaning the lack of pores in that suction (equivalent diameter) range. The α_p value dictates the length of the plateau or the size of the transition between micro and macro pores. For unimodal SLRC the second part of Equation 14 must be zeroed ($\alpha_p = 0$).



(a)



(b)

Figure 23. Unsaturated shear strength and SWRC fitted by Equations 12, 14, and Vilar (2007) expedite model: (a) soil data from Silva (2007); and (b) soil data from Lafayette (2006).

Table 4. Fitting parameters for data presented in Figure 23.

ϕ' (^{0})	c' (kPa)	S_r (-)	ψ_{in} (kPa)	α_p (-)	R^2 – Shear	R^2 – SWRC
32.5	0.0	0.624	6.65	0.373	0.95	0.99
33.6	11.4	0.409	33.7	0.483	0.94	0.99

Where: ϕ' is the effective angle of shear strength; c' is the effective cohesion; S_r is the residual degree of saturation; ψ_{in} is the suction corresponding to the inflection point of SLRC; α_p is the size of the transition between micro and macro pores.

Figure 23 illustrates the fitting of the proposed equations for two bimodal soils in terms of shear strength and SWRC (Lafayette, 2006; Silva, 2007). As observed, there is a good agreement between fitted and experimental values. Table 4 summarizes the fitting parameters adopted.

6. Closing remarks

The impact of Brazilian geotechnical engineering to the development of unsaturated soil mechanics has been demonstrated in this paper. The analysis of the examples presented herein shows that unsaturated soil mechanics has well-established applications across various contexts in geotechnical engineering, with significant impacts on design, operation, and maintenance decisions. By incorporating factors such as suction variation and infiltration, it becomes possible to interpret phenomena that would not be captured by conventional approaches, resulting in more realistic and technically consistent outcomes.

The range of analyzed scenarios, from tunnels to foundations, from filtered tailings stacks to temporary structures, shows that unsaturated soil mechanics is particularly valuable in works exposed to climatic influences or intermittent water presence. In all cases, the ability to anticipate critical behaviors through transient analyses and specific hydraulic parameters translates into improved operational safety and more rational use of resources.

Two major issues were not presented in detail in this paper but require attention. First, numerical modeling plays a central role in the context of unsaturated soils applications. The highly nonlinear nature of the physical processes involved renders closed-form solutions inadequate. The availability of robust, thoroughly verified, and friendly software greatly benefits the implementation of unsaturated soil mechanics in geotechnical practice. Secondly, education and training, at all levels, becomes of paramount importance. The dissemination of unsaturated soil mechanics depends on the adaptation of curricula, so that basic concepts can be introduced not only in the graduate, but also in the undergraduate level.

Multiple present and future challenges faced by society will involve unsaturated soils mechanics and technology. Brazil is being significantly impacted by extreme weather events. Climate change imposes the need for investments towards resilient infrastructures and cities. Compensatory infiltration systems, slope monitoring and management, resilient transportation infrastructure, structures for the prevention of water erosion, and most waste disposal systems are just a few examples of problems and cannot be dealt with disregarding unsaturated soil behavior. Given the rising importance of soil-atmosphere phenomena to engineering structures, it is anticipated that contemporary geotechnical engineering in Brazil will continue to rely on past and future advances in unsaturated soils technology.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Gilson F. N. Gitirana Junior: conceptualization, project administration, writing – original draft, writing – review & editing. Ana Patrícia Nunes Bandeira: conceptualization, writing – original draft. Diones Uiliam Barboza: conceptualization, writing – original draft. Fernando A. M. Marinho: conceptualization, writing – original draft. José Camapum de Carvalho: conceptualization, project administration, writing – original draft. Lara Batista Ferreira de Lima: conceptualization, writing – review & editing. Orêncio Monje Vilar: conceptualization, writing – original draft. Sandro Lemos Machado: conceptualization, writing – original draft. Wai Ying Yuk Gehling: conceptualization, writing – original draft. Washington Peres Núñez: conceptualization, writing – original draft.

Data availability

The availability of datasets presented in this paper must be verified in the original publications cited.

Declaration of use of generative artificial intelligence

Generative artificial intelligence (GenAI) tools or services were not employed in this paper. All aspects of this manuscript were developed solely by the authors, who take full responsibility for the content of this publication.

List of symbols and abbreviations

c'	Effective cohesion
c_m	Cohesion measured for specimens dried until the target maximum suction in a test without suction control, air drained
c_{ult}	Shear strength ultimate or unsaturated residual value
e	Void ratio
k_i	Model regression constants of resilient modulus
r^2	Coefficient of determination
s	Soil suction $(u_a - u_w)$
u_a	Pore-air pressure
$(u_a - u_w)$	Matric suction
u_w	Pore-water pressure
w	Water content
w_{op}	Optimum water content
AEV	Air entry value
C_c	Compression indexes
FEM	Finite Element Method
G_{max}	Maximum shear modulus
GSD	Grain-size distribution
HAEV	High air-entry value
ISSMFE	International Society for Soil Mechanics and Foundation Engineering
M_R	Resilient modulus
NAPL	Non-aqueous phase liquid
OMC	Optimum water content
PI	Plasticity index
S	Degree of saturation
SLRC	Soil-liquid characteristic curve
SPT	Standard Penetration Test
S_r	Residual degree of saturation
SWCC	Soil water characteristic curve
SWRC	Soil water retention curve
TC6	Technical committee (1987)
USM	Unsaturated Soil Mechanics

γ	Unit weight
γ_d	Dry apparent specific weight
γ_{dmax}	Maximum dry apparent specific weight
ε_p	Specific permanent deformation
ε_r	Dielectric constant
κ	Parameter in Fredlund model for predicting shear strength, soil parameter dependent upon the soil type
ρ	Mass weight
ρ_0	Atmospheric pressure
ρ_d	Dry mass density
σ	Total normal stress
σ'	Effective normal stress
$(\sigma - u_a)$	Net total stress
σ_3	Confining stress
$(\sigma_3 - u_a)$	Confining stress
σ_d	Deviator stress
σ_v	Foundation normal stress
τ_f	Shear strength
ϕ	Angle of shear strength
ϕ'	Effective angle of shear strength
ϕ^b	Angle that represents the increase of shear strength with suction
χ	Bishop parameter of effective stress
ψ	Suction
ψ_i	Parameters of the model of permanent deformation
ψ_{in}	Suction corresponding to the inflection point of SLRC
ψ_m	Matric suction
$\Delta\tau_s$	Increment in shear strength due to suction
Θ	Normalized volumetric water content

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