Teaching unsaturated soil mechanics in a South African context

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ABSTRACT: With South Africa's arid and semi-arid climate, geotechnical engineers frequently work with unsaturated soils. Problem soils such as expansive clays, collapsible soils, and sinkholes are primarily influenced by soil water content changes. Tailings storage facilities (TSFs) also involve complex saturated/unsaturated conditions. However, despite its relevance, unsaturated soil mechanics (USM) is often overlooked in geotechnical engineering practice and education in South Africa. A survey of academics and practitioners examined the adoption of unsaturated soil mechanics in industry and education. Academics highlighted the limited time available and the need to balance the teaching of civil engineers and specialist geotechnical engineers. Limited application in industry was noted by practitioners, with key challenges including appropriate laboratory characterisations of unsaturated soils and hesitation in relying on suction. Simple case studies in seepage and stability showed that USM increases seepage by up to 10%, with nominal increases in stability reported. Changes in steady-state seepage and strength gain considerations from suction effects have limited impact relative to modelling uncertainties. While best suited for postgraduate study, a conceptual understanding of unsaturated soil behaviour should be integrated into undergraduate education, especially regarding volume change in problem soils prevalent in South Africa.

Keywords: Unsaturated soils, Problem soils, South Africa

1 Introduction

Great strides have been made to understand unsaturated soil mechanics (USM), also known as partially saturated soils, albeit primarily in the realm of research. The degree to which a soil is saturated is now known to have a significant impact on a soil's permeability, shear strength and volume (Fredlund et al., 2012). The significance of this impact depends on the size of grains making up the soil. In general, as grains get smaller, the larger the suctions that can develop as the degree of saturation decreases. This decreasing saturation will significantly reduce permeability, increase shear strength, and have a variable impact of soil volume depending on the soil type and mineralogy. The extension of this knowledge to teaching of soil mechanics and routine geotechnical engineering practice has been limited (Pantazidou et al. 2024; Fredlund, 2021). Soil mechanics is largely taught and practiced at extremes: soil is either dry or fully saturated (Santamarina, 2015). This no doubt reflects the reality that most theories have been developed and validated at these extremes without seeing them as a subset of unsaturated soils.

Wirth et al. (2017) conducted a review of ten international undergraduate course curricula in the soil mechanics / geotechnical engineering specialisation; only one of the curricula explicitly included flow in unsaturated soils and mechanical behaviour of unsaturated soils. This highlights the challenge of sufficient time and space in the existing geotechnical courses to include unsaturated soils, which may be considered 'advanced' material. The proposed ideal curriculum recommenced that an introduction to USM be included, noting specifically aspects of flow, constitutive stresses and hydromechanical behaviour.

A challenge in the teaching of soil mechanics at an undergraduate level is the appropriate recognition of material that is relevant to students studying civil engineering as a general degree (Wesley, 2015). With limited time available civil engineering students need to develop a general understanding of soil behaviour as opposed to that of a specialist geotechnical engineer. As noted by Barashov in the appendix of Santamarina (2015), “specialisation requires a second degree”. The focus should thus be on laying an appropriate foundation for both general civil engineers and future geotechnical specialists whilst “not saying anything in an undergraduate course that would have to be taken back in a graduate course” (Seed, 1986; cited in Pantazidou et al. 2024).

The main challenge to the adoption of USM in undergraduate teaching appears to be related to the limited time available in the curriculum. So, what are some of the key concepts that should be taught? Wesley (2015) suggests that students lack an adequate understanding of “pore pressure state above the water table” and an appreciation that seepage can take place above the water table, the effects of which can be significant especially in clays. Atkinson (2008) suggests that students should have an appreciation that negative pore pressures can develop giving soils different strengths depending on grain size. These teaching suggestions seem minor, compared to the range of applications of USM suggested in literature: seepage in embankments, infiltration triggered landslides, compacted materials, evapotranspiration cover systems, expansive soils and interpretation of plate load tests (Siemens, 2018; Houston et al., 2023; Fredlund et al., 2012).

Another hurdle to teaching USM at the undergraduate level is a lack of teaching resources. Pantazidou et al. (2024) note the limited coverage on USM in introductory geotechnical textbooks. Presentation of this material would thus require reference to specialist textbooks (e.g. Fredlund et al., 2012; Lu & Likos, 2004) and/or relevant research papers. Most undergraduate students will need significant scaffolding to appreciate the content in these resources with their limited technical vocabulary. For instance, Pantazidou et al. (2024) point out the difficulties in the understanding of the key state variables required to describe the behaviour of unsaturated soils.

Saturated soil mechanics has developed the Terzaghi effective stress as the key state variable that predicts the soil behaviour. Initial attempts at understanding USM attempted to create a similar, single effective stress value using the measured suction and a factor related to the degree of saturation (Bishop, 1959). Later developments considered net stress and matric suction as two separate state variables as they impact soil behaviour in different ways (Fredlund and Morgenstern, 1977). The two different approaches remain prevalent in USM research, with some tension as to what the more appropriate and correct description of unsaturated soil behaviour is (Pantazidou et al., 2024). As an illustration of the impact of these alternate approaches, below is an example of how they would be used to explain the simple problem of how a sandcastle stands up:

- Approach 1 (Single effective stress state variable): Suction provides an additional confining stress on the soil and increases the effective stress by an amount that is proportional to the degree of saturation. The sandcastle stands up because the suction increases the effective stress of the soil.
- Approach 2 (Two independent state variables): Suction and net stress create different responses in the soil and should be considered separately. For positive porewater pressures (saturated soils), these effects disappear, and a single effective stress can be used. The sandcastle stands up because the suction increases the shear strength of the soil.

These nuances are likely a step too far for undergraduate students just coming to terms with a multi-phase material let alone geotechnical engineering lecturers who are non-specialists in USM.

This paper attempts to contextualise the teaching of USM to South Africa. The arid/semi-arid climate of South Africa coupled with residual soils and deep water tables makes USM particularly relevant. Furthermore, the extensive involvement of the geotechnical community in the design and operation of tailings storage facilities requires an appreciation for the impact of unsaturated soil on seepage, strength and volume change. To guide the teaching of USM at the undergraduate level the views of influential South African geotechnical academics and practitioners where sought.

Academics highlighted the limited time available and the need to balance the teaching of civil engineers and specialist geotechnical engineers. Within practice, challenges related to a lack of knowledge and training, limited laboratory facilities for unsaturated soil testing, and a strong tendency for conservatism especially with regards to maintenance of suctions and the magnitude of shear strength increase provided by suctions. Key concepts identified were the need to convey the qualitative impact of unsaturated soil behaviour at an undergraduate level, particularly in the context of problem soils and seepage analyses. Some simple case studies that could be used in teaching the impact of USM on seepage and stability are included for consideration.

2 South African context

2.1 Climate

Using Thornthwaite's Moisture Index values (Thornthwaite, 1988), approximately 85% of South Africa is classified as having a water deficit where loss by evaporation exceeds supply by precipitation (Paige-Green, 2009). This results in deep water tables in these regions. Water surplus areas occur primarily in KwaZulu Natal and Eastern Mpumalanga along the eastern escarpment of the Drakensburg Mountain range and towards the east coast (Paige-Green, 2009). Much of the country therefore constructs geotechnical infrastructure in unsaturated soil zones.

2.2 Problem soils

In South African geotechnical engineering practice, there are five widely recognised problem soils, namely collapsible soils, dispersive soils, soft clays, dolomites, and expansive soils (Day, 2013). Of these, three are directly related to USM: collapsible soils, dolomites and expansive soils (see Table 1). Their problematic characteristics with respect to volume change are related to the change in moisture content of the soil: if the soil was fully saturated or completely dry, these characteristics would not result in problems in engineering applications in soils of these types. In characterising these soils, it is thus imperative to understand the likelihood of a change in moisture content and the amount thereof to quantify the impact of the problematic behaviour.

Table 1. Problem soils in South Africa with behaviour related to unsaturated soil mechanics

Collapsible soils	Dolomites	Expansive soils

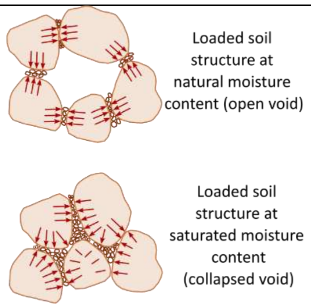
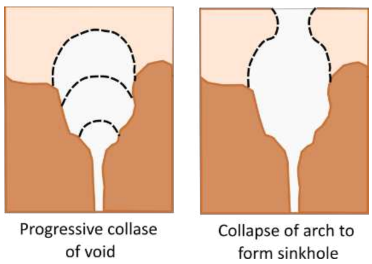
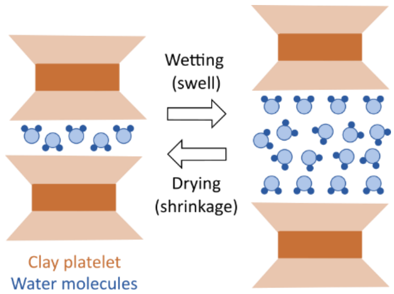

		

Image after Houston et al. (1988)	Image after Brink (1979)	Image after Murison et al. (2023)
Leaching of minerals from residual soil profile causes an open grain structure held under load in a pseudo-stable state with contact cementation and suctions. On wetting, the cementation/suction disappears and sudden large changes in volume occur as the voids collapse (Schwartz, 1985).	Stable voids form in soluble rock supported by soil arching in overburden material; unsaturated nature allows tensile strength in soil. Increase in moisture content results in loss of strength and sudden collapse of void (Wagener, 1985).	Clay minerals with negatively charged surface are loosely held by van der Waals forces; on exposure to water, water enters the between the clay particles and drives them apart causing significant increases in volume. The opposite effect occurs as the clay dries out (Williams et al., 1985).

2.3 Tailings Storage Facilities (TSFs)

Tailings refers to the waste by-product from the processing of mineral ores; this is conventionally deposited as a slurry in large embankment dams known as tailings storage facilities (TSFs). Stability of these facilities relies on the sun-drying of these slurries; therefore, their management relies on reducing the water stored as much as possible to promote the development of unsaturated soil conditions (Wates, 2023, Wilson, 2021).The porewater pressure distribution in the unsaturated soil affects the overall seepage, and as shear strength varies with suction, the stability too (Bella, 2021). Material contained within these embankments is prone to static liquefaction as evidenced by notable failures in South Africa including Bafokeng in 1979, Merriespruit in 1994 and Jagersfontein in 2021. Material with a degree of saturation above 85% is considered potentially liquefiable (Wilson, 2021), so understanding where this transition is above the phreatic surface is crucial to assessing overall stability.

3 Ivory towers: Academic voices

To understand the current level of teaching of unsaturated soils in South Africa, academics at tertiary education institutions in Southern Africa (South Africa and Namibia) were asked to give input on whether USM is included in the curriculum and the perceived benefits and challenges of including this topic. The survey included four open-ended questions. Survey questions requested details of USM included in curricula, the value of USM, content that could be added and anticipated challenges. Responses were received from two participants and collated with the authors' own perspectives and experiences at three institutions in South Africa. It was found that USM was not covered in any undergraduate courses and only partially in postgraduate courses. Problem soils were covered in undergraduate courses either within a geotechnical engineering module or in a preceding engineering geology module. At the postgraduate level coverage was limited to guest lectures on unsaturated seepage modelling and a full-day course on USM principles which closely follows the topics presented in Fredlund (2021).

Respondents noted the value of appropriate understanding of USM with one noting "*it will drastically affect the reliability of design, since suction affects strength and volume change in soils*" and another noting the impact of climate change and increased rainfall on slope stability. Academics highlighted the limited time in the curriculum as a challenge to including additional material. Limited instructor knowledge and the time required to prepare related material, as well as limited capacity of the students and the need to ensure that the basics of soil mechanics are well understood before adding complexities were noted as additional challenges. Unfortunately, responses were too generic to identify specific content to teach.

4 Tin huts: Industry voices

To understand how USM is used in South African practice, prominent geotechnical engineers were sent a survey comprising two open-ended questions. The first asked them to give information on which USM principles they used in practice, with a request to provide details why none were used if this was the case. A second question was asked to find out which USM principles they believed should be taught at university (either at undergraduate or postgraduate level). Three responses were received from 30 invited participants.

Principles highlighted included the use of USM in the design of evaporative covers where an understanding of permeability and seepage properties are important; and the *"appreciation of the role that suction plays in keeping slopes up"*. One respondent provided supplementary information on a case study of the matric suction required to ensure adequate stability on existing slopes in the Atlantic Seaboard region in Cape Town, a region that has experienced some significant slope failures during recent heavy rainfall events. Responses highlight that one of the most significant contributions that USM makes in South African practice relates to rainfall-induced instability of unsaturated slopes.

The responses highlighted two primary challenges in the implementation of USM principles; these were (1) reliance on soil suction and (2) access to laboratory testing. In relation to the reliance on suction, one respondent noted that *"practitioners are scared that the conditions can or will change with time or influenced by environment"* and another the *"possibility of soil wetting under flood or ponding conditions i.e. one must assume that the soil will become saturated over the design life of the facility, even in semi-arid climates"*. The fact that *"saturated soil parameters are conservative"* was noted as a corollary to this statement. A related challenge to the reliance on soil suction noted was the difficulty in establishing the in-situ moisture and suction regime, especially using rotary core drilling.

Fundamental to the correct application of USM is the measurement of the soil water retention curve SWRC (alternatively known as the soil water characteristic curve, SWCC). The SWRC relates soil suction to volumetric water content, gravimetric water content, or degree of saturation (Klute, 1965). SWRCs are a basic requirement for USM principles that expresses permeability, strength and volume change as a function of suction (Fredlund, 2021). In international contexts where USM research is more prevalent, the ability to measure the SWRC is readily available and affordable (Fredlund, 2021). However, in the South African context, the situation is different as noted by two respondents *"To my knowledge only UP [University of Pretoria] does SWRC testing; more labs need to do this"* and *"Instruments and methods to measure soil suction, and develop a soil-water characteristic curve, are not offered in commercial laboratories."*.

The lack of the laboratory measurement of the SWRC does not preclude the use of USM principles – as noted by a respondent, these can be estimated from "*empirical methods from grading and Atterberg Limits*". Although not as reliable as direct measurement, these would give sufficient information to understand the change in behaviour from considering saturated/dry material only to including the effects of unsaturated material. This suggests that a related challenge in the application of USM is the lack of awareness and appropriate training for practitioners, although this was not noted by any of the respondents. When considering what aspects of USM should be taught at university, the comments were *"the theory of suction and its contribution to shear strength should be taught"* and *"strength, seepage and volume change with examples of how to test and use in practice"*. Another simply commented that *"all concepts and theories [should be taught] at post graduate level"* without clarifying specifically what the key aspects of these concepts and theories are.

These views largely reinforce factors highlighted by Fredlund (2021) for the slow adoption of USM in routine practice. These factors included complex theories, measurement of suctions in the field, permanency of soil suctions / inability to rely on suctions (disappear after rain) and appropriate laboratory characterisation of soils.

5 Simple case studies

Following are some simple case studies of calculations that can be performed with readily available software (in this case Rocscience's Slide 2 limit equilibrium software) to illustrate the capabilities of USM and implications compared to assuming that soil is saturated or dry only. At an undergraduate level these case studies would most likely only be for affective purposes, which is to excite and motivate students (Orr & Pantazidou, 2012). At an undergraduate level there is unlikely enough time to fully explain the underlying theory.

5.1 Vadose zone seepage

This case study is used to quantify the effects of the inclusion of unsaturated soil behaviour on total seepage volumes in a simple model of groundwater seepage through a slope. The model comprised a 10 m high, 1:2 slope with a known phreatic surface at a height of 7 m above the toe at the boundary and ponded water with a depth of 1 m at the toe; the model setup is shown in Figure 1 The soil was assigned a saturated permeability, k_s, of 5x10^{-7} m/s, with a vertical to horizontal permeability ratio of 0.5 (more permeable in the horizontal direction).

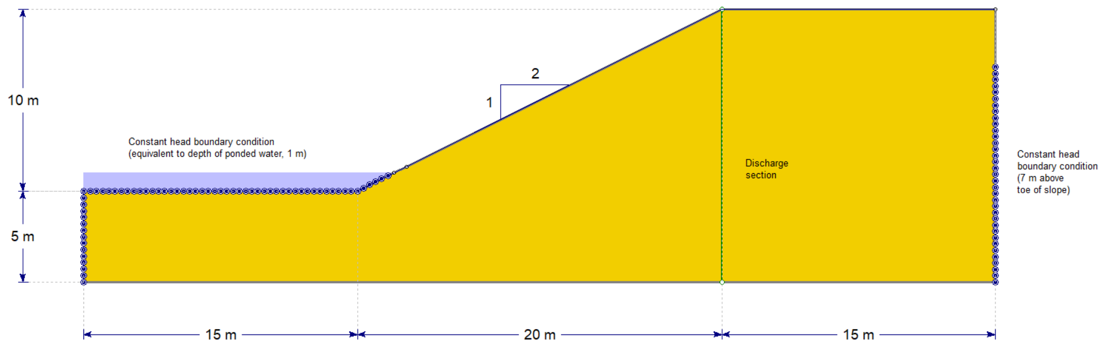


Figure 1. Simple slope limit equilibrium model showing hydraulic boundary conditions

Permeability varies as a function of suction; the particle size significantly impacts the suction that a soil can hold with finer soils able to hold more water and thus sustain greater suctions. This means that more flow can occur in the unsaturated region compared to a coarse-grained soil. The relative permeability, k/k_s, as a function of suction, ψ (measured in kPa), for a sand, silt and tailings are shown in Figure 2 using relationships for example materials from Leong and Rahardjo (1997). The A-value gives an indication of the air entry value (AEV) at which point the air phase becomes continuous and permeability rapidly decreases. To simulate no flow in the unsaturated region, the permeability for negative pore water pressures was set to 1x10^{-13} m/s. The results showed an increase in seepage quantity of 1.9%, 6.1% and 9.6% for the sand, silt and tailings from the case where no flow is assumed in the unsaturated soil to where unsaturated flow is included. This result is similar to that reported by Siemens (2018) in an analysis of an embankment dam where a 7.6% increase was noted. The phreatic surface was minimally increased with the seepage face exiting a vertical height of 0.5 – 1 m higher on the slope in the case with unsaturated flow. A sample result of the flow vectors for the unsaturated flow in the silt is shown in Figure 3; this highlights the portion of flow that occurs in the unsaturated region primarily below the AEV (8.55 kPa).

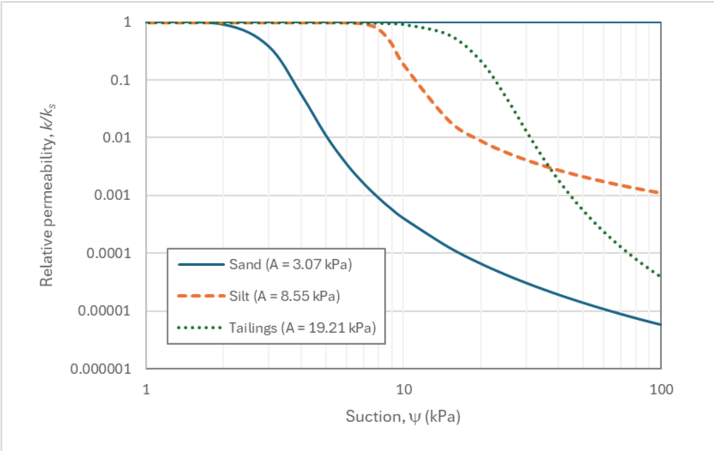


Figure 2. Relative permeaiblity of three sample materials (sand, silt and tailings) showing the significantly reduced permeabilty once the AEV (indicated by the A-value) is exceeded

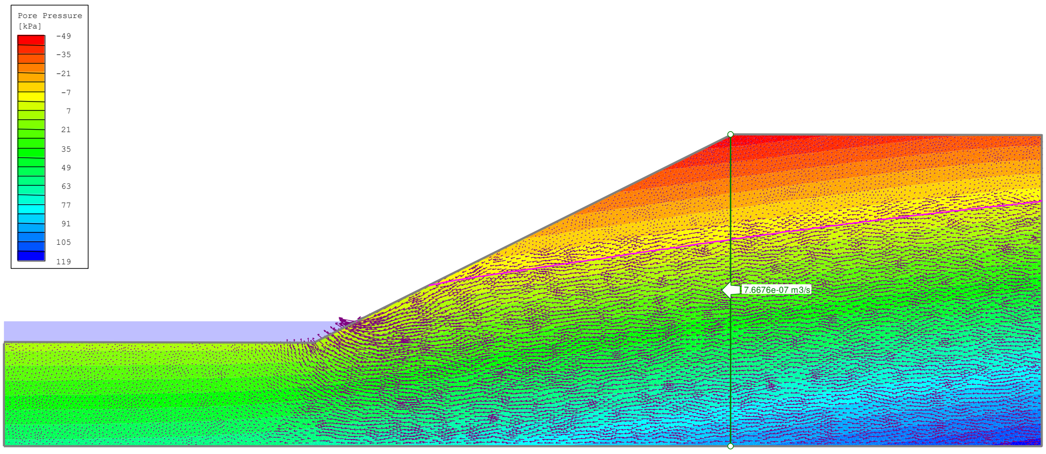


Figure 3. Flow vectors for saturated and unsaturated flow in a silt material

These results could be used to show that it is not correct to assume that no flow occurs above the phreatic surface. Although such an assumption has limited impact on the level of the phreatic surface, it is important to appreciate that flow does occur in unsaturated soils and increases expected seepage in a slope or embankment. For finer-grained soils where the water content remains high as suction increases, the impact of considering flow in the unsaturated region is greater.

5.2 Including suction in a stability analysis

The second case study shows how the factor of safety (FOS) increases because of including strength due to suction in the unsaturated zone. The phreatic surface and pore pressure regime from the seepage model with the silt material (A = 8.55 kPa) and the inclusion of flow in the unsaturated soil was used in the stability model. The soil was assigned an internal angle of friction, ϕ, of 35°, and effective cohesion, c’, of 5 kPa. Slide2 assigns unsaturated shear strength, τ, according to Equation 2:

$$\tau = c' + (\sigma_n - u_a) \tan \phi' + \psi \tan \phi^b \quad (2)$$

where $(\sigma_n - u_a)$ is the net stress and ϕ^b is the unsaturated shear strength angle assigned when the suction exceeds the AEV. Two unsaturated strength models were considered, one where $\phi^b = \phi'$, termed the 'maximum model' as this is the upper limit of the suction-induced shear strength increase, and the second with $\phi^b = 0°$, termed the 'conservative model' due to the limiting value applied to the suction-induced shear strength increase. The shear strength envelopes are shown in Figure 4.

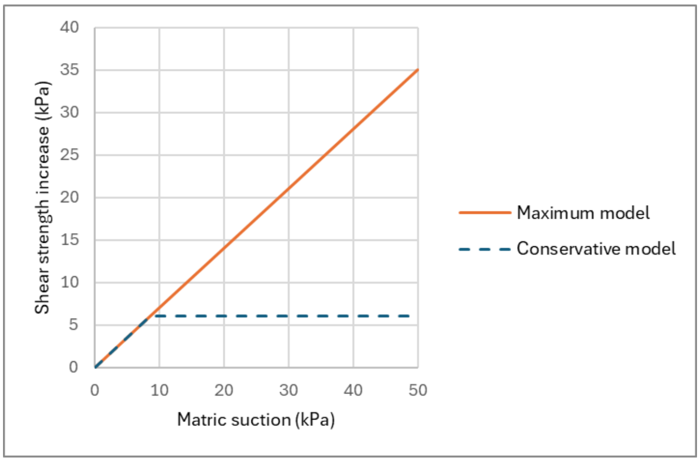


Figure 4. Unsaturated shear strength models used

The FOS results are shown in Table 2 with the corresponding slip surfaces in Figure 5. The simple unsaturated model results in an increase in the FOS by 4.8%; in this model the maximum possible increase in strength in the soil is at the crest of the slope and is 33 kPa (corresponding to 47 kPa of suction), although this is outside of the identified slip circles. The conservative model using a constant shear strength increase after the air entry value gives a slightly lower FOS increase of 4.1% with a maximum shear strength increase of 6 kPa for all regions where the suctions exceed the AEV. These are minor increases in stability which, critically, disappear if only two significant figures are considered which is common in the reporting of slope stability results. However, it is noted that in borderline cases, suctions could contribute to improved stability of slopes as noted by the practitioners in the survey response.

Table 2. FOS safety results

	No unsaturated shear strength	Maximum unsaturated strength ($\phi^b = \phi'$)	Conservative unsaturated strength ($\phi^b = 0°$)
FOS	1.45	1.52	1.51
% increase	-	4.83	4.14

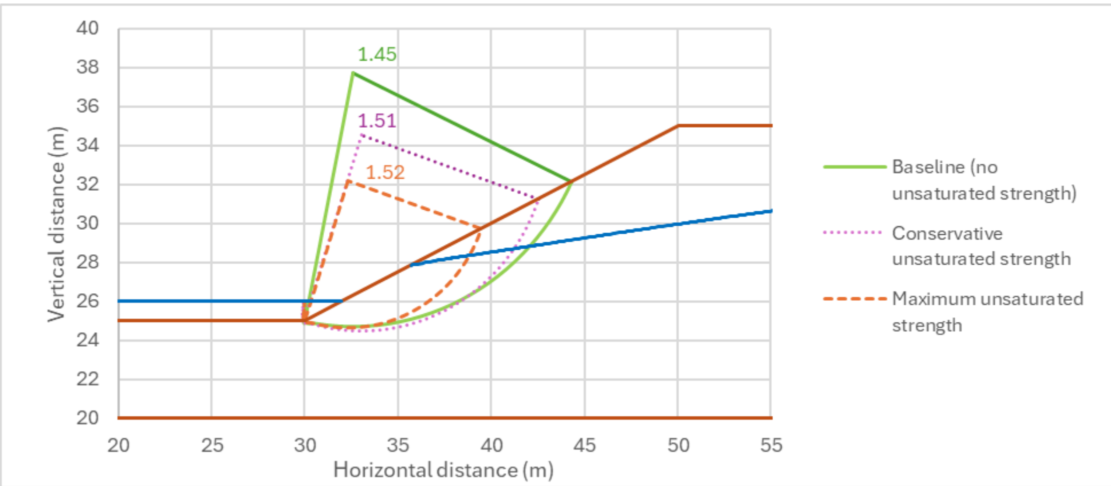


Figure 5. Slip surfaces resulting from saturated and unsaturated shear strength

5.3 Seepage induced instability

The final illustrative example considers the loss of suction due to rainfall infiltration. A transient seepage analysis was conducted with a vertical infiltration flux equal to the saturated permeability applied along the exposed surface of the slope and crest; this is the maximum infiltration that can occur into the soil. For the saturated permeability in the model, this infiltration is equivalent to a constant rainfall of 43.2 mm/day. The porewater pressure profile at the crest of the slope is shown in Figure 6. This shows the relatively slow progression of the wetting front through the slope with only 1 m of infiltration after 20 continuous days of influx (this equates to roughly the mean annual precipitation for South Africa falling in 20 days).

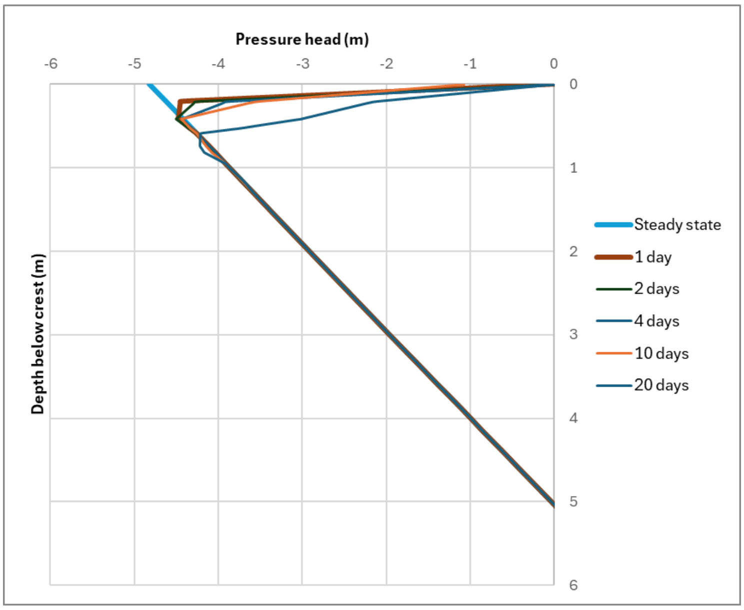
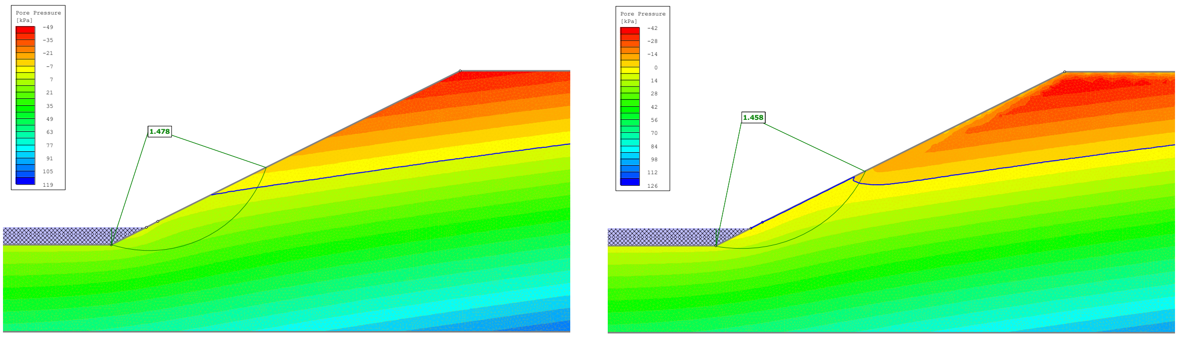


Figure 6. Pressure head profile below the crest of the slope in the transient seepage analysis

The porewater pressure, phreatic surface and stability results are shown in Figure 7 for the initial steady-state condition and after 20 days of infiltration. The results show a limited impact on the phreatic surface and minor reduction in FOS; the maximum strength in the unsaturated zone was used giving an upper bound to the results. This analysis highlights the possibility of relying on suction in the given scenario and provides a tool to allow practitioners to make an informed decision about the implication of relying on suction and the possible range of changes in the pore pressure profile should changes in environmental conditions occur.



(a) Initial conditions, FOS =1.48 (b) After 20 days, FOS =1.46

Figure 7. Pressure distribution, phreatic surface and stability results for the transient seepage analysis with infiltration equal to the saturated permeability of the soil

6 Concluding remarks

This paper attempts to contextualise the teaching of USM to South African undergraduates with a focus on local relevance and practice. Due to limited time in the curriculum and the desire to ensure adequate development of core soil mechanics knowledge, detailed presentation of USM principles, including any equations or discussion of relevant state variables, should be left for advanced study. An undergraduate engineer should appreciate that soil is not either dry or saturated, but that a range of conditions exist between these limits. The presence of both air and water in the soil results in suction, which is strongly influenced by particle size. The suction affects the seepage, strength and volume change characteristics of the soil and undergraduates should be able to give a qualitative description of the impacts on soil behaviour; the final observations are structured according to these three areas of influence.

Seepage: all engineers should clearly recognise that flow can occur in unsaturated soils, and that this effect is perhaps counter-intuitively more significant for fine-grained soils. This is because these soils hold onto the water for longer and thus have a higher degree of saturation and consequently higher permeability up to several metres above the water table. This has practical implications in layered soil systems (for instance in waste facilities composed of fine and coarse material) and seepage barriers (gravel layers can be used to break capillary seepage). Characterisation of the seepage influence requires measurement of the SWRC, but this can also be estimated from the grading curve. It is noted however, that unsaturated seepage is likely to have up to 10% effect on steady-state seepage considering saturated flow only. Considering the range of uncertainties in seepage modelling and effect of minor inhomogeneities, modelling results can easily be invalid when compared to reality.

Strength: it is unfortunate that our undergraduate students may graduate without the ability to explain why a sandcastle stands up, one of the first areas of exposure that many have to soil mechanics. Students should appreciate that suction increases the shear strength of the soil and functions similarly to the effective cohesion. This can be used to explain why cut slopes may be more stable in the short-term than in the long-term as the slope dries out. Significant and prolonged rainfall is required to remove suctions, so these can be relied upon where they exist in great degree (e.g. clays). This should be treated with caution however: the examples showed almost insignificant increases in FOS strength for the silt modelled. Suction is only expected to have more marked effects in stability of slopes in fine-grained soils. Variability and uncertainty in estimating primary strength parameters will in most cases have more impact than the suction strength, which is often tacitly accounted for in the nominal effective cohesion values of 2-10 kPa used in coarse materials.

Volume change: USM in the South African context has the largest impact in recognising likely volume change in problem soils. The magnitude of this volume change is not easily demonstrable using readily available software as per the seepage and strength effects, however, qualitative discussions on the USM principles driving the behaviour and where possible physical demonstrations of problem soils should be given. These should show an appreciation of the in-situ moisture content and effect of changes in moisture content on the volume change.

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