Supplement to article "Alert soil mechanics instructors of the main unsaturated soil issues: What and how to teach when experts disagree" by M. Pantazidou, S. Houston, J. McCartney, A. Tarantino and M. Bardanis, submitted to ECSMGE 2024

S1. SUGGESTED LIST OF IMPORTANT POINTS TO INTRODUCE UNSATURATED SOIL MECHANICS

1. *Pore Water Pressures are Negative, and Soil Suction exists in the soil profile above the GWT (GWT including regional and perched). Soil suction is related to the energy required to remove water from the soil and includes capillary forces and physico-chemical particle surface forces (van der Waals, double layer forces, cementation, ...). Matric suction, s (also represented by u_a-u_w), is the stress that is the measurable (or controllable) embodiment of these particle forces.*

NOTE: To avoid inconsistencies, select one of the options 2A, 2B, or 2C, corresponding, respectively, to the expert opinions of Sections 2.2.1, 2.2.2, 2.2.3 of the paper.

2A*. TWO INDEPENDENT STRESS VARIABLES DESCRIBE THE STRESS STATE There are two stress variables, Net Total Stress (total stress minus air pressure) and Soil Suction (a strong function of soil water content), that must be considered for unsaturated soils, and these two stress variables cannot be combined to obtain a single-valued stress variable that is equivalent to the effective stress used in saturated soil mechanics. Thus, for unsaturated soils there are two stress variables that control the shear strength and volume change response of the soil.*

2B. *ONE –MODIFIED– EFFECTIVE STRESS DESCRIBES THE STRESS STATE It is preferable to use effective stress over independent stress state variables so that similar mechanics equations can be used for saturated and unsaturated soils, albeit with different yielding conditions in unsaturated conditions. Several different equations have been proposed for the effective stress in unsaturated soils, but an approach that permits incorporation of the Soil Water Retention Curve (SWRC) into the effective stress is particularly useful. The two preferable equations to use in practice are those of Khalili and Khabbaz (1998) and Lu et al. (2010) as they both have a way of integrating the shape of the SWRC into the effective stress definition. [See references on page 12]. The effective stress is directly proportional to the shear strength and elastic volume changes in unsaturated soils. Consideration of plastic volume changes requires a more complex elasto-plastic model that can consider the impacts of suction on the yield stress.*

2C. *TWO EFFECTIVE STRESSES DESCRIBE THE STRESS STATE About the two stresses to describe behavior, different pairs can be used (e.g. Bishop stress and suction, or net stress and suction), depending on* *convenience. However, a comment on terminology may be useful, concerning the alternative terms "two stress state variables" vs "two effective stresses". Strictly speaking, the variables governing behavior are effective stresses (in the plural). However, it would be difficult to spot the subtle difference between the effective stress for saturated soil (in the singular) and effective stressES for unsaturated soils (in the plural), one could easily get confused. The term "stress state variables" marks the difference much more effectively. So whereas "effective stresses" may be chosen with the criterion of rigor, "stress state variables" may be chosen if the priority is to pass the message that we have two stresses to deal with, in contrast to saturated soils.*

***3.** Behavior/Response of unsaturated soils at a given (confining) net total stress is strongly dependent on water content and changes in water content. For this reason, it is important to understand potential sources of soil wetting and drying, and such a study needs to be added to the geotechnical site investigation.*

For most engineering applications, it is the change in water content (usually increase in water content) that results in problematic unsaturated soil response [e.g., volume change (expansion or compression) or shear strength change]. Therefore, laboratory testing of unsaturated soil needs to include response-to-wetting with respect to volume change and/or shear strength.

***4.** Water moves differently through unsaturated soils than saturated soils. The hydraulic conductivity of an unsaturated soil is a strong function of soil suction (degree of saturation/water content). Depending on the soil water content, a sand may have a hydraulic conductivity that is higher OR lower than a clay.*

***5.** Unsaturated soil response to changes in stress state is highly nonlinear and it is therefore difficult to intuit behavior. For this reason, adoption of a Stress Path approach in laboratory testing and modeling and addressing problems is advised. Briefly, a stress path approach entails configuration of lab test such that the representative lab test specimen is made to follow a path in the lab that matches that of the corresponding element of soil in the field- in terms of net total stress and suction. This is particularly important for unsaturated soils, because the soil water retention curve is hysteretic and unsaturated soils exhibit elastoplastic behavior, in general.*

S2. CASE STUDIES SUITABLE FOR INTRODUCING UNSATURATED SOILS

Suitable case studies for introducing unsaturated soils are those related to the usual geotechnical problems covered in introductory courses, e.g. slope stability, retaining structures, and those that demonstrate the critical role of the soil water content. Three such examples are listed below with commentary.

- Alonso, E., Lloret, A. and Romero. E. (1999). **Rainfall induced deformations of road embankments**, Rivista Italiana di Geotecnica N.1/1999, pp. 8-15.

Heavy rains caused near-surface soil sliding at embankments constructed of low plasticity clay compacted dry of optimum. Oedometer tests on undisturbed samples revealed the potential of collapse upon wetting (Figure 4) as a function of vertical stress (Figure 5). The shear strength envelope was determined as a function of two variables, net vertical stress (σ - u_a) and suction (u_a - u_w) (Figures 6 and 7). The soil water retention curve was obtained with suction-controlled oedometer tests (Figure 8). The following two analyses were carried out with a hydromechanical numerical code to investigate how a 7m high embankment will behave in the future.

(I) Limit equilibrium analysis combined with infiltration analysis, which require as input a) the unsaturated shear strength envelop (from Figures 6 and 7), b) the soil water retention curve of the soil

(Figure 8) and its relative permeability (estimated through the soil water retention curve, Table II), and c) rain water infiltration (details not given). This analysis showed that if rains continue, the embankment is stable.

(II) A coupled flow-deformation analysis, which required as further input volumetric collapse or swelling strains (Figure 5) as a function of net vertical stress and suction (Table II). Since the input stress-strain relationship is only volumetric, the computed vertical and horizontal deformation is isotropic, but this is consistent with visual observations of the actual deformations observed at the embankment. This analysis showed that if rains continue for 10 days, the embankment will settle an additional 1 cm.

• Rahardjo, H., Satyanaga, A., Gofar, N., Leong, E. C., Kew, J. H., Wang, C. L. and Wong, J. L. (2019). **Geobarrier System for Protection Against Rainfall-induced Slope Failure**, Int. J. of Geoengineering Case Histories, 5(1):26-42. http://dx.doi.org/10.4417/IJGCH-05-01-03

Rahardjo et al. (2019) describe a geobarrier system that protects a slope from rain infiltration, thanks to a combination of a coarse-grained layer in contact with the retained soil and a fine-grained layer in contact with the vegetative layer protecting the slope surface. Due to the distinct difference in unsaturated hydraulic properties, the fine-grained layer helps the coarse-grained layer remain dry and, in its turn, the coarse-grained layer protects the native soil from rain infiltration. The paper explains the design of the geobarrier system, which was constructed in three alternative configurations using different recycled materials. The slope was instrumented to measure water content. Numerical analysis results matched measurements obtained during an extreme rainfall event, which confirmed the satisfactory performance of the protective geobarrier system.

In this example, prior knowledge of unsaturated soil behavior helps us understand the somewhat counter-intuitive idea of capillary barriers, namely that water from a fine-grained material will imbibe into a neighboring coarse-grained material only for a very high saturation of the fine-grained material. Figure S1 from Khire et al. (2010) explains the idea of a capillary barrier. Because water at the point of contact of the two materials has the same pressure (same matric suction ψ_B in the figure), the water content of the fine-grained layer should become very high (point B_F in Figure S1a) before water imbibes in the coarse-grained later (point B_C in Figure S1a) and, even then, it imbibes at a lower hydraulic conductivity compared with the hydraulic conductivity of the saturated soil (see Figure S1b).

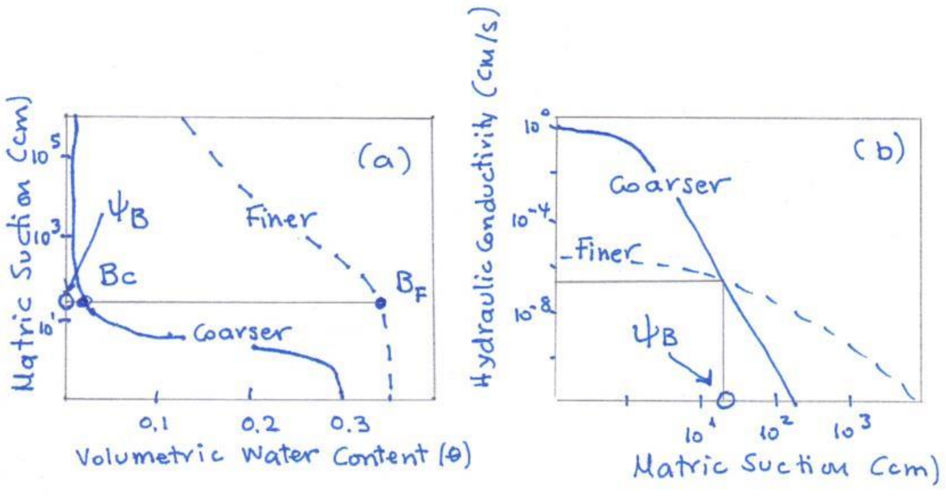

Figure S1. (a) Soil water characteristic curves and (b) Hydraulic conductivity functions for finer- and coarser-grained soils (from Khire et al., 2010).

Reference

Khire, M.V., C.H. Benson and P.J. Bosscher, 2010, Capillary barriers: Design variables and water balance, ASCE J. of Geotech. and Geoenviron. Eng., 126(8):695-708. https://doi.org/10.1061/(ASCE)1090-0241(2000)126:8(695)

• Saleh, M. and Vanapalli, S.K. (2022). **Analysis of Excavation Support Systems Considering the Influence of Saturated and Unsaturated Soil Conditions**, ASCE J. of Geotech. and Geoenviron. Eng., 148(6): 04022034. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002788

The incentive for the work presented in this paper was the realization that the measured deformations of excavation support systems are typically lower than predicted values, which are obtained from conventional design methods: the difference can be attributed to the higher shear strength of unsaturated soils that is not taken into account in conventional design. The authors describe a five-step approach for designing excavation support systems in unsaturated soils. They used their method to compare the effect of soil saturation on soil properties and the deformations of a hypothetical wall. Then, they applied their method using data from a case history of an anchored-diaphragm wall in unsaturated soil and obtained good agreement between measured and calculated wall deformations. On the contrary, conventional design methods resulted in a significant overestimation of wall deformations.

S3. TWO VERSIONS OF FOUR REFERENCES MADE TO UNSATURATED SOILS BY A NON-SPECIALIST BEFORE AND AFTER BEING EVALUATED BY SPECIALISTS

Version 1, before the evaluation by specialists

1 Sand Castles & Prof Burland's video "The Effect of Water on Soil Strength" [link].

2 Effective stress equation for unsaturated soils, which helps me explain the stiffness of vacuum-packed foods: **Bishop's equation, in the more instructional version given in Briaud's (2013) textbook**:

$$\sigma' = \sigma - \alpha_w u_w - \alpha_a u_a \qquad (1)$$

α_w = water area ratio, α_a= air area ratio, $\alpha_w + \alpha_a = 1$

3 Slide with distributions of quantities above the water table

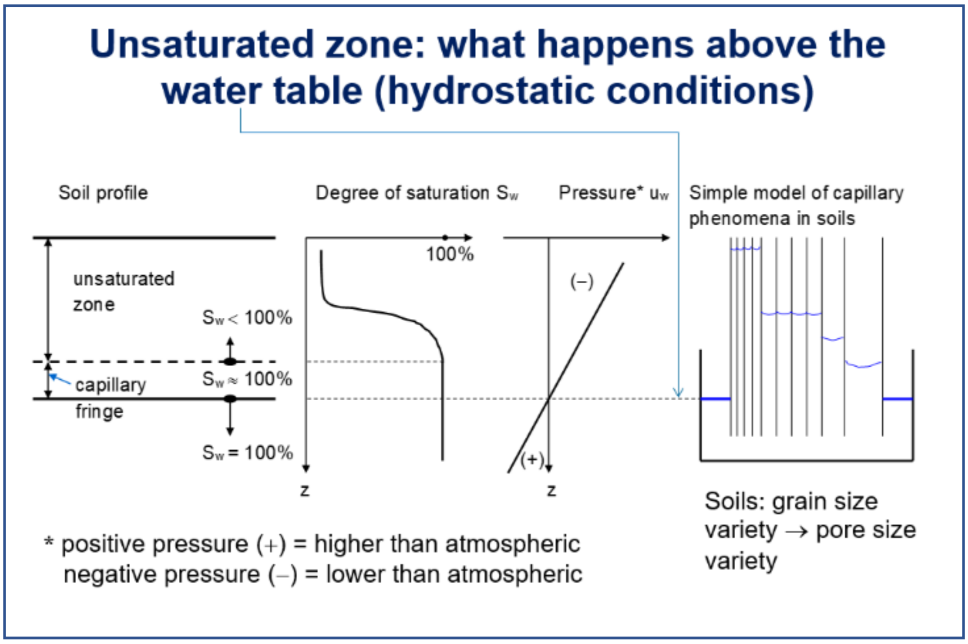

Figure S2. Soil profile above the water table: distribution of (a) water saturation and (b) pore water pressure for hydrostatic conditions.

4 Shear strength of unsaturated soils

Equation for shear strength τ of unsaturated soils – reference needed:

$$\tau = c' + \sigma \tan\phi' + f(s, S) \tan\phi'$$

where where c' is the saturated soil effective cohesion intercept (typically equal to zero unless the soil is cemented), ϕ' is the saturated soil effective angle of shearing resistance and $f(s,S)$ is a function of suction (s) and degree of saturation (S).

Version 2, after the evaluation by specialists & comments

1 Sand Castles & Prof Burland's video "The Effect of Water on Soil Strength" [link].

No change

2 Effective stress equation

Saturated soil: $\sigma' = \sigma - u_w$ Demonstration: piston-and-spring analogy

Dry Soil: $\sigma' = \sigma - u_\alpha$ Demonstration: vacuum-packed coffee

Unsaturated soil: No equation given, only comments: Three-phase soils are more complicated than two phase soils. i.e. saturated or dry. One of the existing approaches uses two effective stresses to describe their behavior (Section 2.2.3 in paper), while another approach is to name two specific variables that control behavior, net total stress and suction (Section 2.2.1 in paper).

3 Slide with distributions of quantities above the water table

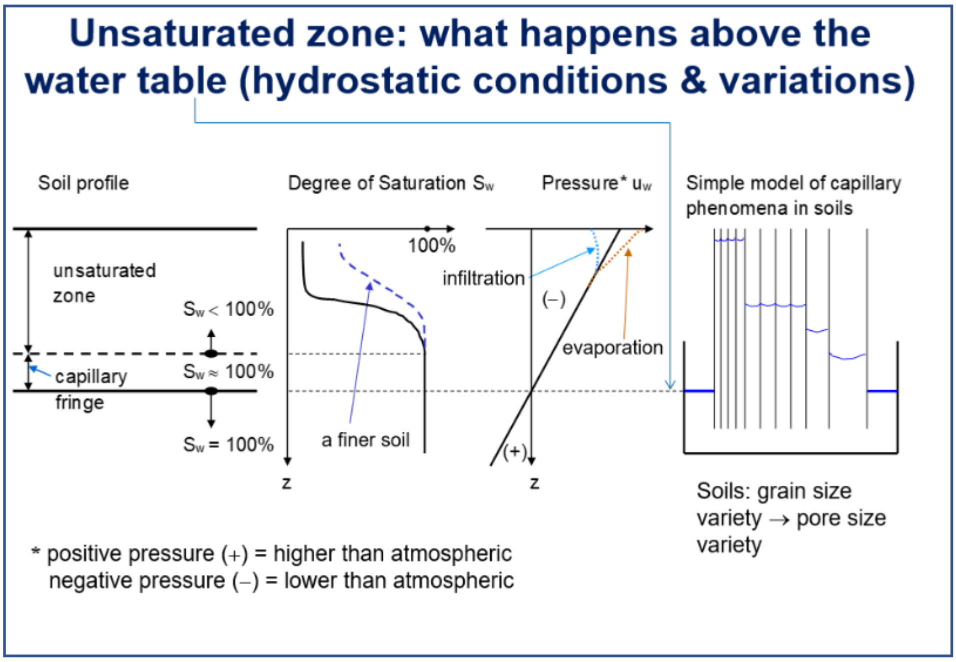

Figure S3. Revised soil profile above the water table: distribution of (a) water saturation and (b) pore water pressure for hydrostatic conditions and variations of infiltration and evaporation.

In line with the specialists' suggestion to consider the hydrostatic distribution as an idealized reference case, the revised version of the slide shows variations of the pore water pressure (higher values for infiltration and lower values for evaporation). It also includes a second distribution of saturation for a finer soil.

4 Shear strength of unsaturated soils

Equation for shear strength of unsaturated soils [Equation 18 from Vanapalli et al. (1996) for air pressure $u_\alpha = 0$]:

$$\tau = c' + \sigma \tan\phi' + f(s, S) \tan\phi'$$

Reference: Vanapalli, S.K., Fredlund, D.G., Pufahl, D.E. and Clifton, A.W. (1996). Model for the prediction of shear strength with respect to soil suction. Canadian Geotechnical Journal 33(3):379–392.

S4. LIST OF PUZZLEMENT QUESTIONS ABOUT UNSATURATED SOILS PHRASED BY A NON-SPECIALIST

Group A of questions: Soil profile above the water table

• **1.** What is the distribution of pore water pressure above the water table in the field? In a soil column?

• **2.** May we talk of an "equilibrium" water pressure distribution in the field other than hydrostatic?

• **3.** Is it reasonable to assume that equilibrium conditions are rare in the field for low permeability soils?

Group B of questions: "Effective stress" or in general "variables we need to keep track of in order to describe and predict soil behavior"

• **4.** From the perspective of an unsaturated soils specialist, can the existing alternative expressions for effective stress that include both air pressure and water pressure be excusable for explaining concepts in an introductory course? [Example: Bishop's Equation: $\sigma' = \sigma - u_a + \chi (u_a - u_w)$]

• **5.** What is really the "claim to prediction" of effective stress? (Textbooks do not agree: see examples in Appendix) If we have excused other description/prediction failures of the effective stress for saturated soils, then why are we so strict for the failure of effective stress to describe/predict states in unsaturated soils?

Group C of questions: Sandcastles & other demonstrations for effective stress (e.g. Elton, 2001)

• **6.** Is it wrong to tell students that sand castles stand due to higher effective stress? Should we say instead that the castle stands due to higher shear strength?

• **7.** Is it wrong to tell students that vacuum-packed coffee is strong due to higher effective stress?

Group D of questions: Shear strength

• **8.** In my course, I teach the Mohr-Coulomb criterion for shear strength ($\tau' = c' + \sigma' \tan\phi'$). I see that in unsaturated soil mechanics there are a few alternative expressions, e.g. Jaksa (2020) gives the following two:

$$\tau_f = c' + \left[(\sigma - u_a)_f + \chi_f (u_a - u_w)_f\right] \tan\phi' \quad (1)$$

$$\tau_f = c' + (\sigma - u_a)_f \tan\phi' + (u_a - u_w)_f \tan\phi^b \quad (2)$$

I do not know what to make of this variety, so I prefer say nothing about unsaturated strength to my students. Do I have a simple better alternative than say nothing?

• **9.** Is there any simple demonstration based on principles (not on examples, e.g. sand castles) of suction contributing to shear strength?

Group E of advanced questions: Motivation

• **10.** I get the impression that the answer to the question "which shear strength equation to use" is contested within the unsaturated soils community (see also Question No 8). Is this question a main issue for unsaturated soil mechanics? If not, perhaps we could withhold judgement and focus on more important/applied issues?

• **11.** Which geotechnical problems require unsaturated soil mechanics for the analysis that will produce their solution?

• **12.** Are there any applications of unsaturated soil mechanics in the field? Has the unsaturated soils community recorded some case studies?

Group F of advanced questions: Evidence

• **13.** After so many years of being taught and teaching about effective stress, it is hard to give it up. Do I understand correctly that its main failure for UNSAT soils is in predicting volume change? Or deformation? Or both?

• **14.** Please give me some carefully selected annotated results, ideally both in the lab and the field, showing the inability of effective stress to predict … (whatever is the answer to Question 13 above) and the successful prediction of a suitable unsaturated soil mechanics UNSAT SM approach.

APPENDIX

What do we read about effective stress in current textbooks (e.g., Atkinson, 2007; Briaud, 2013; Budhu, 2011; Powrie, 2014).

Atkinson (2007: p 70) quotes Terzaghi's (1936) strong definition: "all measurable effects of a change of stress, such as compression, distortion, change of shearing resistance, are due exclusively to change in effective stress". Then on page 71 he comments: "No conclusive evidence has yet been found that invalidates Terzaghi's original postulate, at least for saturated soils at normal levels of engineering stress, and the principle of effective stress is accepted as an axiom in Soil Mechanics".

Let's see also the rendition of Terzaghi's effective stress principle by Jennings and Burland (1962):

"Terzaghi's effective stress principle may be stated in the form of two propositions:

(i) Changes in volume and shearing strength of a soil are due exclusively to changes in effective tress.

(ii) The effective stress σ′ of a soil is defined as the excess of the total applied stress σ over the pore pressure u."

Briaud (2013: p 252) says only that the effective stress "is one of the most important parameters to know when dealing with soils".

Budhu (2011: p 152) says in bold italics "***Deformations of soils are a function of effective stresses, not total stresses***."

Powrie (2014: p 22) states "It is the effective stress which controls the volume and strength of soil."

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Briaud, J.-L. (2013). Geotechnical Engineering: Unsaturated and saturated soils, John Wiley & Sons, Inc., Hoboken, New Jersey.

Budhu, M. (2011). Soil Mechanics and Foundations, 3rd Ed. (1st Ed. 2000), John Wiley & Sons, Inc., Hoboken, New Jersey.

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Conf. Geotechnical Engineering Education GEE 2020, Athens, Greece, June 23-25, https://www.issmge.org/uploads/publications/3/102/Jaksa.pdf (accessed March 25, 2023).

Jennings, J.E.B. and Burland, J.B. (1962). Limitations to the use of effective stresses in partly saturated soils, Géotechnique, 12(2):125-144.

Powrie, W. (2014). Soil Mechanics Concepts and Application, 3rd Ed. (1st Ed. 1996), CRC Press, Taylor & Francis Group, Boca Raton, Florida.

S5. ANSWERS OF SPECIALISTS Sandra Houston (SH), John McCartney (JMcC) and Alessandro Tarantino (ST) TO THE PUZZLEMENT QUESTIONS OF A NON-SPECIALIST

Group A of questions: Soil profile above the water table

• **1.** What is the distribution of pore water pressure above the water table in the field? In a soil column?

SH *It depends on the boundary conditions with respect to water table, atmosphere (climate), and any potential "lateral" sources of soil wetting (or drying, but usually wetting). In general, estimation of pore water pressures above the water table for field conditions requires an empirical/statistical approach that may also involve "calibrated" unsaturated flow modeling to address "what if" questions with respect to changes in boundary conditions.*

JMcC *This depends on the infiltration or evaporation rate from the ground surface. It is simplest to introduce the hydrostatic pore water pressure profile in an undergraduate course, but to note that the shape of the profile will change as water moves in or out from the soil surface. It is important to understand the average climatic conditions in a specific location as well to determine the pore water pressure profile. There are a number of good case histories from the perspectives of water flow through unsaturated soil layers. Good examples are those from evapotranspirative cover case histories (Albright et al., 2006a, 2006b; Zornberg and McCartney 2005). There are also many case histories on rainfall induced landslides (e.g., Collins and Znidarcic, 2004). Centrifuge and column scale studies have investigated different flow processes in soil layers with different boundary conditions (McCartney and Zornberg 2010a, 2010b; Zornberg et al. 2010).*

Albright, W.H, Benson, C.H., Gee, G.W., Abichou, T., McDonald, E.V., Tyler, S.W.; and Rock, S.A. (2006a). Field Performance of a Compacted Clay Landfill Final Cover at a Humid Site, Journal of Geotechnical and Geoenvironmental Engineering, 132(11):1393-1403.

Albright, W.H, Benson, C.H., Gee, G.W., Abichou, T., McDonald, E.V., Tyler, S.W.; and Rock, S.A. (2006b). Field Performance of Three Compacted Clay Landfill Covers, Vadose Zone Journal 5(4):1157–1171.

Collins, B.D. and Znidarcic, D. (2004). Stability Analyses of Rainfall Induced Landslides, Journal of Geotechnical and Geoenvironmental Engineering, 130(4):362-372.

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Zornberg, J.G., and McCartney, J.S. (2005). "Evaluation of evapotranspiration from alternative landfill covers at the Rocky Mountain Arsenal." Proceedings of the International Symposium on Advanced Experimental Unsaturated Soil Mechanics (Experus 2005). Trento, Italy, Jun. 27-29. A.A. Balkema, Rotterdam. pp. 555-561.

Zornberg, J.G., Bouazza, A., and McCartney J.S. (2010). "Geosynthetic capillary barriers: State-of-the-knowledge." Geosynthetics International. 17(5), 273–300.

AT *The pore-water pressure above the water table can be hydrostatic (if no flux occurs in the flow domain, i.e., water is 'static') or different from hydrostatic if water flow occurs in the ground if the hydraulic head is not uniform and/or a flux is applied In this respect, there is no difference with saturated soils.*
Under static conditions, the pore-water pressure is still given by the unit weight of water multiplied by the distance of the point in question with respect to the water table (table where uw=0). If the point lies above the water table, pore-water pressure is negative.
If a flux is applied at the surface (evaporation or rainfall), pore-water pressure is more negative than hydrostatic (evaporation, water outflow) and less negative than hydrostatic (rainfall, water inflow). This is associated with the hydraulic gradient that should be positive upward for evaporation or positive downward for infiltration. There is no difference here with saturated soils, the same occurs for the flow around a retaining diaphragm (typically analysed with the flow net in an UG class).

• **2.** May we talk of an "equilibrium" water pressure distribution in the field other than hydrostatic?

SH *Yes, we can talk about a pseudo-equilibrium condition (steady state or more or less steady, particularly below regions of seasonally driven soil water content change). We can also talk about hydrostatic conditions as a reference state.*

JMcC *Yes, for compacted low permeability soils, it will take a very long time to reach hydrostatic conditions. A uniform water pressure profile could be assumed in some cases such as short-term analyses immediately after construction of compacted low permeability soils placed at a constant water content. The initial water pressure profile can be estimated from the Soil Water Retention Curve (SWRC) of the soil. For longer-term analyses a hydrostatic analysis should be used considering the effects of infiltration and evaporation from the surface.*

AT *Yes, the same way we can have non-hydrostatic distributions of pore-water pressure in saturated soils.*

• **3.** Is it reasonable to assume that equilibrium conditions are rare in the field for low permeability soils?

SH *True equilibrium conditions are rare for low or high permeability soils, but we do often see near-equilibrium conditions (steady state), see answer to question 2.*

JMcC *It depends if the low permeability material was compacted in place at a constant water content, or if it is naturally occurring and has had time to equilibrate with the atmospheric boundary conditions.*

AT *Steady-state conditions are rarely achieved because the hydraulic boundary condition at the ground surface (rainfall and evaporation) changes rapidly with time. It is true that there is a depth (active zone) beyond which the pore-water pressure is not affected by the variable flow applied at the surface and pressure remains hydrostatic. This depth is typically 1-2m although its extent depends on the soil, the depth of the ground water table, and the rainfall/evaporation duration and intensity. The distinction between low permeability (fine-grained soils) and high permeability (coarse-grained soils) does not hold in the unsaturated state. Clays can be much more permeable than sands.*

BUT, ARE THERE ANY FIELD MEASUREMENTS IN THE UNSATURATED ZONE ABOVE THE WATER TABLE THAT SHOW THIS ACTIVE ZONE AND A HYDROSTATIC DISTRIBUTION BELOW?

"AT2" (i.e. MP notes from an online meeting) *Suction measurements are difficult in the field and rare below 1.5m, for anything deeper than 1.5m, we would need to open a borehole. I do not know of any measurements, but I could tell you what kinds of measurements I would like to have. (1) Two CPTs (MP: with pore water pressure measurements or not necessarily?), that would show no difference beyond a certain depth. (2) Resistivity mapping with Electrical Resistivity Tomography (ERT).*

Group B of questions: "Effective stress" or in general "variables we need to keep track of in order to describe and predict soil behavior"

• **4.** From the perspective of an UNSAT SM specialist, can the existing alternative expressions for effective stress that include both air pressure and water pressure be excusable for explaining concepts in an introductory course? [Example: Bishop's Equation: $\sigma' = \sigma - u_a + \chi (u_a - u_w)$]

SH *No. When dealing with unsaturated soils you need to think, simultaneously, about two stress variables. The stress variables are: Net Total Stress (total stress minus air pressure) and Soil Suction (a strong function of soil water content) (Matyas and Radhakrishna, 1968; Fredlund and Morgenstern, 1977; Fredlund and Rahardjo, 1993; Alonso, Gens and Josa, 1990).*

In your study of saturated soils, you have learned that you can combined the stress variables of Total Stress and Pore Water Pressure into one Effective Stress variable that controls soil response. However, for unsaturated soils it is not generally possible to combine the two stress variables into one variable that controls soil response over the full range of conditions and problems that practicing engineers and constructors must deal with, sometimes simultaneously – including: (1) volume change such as collapse or expansion due to wetting, leading to settlement or heave, and (2) shear strength assessment, as needed for applications such as slope stability evaluations and trench stability. Indeed, in the first step in studying soil behavior it is necessary to use two independent stress variables for all laboratory testing. For saturated soils we find that we can subsequently combine the two stress state variables in one single-valued effective stress that controls volume change and shear strength of saturated soils. However, for unsaturated soils we find that it is not possible to combine these two variables for many interesting applications of shear strength or volume change applications.

In saturated soil mechanics, it is taught that an increase in effective stress results in a decrease in volume and an increase in shear strength, while a decrease in effective stress results in increase in volume and a decrease in shear strength. For unsaturated soils, a Bishop's-type "effective stress" formulation gives a decrease in "effective stress" when the soil is wetted, yet when wetting a clean sand from an extremely dry condition the shear strength will actually increase (sandcastle example). Further, Bishop's type "effective stress" formulations give an increase in "effective stress" when a clean sand is dried, yet the shear strength of a sand can decrease despite a computed (using Bishop's type equation) increase in "effective stress." Regarding volume change applications, when an unsaturated clay is wetted the computed Bishop's type effective stress decreases, the volume change can be either compressive or expansive, depending on the soil density and the net total confining stress. One additional result of the above soil response complexities is that attempts to define an "effective stress" for unsaturated soils have been unsuccessful in finding any one expression that could be used for both shear strength and volume change response. In other words, any expression required for volume change would be different than an expression for shear strength – which is not consistent with the concept of effective stress put forth by Terzaghi for saturated soils wherein the effective stress for volume change is the same as for shear strength.

Fredlund, D.G. and Morgenstern, N.R. (1977). Stress state variables for unsaturated soils. ASCE J. of the Geotechnical Engineering Division, 103(5):447-466.

Fredlund, D.G. and Rahardjo, H. (1993). Soil Mechanics for unsaturated soils, Wiley.

Matyas and Radhakrishna, 1968

JMcC *Several different equations have been proposed for the effective stress in unsaturated soils. It is preferable to use effective stress over independent stress state variables so that similar mechanics equations can be used for saturated and unsaturated soils, albeit with different yielding conditions in unsaturated conditions. An approach that permits incorporation of the SWRC into the effective stress is particularly useful. The two preferable equations to use in practice are those of Khalili and Khabbaz (1998) and Lu et al. (2010) as they both have a way of integrating the shape of the SWRC into the effective stress definition. I use the equation of Lu et al. (2010) in my research as it permits integration of the SWRC directly:*

$\sigma' = (\sigma - u_a) + S_e(u_a - u_w)$

S_e *= effective saturation, connected to* $u_a - u_w$ *through the van Genuchen (1980) SWRC for example.*

Khalili, N., and Khabbaz, M. H. (1998). A unique relationship for χ for the determination of the shear strength of unsaturated soils, Géotechnique, 48(5):681-687, https://doi.org/10.1680/geot.1998.48.5.681.

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AT *Once it is clarified that the concept of effective stress is more complex for unsaturated soils and there is almost universal consensus that the mechanical behaviour of unsaturated soils needs to be represented by two effective stresses, it can be stated:*

1) *As far as the shear strength is concerned, the Bishop effective stress (with χ=Sr) is an appropriate effective stress for coarse-grained materials and can be considered acceptable from a qualitative standpoint for fine-grained materials*
2) *For deformation problems, the Bishop effective stress is not generally sufficient to interpret/model the mechanical response of unsaturated soils, even from a qualitative standpoint*

• **5.** What is really the "claim to prediction" of effective stress? (Textbooks do not agree.) If we have excused other description/prediction failures of the effective stress for saturated soils, then why are we so strict for the failure of effective stress to describe/predict states in unsaturated soils?

SH *For saturated soils some have cited problems with using effective stress, but for saturated soils effective stress usually works adequately for our engineering problems. Although shear-induced dilatancy is sometimes cited as an example of failure of effective stress for saturated soils, Terzaghi presented his effective stress concept for isotropic loading and via the 1-D consolidation test, and it could be argued that a loading path including shear loading to failure is not an entirely legitimate test of the reasonableness of Terzaghi's effective stress definition for saturated soil. It is the stress state relative to the critical state that determines how much and what kind of volume change occurs – a key feature of critical state soil mechanics, during which theory development there did not appear to be any outcry of failure of effective stress for saturated soils. Another case where effective stress for unsaturated soils is sometimes cited as inadequate is that of metastable saturated soils (e.g., quick clays). Quick clays have in common with unsaturated collapsible soil high void ratio and high bond strength, but the similarities more or less end there. With quick clays, whether loaded isotropically or*

1-D K_o, an increase in effective stress is required to initiate rupture of the particle bonds and subsequent densification (qualitatively consistent with Terzaghi's effective stress concept for saturated soil). In contrast, when unsaturated collapsible soil is wetted under substantial confining stress the response is densification, but any Bishop's type "effective stress" would give a decrease in "effective stress" for wetting under constant confining stress (giving quantitatively the wrong result, and with the wrong sign with respect to the accepted concept of effective stress for saturated soils).

Thus, it could be reasonably argued that there are no violations of effective stress for saturated soils, and certainly none for isotropic or 1-D, K_o loading- or for shear strength. However, it is not possible to think in terms of a single-valued effective stress for unsaturated soils that is widely applicable to both volume change response and shear strength change response. If it is suggested to students and non-experts that there is also an "effective stress" for unsaturated soils, it is likely that the expectation of non-experts or students would be that an "unsaturated soil effective stress" could be considered to be "equivalent" in performance to Terzaghi's effective stress for saturated soils and that it could be used as a direct substitution in saturated soil effective stress constitutive models. This is not supported by available data, in general.

There are two primary problems in presenting an "effective stress for unsaturated soils" for volume change: (1) For a Bishop's type formulation (which is essentially every proposed "unsat effective stress" equation), the χ parameter is not well-behaved. In fact, the back-calculated χ parameters extend well outside the range of 0 to 1 (effective degree of saturation range) and even vary in sign (+/-) in the collapse zone. Given that all proposed χ parameters are positive, a Bishop's type "effective stress" cannot be relied on even as a indicator of the sign of volume change for unsaturated soils – even under isotropic conditions. (2) There is no clear definition of "effective stress for unsaturated soils" when elastoplastic response is considered (which it must be). Using the data of Brackley (1973), Zhang and Lytton (2009) demonstrated divergence of the yield curve and the constant volume curve for unsaturated soils. For unsaturated soils, the very common volume-change based definition of effective stress (i.e., there is no volume change unless there is change in effective stress) results in the uncomfortable conclusion that a soil yields under constant "effective stress" conditions. For saturated soils this problem does not arise because the constant volume curve and the yield curve are coincident for saturated conditions.

Once a clear understanding of the role of net total stress and soil suction in unsaturated soil behavior is obtained, some problems can be handled using empirical approaches for limited soil types or stress ranges that may have the appearance of ''effective stress" applications for unsaturated soils. Unsaturated Soil Shear Strength is an example of this, but even here, sand is an important exception. It should be noted that there is no "effective stress" for unsaturated soils that is consistent with the saturated soil effective stress concepts previously learned.

JMcC *Effective stress only provides a 1:1 relationship with deformations in the elastic regime. Otherwise, the effective stress needs to be used in an elasto-plastic framework to predict deformations.*

AT *We are so strict to pass the message that the response of unsaturated soils is controlled by two independent effective stresses and that, unlike saturated soils, one single effective stress is not sufficient to describe/model unsaturated soil mechanical behaviour, not even from a qualitative standpoint.*
The point is not just the quantitative prediction, a single effective stress fails to explain unsaturated soils also from a qualitative standpoint.

Group C of questions: Sandcastles & other demonstrations for effective stress (e.g. Elton, 2001)

• **6.** Is it wrong to tell students that sand castles stand due to higher effective stress? Should we say instead that the castle stands due to higher shear strength?

SH *Yes, it is wrong to use "effective stress" to explain sandcastle construction. It is best to say that sandcastles stand due to higher shear strength associated with water contents intermediate between wet and very dry. For clean sand, Bishop's type effective stress will fail as the sand is dried fully from a moist state or heavily wetted from a moist state.*

In the discussion of sand castles, it would be good to discuss that "professional" sandcastle builders/artists understand that the addition of a little bit of clay not only increases the height to which one can build a sand castle, but also "preserves" the sand castle for future viewing in spite of drying – this is due to lasting increased shear strength of clay that occurs during drying, no matter how dry. Consider using clay balls dried to different levels as an example to show the difference between sand and clay response to suction increase caused by drying – and to point out that suction includes more than just capillary stresses - and that shear strength increases with increasing suction except for clean sand.

JMcC *The shear strength permits the sand castle to form, and the shear strength depends on the effective stress. The effective stress arises from the right combination of suction and degree of saturation in the sand. So they are interlinked.*

AT *For the sand in a stability problem (as is the case of sandcastles), we can assume that the shear strength is controlled by a single 'shear strength effective stress'. In this case, we can say both (having in mind we are referring to the 'shear strength effective stress', i.e., the single effective stress that has been proven to control shear strength of coarse-grained soils).*

More in general (say silt/clay castles), it is more appropriate to say that it is the higher shear strength that makes the castle stable.

• **7.** Is it wrong to tell students that vacuum-packed coffee is strong due to higher effective stress?

SH *Yes, it is wrong. The vacuum-packed coffee is stiff primarily because the net total stress is increased due to the vacuum.*

JMcC *The high negative air pressure contributes to a positive effective stress on the coffee, giving it a high shear strength. This was the approach used in early shear strength testing on sands.*

AT *No, this is a two-phase material (soil and air) and single pore-fluid (air). The mechanics of saturated soils applies here. If the pore-pressure decreases, the effective stress increases.*

Group D of questions: Shear strength

• **8.** In my course, I teach the Mohr-Coulomb criterion for shear strength ($\tau' = c' + \sigma' \tan\phi'$). I see that in UNSAT SM there are a few alternative expressions, e.g. Jaksa (2020) gives the following two:

$$\tau_f = c' + \left[(\sigma - u_a)_f + \chi_f (u_a - u_w)_f\right] \tan\phi' \quad (1)$$

$$\tau_f = c' + (\sigma - u_a)_f \tan\phi' + (u_a - u_w)_f \tan\phi^b \quad (2)$$

I do not know what to make of this variety, so I prefer say nothing about unsaturated strength to my students. Do I have a simple better alternative than say nothing?

SH *These unsaturated soil shear strength equations are basically the same, and both are empirically developed. The tan-ϕ^b is a function of suction and tan ϕ' can always be factored out of the expression - and χ_f is also function of suction. There are many similar-looking expressions for unsaturated shear strength, and all are empirical in nature, having been fitted to directly measured unsaturated soil shear strength values. These and similar expressions have been shown to work reasonably well within the range of suction from air-entry value (AEV) to near residual for silts and clays, but not for sands. Given the empirical nature of such expressions it is desirable to understand the database (stress range, clays, silts, sand….) that was considered in development of the expression for shear strength. (Note: This discussion also requires description, as a minimum, of the "zero" confinement Soil Water Characteristic Curve (SWCC), including AEV and residual).*

JMcC *The shear strength of unsaturated soils can be expressed simply using the Mohr-Coulomb failure criters:*

$$\tau_f = \left[(\sigma - u_a)_f + S_e(u_a - u_w)_f\right]\tan\phi'$$

Where the friction angle is the same as that used for saturated or dry soils. Studies that have used the second equation show that the relationship for tan(φ_b) ends up acting in a similar way to the χ parameter in the effective stress, leading to the same result. In my opinion, it is better to use the Mohr-Coulomb failure envelope with the effective stress as it permits seamless transitions from saturated to unsaturated soils (and avoids significant confusion from undergraduates). Incorporating a drained cohesion into this equation is only applicable to cemented soils. It is difficult to detect this in laboratory tests because of sample disturbance. It may be present in the field. It is conservative to not include this term in the shear strength definition.

AT *Eq. 2 is conceptually and practically incorrect. Eq. 1 is OK, using χ=S_r is also fine (with the caveat that is not very accurate for quantitative prediction of fine-grained soils).*

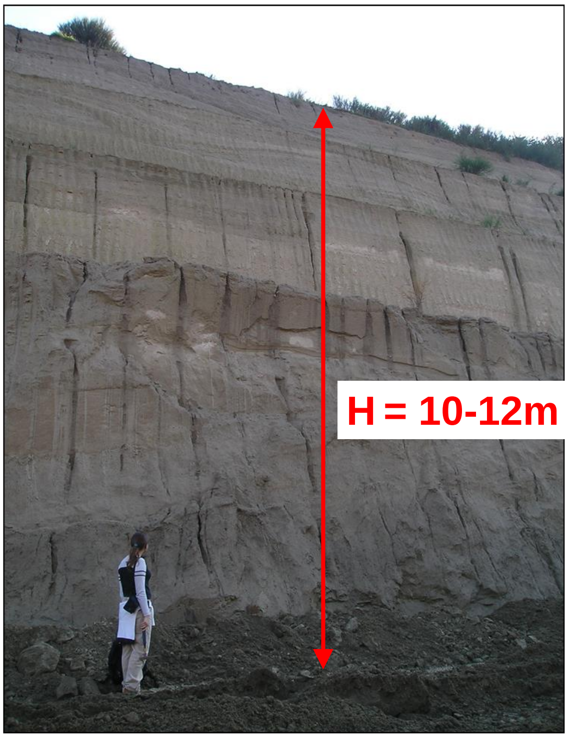
• **9.** Is there any simple demonstration based on principles (not on examples, e.g. sand castles) of suction contributing to shear strength?

SH *Probably it is best to stick with examples.*

Sandcastle – capillary suction only (or predominantly); Different balls of clay dried for various length of time (longer time, higher suction, high shear strength/stiffness).

JMcC *The papers of Lu et al. (2010) and Khalili and Khabbaz (1998) mentioned above both show that the shape of the SWRC plays a key role in the effective stress and shear strength of the soil. A specific reference is Equation 24 in Lu et al. 2010. Suction does not contribute to shear strength, effective stress does. You could have a soil that is completely dry and has an incredibly high suction. But you need to weight the amount of water and the energy in the water together via the effective stress to determine the effective stress.*

AT *Cave excavated in unsaturated silty sand Lopes & Tarantino (2021), see Question 12 for full reference*



Vertical cut in unsaturated silty sand

Group E of advanced questions: Motivation

• **10.** I get the impression that the answer to the question "which shear strength equation to use" is contested within the UNSAT SM community (see also Question No 8). Is this question a main issue for UNSAT SM? If not, perhaps we could withhold judgement and focus on more important/applied issues?

SH *Unsaturated soils shear strength equations are empirical and therefore which equation to use can often be addressed by simply matching the soil type, stress range, etc. with the application at-hand. This may be a better approach than arguing about which empirical shear strength equation is "best".*

Rather, consider the following list to identify important issues for Introduction to unsaturated soils:

1. Pore Water Pressures are Negative, and Soil Suction exists in the soil profile above the GWT (GWT including regional and perched). Soil suction is related to the energy required to remove water from the soil and includes capillary forces and physico-chemical particle surface forces (van der Waals, double layer forces, cementation, ….). Matric suction, s (also represented by u_a-u_w), is the stress that is the measurable (or controllable) embodiment of these particle forces.

2. There are two stress variables, Net Total Stress (total stress minus air pressure) and Soil Suction (a strong function of soil water content), that must be considered for unsaturated soils, and these two stress variables cannot be combined to obtain a single-valued stress variable that is equivalent to the effective stress used in saturated soil mechanics. Thus, for unsaturated soils there are two stress variables that control the shear strength and volume change response of the soil.

3. Behavior/Response of unsaturated soils at a given (confining) net total stress is strongly dependent on water content and changes in water content. For this reason, it is important to understand potential sources of soil wetting and drying, and such a study needs to be added to the geotechnical site investigation.

For most engineering applications, it is the change in water content (usually increase in water content) that results in problematic unsaturated soil response (e.g., volume change (expansion or compression) or shear strength change). Therefore, laboratory testing of unsaturated soil needs to include response-to-wetting with respect to volume change and/or shear strength.

4. Water moves differently through unsaturated soils than saturated soils. The hydraulic conductivity of an unsaturated soil is a strong function of soil suction (degree of saturation/water content). Depending on the soil water content, a sand may have a hydraulic conductivity that is higher OR lower than a clay.

5. Unsaturated soil response to changes in stress state (net total stress and suction) is highly nonlinear and it is therefore difficult to intuit behavior. For this reason, adoption of a Stress Path approach in laboratory testing and modeling and addressing problems is advised. Briefly, a stress path approach entails configuration of lab test such that the representative lab test specimen is made to follow a path in the lab that matches that of the corresponding element of soil in the field- both in terms of net total stress and suction.

JMcC *I don't think that it is a major issue. Different equations are available to represent the shear strength, and it is important to verify that the equation works for the soil under investigation and the conditions being considered and can be applied to saturated, unsaturated, and dry soils. Most lead to the same answer. It is important to use the simplest equation that can be defined from the simplest tests (SWRC and shear strength tests on saturated or dry soil). The major issue is that unsaturated soil mechanics is a more generalized case compared to dry and unsaturated soils. You need to consider the coupled interactions between all three phases. Air is very compressible, but its presence leads to capillary forces that help hold the particles together. Air can dissolve into the water. Drainage conditions are critical for controlling the behavior*.

AT *The shear strength equation 1 is perhaps the only non-controversial equation in unsaturated soil mechanics. It also allows to introduce unsaturated soil mechanics one step at the time, because it serves the shear strength of unsaturated soils in a very similar way as saturated soils (based on one single 'effective' stress).*

• **11.** Which geotechnical problems require UNSAT SM for the analysis that will produce their solution?

SH *Any problem dealing with soils above the gwt, compacted soils or natural soils. There are even some applications below GWT or below the ocean surface where there is air within the soil pores.*

JMcC *Problems where a water flow or heat transfer process leads to a change in the effective stress of the soil, leading to changes in stiffness or shear strength. This is very relevant in pavements, retaining walls, and even in shallow and deep foundations.*

AT *Rainfall-induced instability of man-made and natural slopes, building damage due to drought-induced foundation subsidence (just to consider geotechnical routine problems).*

• **12.** Are there any applications of UNSAT SM in the field? Has the UNSAT SM community recorded some case studies?

SH *Yes. Examples: Soil expansion upon wetting, soil collapse upon wetting, rainfall induced slope failure, buried pipelines, earth dams, retaining wall systems, cover systems, and pavements.*

Here are two:

1. Lateral Load-Displacement Behavior of Pipelines in Unsaturated Sands, D. J. Robert1; K. Soga; T. D. O'Rourke; and T. Sakanoue, J. Geotech. Geoenviron. Eng., (2016), DOI: 10.1061/(ASCE)GT.1943-5606.0001504.. Although not a true case study, it is a full-scale study and it is almost impossible to expect case studies for earthquake (you have to wait too long). "The full-scale tests and FE simulations show that increased strength and stiffness associated with soil suction increases lateral loads on pipelines and thus need to be considered when designing pipelines for externally imposed ground movement. The modeling procedures and results can be used to predict lateral loads on underground pipelines subjected to construction and earthquake induced ground movements, landslides, and subsidence. Because most pipelines are buried in unsaturated soil, the results have widespread relevance in design and construction."

2. Geobarrier System for Protection Against Rainfall-induced Slope Failure, H. Rahardjo, A. Satyanaga, N. Gofar, Eng Choon Leong, J. H. Kew,C.L. Wang, J. L. H. Wang (2019). Slope failures are a common occurrence in tropical regions with a high intensity of rainfall. ISSMGE International Journal of Geoengineering Case Histories, Vol. 5, Issue 1, pp. 26-43 (2019). "The negative pore-water pressure in unsaturated soil is highly influenced by the changes in the flux boundary conditions, resulting from the variation in climatic conditions .On the other hand, the negative pore-water pressure contributes additional shear strength to the unsaturated soil. As water infiltrates into the slope, pore-water pressure in the slope increases (matric suction decreases), and the additional shear strength due to matric suction will decrease, causing the slope to be more susceptible to failure. Singapore is a land scarce country with a critical need to optimize land utilization. Steepening slopes or cutting back slopes and supporting them using a retaining structure is one way to create new spaces. In this study, a new type of retaining structure, Geobarrier System (GBS) is proposed. A GBS is a man-made three-layer cover system designed as a vegetative layer combined with a two-layer unsaturated system, which harnesses the distinct difference in unsaturated hydraulic properties between a fine-grained layer and a coarse-grained layer. GBS consists of recycled materials and does not use steel or concrete and is hence more cost effective, thereby making it economical for use in urban areas. Geobag for the vegetative layer is supported by specially designed pockets for planting different types of sustainable plant species. The paper presents the design, construction procedures, material selection and field performance of a GBS constructed at an inclination angle of 70o in response to rainfall infiltration. In addition, the results of the finite element seepage and slope stability analyses of the GBS subjected to extreme rainfalls are also presented. The results from field instruments and numerical analyses showed that GBS was able to protect the slope from rainfall infiltration; therefore, the stability of the slope retained by GBS was not affected by the rainfall."

JMcC *Wetting induced collapse, foundations on expansive soils, nuclear waste repositories, energy piles in unsaturated soil layers, etc. In addition to the case histories on evapotranspiration covers and rainfall induced landslides, the EB and FEBEX project are great examples (e.g., ENRESA 2000; Gens et al. 2021). Centrifuge modeling is a great tool to get information that can be extrapolated to field conditions, for example interpreting the effects of unsaturated conditions on the behavior of energy piles (Behbehani and McCartney 2022) and interpreting the effects of seismic compression (Ghayoomi et al. 2011, 2013). Both of these topics are very difficult to measure and interpret in field case studies, but useful information can be gained from centrifuge models.*

Behbehani, F. and McCartney, J.S. (2022). "Impact of transient heat transfer and water flow on the long-term thermal response of energy piles in unsaturated soils." 20th International Conference on Soil Mechanics and Geotechnical Engineering. Sydney. Apr. 1 – May 5. pp. 1-6.

ENRESA. FEBEX project. Full-scale engineered barriers experiment for a deep geological repository for high level radioactive waste in crystalline host rock. Final report. Publicación Técnica 1/2000, ENRESA, Madrid. 2000.

Gens, A., Alcoverro, J., Blaheta, R., Hasal, M., Michalec, Z., Takayama, Y., Lee, C., Lee., J., Kim, G.Y., Kuo, C.W., Kuo, W.J., Lin, C.Y. 2021. HM and THM interactions in bentonite engineered barriers for nuclear waste disposal. International Journal of Rock Mechanics and Mining Sciences, 137: 104572.

Ghayoomi, M., McCartney, J.S., and Ko, H.-Y. (2011). "Centrifuge test for seismic compression of partially saturated sands." ASTM Geotechnical Testing Journal. 34(4). 321-331.

Ghayoomi, M., McCartney, J.S. and Ko, H.-Y. (2013). "Empirical methodology to estimate seismically induced settlement of partially saturated sand." ASCE Journal of Geotechnical and Geoenvironmental Engineering. 139(3), 367-376.

AT *These are the ones I worked on*

Flood embankment
Amabile, A., Pozzato, A. and Tarantino, A. (2020). Instability of flood embankments due to pore-water pressure build-up at the toe: lesson learned from the Adige River case study, Canadian Geotechnical Journal, 57(12):1844-1853, https://doi.org/10.1139/cgj-2018-0372

Rainfall-induced instability
Balzano, B., Tarantino, A., Nicotera, M.V., Forte, G., de Falco, M. and Santo, A. (2019). Building physically based models for assessing rainfall-induced shallow landslide hazard at catchment scale: case study of the Sorrento Peninsula (Italy), Canadian Geotechnical Journal, 59(9):1291-1303, https://doi.org/10.1139/cgj-2017-0611

Balzano, B., Tarantino, A. & Ridley, A. (2109). Preliminary analysis on the impacts of the rhizosphere on occurrence of rainfall-induced shallow landslides, Landslides, 16:1885-1901, https://link.springer.com/article/10.1007/s10346-019-01197-5

Excavation
Lopes, B. de C.F.L. & Tarantino, A. (2021). Stability analysis of a cave excavated in granular cohesionless material, Géotechnique 71(12):1085-1098, https://doi.org/10.1680/jgeot.19.P.269

Group F of advanced questions: Evidence

• **13.** After so many years of being taught and teaching about effective stress, it is hard to give it up. Do I understand correctly that its main failure for UNSAT soils is in predicting volume change? Or deformation? Or both?

SH *A single-valued "effective stress" that is widely applicable over a wide range of soil types and stress magnitudes does not exist for unsaturated soil applications (volume change/deformation or shear strength). For certain soils and ranges of suction one may be able to get away with an empirical solution that has a "feel/look" of an "equivalent effective stress" but it is always necessary to consider the independent role of net total stress and suction for the general case and to ensure that major errors are not made. For example, with respect to volume change, one might be able to use an "effective stress looking" type approach for cases where suction reduction (wetting) results in soil expansion – but it is a slippery slope because any clay can become collapsible when wetted if the net total confining stress is sufficiently large. You need data to confirm such empirical relationships. Laboratory testing using controllable or measurable independent stress variables is needed to check/validate unsaturated soil constitutive relationships. For unsaturated soils, attempts to use a single-valued effective stress can get you into trouble too often, over normal ranges of net total stress and suction for practice applications. (Also see discussion under items 4 and 5 above, and note that it is difficult to even define effective stress for unsaturated soils without losing its physical meaning per Terzaghi.)*

JMcC *Effective stress must be used in an appropriate elasto-plastic framework to define volume changes in both saturated and unsaturated soils (Khalili et al. 2004). Any failures in the past were a result of not using the appropriate elasto-plastic framework. An example of an appropriate framework would be Wheeler et al. (2003), but there are many others.*

Khalili, N., Geiser, F. and Blight, G.E. (2004). Effective Stress in Unsaturated Soils: Review with New Evidence, ASCE International Journal of Geomechanics, 4(2):115-126, doi:10.1061/(ASCE)1532-3641(2004)4:2(115)

Wheeler, S. J., Sharma, R. J. & Buisson, M. S. R. (2003). Coupling of hydraulic hysteresis and stress–strain behaviour in unsaturated soils, Géotechnique 53(1):41–54, https://doi.org/10.1680/geot.2003.53.1.41

AT *Yes, this is the point. But it is not surprising, there are two phases in saturated soils and we end up with one effective stress, there are three phases on an unsaturated soil and we end up with two effective stresses (number of phases minus one).*

• **14.** Please give me some carefully selected annotated results, ideally both in the lab and the field, showing the inability of effective stress to predict … (whatever is the answer to Question 13 above) and the successful prediction of a suitable UNSAT SM approach.

SH *Volume change is the easiest to demonstrate. In saturated soil mechanics, it is taught that an increase in effective stress results in compression of the soil and a decrease in effective stress results in soil expansion. Numerous publications show data where wetting of an unsaturated soil (depending on initial density) results in expansion under light confining stress and collapse under high confining stress. This is a case where a Bishop's-type formulation gives a decrease in "effective stress" yet the volume change can be either expansion or compression. Therefore, the volume change response to wetting is not well captured by a Bishop's type "effective stress," and in fact, even the sign (direction) of volume change can be wrong. There are numerous case studies related to this topic. (Also see discussion under* *items 5, and note that problems with "effective stress" for volume change are not resolved even when considering elastoplastic response).*

Another example that is easy to demonstrate relates to shear strength of sand. For unsaturated soils, a Bishop's-type "effective stress" formulation gives a decrease in "effective stress" when the soil is wetted, yet when wetting a clean sand from an extremely dry condition the shear strength will actually increase. This case of soil-structure interaction for buried pipeline from question 12 above is a good example of the role of soil suction in performance of soil-structure interaction analyses.

JMcC: *The paper by Khalili et al. (2004) mentioned above has a good description of wetting induced collapse and how it can be considered using effective stress, and addresses the "failure" that was raised by Jennings and Burland. Also, the seminal paper by Skempton (1961) has a deep exploration of effective stress in saturated and unsaturated soils, as well as in concrete and rocks. I do not think that effective stress has failed. It is the only approach to follow. Skempton (1961) shows how the effective stress of all soils, saturated, unsaturated or dry, requires a material property as part of its definition. For the case of soils, the compressibility of the soil skeleton is much greater than that of the pore fluid, so the material properties cancel and you fortuitously have an effective stress that is only dependent on the total stress and pore water pressure. However, you should strictly incorporate this parameter to represent the "effective" stress state in soils and rock.*

Skempton, A.W. (1961). Effective Stress in Soils, Concrete and Rocks, Pore Pressure and Suction in Soils, Butterworths, London.

AT *El Mountassir, G., Sánchez, M. and Romero, E. (2014). An experimental study on the compaction and collapsible behaviour of a flood defence embankment fill, Engineering Geology, Volume 179, 4 September 2014, Pages 132-145, https://www.sciencedirect.com/science/article/abs/pii/S0013795214001562*

Alonso Eduardo - Lloret Antonio - Romero Enrique (1999) , Rainfall induced deformations of road embankments Rivista Italiana di Geotecnica N.1/1999, pp. 8-15.

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Elton, D. (2001). Soils Magic, Geotechnical Special Publication 114, ASCE, Reston, Virginia.

Jaksa, M.B. (2020). Reflections on some contemporary aspects of Geotechnical Engineering Education – From critical state to virtual immersion, 2nd John Burland Lecture, Proceedings of the ISSMGE Int. Conf. Geotechnical Engineering Education GEE 2020, Athens, Greece, June 23-25, https://www.issmge.org/uploads/publications/3/102/Jaksa.pdf (accessed March 25, 2023).

S6. LINK WITH PRESENTATIONS FROM PANEL DISCUSSION AT UNSAT 2023: "UNSATURATED SOIL MECHANICS INSTRUCTION: GUIDING THE NON-SPECIALIST INSTRUCTOR"

https://www.erasmus.gr/microsites/1259/panel-discussion-on-education