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Alert soil mechanics instructors of the main unsaturated soil issues: What and how to teach when experts disagree

Alerter les formateurs en mécanique des sols sur les principales questions relatives aux sols non saturés: Quoi et comment enseigner lorsque les experts ne sont pas d'accord

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ABSTRACT: The team project described in this paper is a brainchild of technical committee TC106 on Unsaturated Soils, which has been advocating for years the teaching of unsaturated soil mechanics, and technical committee TC306 on Geo-engineering education, which learned in 2020 about a technical disagreement within the unsaturated soils community. The 8th International Conference on Unsaturated Soils (UNSAT 2023) was an opportunity for the two committees to collaborate on tackling together the specific issue of teaching unsaturated soil mechanics and the broader issue of expert disagreement. Understanding the nature of the disagreement was attempted mainly by having specialists answer a list of questions phrased by the non-specialist first author after having been tutored by the last author, also a specialist. The answers revealed a significant disagreement on the variables selected to describe the behavior of unsaturated soils. Until the disagreement is satisfactorily settled within the unsaturated soils community, interim solutions are proposed for instruction.

RÉSUMÉ: Le projet d'équipe décrit dans cet article est une idée du comité technique TC106 pour les sols non saturés, qui préconise depuis des années l'enseignement de la mécanique des sols non saturés, et du comité technique TC306 pour l'enseignement de la géo-ingénierie, qui a appris en 2020 l'existence d'un désaccord technique au sein de la communauté des sols non saturés. La 8e conférence internationale sur les sols non saturés (UNSAT 2023) a été l'occasion pour les deux comités de collaborer pour aborder ensemble la question spécifique de l'enseignement de la mécanique des sols non saturés et la question plus large du désaccord entre experts. La compréhension de la nature du désaccord a été tentée principalement en demandant à des spécialistes de répondre à une liste de questions formulées par le premier auteur, non spécialiste, après avoir été encadré par le dernier auteur, également spécialiste. Les réponses ont révélé un désaccord important sur les variables choisies pour décrire le comportement des sols non saturés. En attendant que ce désaccord soit résolu de manière satisfaisante au sein de la communauté des sols non saturés, des solutions provisoires sont proposées pour l'enseignement.

Keywords: Geotechnical engineering education; unsaturated soils instruction; effective stress.

1 INTRODUCTION

Unsaturated soil mechanics is moving from research to instruction primarily in courses taught by unsaturated soils specialists, including members of the technical committee TC106 on Unsaturated Soils of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) (Houston et al., 2014; McCartney, 2021). With the exception of a section on compacted soils, few introductory geotechnical engineering textbooks cover or even draw attention to unsaturated soils. The ISSMGE technical committee TC306 on Geo-engineering Education became aware of a technical disagreement within the unsaturated soils community thanks to the 2nd Burland Lecture and accompanying paper by Jaksa (2020), who presented two different expressions for the shear strength of unsaturated soils.

This paper describes a collaborative project of TC106 and TC306 targeting non-specialist soil mechanics instructors who would be interested in presenting in their courses some elements of unsaturated soil mechanics, provided they are aware of the main issues. The opportunity for the collaboration was given by the organization of the UNSAT 2023 conference and a proposal of the last author (the conference chair) to the first author to organize a panel session on education. Together, they decided to help non-specialist instructors understand in broad strokes the disputed issues. Guidance to the non-specialists would be given mainly in a question-and-answer form. To this end, a set of 14 questions was prepared by the non-specialist first author after being tutored by the specialist last author. This collaboration was crucial: without the specialist's involvement, the non-specialist would not have the necessary stamina to translate bewilderment about outstanding issues in unsaturated soil mechanics into questions. The three other specialist authors of this paper accepted the invitation to participate in the panel and agreed to provide written answers. In addition, they agreed to evaluate educational material used by the non-specialist member of the author team in an introductory course in soil mechanics.

The goal of the paper is three-fold: (i) to advance the collective understanding (i.e. within the wider geotechnical engineering community) of the technical disagreement within the unsaturated soils community (Section 2), (ii) to explore approaches to handle technical disagreement (Section 3) and (iii) to offer interim suggestions for teaching (Section 4) until the disagreement is resolved or becomes irrelevant. The paper provides a record of the aforementioned novel inter-committee collaboration and its outcomes so far, including a link to all the background materials produced, which are available in an online supplement (Houston et al., 2023).

2 UNSATURATED SOILS QUESTIONS AND DISCUSSION OF ANSWERS

Table 1 includes somewhat shorter forms of the 14 questions posed to three of the specialist co-authors, arranged in six groups, A through F. The full questions and the complete answers provided by the three specialists are available in the Supplement (Houston et al., 2023). Instructors reading the complete answers will notice that some combine technical and pedagogical/didactical arguments. These instances do not come through in the discussion of this section, which attempts when possible, for each of the six groups of questions, a rough synthesis of only the technical arguments of the answers.

2.1 Soil profile above the water table

The specialists agree that, above the water table, the pore water pressure is negative and a wide variation is expected for pore water pressure and its associated variables saturation and water content. Some of the earliest measurements of field suction for geotechnical applications concerned slope stability (Sweeney, 1982). In general, there seems to be a dearth of pressure measurements to sizeable depths: one such record (9-meter long) was located in Herraman (2019: Figure 4). One approach would then be to consider an equilibrium hydrostatic distribution as an idealized reference case. In cases of net rain infiltration, higher pressures than in the hydrostatic case will exist (less negative), while net evaporation will result in water pressures lower than hydrostatic, see also Houston et al. (2023).

2.2 Effective stress & state variables

This is an area of considerable disagreement, which could be described with the question "may we find a single expression for a saturated soil-equivalent effective stress for unsaturated soils?", such as the expression proposed by Bishop (1959):

$$\sigma' = \sigma - u_a + \chi\,(u_a - u_w) \qquad (1)$$

where σ' and σ are effective and total stress, u_a and u_w are air and water pressures, and χ is a parameter that depends on the type of soil. The term "equivalent" is key here, since there is no full agreement even in soil mechanics textbooks about what effective stress is capable of describing (Houston et al., 2023) – but this bigger discussion is beyond the scope of this paper. Three answers, summarized from the experts' differing opinions, are delineated next.

2.2.1 Opinion 1 – two state variables: net stress and suction

When dealing with unsaturated soils, we cannot use a single equation, but we need to think, simultaneously, about two stress variables. The measurable and controllable stress variables which have been found to govern the behavior of unsaturated soils are: net total stress (or net stress) ($\sigma - u_a$) and soil suction $s = (u_a - u_w)$, which is a strong function of soil water content (Fredlund and Morgenstern, 1977).

Table 1. Puzzlement questions about unsaturated soils phrased by a non-specialist.

No	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 Houston et al., (2023).] 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: Sand castles & 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	Considering that there are several alternative expressions for Mohr-Coulomb-type failure criteria for shear strength, non-specialist instructors are likely to avoid mentioning unsaturated soils in the context of soil behavior under shear stress. Do they have a better simple alternative?
9	Is there any simple demonstration based on principles (not on examples, e.g. sand castles) of suction contributing to shear strength?
10	If the answer to the question "which shear strength equation to use" is contested within the unsaturated soils community (Question No 8), a follow up question is whether the choice of shear strength criterion is a main issue within the community. If not, perhaps other more important/applied issues should take precedence.
	Group E of advanced questions: Motivation for teaching unsaturated soil mechanics
11	Which geotechnical problems require knowledge of unsaturated soil behavior 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 for the practical need of an unsaturated soils approach
13	If instructors are to give up effective stress, they need to understand its main shortcoming(s) for unsaturated soils. Does it fail to predict volume change? Or deformation? Or both?
14	What would be a good set of experimental results, ideally from both the laboratory and the field, showing the inability of effective stress to predict … (whatever is the answer to Question 13) and the successful prediction of a suitable unsaturated soil mechanics approach.

2.2.2 Opinion 2 – Bishop effective stress and its variations

It is possible to use a single expression for the effective stress when interpreting the shear strength of unsaturated soils (e.g. Lu et al., 2010) or the elastic volume change of unsaturated soils (e.g. Khalili et al., 2004). A single expression of effective stress can also be used to represent inelastic deformations of unsaturated soils as long as an elasto-plastic model is used with a yield function that depends on suction (e.g. Mun and McCartney, 2017). Several different equations have been proposed for the effective stress in unsaturated soils, including one where χ in Equation (1) is replaced with the effective saturation, $S_e = (S - S_r)/(100 - S_r)$, where S is saturation and S_r is residual saturation (Lu et al., 2010).

2.2.3 Opinion 3 – Two effective stresses

Once it is clarified that the concept of effective stress is more complex for unsaturated soils to the point that the mechanical behavior of unsaturated soils needs to be represented by two effective stresses (or, equivalently, two stress state variables), it can be stated that:

- As far as the shear strength is concerned, the Bishop effective stress, i.e. Equation (1), (with $\chi = S_e$) is an appropriate effective stress for coarse-grained materials and can be considered acceptable from a qualitative standpoint for fine-grained materials.
- 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.

2.3 Sand castles and other demonstrations

This group of questions concerns only teaching and in particular the choice of comments that accompany the demonstrations used for explaining the implications of the particulate nature of soil. The answers of the specialists to this group of questions reflect their perspectives on effective stress. To avoid disagreeing with any specialist, instructors may choose to state that sand castles stand due to higher shear strength associated with the existence of suction in moist sand. Proponents of Equation (1) may say either one, i.e. due to higher effective stress or higher shear strength.

2.4 Shear strength

Although TC306 became aware of technical disagreements within the unsaturated soils community regarding the expression for shear stress at failure (Jaksa, 2020), the specialists agree (Question 10) that this is not a key issue in unsaturated soils, since any disagreements are due to the empirical nature of the equation. In fact, they all accept as useful (see also Table 2) the following expression for shear strength τ (for $u_\alpha = 0$):

$$\tau = c' + \sigma \tan\varphi' + f(s, S) \tan\varphi' \qquad (2)$$

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 and degree of saturation that expresses their contribution to the shear strength of the soil.

2.5 Motivation for teaching unsaturated soils

Some answers to Question 11 seem not to address the question about performing design calculations for unsaturated soils cases but rather the related question about studying unsaturated soil problems. Examples given include problems involving water flow that lead to changes in stiffness or shear strength, which are relevant to pavements and retaining walls, rainfall-induced instability of man-made and natural slopes, and damages of buildings caused by drought-induced foundation subsidence. The case studies offered as examples to Question 12 concern either unusual critical structures or research projects (see also Section 2.6). An exception is the practical application reported by Rahardjo et al. (2019), which is described in some detail in the Supplement, together with two more case studies deemed appropriate for an introduction on unsaturated soils (Houston et al., 2023).

2.6 Evidence from unsaturated soil studies

This group of questions gave the specialists the opportunity to express some closing remarks on the perspectives presented in Section 2.2. From this group of answers, it is worth mentioning a nicely presented case study, of the research project type (Alonso et al., 1999): with inspiration from a partial slope failure due to heavy rainfall, the authors investigated with the use of a numerical code some “what if” scenarios for continuing rainfall (for additional details see Houston et al., 2023).

3 FRAMING DISAGREEMENT

An equal-distances attitude may help in studying disagreement. Such a stance has already been expressed within the unsaturated soils community. Recently, Ng et al. (2023) reproduced the following statement by Gens et al. (2006) “Bishop stresses and net stresses stand on an equal footing and the matter of adopting one or the other must be decided using criteria of convenience”, who compared the two stresses from a work rate point of view. A more liberal interpretation of the quoted statement, but also more useful to the non-specialist, is as follows: the pair made of “Bishop stress and suction” and the pair made of “net stress and suction” stand on an equal footing when interpreting unsaturated soils phenomena.

Given the foundational nature of the disputed concepts for soil mechanics, it is useful to seek insights on how to approach disagreement in different geotechnical engineering problems, such as the case study presented by Alonso (2023): a heaving claystone was being described for years with a suction-based model, until mounting evidence and an equally good-fitting model showed that it was a crystal growth problem. The ability of two models based on markedly different mechanisms to reproduce well the actual laboratory and field behavior may serve as a potent reminder to abstain from taking sides. Stepping further aside from unsaturated soils to a different thematic field may also be useful. Biology can be a source of inspiration because, like soil mechanics, concepts play a greater role in theory formation than laws, according to the prominent biologist and philosopher of biology Mayr (1997). The similarity between the two fields can be understood by comparing the role of (i) Terzaghi’s effective stress in the theory of consolidation and the birth of soil mechanics to (ii) Darwin’s natural selection in the birth of evolutionary biology. Seeking inspiration in biology is useful because it has experienced quite a few controversies that were ultimately resolved. After the resolution of the disputes, it was clear that even the “wrong” alternatives had valid portions to offer, which may be overlooked if we hasten to take sides.

Another source of disagreement that should not be neglected is the instructors' pedagogical beliefs regarding how much to expose undergraduate students to contested and complex topics, typically slated for graduate courses. Instructional decisions on controversial topics must take into account the centrality of these topics within a thematic field; for key foundational topics, it is recommended that the controversy is mentioned in an introductory course and explained later in an elective or graduate course. Whether a topic is contested or merely complex, the advice from the late professor Harry Seed (1986) is apropos herein: "I would not say in an undergraduate course anything that I would have to take back in a graduate course".

4 PROPOSALS FOR TEACHING

The Supplement includes a five-point list to introduce key issues in unsaturated soils, with variations to accommodate different perspectives (Houston et al., 2023). After having been made aware of the disputed issues, instructors will likely elect to adapt suggestions according to a gradation of different aims, such as:

- Instructor aims to remove something that is "plainly wrong" (unacceptable) from any unsaturated soils perspective. The respective aim for the students is that they would not have to "unlearn" something before expanding their own knowledge of unsaturated soils in a subsequent course (Harry Seed's advice).
- Instructor aims to clarify that a statement or an equation is –from an unsaturated soils perspective– a simplification, and state the range of validity of the statement/equation. The focus here is on alerting the students that they learn principles and calculations suitable for only subsets of reality (e.g. saturated soils).
- Instructor aims to create "receptors" for future knowledge about unsaturated soils, i.e. when students later see something in a more advanced geotechnical engineering course, they will recognize that it fits with what they have seen in the introductory course.

The specialists' evaluation of the educational materials created by the non-specialist first author for an introductory soil mechanics course provides an example of the necessity to modify existing material in light of the answers to the questions in Table 1, filtered through the pedagogical beliefs of an instructor. The Supplement (Houston et al. 2023) includes four items that make reference to unsaturated soils, both before and after the evaluation by the three specialists, who were asked to rate the "before" version as useful (3 points), acceptable (1 point), excusable (0 points) or unacceptable (-3 points). The four items are summarized in Table 2, which also includes the grades provided by the specialists. Disagreement among specialists is reflected in the spread of the grades, which creates decision space for the instructors.

From the four items, only item 2, Equation 3 for the effective stress in unsaturated soils, requires immediate attention to at least eliminate the unacceptable rating (-3 points) given by two of the three specialists. The low rating of this item came as a surprise to the non-specialist author, since the effective stress Equation 3 in Table 2 is an alternative way to write Equation 1, i.e. the Bishop effective stress, with $\alpha = \chi$ and $\beta = 1 - \chi$. However, the specialists did not approve of the fact that suction ($u_a - u_w$) and net stress ($\sigma - u_a$) are not recognizable in this alternative version. They also did not approve of calling α and β area ratios. Considering that all three specialists do not approve of Equation 3, and two of the three specialists are at least skeptical about the validity of its original version, i.e. Equation 1, the non-specialist will stop including in her course an equation for effective stress for unsaturated soils.

Table 2. Four references made to unsaturated soils by a non-specialist and respected ratings by three specialists.

No	Item referenced	Ratings[a]
1	Sand castles & video by Burland (2023) "The effect of water on soil strength" [link]	3, 3, 3
2	A version of Bishop's equation for effective stress that separates water pressure from air pressure (Briaud, 2013: Eq. 10.54): $\sigma' = \sigma - \alpha\, u_w - \beta\, u_a$ (3) where α and β are water and air area ratios ($\alpha + \beta = 1$)	-3, -3, 0
3	Distribution of quantities above the water table (see Figure S2 in Supplement)	1, 3, 1
4	Equation 2 for shear strength of unsaturated soils, $\tau = c' + \sigma \tan\varphi' + f(s, S) \tan\varphi'$	1, 1, 3

[a] 3 = useful, 1 = acceptable, 0 = excusable, -3 = unacceptable.

5 CONCLUSIONS

The team project described herein set out to answer the question what and how can instructors teach when experts disagree. A complementary question that comes up is whether it is best to avoid in instruction topics associated with debates, especially since such situations are considered to be rare in engineering education and collective experience on how to approach them is missing. Understanding the nature of the disagreement was attempted in two complementary ways, by having specialists (i) answer a list of questions phrased by the non-specialist author after being tutored by the last author, also a specialist and (ii) evaluate educational material created by the non-specialist author for an introductory soil mechanics course. This combined approach revealed, as expected, differences in the preferred variables to use in theory and constitutive modelling of unsaturated soils. There is agreement that unsaturated soil behavior is controlled by net total stress and suction, but there is also open debate concerning the use of the term effective stress for unsaturated soils. Given the centrality of the concept under dispute, it does not seem prudent to avoid it, even in introductory courses. For non-specialist instructors, a sensible approach would be to acknowledge the opposing approaches and focus on topics where viewpoints diverge the least. Such a topic is shear strength of unsaturated soils.

Judging by the relative dearth of design case studies, geotechnical engineering practice does not signal that there is current understanding for a need for professionals cognizant of unsaturated soils theory, in spite of the actual prevalence of applications involving soils in an unsaturated state. But, this may be a chicken-and-egg situation. Considering that geotechnical engineering researchers are branching out to a variety of research topics, better funded than and further removed from core topics of soil mechanics, it is possible that the unsaturated soils community will bring about the next breakthrough in understanding better the fundamental behavior of soils.

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