Teaching unsaturated soil mechanics through rammed earth

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ABSTRACT: From a soil mechanics point of view, rammed earth is a highly compacted unsaturated soil which can also be stabilised. The quirk is that the material is used for construction, i.e. the material finds itself in situations unlike those for 'normal' geotechnical structures. However, the material is tangible and easy for undergraduates to imagine. One distinct aspect of rammed earth is that it dries to much lower water contents than would be found, say, at the ground surface, and so it is particularly vulnerable to moisture (i.e., weakening the material and causing failure). This paper presents a short overview of how basic concepts from unsaturated soil mechanics can be introduced into an undergraduate/post-graduate unit through using rammed earth concepts, such as: Soil Water Retention Curves, matric suction and capillarity, and the contribution of suction to strength through an 'extended' Mohr-Coulomb framework.

Keywords: Unsaturated soil, Suction, Rammed earth, Geotechnical education, Student learning

1 Introduction

Environmental geotechnics examines how geotechnical infrastructure impacts and interacts with the environment, for example with respect to groundwater seepage, static and cyclic liquefaction, slope stability, and contaminant transport. However, typical environmental geotechnics topics taught at undergraduate and postgraduate levels involve passive or reactive environmental solutions, which revolve around verbs such as "mitigate", "confine", "contain", "reduce", "remediate".

One method to teach unsaturated soil concepts is to consider rammed earth construction. Rammed earth is, with respect to geotechnical engineering, a highly unsaturated, highly compacted loamy soil, which has been used to construct freestanding structures for millennia (Minke, 2006). Rammed earth is not a traditional geotechnical engineering material or structure or environmental geotechnics solution. However, as a tangible material on the 'human' scale, it is something which students can imagine and understand and, circumstances permitting, with which they can experiment. Furthermore, rammed earth offers an active and positive environmental engineering 'solution' given its association with low or zero carbon footprint construction (Meek et al., 2021), its ability to regulate the hygrothermal behaviour of an enclosed space (McGregor et al., 2016), and the ability to recycle the material *ad infinitum*, introducing with that the ideas of the circular economy (Morel et al., 2021). Lastly, the long history of rammed earth means that structures can be found relating to every culture on every continent (Figure 1), transcending any issues of colonialism.

In this paper, we present the structure of the introductory unsaturated soil mechanics concepts taught in the Environmental Geotechnics unit at the School of Engineering, the University of Western Australia. This is a fourth-level optional unit, and students who choose to take it have already been taught the principles of soil mechanics in previous years. As such, they already come equipped with an understanding of stress state, void ratio, excess pore-water pressure, etc. An introduction to unsaturated soil mechanics is taught over a two-week period. The unit is taught in the flipped mode by means of asynchronous online lectures and synchronous practical workshops, which suits the unit's students who may be working remotely or scheduling studies around work commitments. The workshops are taught using real-life consultancy industry scenarios (i.e., case studies) and the basic concepts of unsaturated soil mechanics are studied through rammed earth applications.

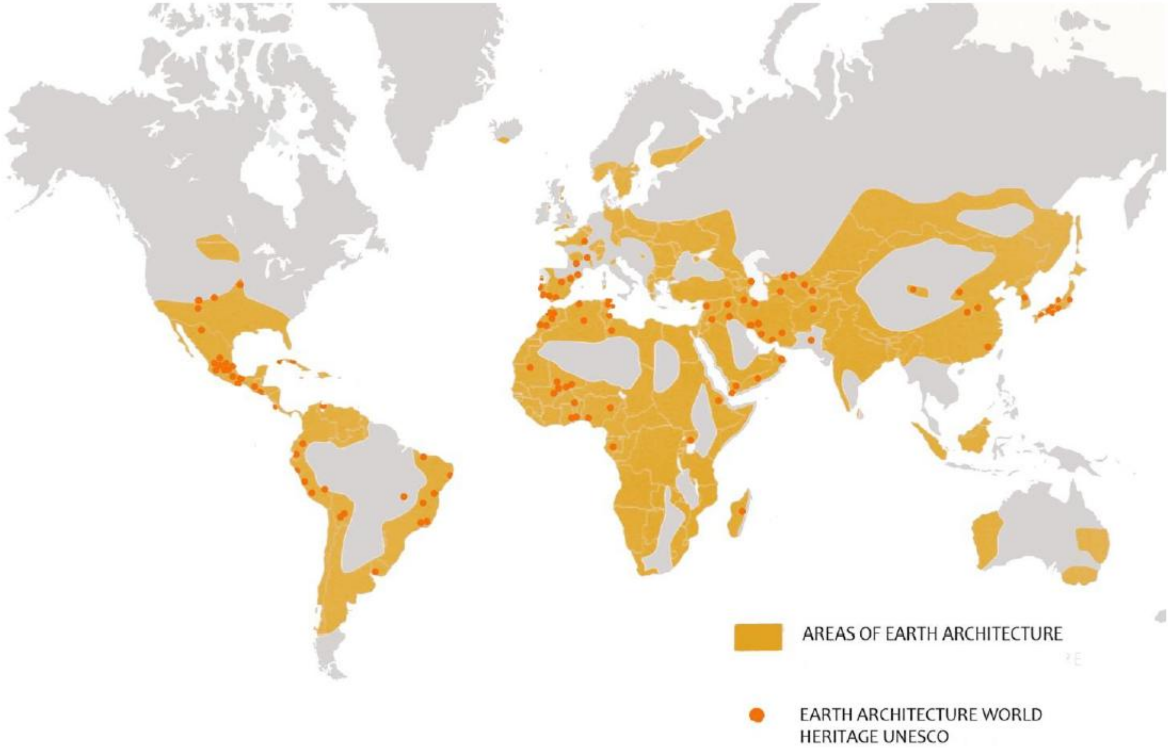


Figure 1. Prevalence of rammed earth structures (Alex, 2018; after Anger and Fontaine, 2009)

2 Teaching using case studies

A definition for 'case studies' is provided by Seshan *et al.* (2021):

"*Case study analysis is an active, problem-based, student-centred, teacher-facilitated teaching strategy preferred in undergraduate programs.*"

It is fitting for how case studies are used in the Environmental Geotechnics unit. Similar to Seshan *et al.* (2021), teaching through case studies in Environmental Geotechnics is meant to stimulate:

- knowledge development;
- critical thinking and problem solving; and,
- communication and collaboration.

The purpose of using case studies in teaching often difficult and/or abstract concepts is to bridge the gap between theory and practice; students get to understand and appreciate how sound theoretical knowledge can be used in solving real world problems such as designing a rammed earth structure. The use of case studies also helps to reduce the gap between a learning environment (the classroom) and engineering practice (e.g., a consultancy firm). This is especially important since the Environmental Geotechnics unit caters to students in the last year of their undergraduate studies.

Through case studies, students are helped to distil difficult theoretical notions (e.g., unsaturated soil mechanics) by immersing themselves into a realistic geotechnical engineering application (e.g., the design of rammed earth wall). There is a secondary, but equally important aspect, in that case studies help students to build confidence in tailoring bespoke engineering solutions to realistic real-life problems. They get accustomed to the idea that there is not a single engineering solution but a multitude of solutions that work in practice as long as they use sound theoretical notions. This means that potentially difficult topics like unsaturated soil mechanics can be successfully taught at undergraduate level in a short span of time using a number of teaching tools (e.g., flipped classroom, use of case studies, synchronous and asynchronous learning).

3 Unsaturated soil mechanics using the Geotechnical Triangle

Solving real-life geotechnical engineering problems using “empiricism and well-winnowed experience" requires the knowledge of three interlocked aspects (Burland, 1987):

- ground profile;
- soil behaviour; and
- applied mechanics.

Burland (1987, 2008) used these aspects to develop the “Geotechnical Triangle”, shown in Figure 2, which, according to the author, should form the framework for teaching soil mechanics and geotechnical engineering. The Environmental Geotechnics unit leverages the Geotechnical Triangle framework in the design and delivery of its curriculum. This extends to teaching the unsaturated soil mechanics topic, making use both of aspects already included in the original framework (n.b., highlighted in blue in Figure 2) as well as the introduction of new concepts such as the ‘Soil Water Retention Curve’ and ‘suction’ (n.b., highlighted in red in Figure 2).

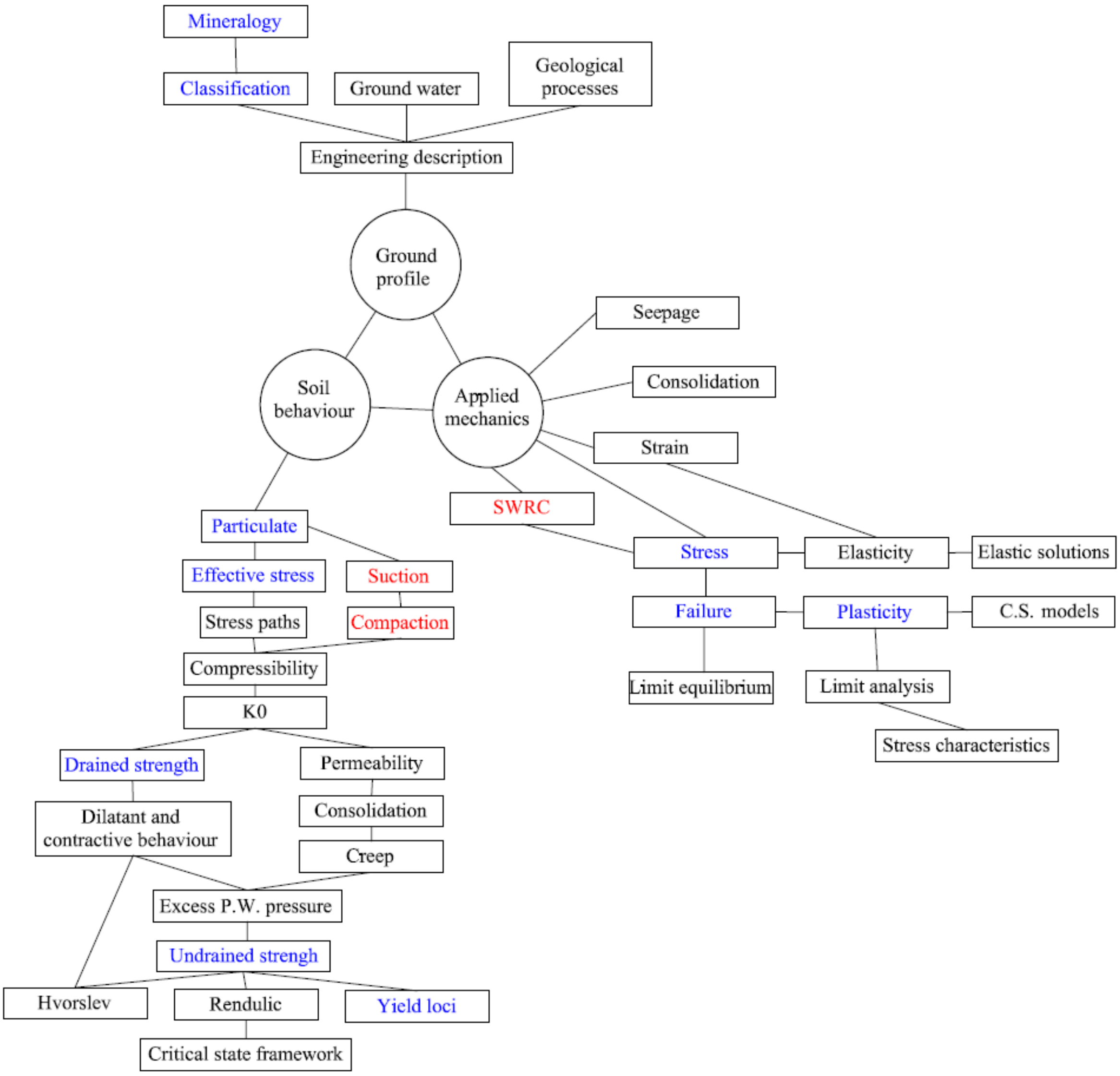


Figure 2. Elements of a basic course in soil mechanics (after Burland 1986) with additions for teaching unsaturated soil mechanics concepts

As mentioned previously, undergraduate engineering students that elect to study Environmental Geotechnics come already equipped with prior knowledge of both basic soil mechanics and advanced geotechnical engineering. Environmental Geotechnics represents at least the third soil mechanics/applied soil mechanics unit that they take. Figure 3 illustrates, in broad terms, that students have already acquired a foundational understanding of the theoretical aspects encompassed by the Geotechnical Triangle and have developed competencies in designing conventional geotechnical engineering applications (for example retaining walls, shallow foundations, and embankments). The Environmental Geotechnics unit builds upon this foundation by offering opportunities to deepen knowledge in advanced geotechnical topics such as cyclic and static liquefaction and unsaturated soil mechanics. This is facilitated through case studies focusing on tailings storage facilities, landfills, and, for the latter, rammed earth structures.

Unsaturated soil mechanics is taught in two distinct parts, presented in greater detail in Figure 3:

- Ground profile: This section revisits fundamental soil mechanics concepts, helping students to consolidate their understanding of topics such as mineralogy, particle size distribution, soil classification, and compaction. This foundational knowledge is critical for analysing and interpreting unsaturated soil behaviour and is reintroduced to the students to emphasise how familiar concepts extend to studying the new phenomena.
- Applied mechanics: This part introduces advanced concepts, including matric suction, the Soil Water Retention Curve (SWRC), and the influence of suction on soil strength. These ideas are demonstrated using an 'extended' Mohr-Coulomb framework, which integrates the effects of suction into traditional strength theories.

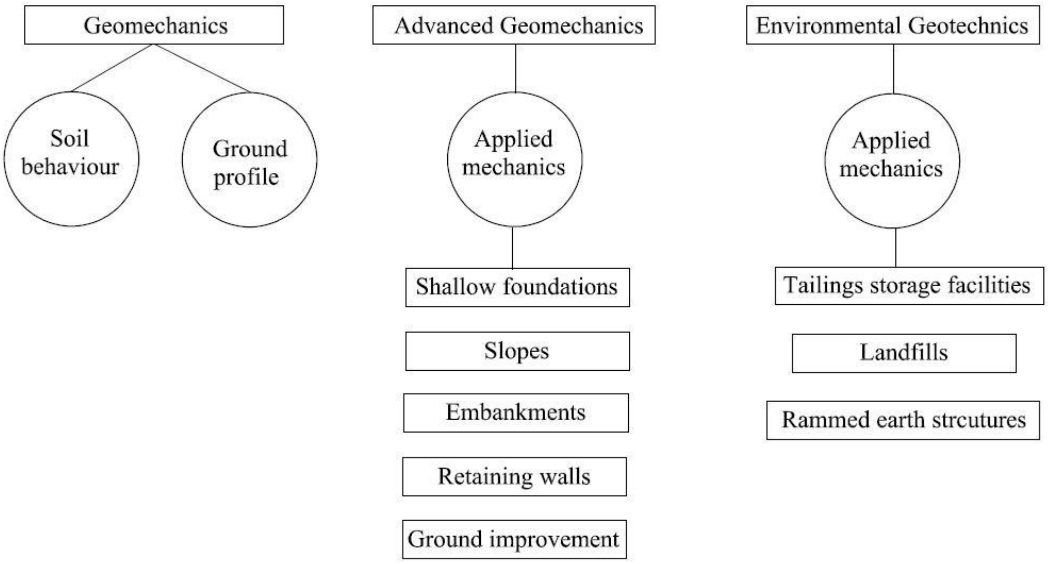


Figure 3. Soil mechanics and geotechnical engineering units at the University of Western Australia

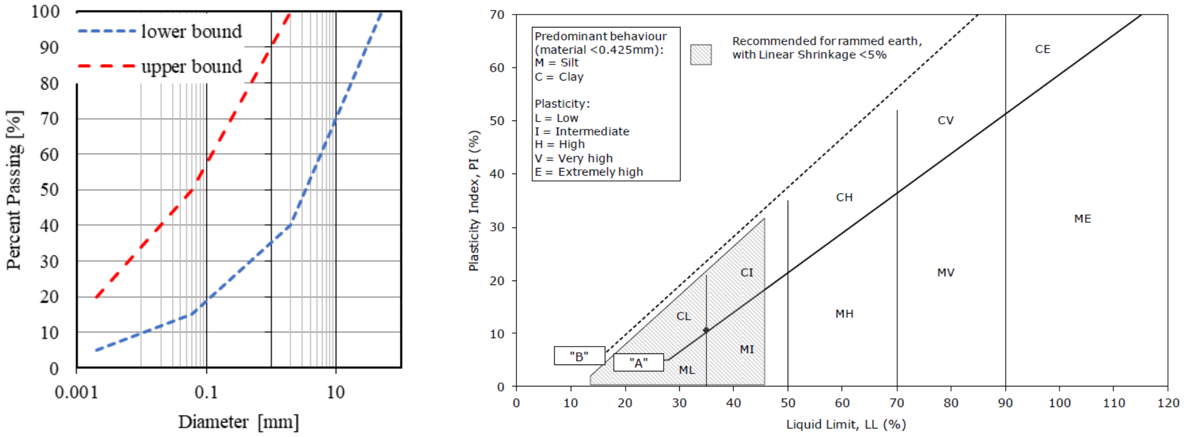
3.1 Ground profile - remembering the basics

3.1.1 Particle size distribution and plasticity

Rammed earth requires a large distribution of soil particle sizes from clay to gravel. Whilst very fine soil is essential in rammed earth, the presence of too much clay, or highly swelling clay, can also lead to structural cracks in the rammed earth walls due to shrinkage.

Particle size distribution by means of wet sieving and characterisation tests (i.e., Atterberg limits) are required in order to establish if a site contains soils suitable for rammed earth. Once the soil particle distribution has been calculated it can be plotted against the allowable particle distribution shown in Figure 4a (Walker et al., 2005). Following sieving, the plasticity of the clayey particles is determined using the Casagrande Cup or Fall Cone apparatus for the liquid limit and the 'rolled threads' for the plastic limit. These test results are then plotted on a plasticity chart (see Figure 4b) to determine if the soil would undergo linear shrinkage < 5%, namely the plasticity recommended for rammed earth soils (Walker et al., 2005).

The students undertaking Environmental Geotechnics have already studied these basic classification tests in their second year of study through the Geomechanics unit. The have also carried out these laboratory tests in their second year while undertaking the Geomechanics unit. The revisiting of this content in the current unit was deliberate – it offers the students another opportunity to retread what they have studied previously as well as solidifying the concept that basic ground profile investigation is essential in geotechnical engineering practice.



(a) (b)

Figure 4. Basic ground profile testing for rammed earth materials: a) particle size distribution plot, b) soil plasticity chart from ASTM Standard D 2487-93

3.1.2 Compaction - Modified Proctor tests

Rammed earth materials are compacted at their optimum water content (OWC) in order to ensure the highest dry density and, by extension, achieve a more stable material with high strength and load-bearing capacity. Laboratory determination of the OWC is generally carried out using:

- the Standard Proctor Test (SPT);
- the Modified Proctor Test (MPT).

The MPT has a compactive effort very similar to that used on-site for rammed earth construction (Beckett et al., 2018) and is a well specified, codified, and widely established test and hence repeatable in any laboratory.

Students have already been introduced to the concepts of soil density (e.g., bulk and dry density) and compaction. The topic of compaction was initially explored within the Environmental Geotechnics unit in the context of compacted clay liners, where the primary objective is to create a continuous hydraulic barrier and to mitigate post-construction settlement. Subsequently, compaction was revisited in the discussion of unsaturated soil mechanics, particularly in relation to rammed earth, where its primary function is to create a sufficiently dense material to be self-supporting and to minimise post-construction shrinkage. The dual examination of compaction from these two perspectives serves to broaden students' understanding of the diverse applications of a fundamental soil behaviour. For rammed earth, the immediate need to achieve a high density (i.e., to create a material of sufficient density to be self-supporting) is obvious.

Revisiting the concept of compaction in different contexts helps students not only to deepen their understanding of soil behaviour but also develops the critical skill of applying foundational principles to solve a variety of real-world problems. Encouraging students to view a single soil behaviour from multiple perspectives fosters creativity and lateral thinking, which are essential for geotechnical engineers.

3.2 Applied mechanics – learning advanced geotechnical engineering notions

In this part, students are introduced to advanced notions in geotechnical engineering, focusing on the behaviour of unsaturated soils. Key topics include:

- Matric suction: understanding the role of pore water pressure and surface tension in influencing soil behaviour.
- Soil Water Retention Curve (SWRC): exploring the relationship between soil suction and water content, a critical tool for characterising unsaturated soils.
- Effect of suction on strength: examining how suction impacts soil strength parameters, demonstrated through the integration of suction effects into an ‘extended’ and linearised Mohr-Coulomb framework.

These concepts provide students with the tools to analyse and design rammed earth structures, bridging theoretical knowledge with practical application. These topics are presented in lectures and, once complete to the required level, are explored experimentally in the accompanying laboratories.

3.2.1 Matric suction

Matric suction is the component of suction that arises from the curvature of the contractile skin phase. Although osmotic suction will always be non-zero in real soils, owing to dissolved minerals, matric suction can become orders of magnitude greater than the osmotic suction and so is most commonly associated with causing the change in behaviour of a soil between its saturated and unsaturated states (Fredlund and Rahardjo, 1993).

Students taking Environmental Geotechnics have already been introduced to negative pore water pressures through the concept of capillary rise. In most analyses of design cases, however, capillary zones are assumed to be saturated, with the soil taken to be dry above the capillary fringe. Introducing matric suction and its derivation from capillarity encourages students to rethink their understanding of the capillary fringe, for example asking the question of what happens at the air-water interface that must exist in the simplified model of a saturated capillary fringe and the ‘dry’ soil above.

3.2.2 Soil Water Retention Curve

The degree of saturation in rammed earth is initially around 80-90%, corresponding to the optimum water content at compaction, and drops to below 5% as it dries. This exceptionally low degree of saturation is possible as rammed earth elements are exposed on all sides to the atmosphere, and so dry to a total suction value equivalent to that given by the Kelvin equation for that atmospheric temperature and relative humidity (Beckett et al., 2018). Rammed earth therefore experiences all of the main phases of the SWRC (capillary, funicular, pendular, and adsorbed water). By extending the idea of capillarity into matric suction, as discussed above, students can also understand how the drying and wetting branches of the SWRC are traced out by the emptying or filling of pores of different sizes (and, later, to consider how stress changes induce changes in that pore size distribution and, so, the SWRC). In Environmental Geotechnics, students use the SWRC in three different forms: suction versus the degree of saturation; gravimetric; or volumetric water content, depending on which is the most relevant for the topic at hand, and to become comfortable with selecting appropriate parameters for given tasks.

3.2.3 Suction and strength

Compressive strength is essential to rammed earth. Strength is an intuitive property, indelibly linked to previous soil behaviour topics (Figure 2). Exploring how suction affects soil strength therefore helps to create some continuity across the different taught aspects of Civil Engineering curricula.

As discussed above, Environmental Geotechnics students are familiar with Terzaghi's formulation of effective stress and that a negative pore water pressure will cause an increase in effective stress. In this circumstance, one implicitly assumes that the soil remains saturated or is at a degree of saturation sufficiently high that the change in effective stress equates directly to the change in pore water pressure. However, when the capillary pore water distribution becomes discontinuous, the change in effective stress is no longer directly related to the change in the pore water pressure (Zhou et al., 2016). The simplest method to account for the impact of discontinuous pore water on the effective stress σ' is Bishop's Chi (χ) factor:

$$\sigma' = \sigma - \chi\psi \tag{1}$$

where σ is the total stress, ψ is the matric suction (the negative pore water pressure) and χ takes a value between zero and unity, where it is zero for a degree of saturation $S_r = 0$ and unity for $S_r = 1$. As the degree of saturation also varies between zero and unity, a simplification of Eqn. 1 is:

$$\sigma' = \sigma - S_r\psi \quad (2)$$

i.e. $\chi = S_r$. Fredlund and Rahardjo (1993) showed that Eqn. 2 is valid to extend the Mohr-Coulomb criterion for shear strength in sands. However, Eqn. 2 significantly overestimates the increase in shear strength arising from suction for well-graded soils, for example rammed earth. For sands, the success of Eqn. 2 is predominantly because the air entry value for sands is low (say, 10 kPa) and the degree of saturation rapidly approaches zero thereafter, so that the predicted increase in effective stress is limited. However, the air entry value for rammed earth is higher (approximately 100 kPa) and it can retain water to much greater suctions (>> 100 MPa), owing to the small pore sizes of its clay fraction. At these suctions, the water phase exists as menisci trapped in the smallest soil pores and adsorbed to the surface of the soil particles, i.e. not all of the water present is able to affect the solid skeleton, as $\chi = S_r$ implies (Beckett et al., 2018). Studying rammed earth therefore gives students the opportunity to see three stages of the Terzaghi formulation of effective stress:

- the traditional formulation, which is only appropriate for saturated soils (suctions less than the air entry value);
- introducing Bishop's χ (Eqn. 1) and equating it to the degree of saturation (Eqn. 2), which is acceptable for sands but is invalid for soils with pore sizes in the microscopic range;
- modifying the Terzaghi relationship further to account for the discontinuous nature of the capillary water phase at low degrees of saturation, which creates a non-linear relationship between suction, degree of saturation, and strength.

For example, from Beckett et al. (2018), the degree of saturation at a suction of approximately 30 MPa is approximately 10% for rammed earth of a typical particle grading and compacted density (Figure 5a). Taking u_w = - 30 MPa in Terzaghi's formulation gives an effective stress of 30 MPa (before loading), which is demonstrably unrealistic (e.g. shear strengths may exceed 20 MPa for reasonable friction angles). Using $S_r = 0.1$ in Eqn. 2 gives an effective stress of approximately 3 MPa before considering any loading effects, which gives a considerably smaller but still unrealistic approximation of soil strength if also considering typical friction angles for rammed earth of approximately 40 degrees (Jaquin *et al.*, 2009). Instead, a realistic unconfined compressive strength of rammed earth equilibrated to an atmosphere of modest temperature and humidity will be between 1 and 3 MPa (Beckett et al., 2018 and Figure 5b), i.e. $\chi < S_r$.

3.2.4 Contribution of suction to strength through an 'extended' Mohr-Coulomb framework

Because of the non-linear relationship between degree of saturation, suction, confining stress, and strength, it is useful to dissociate the mechanical and hydraulic contributions to strength via an 'extended' Mohr-Coulomb framework, in which the contributions of suction ($u_a - u_w$) and net stress ($\sigma - u_a$) to the shear strength (τ_f) are considered separately:

$$\tau_f = c' + (\sigma - u_a)\tan(\phi') + (u_a - u_w)\tan(\phi^b) \quad (3)$$

where c' is the effective cohesion, u_a is the pore air pressure (taken as zero), ϕ' is the drained friction angle, and ϕ^b represents the contribution of suction to strength (the term $(u_a - u_w)\tan(\phi^b)$ can be considered an 'unsaturated cohesion').

Fredlund et al. (1987) showed that the surface described by Eqn. 3 is non-linear, i.e. that the values of ϕ' and ϕ^b are not constant, however that, for sands, the surface can be linearised if only considering suction values above the air entry value. Beckett et al. (2018), and, subsequently, others, extended this concept to show that for suctions exceeding the residual value, the failure envelope described by Eqn. 3 also becomes linear (or planar), i.e. ϕ' and ϕ^b are constant (but, notably, ϕ^b is considerably smaller than its value for suctions below the residual value). The linearised failure envelope is shown in Figure 5c and the success of the method to describe changes in compressive strength with suction is shown in Figure 5d. This simplified description makes it easier to introduce the concept of a multi-dimensional failure envelope to students, who must otherwise contend with the ideas that parameters formerly assumed to be constant (ϕ') are not for unsaturated soils. Two example stress states are shown in Figure 5c, where one sample (1, in red) is tested at a higher suction value than a second sample (2, in blue) but achieves a lower shear strength as the net stress for sample (1) is lower. Furthermore, a planar failure envelope lends itself well to experimental verification; rammed earth specimens can be equilibrated to different atmospheric conditions (wherein the total suction is given by the Kelvin equation) and students can measure the change in strength (compressive, for ease) between different equilibration conditions, relating that strength change to the design of structural components and thus combining the ideas of the extended Mohr-Coulomb framework, the SWRC, the pore size distribution, the Atterberg limits, and the particle grading in one experimental campaign.

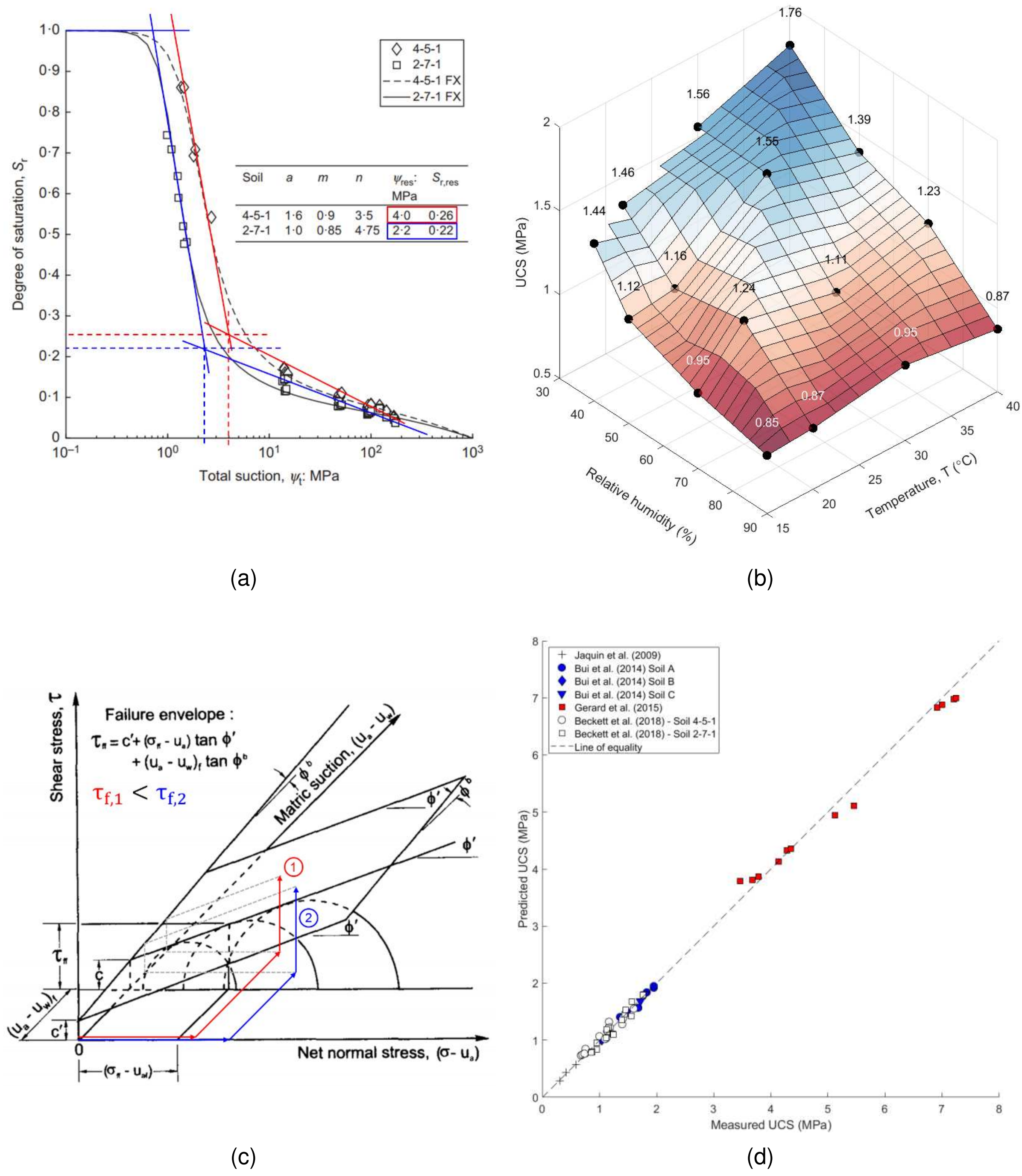


Figure 5. Developing the failure envelope for rammed earth materials: a) identifying the residual suction abd degree of saturation ψ_{res} and $S_{r,res}$ (modified from Beckett et al., 2018 where a, m, and n are fitting parameters); b) unconfined compressive strength (UCS) results at different relative humidity and temperature values (redrawn from Beckett et al., 2018); c) linearised 'extended' Mohr-Coulomb failure envelope (modified from Fredlund and Rahardjo, 1993); d) predicted versus measured UCS results for different rammed earth materials under different suction conditions (redrawn from Beckett et al., 2018)

4 Conclusions

This paper has presented how unsaturated soil mechanics is taught in an optional undergraduate unit (Environmental Geotechnics in the School of Engineering at the University of Western Australia) via the platform of rammed earth construction. Rammed earth is essentially a highly compacted unsaturated soil and the technique requires particular soils for construction to achieve the required unconfined compressive strength to support structural loads. It therefore provides an opening to the unfamiliar topic of unsaturated soils from the familiar concepts of (saturated) soil mechanics and structural engineering. The advantages of teaching unsaturated soils from the perspective of rammed earth are threefold:

i) rammed earth materials span the full range of the degree of saturation, providing an opportunity to discuss the evolution of the soil water retention curve;

ii) rammed earth failure can be described by a planar failure envelope, which can be interpreted readily by students;

iii) rammed earth specimens are simple to produce and test in a laboratory, providing students with hands-on experience and personal validation of the effects of suction on unsaturated soil strength.

Overall, the unit is taught in flipped mode and uses case studies in order to stimulate student understanding of difficult abstract topics, and creativity in problem solving. Students revisit basic soil mechanics aspects such as particle size distribution and plasticity, to consolidate the concept that basic ground profile investigation is essential in geotechnical engineering practice, and learn how suction is the key mechanism behind strength and strength gain, modelled according to an 'extended' Mohr-Coulomb failure envelope. By reinforcing the importance of context-specific applications through case studies and linking these to broader geotechnical principles, it is hoped that students develop a more holistic and adaptable approach to problem-solving. This aligns well with geotechnical consultancy industry practice, which also relies on understanding soil behaviour and creative thinking.

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Dr Christopher Beckett is a Senior Lecturer in Geotechnical Engineering and the Deputy Director and Programme Manager for Civil and Environmental Engineering at the University of Edinburgh. He is also an Adjunct Research Fellow at the University of Western Australia. His research focuses on the behaviour of unsaturated soils under extreme states, for example at high temperatures, low degrees of saturation, and when rendered hydrophobic. He teaches advanced geotechnical engineering at the undergraduate level and has been nominated for several teaching excellence awards in his time at Edinburgh. Chris is the Chair of Standard Australia committee BD-083: Australian Earth Building, the Deputy Chair for RILEM TC 319-MAE, Mechanical performance and durability assessment of earthen elements and structures, and the Young Person's Representative for ISSMGE TC-109 Unsaturated Soils.

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