General report: Fundamental soil behaviour (Part II) – a wider perspective of hydro-mechanical and thermal behaviour of unsaturated soils

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ABSTRACT: This paper looks into a wider perspective of unsaturated soil behaviour based on the authors' own experiences and the information collected from selected papers presented at the conference. The commentary is sectioned under the following topics: structure, strength, stiffness, volume change, cyclic effects, heat and hydraulic properties. A brief introduction to the subject matter is presented which is followed by a description of each paper and the key findings.

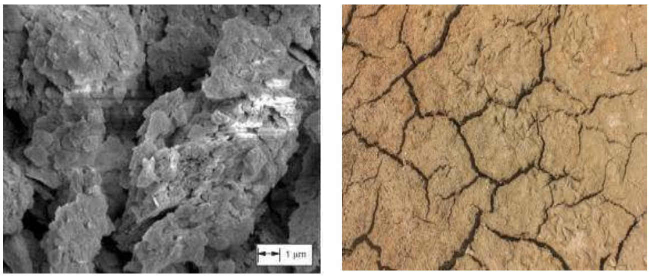
1 INTRODUCTION

Recent deposits are often saturated and considered to be normally consolidated. There are many advanced analytical and numerical tools currently available to understand such soil behaviour. The saturated soils can become overconsolidated due to a variety of reasons, during which the soil gains strength and stiffness. Again, the predictions of the behaviour of such soils are reasonably straightforward. However, the saturated soils can become unsaturated mainly due to two reasons: (a) environmental impact in the form of drying-wetting cycles; and (b) compaction of competent soils in building embankments or other form of geo-structures in which the soils are removed from their original state and re-deposited using compaction methods. In both of these cases, it is possible that the soil may lose its previous stress history and stiffness. For example, when a very stiff clay rich soil is re-worked in forming an embankment or used in backfilling operation, depending upon the conditions at the placement, the newly formed deposit could become normally consolidated upon saturation (Palmer & Wilson, 2011).

The quest to understand the unsaturated soil behaviour begun at the same time as that for the saturated soils. However, the progress on developing analytical predictive tools was not significantly forthcoming until the late 1980s, when for the first time, a conceptual framework was proposed to model unsaturated soil behaviour (Alonso et al., 1987). In addition, the measurement of negative pore water pressure (namely suction within the context of modern unsaturated soil mechanics) is not an easy task. Additionally, various other factors have a profound influence on the behaviour of unsaturated soils, for example; minerology, structure and temperature (Sivakumar et al., 2015; Boyd & Sivakumar, 2012; Thom et al., 2007; Baille et al., 2014; Tripathy et al., 2014(b)). As a geotechnical engineer, one would be interested in settlement, deformation and strength of geo-structures which are or were unsaturated initially and subjected to saturation or cycles of saturation and unsaturation due to environmental conditions. Since the late 1980s, significant progress has been made in understanding the behavior of unsaturated soils, culminating with this 7th International conference on the subject in Hong Kong 2018. The purpose of this article is to discuss the fundamental aspects associated with unsaturated soils in a collective manner based on the author's experiences and some of the interesting findings appeared in the selected papers presented in the conference.

2 STRUCTURE OF UNSATURATED SOILS

The natural drying process or compaction of fine granular soils leads to a complex structure in which the particles tend to form aggregates or packets as shown in Figure 1, leaving the soil with a bi-modal pore size distribution.

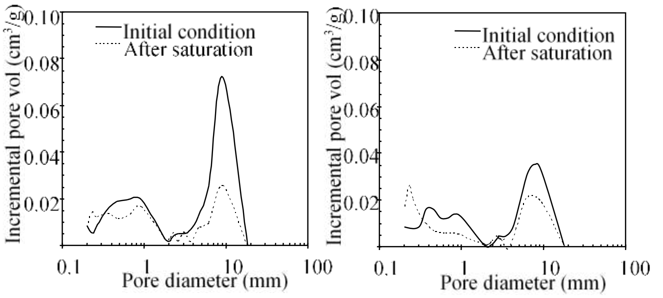


(a) Compacted soils (b) Natural soils

Figure 1. Structure of unsaturated soils.

The structure is an important characteristic that affects both saturated and unsaturated soils in a profound manner. The impact of aggregation of particles on the behavior of unsaturated soils is far from fully understood. In such aggregated structure, under equilibrium conditions the voids between the aggregates are filled with air and the voids within the aggregates are generally assumed to be filled with water. Upon the application of loading, the soil mass can be considered as a continuum model in which the aggregates act, in some respect, as 'large particles' that are compressible, deformable and friable. The stresses acting on and within the aggregates are complex. The structure is therefore an unquantifiable parameter. However, some attempts have been made to include structure into stress-strain variables (Alonso et al., 2010).

Within the context of fine-grained unsaturated soils, different structures result from compaction depending upon the compaction water content or the level of desiccation caused by drying (Bardon and Sides 1970; Gens et al. 1995; Alonso et. al. 1995; Lloret et al. 2003; Romero et al. 2003; Thom at al. 2007). The form of structure influences the hydro-mechanical behaviour of unsaturated soils. Some very basic highlights are extracted from Thom et al. (2007) on this aspect.



(a) Lightly compressed sample IS(A)   (b) Heavily compressed sample IS(B)

Figure 2. Evolution of bi-modal distribution upon wetting of compacted kaolin.

Figure 2 shows the evolution of bi-modal pore-size distribution upon wetting of compacted kaolin prepared at two different compaction efforts but at the same initial water content. Both samples exhibited overall swelling during wetting; however, the magnitude of swelling in the case of heavily compressed sample was far higher than that of lightly compressed sample which was contributed by the interaction between the aggregates.

The particle aggregation is widely thought to be the result of suction effects. However, Stott & Theron (2018) presented some very interesting data that show particle aggregation can still take-place when fine materials are in mere suspension, as in the case of a solution prepared for particle size distribution determination. Particle-size distribution is the very basic information required for characterization of fine-grained soils. It is generally obtained through the hydrometer or pipette method (British Standard BS 1377-2). Possible aggregation of particles during sedimentation may lead to unreliable results (Nettleship et al., 1997). Particle aggregation implies a formation of assembled particle structure. Stott & Theron (2018) assessed the effects of aggregation of particles during the sedimentation analysis using microscopic observations concluded that aggregation of particles occurs and that the aggregates are resistant even to high-energy mechanical dispersion. They also concluded that the aggregation depends upon the soil type, as the minerology of the soil has a significant influence on the repulsive and attractive forces (Tripathy et al., 2006, 2014b; Schanz et al., 2018).

It is certain that the wetting of soils that were previously unsaturated, alters the macro-micro void distribution. However, Azizi et al. (2018) reported some interesting observations in relation to cyclic wetting and drying on the evolution of bi-modal pore size distribution. Based on their observations, cyclic wetting and drying resulted in the soil having enhanced macro porosity and consequently, behaved as a more granular soil but with deformable aggregates. Under these conditions it is possible to expect relatively high compressibility of the soil and a dilatancy response upon shear loading. The suction history plays a significant role on volume change (Tripathy & Subba Rao 2009) and peak strength.

In an interesting study, Abduljauwad & Ahmed (2018) examined the structure of compacted samples of various soils at molecular level using molecular mechanics, molecular dynamics, and Monte Carlo techniques. Development of different forms of fabric of the clay minerals matrix in rocks and soils have been examined under varying conditions. The authors demonstrated that the structure of different forms, such as dispersed, flocculated, and agglomerated can be correlated to the corresponding volume change behaviour of the argillaceous rocks and soils.

Ghabezloo et al. (2018) reported a new method based on the pore network modelling to develop a more realistic evaluation of soil porous structure, which was validated with the results obtained on two soils. The authors presented data to show that the capillary tube model, which overlooks the connectivity present among different pores and the real morphology and topology of soil porous structure, gives an underestimation of larger pores. The authors stated that the procedure can also result in an overestimation of micropores, depending upon the range of soil coordination number and throat size distribution. In order to evaluate the performance of different approaches, an attempt was made to obtain the pore size distribution obtained from imaging techniques.

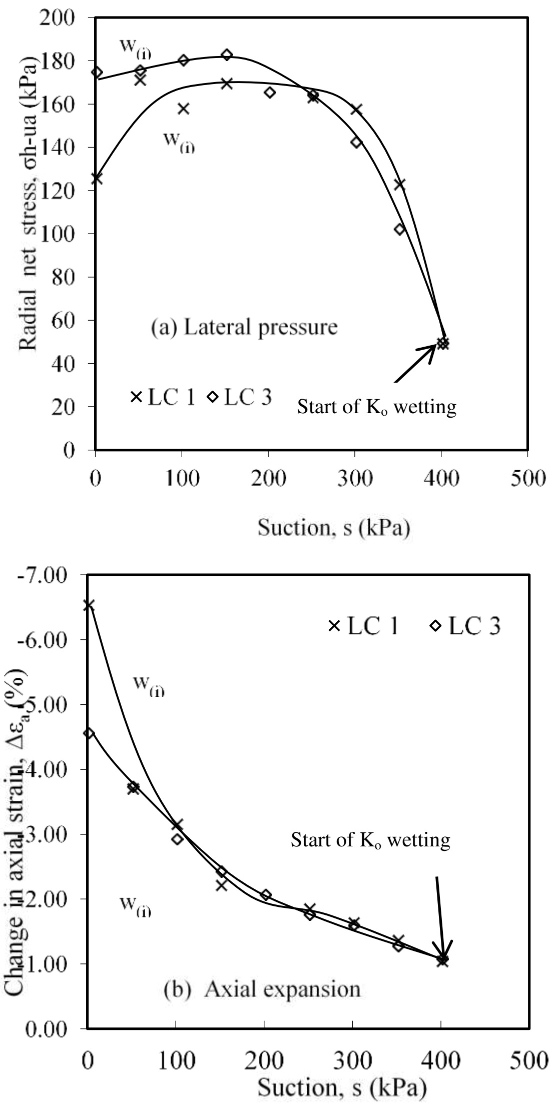


Figure 3. Evolutions of lateral stresses upon wetting of London clay under laterally restrained conditions.

Compacted sand-bentonite mixtures are used for containing hazardous materials in nuclear waste repositories (Tripathy et al., 2017(a)). Under such containments, various factors influence the hydro-mechanical behaviour of the material, including high temperature and pressure. When highly expansive soils are exposed to access water, under containment, the pressure in the barrier will increase substantially. Sivakumar et al. (2015) reported such increase in stresses in various soils having different plasticity under laterally restrained conditions. Figure 3 shows high plasticity London clay when subjected to wetting under K_o-condition and the observations have shown a substantial increase in the lateral stress and axial swelling. Under containment of nuclear waste, the temperature plays a crucial part on the overall behaviour (Tripathy et al., 2017(a), (b)). Also, straining of the barrier material is highly restricted and thus the pressure could build-up.

Qin et al. (2018) examined the influences of temperature and confining pressure on compacted bentonite under different vertical pressures and temperatures. The findings are very interesting and show a substantial reduction in the macro void with the vertical pressure. The swelling is not significantly affected by the temperature. However, the micro voids generally remained unchanged, or marginally reduced with the external loading and temperature, except at high pressures, the macro voids seem to increase at low temperatures. With the elevation of temperature, the swelling strain reached equilibrium more quickly, and the final equilibrium swelling strain decreased. Under elevated temperatures the water vapor movement due to temperature gradient and liquid water movement due to suction gradient dictate the hydro-mechanical behaviour.

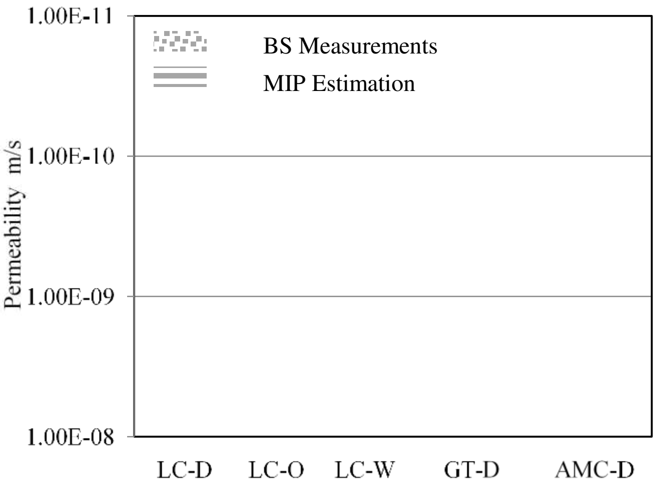


Figure 4. Permeability measured using British Standard method and calculated values based on MIP.

The pore size distribution can be used to evaluate soil-water characteristic curve (SWCC) and therefore various geotechnical aspects can be assessed. Simms & Shunchao (2018) established pore-size distributions (PSDs) of mine tailing samples at various water contents. Differences in the PSDs were noted due to the differences in the void ratio of the material which contained a significant amount of clay-size fraction. In addition to the cumulative PSD function, the plastic strain was accounted for by considering a shifting function of the PSD with void ratio that linked to the air-entry value (AEV) changes of the material. The limitation associated with fitting SWCCs with a log-linear function is discussed. The authors advocated the use of a new function that represented well the plastic strain and shifting of the PSD of the material studied that may have some impact on establishing the relevant geotechnical parameters. This agrees favorably with the observations reported by Anderson (2011) whereby the coefficient of permeability determined based on MIP and British standard measurements were compared at different compaction water contents (samples were saturated before MIP or British standard measurements) as shown in Figure 4. The information clearly suggests that the permeability derived based on MIP is consistently higher than that of direct experimental measurements regardless of soil type or the compaction water content.

3 STRENGTH OF UNSATURATED SOILS

Soils cannot be tied down to having a single strength. Strength very much depends on the test carried out and the problem being analyzed. Consequently, soils may be described as having an undrained strength (described in terms in total stress or effective stress parameters) or a drained strength ('effective' stress parameters), with further subdivisions into peak strength, critical state strength or residual strength. And the combination of stress variables used to describe the strength also varies. In unsaturated soils the strength is complicated by the fact that both air and water are in the pore spaces as opposed to saturated soils where only water is present in the pores, or perfectly dry soils where only air is present in the pores.

In unsaturated soils, quantifying the controlling stresses is essential if the strength is to be fully understood and adequately assessed for practical problems. An essential component of the stresses in unsaturated soils is the matric suction: the difference between the air and water pressures in the pores. The role of suction as a major factor influencing the mechanical behaviour of unsaturated soils was originally investigated at the Road Research Laboratory, UK by Croney & Coleman (1948, 1954, 1960). Developments in the mechanics of unsaturated soils since this time can be divided into four notable stages (Murray & Sivakumar 2010(a); Fredlund et al., 2012; Lu & Likos, 2006):

- In the first stage, researchers tried to find a single 'effective' stress equation to explain mechanical behaviour, as had previously been established for saturated soils. However, comparison with experimental data has shown that unsaturated soil behaviour cannot be adequately modelled using a single 'effective' stress.
- In the second stage, researchers developed constitutive frameworks to explain the shear strength and volume change characteristics of unsaturated soils in terms of two independent stress state variables. The independent stress state variables employed have generally been the net stress $(\sigma - u_a)$ and matric suction $(u_a - u_w)$. This approach has resulted in some successes.
- In the third stage, researchers have attempted to analyze unsaturated soil behaviour in terms of constitutive relationships linking volume change, shear strength and shear deformation in a single elasto-plastic model. While considerable progress has been made through this approach, and researchers are now able to explain many features of soil behaviour, there are also anomalies that are not readily explained.
- The fourth stage of the development has witnessed increased research into the introduction of hydraulic hysteresis and anisotropic yielding into an elasto-plastic framework.

Classical soil mechanics generally assumes that for most practical purposes the behaviour of a water-saturated soil is governed by a single stress state variable given by Terzaghi's (1936) effective stress: $\sigma' = (\sigma - u_w)$. This is very handy as it means that there is no need to include any volumetric term in the analysis. The effective stress together with the shear stress is sufficient to define the stress regime in a saturated soil.

Engineers have faced challenging problems where the assumptions of saturated conditions are unreasonable. In this section we will be particularly concerned with the shear strength of unsaturated soils. In order to appraise the shear strength - as well as the stress-strain behaviour, shrinkage and swelling, yielding and collapse in unsaturated soils - there has been concerted research into the controlling stress regime. Bishop (1959) proposed a single stress variable equation for unsaturated soils which has proved unreliable. Other forms of 'effective' stress equation for unsaturated soils have been proposed but have also proved unreliable when tested against experimental data.

As a consequence of the lack of success with finding a single stress state variable for unsaturated soils, Burland (1964, 1965) suggested that the behaviour should be related independently to the net stress and matric suction. This formed a change of emphasis in research activities with researchers using the uncoupled stress state variables to investigate strength and volume change characteristics. In accordance with the findings of Fredlund & Morgenstern (1977) from theoretical considerations, any two of the three stress state variables of the net stress $\bar{\sigma} = (\sigma - u_a)$, the effective stress $\sigma' = (\sigma - u_w)$ and the suction $s = (u_a - u_w)$ can be used to describe the behaviour of unsaturated soils. The independent stress state variables have been used to develop constitutive equations from experimental evidence and in this way tentative steps have been made towards formulating a general constitutive framework for unsaturated soils.

The use of independent stress state variables in constitutive modelling is an empirical but practical approach to a complex problem that has found a good degree of success. However, in such an approach, unless account is taken of all the relevant variables, parameters derived from experimental observations incorporate the influence of undefined variables which render the analysis highly dependent on test conditions. The result is that extrapolation of conclusions from a particular test to other test conditions or other soils leads to anomalies.

Fredlund & Morgenstern (1977) proposed that the two uncoupled, independent stress state variables of $\bar{\sigma} = (\sigma - u_a)$ and $s = (u_a - u_w)$ were best suited to describe unsaturated soil behaviour. Murray & Sivakumar (2010a) have shown that, consistent with the use of independent stress state variables, it is necessary to consider carefully what volumes these act through. Using the stress state variables of $\bar{\sigma} = (\sigma - u_a)$ and $s = (u_a - u_w)$, the conjugate variables are, respectively, the total volume and the combined volume of the solid and water phases (which comprise the aggregates present in fine-grained soils). And the conjugate strains are the strains associated with these volumes. Is such an approach necessary? It can be argued that the inclusion of volumetric terms with the stress state variables adds a degree of complexity. But it avoids the pitfall of hidden variables influencing results and clarifies apparent data anomalies found when the stress state variables are used without their conjugate volumetric or strain variables (Murray et al., 2002; Murray & Sivakumar 2010(a), 2010(b), 2012).

Frequently, in practice, where suction is taken into account in stability analysis, it is assumed to act through the whole soil mass. This is not the case. Suction does not act through the air phase; it acts through the aggregates comprising the soil particles and water. This is an example that highlights the importance of considering the conjugate stress state variables and volumetric terms.

The product of a stress state variable with its conjugate volume relates to energy, and the product of a stress state variable with its conjugate strain relates to energy change per unit volume. This links unsaturated soils to the fundamental science of thermodynamics from which the concepts are derived. Murray & Sivakumar (2010(a), 2012, 2014(b)) show such an approach can be beneficially used to analyse the energy changes in unsaturated soils at the aggregate level of unsaturated soil structure, and thus to examine how an unsaturated soil's strength and deformation change under shear loading. Depending on triaxial test protocol and specimen preparation, analysis of straining at the aggregate level in an unsaturated fine-grained soil has led to the detection of phenomena such as:

- Singularities in behaviour where shearing has resulted in dramatic reversal of the energy-dispersion directions within and between the aggregates.
- Increase in air voids axially, tentatively suggested as progress towards vertical fissuring consistent with 'barrelling' under axial compression.
- Chaotic behaviour were small differences in specimen preparation have led to significant differences in behaviour at the aggregate level of structure.
- Apparent plastic straining at the aggregate level of mechanical straining which is not evident at the macro-mechanical level.

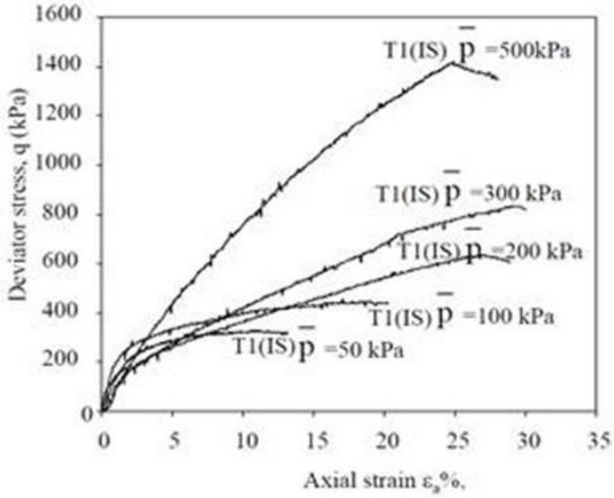


Figure 5. Deviator stress vs axial strain under constant water mass conditions.

While engineers frequently have to make simplifications based on detailed research in order to arrive at a workable solution to a practical problem, this should preferably be made in full knowledge of the effects of the simplifications and places a burden on researchers to first appreciate in detail the complex behaviour of unsaturated soils (Murray et al., 2013, 2014(a)). Overconsolidated clays and dense sands exhibit a peak strength followed by a reduction to the critical state strength. Normally consolidated clays and loose sands achieve peak strength at the critical state. The critical state thus represents a stress condition that a soil specimen subjected to shearing must experience irrespective of its initial state. The question that is frequently posed is: What gives rise to the peak strength? Arguments have been put forward that the peak effective strength of a saturated soil is principally a function of the test conditions and the rate of shearing with the soil not allowed sufficient time to equilibrate under test conditions. A far more complex question is: Does an unsaturated soil have a peak strength? And this leads on to the question: 'What is cohesion in an unsaturated soil? Much test data suggests that unsaturated soils do not exhibit a clear peak strength greater than the critical state strength (Sivakumar et al., 2010(b)) as shown in Figure 5 where compacted kaolin samples were subjected to constant water mass shearing under different confining pressures.

It is generally assumed that shear strength and volumetric conditions remain relatively unchanged subsequent to achieving the critical state. However, continued shearing to very large strains can result in reduction of soil strength and further volumetric changes as a soil approaches its residual state. Saturated, plastic clays can exhibit a significant reduction in shear strength beyond the critical state to the residual state. A low residual strength is characterized by alignment of particles (Lupini et al., 1981). However, soils that comprise round particles do not exhibit alignment and may not experience significant change beyond the critical state (Sivakumar et al., 2018). In such soils, turbulent behaviour and randomly orientated particles is evidenced on shearing. Unsaturated fine-grained soils comprise aggregations of particles that can be expected to exhibit a degree of rigidity and resilience dependent on the level of suction. Their behaviour may thus be perceived as complying more closely with that of a rotund particle structure: does it? (Sivakumar et al., 2018).

A popular approach to defining the strength and deformation behaviour of a saturated soil is provided by the critical state soil mechanics. This forms the basis of the Original Cam Clay Model described by Schofield & Wroth (1968) and the Modified Cam Clay Model described by Roscoe & Burland (1968), as well as other modifications to extend the ideas to a more general class of soil. The critical state concepts have been extended to unsaturated soils. The constitutive elasto–plastic critical state frameworks have also been extended to unsaturated soils as in the Barcelona Basic Model (BBM) and have been further developed over time. But other models put forward for the strength and deformation behaviour of unsaturated soils exist, amongst them are: Toll (1990), Toll & Ong (2003), Wheeler (1991), Alonso et al. (1992) and Wheeler & Sivakumar (1995). Frequently a smooth transition appears to be assumed between unsaturated and saturated conditions: Is this true? The transition of critical state strength from unsaturated to saturated conditions in fine-grained soils can exhibit abrupt changes as a result of soil fabric changes from an aggregated to a more dispersed soil structure, with the soil endeavoring to relax to a lower, more stable, potential state. It can be argued that the suction acts as an 'energy barrier' to the changes (Murray et al., 2008).

Cai et al. (2018) have examined the critical state concepts for unsaturated soils for saturated and unsaturated silty sand from Beijing. This paper deals with the evaluation of the critical-state parameters with respect to the net stress, matric suction and density. Suction-controlled triaxial drained shear tests on compacted soil specimens with different initial densities were carried out. The critical state line equations on the planes of $q - p'$, $v - \ln(p')$ and $v_w - p'$ are proposed. The triaxial tests of the unsaturated soils show that, as expected, at a given net stress, the strength increases as the suction increases. Under a given suction, the strength also increases as the net stress increases. This experimental study further demonstrates that matric suction had no influence on the parameters M and λ (which were equivalent to those for a saturated soil), while $\lambda_w$was dependent on suction. These findings seem consistent with what others have found for sands but the question needs to be asked: is this true for clays? Compared with the saturated soil, a lower shear rate and a larger axial strain were required for the unsaturated silty sand to reach a critical shear state.

Li & Zhang (2018) used a triaxial apparatus to examine deformation and suction variation of an unsaturated silt: kaolin mixture during constant water content tests with the pore air vented to the atmosphere. Their primary interest was the soil suction variation and shear plane evolution under different confining stresses and water contents. A photogrammetry based method was used in deformation measurements and miniature high-capacity tensiometers were used to monitor suction variations. The soil suction measurements indicated uniform soil suction before the development of a shear plane in the specimen. Soil-suction non-uniformity was recorded subsequently. The deformation measurements indicated a clear shear band evolution at low confining stress but a more barrel-shaped response at higher confining stress. The fact that the suctions became non-uniform after shear plane formation suggests that the specimens were tested at such a rate that there was insufficient time for suction to equilibrate. This has implications to the appropriate rate of testing of unsaturated soils as the assumption is usually made of uniformity of suction throughout a test specimen.

Liu et al. (2018) presented experimental data in examining a fill material comprising a poorly graded gravel with sand used in construction of the Chongquing airport as part of the China Western Development. This includes SWCCs, and triaxial tests under saturated and unsaturated conditions. The triaxial testing was carried out in an upgraded double-cell triaxial system with a custom-built pedestal. The results are interesting in part because some of the data on the suction influence on the water volume change is counter-intuitive if compared to the volumetric strain. A framework for this material under unsaturated conditions is to be developed with the availability of future data. The testing shows the need to review current models continuously as further experimental data becomes available.

While soil structure and density are very important in fine-grained soils their role in more granular materials cannot be ignored. Imam et al. (2018) presented data on the shear strength of unsaturated sand at different relative densities in direct shear tests. They also present SWCC test results. The authors demonstrated that the initial density had a significant impact on the SWCC, shear strength and effective stress. Large matric suction was developed in the sand when in a dense state leading to an increase in shear strength as would be expected. The shape of the stress-displacement curve and failure mode were also influenced by degree of saturation and density.

Clays and granular materials have different properties that are beneficial in different circumstances. In certain applications sand-clay mixtures are used in geotechnical engineering practice when a fill material must have properties that are attributable to the sand fraction, such as high shear strength or low compressibility, and aspects attributable to the clay fraction, such as low permeability. Mun et al. (2018) have presented the undrained shear strength and compression behaviour of compacted sand-clay mixtures. The tests carried out include unconsolidated-undrained triaxial compression tests (at different rates of strain), oedometer tests, and isotropic compression tests. The triaxial compression tests indicated that the sand-clay mixtures had lower undrained shear strength than the sand or the clay studied. The clay was observed to have the highest undrained shear strength that was attributed to negative pore water pressures generated during undrained shearing. The oedometer tests indicated that suction in the clay matrix had an important effect on the preconsolidation stress of the sand-clay mixture. The isotropic compression tests indicated that all mixtures had a softer initial response than pure sand. At mean effective stresses greater than 30 MPa the specimens with clay content less than 10% followed the compression curve of the pure sand, while those with clay content greater than 20% approached the compression curve of the clay.

Slope stability is a very important aspect of geotechnical engineering. But slope analysis is subjected to many uncertainties. This includes the influences of seasonal water fluctuations and the ratcheting effects of periodic wetting and drying. Huang et al. (2018) have presented a paper that looks at the mechanical behaviour of unsaturated soil specimens in the laboratory under multiple cycles of drying and wetting and the role that electrical resistivity in determining the subsurface moisture and geotechnical property changes. The results from a series of resistivity, suction, and undrained shear strength measurements on a glacial till under multiple cycles of drying and wetting are presented. The behaviours of resistivity, shear strength and suction are different in different cycles. Interrelationships between soil water content, resistivity, shear strength and suction were established. The results indicated that, within the same cycle, the specimens on the drying path had higher undrained shear strength (C_u) and matric suction than those on the wetting path due to hysteresis. Hysteresis in soil shear strength-moisture relationships and soil water retention behaviour were more significant in the first drying and wetting cycle and reduces as the number of cycles increases as shown by Tripathy et al. (2002). Deteriorations in shear strength and suction were found during multiple cycles of drying and wetting. For soil resistivity, hysteresis was observed between drying and wetting paths in the same cycle and between different cycles and was attributed to the volumetric changes and cracks developed during cycles of drying and wetting. It is proposed that these changes in property interrelationships may be caused by changes in the structure of the soil through the formation of micro-cracking and other shrink-swell related mechanisms. Here again the authors conclude that soil structure is of major significance to understanding and interpreting the behaviour of unsaturated soils. The microstructure of a fine-grained soil is known to greatly influence its behaviour.

Sadeghi & Ng (2018) have examined the shear behaviour of a desiccated loess with three different microstructures. The authors stated that wind-blown loess has a natural honeycomb structure that differs from that of laboratory prepared specimens. They have examined how the initial microstructure affected the shear behaviour of loess specimens prepared with three different microstructures: intact, compacted, and reconstituted. The loess specimens were sheared at low relative humidity by utilizing a humidity controlled shear box chamber. The data obtained indicated a brittle failure mode coupled with high dilation rate for all microstructures considered. Of particular interest was the greater dilation and hence peak strength of compacted loess compared with the intact loess specimens. This is attributed to the more uniform pore size distribution in the compacted specimens than the intact specimens though the initial void ratio was almost identical. Reconstituted loess, on the other hand, had the highest dilation rate and peak strength because, it is argued, of its lower void ratio at the same net stress and suction. The authors also concluded that their results also revealed that a classical stress-dilatancy relationship for saturated coarse-grained soils may not give satisfactory predictions for a desiccated fine-grained soil unless the contribution of suction to the stress ratio is properly defined. The paper highlights the importance of understanding and interpreting soil structure in assessing soil behaviour and that specimens prepared in the laboratory must replicate site conditions for practical applications**.**

The interaction between unsaturated soils and structures and an interpretation of the significance of test data is invaluable to practicing engineers. But there is limited information in the literature on the very practical question of the interface shear strength between structures, such as a retaining walls or piles, and unsaturated soils. The papers by Jumanah Hajjat et al. (2018) and Liu & Vanapalli (2018) are welcome in this respect. Jumanah Hajjat et al. (2018) address shear-interface behaviour of a highly expansive soil under saturated and unsaturated conditions in the laboratory using a modified traditional direct shear apparatus. An acrylic square plate with a smooth face and a spiral-circular grooved surface were used to simulate the structure. The shear strength parameters of friction angles and ‘adhesions’ based on total stresses were recorded. The experimental results indicate the significant effect of interface roughness on the shearing behaviour of soils under different initial moisture conditions. The interface effect was more pronounced in unsaturated samples than in saturated samples and this is attributed to the large impact of matric suction. The authors do not measure the suctions in the soil and do not make clear the significance of the suction to the measured adhesion or to its effect on the soil structure. It would have been interesting to have had some comment from the authors on whether the adhesion - particularly that related to suction – could be relied on in design particularly in the long term or at large strains. These questions are addressed to some extent in the paper by Liu & Vanapalli (2018). They examined the interface shear strength for an unsaturated expansive clay against a rough steel interface in laboratory direct shear tests. The peak and residual shear strength results both increased with increasing suction. The contribution of suction towards the shear strength at soil interface under unsaturated conditions has been explained from two aspects: first, suction enhances soil aggregation and contributes to the shear strength. Secondly, matric suction significantly contributes to the peak strength. However, after reaching peak shear strength, the area of water-air menisci was considered to greatly reduced due to the rearrangement and sliding of soil particles due to extended displacement. There was thus a limited contribution from suction towards the residual interface shear strength.

Amongst the numerous soil improvement techniques available is the use of lime in treating clays principally to improve the soils strength and volume change potential. Its long term efficacy can be affected by carbonate reactions. Vitale et al. (2018) report on the carbonation influences on the chemo-mineralogical evolution of lime treated kaolin on the time scale at which the reaction mechanism takes place. Mineralogical and microstructural changes induced by carbonation as detected by X-ray diffraction (XRD), Thermogravimetric analysis (TGA), mercury intrusion porosimetry (MIP) are reported on; while the hydro-mechanical behaviour has been investigated by testing saturate specimens under drained consolidated triaxial cell conditions. The mineralogical investigations on treated samples exposed to the atmosphere have shown consumption of available portlandite and precipitation of calcium carbonate in the short term and the inhibition of pozzolanic reactions in the long term. Triaxial tests results highlighted a reduction of performance or durability of lime treated samples when precipitation of calcite takes place due to carbonation. Chemical influences in geotechnical engineering are often ignored as being too problematic to solve but in lime treated soils such influences are ignored at the designer’s peril.

Thin slabs and roads can suffer detrimentally due to water influences on the underlying soils. Lin & Zhang (2018) report on a ‘wicking’ fabric that they conclude has the potential to dehydrate the base soil under unsaturated conditions enhancing the long-term road performance. Inadequate drainage of the underlying soil can lead to significant problems, such as with soil volume changes and detrimental effects on soil strength and stiffness. Over time this leads to development of cracks on road surfaces which widen and deteriorate the joints and edges. Normal subsurface drainage design methods usually consider water flowing under gravitational force and capillary water is considered undrainable. A recently developed geotextile with ‘wicking’ fabrics has the potential to dehydrate the underlying soil under unsaturated conditions. Both laboratory and field tests have proved its efficacy. The purpose of the paper by the authors was to present an evaluation of the geotextile drainage efficiency when applied with different types of soil. Two types of soil were used to simulate good and inferior drainage conditions. The test results indicated that the geotextile with ‘wicking’ fabrics is effective and capable to drain capillary water out of the soils. The use of geotextiles in geotechnical engineering has increased phenomenally since they were first introduced and the ‘wicking’ fabrics seem to provide a valuable addition to the materials available.

4 STIFFNESS OF UNSATURATED SOILS

Stiffness, particularly for small strains, forms an important component of experimental research. In unsaturated soils the research has been limited on this aspect. In many instances, if not most instances, the practicing engineer is concerned with relatively small strains that can nevertheless be important to structural performance. The use of local strain measurement techniques (bender elements, LVDTs, Hall transducers etc.) to determine shear stiffness form an important component in laboratory tests as in the triaxial and modified triaxial cell set-ups. It is sometimes considered that the overall specimen strains, such as the secant modulus, is misleading in deducing stiffness under practical loading conditions. That is not to say that overall soil specimen strains and their measurements in response to loading are not important, and the interpretation of local strain and overall strain measurements must be viewed in the light of their applicability to practical applications.

Mohyla et al. (2018) have reported on a laboratory test program to examine the strength and stiffness of a reconstituted and recompacted low plasticity silty clay with variable degrees of saturation. The tests were carried out in conventional and double-walled triaxial devices. The tests on unsaturated soil were controlled using the concept of net stress and suction with strains measured using bended element and LVDT techniques. The experiments were aimed at determining parameters and testing the applicability of a hypoplastic constitutive model (Wong & Mašín, 2014) for unsaturated soils. In processing the data and in the calibrations the effective stress concept of Bishop (1959), with the effective stress parameter χ (Khalili & Khabbaz, 1998) was used. The authors concluded that the results provided confirmation of the applicability of the constitutive model. A simple way of determining the immediate undrained strength of an unsaturated silty clay for conventional undrained stability analyses was also presented.

Patil et al. (2018) have examined the strength and stress-dilatancy of a compacted silty sand in conventional suction-controlled drained triaxial tests. The results were aimed at investigating the effects of suction and confining pressure on stiffness (secant modulus), dilatancy and to analyse the stress-dilatancy relationship. The strains dealt with were based on overall specimen measurements. An increase in suction caused a nonlinear increase in dilatancy rate, peak strength, and critical state strength at constant confining stress. And an increase in confining stress suppressed the tendency of specimens to dilate. An upward shift in strength envelope both at critical and peak state was observed with increasing suction. Predictions from the stress-dilatancy models proposed by Rowe (1962) and Schofield & Wroth (1968) were compared with experimental data obtained from the suction controlled tests and the authors reported a good correlation.

In unsaturated soils, straining occurs due to changes in air voids and changes in the saturated regions, frequently taken as in the aggregates. How important is it to distinguish between the two forms of straining and how does this relate to the type of laboratory test? Murray & Sivakumar (2010) and Murray et al. (2014) demonstrated how laboratory triaxial shear tests can be analysed to examine the energy dispersion and dissipation and thus the contributions of the air phase and saturated aggregates strains to total strains.

5 VOLUME CHANGE CHARACTERISTICS

Volumetric responses of unsaturated soils are very complex, influenced by several factors that include: loading magnitude, suction, compaction level (or compaction density), compaction water content and sample preparation method. Many of these factors will give rise to inherent structure within the soils, which also influences the overall responses of the unsaturated soils during external or environmental loading conditions. The most difficult aspect of testing unsaturated soils is the measurements of sample volume change. One-dimensional loading conditions have been adopted in order to alleviate the problems; however, the conditions at insitu in many cases not one-dimensional. Therefore, triaxial stress conditions are desirable for laboratory testing environments. In this case several procedures have been adopted to measure the sample volume change, namely: internal strain gauges, digital tracking and double wall cells.

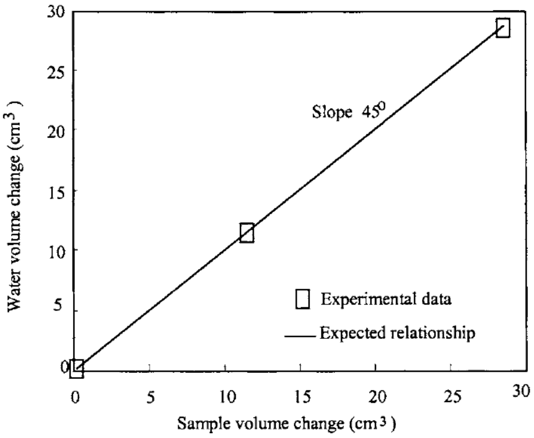


Figure 6. Comparison of volume changes measured using the flow of water in or out of the cell and water drainage of saturated soils.

Sivakumar et al. (2010a) developed a twin-cell (a modified version of the double-wall cell; Wheeler, 1988) and the system allowed precise measurements the volume change of sample as indicated in Figure 6 where a saturated sample was tested in which the volume change of the sample was detected using the flow of water in or out of the inner cell was compared with the water drained out from the sample.

Sivakumar & Wheeler (2000) reported the test results obtained from samples of kaolin statically compressed into a one-dimensional mould to two different initial dry densities. The work showed that the state of the unsaturated soils when undergoing isotropic hardening was influenced by the initial conditions of the samples. The compaction process inevitably introduces a degree of stress-induced anisotropy in the samples, and a complex soil fabric. In conclusion, there were no significant evidence to suggest that there appears to be a unique normal compression line for unsaturated soils at a given value of suction. This aspect was re-evaluated by Sivakumar et al. (2010) in which the samples prepared by isotropic compression to two different initial conditions were subjected to loading at various values of suctions and the findings (Figure 7) is a strong evidence to suggest that the concept of a unique normal compression line is valid for unsaturated soils.

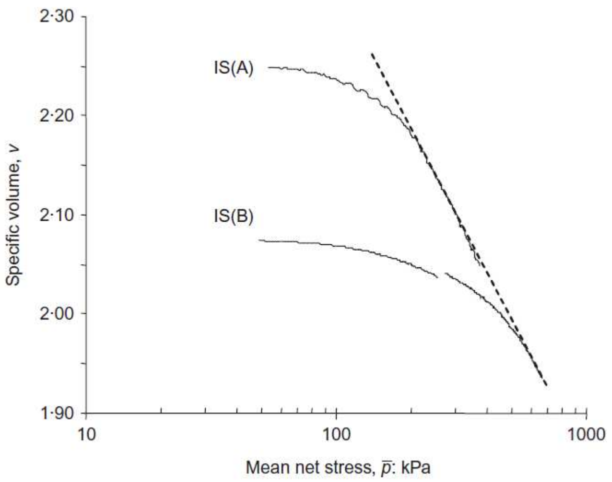


Figure 7. Pressure-volume characteristics of compacted kaolin at different densities at suction value of 200 kPa.

Digital technology is becoming an integral part of civil engineering research and applications in various ways (for example, structural health monitoring). Attempts have been made to use laser technology for measuring sample volume change. Some very interesting information is presented in this conference with respect to volume change measurements of unsaturated soils.

Xia at al. (2018) reports an automatic detection of coded targets for rapid measurement of volume change under triaxial stress conditions. In the article, the authors adopted a simple and efficient way of measuring sample volume change using photogrammetry-based method. The approach only requires a commercially available digital camera to take images from which the three dimensional model of the soil specimen can be reconstructed. Identical coded targets in multiple images were recognized using a signature-based shape feature extraction technique. The authors have presented a validation of the approach; however, there appears to be no direct validation of the approach that would put the method for wider applications.

Cuomo et al. (2018) also examined the application of digital technology to measure axial strains for unsaturated samples both locally and globally. This was investigated in a modified suction-controlled oedometer (made of Plexiglass). Granular material containing some targets (particle coated with white colour) were subjected to vertical loading at a certain suction and then subjected to wetting. By tracking of the targets the authors were able to compare the local and global axial strains. The comparisons are good; however, the standard deviation of the local axial strain measurements is considerably high which gives rise to possible influence of other factors that may prevails during wetting, such as rotation and lateral displacements. The authors have rightly acknowledged such shortcomings.

Opukumo et al. (2018) examines a very interesting topic on the role of calcium carbonate on the collapse potential of unsaturated calcareous silty clay (artificially manufactured kaolin clay, quartz silt and CaCO3), with the latter to enrich bonding. The tests were carried out in an oedmeter and samples were flushed using pure and acid water (5% concentration) to disable the bonding effect. Laboratory tests were also carried out on non- calcareous soils. The axial strains were used as an indicator to quantify the collapse potential during flushing. Not surprisingly the flushing with acid water in the case of calcareous soils resulted in a high collapse potential however beyond a certain level of CaCO3 this may not lead a substantial collapse, unless otherwise the tests were carried out under a very high external loading whereby the bonding can be disabled in mechanical manner.

Villar & Lloret (2018) examined the volumetric response of highly compacted bentonite subjected to cyclic changes of suction. The durations of the tests were well over 1 year in many cases. The suction was controlled by the vapour transfer technique whereby the suction was increased to up to 500 MPa during which a low vertical stress was applied under one-dimensional loading conditions. The authors report that the bentonite showed a stiff behaviour when suction increased from its initial condition to very dry state (500 MPa suction). However, upon wetting to slightly lower value of suction 300 MPa the vertical strains were small. In one of the figures in their article, it indicates that some of the sample did in fact compressed upon wetting to this value of suction. Could it be due to possible discontinuity in the lateral boundary of the testing cell and the sample? The authors also found that first drying did not modify the swelling capacity of the sample; however, during subsequent hydration and surprisingly swelling observed during wetting was found to be larger in the samples previously dried to 500 MPa. Would it be due to formation of larger macro pores within the sample during drying? This observation resembles to some extent the findings reported by Azizi et al. (2018). It also ties with the time taken for the stabilization as the movement of water or vapour can take place at a faster rate if the macro pore volumes are high.

Crisci et al. (2018) reported a very interesting observation made on Opalinus clay often considered as barrier material for hazardous waste disposal. The response of the compacted clay was observed under drying-wetting and re-drying to very high values of suction. The intriguing nature of the work is the measurements of lateral and vertical strain during the above processes and the observations have clearly demonstrated different volumetric responses in the respective directions with a considerable straining in lateral direction than the vertical. The higher lateral strain implies that under restricted confinement there will be a significant development of lateral stresses than vertical stresses as reported by Sivakumar et al. (2015) (Figure 3). It also appears that the two subsequent wetting leads to an overall increase in the volumetric strain. This is also comparable with the earlier comment on progressive increase of macro voids upon drying and wetting (Azizi et al., 2018).

Osele & Kasangaki (2018) examined the effects of water content on the collapse behaviour of laterites prepared at different water contents and relative densities. The suctions in these cases were measured using filter paper technique. Understandably the matric suction was higher for soils compacted dry of optimum, regardless of the value of density achieved, however the dry density also has some influence on the suction value. Based on the observations, the authors concluded that it would be risky to rely on specifications based on the degree of compaction alone for preparing ground, for example highway constructions, without giving an adequate consideration to compaction water content which ties reasonably well with the conclusions of Sivakumar et al. (2013).

6 CYCLIC EFFECTS

Resilient modulus gives a measure of the elastic property of a soil, particularly when assessing the stiffness of the soil subjected to repeated loading. This resilient modulus is not a unique property of the soil and depends upon several factors: stress state, soil type and structure or soil physical state. Recent studies have shown a link between suction and the effect of net confining pressure on the resilient modulus. Repeated or cyclic loading of unsaturated soils is encountered in many situations, including subsoils supporting a road pavement and rail track structures (Pumphrey et al., 1986).

Some valuable information is available in the literature in relation to the effects of compaction water content and the post-compaction process on the resilient modulus. Sivakumar et al. (2013) examined the unsaturated soil behaviour in relation to resilient modulus and suction changes during cyclic loading. Attention is also drawn to Proctor compaction in order to assess how the level of compaction effort can sustain permanent deformation under repeated loading. The tests were performed on compacted kaolin samples that were subjected to cyclic loading while the measurements of suction (using psychrometer) and strains (using internal strain gauges) were made. The key findings from the research are presented in Figure 8 where the cyclic loading leads to continuous reduction in suction and the rate of reduction increased with the compaction water content. Figure 9 shows the effects of confining pressure and the loading amplitude on the final resilient modulus which shows an interesting pattern that the maximum resilient modulus appears to be at a suction of 800 kPa which corresponds to the optimum water content.

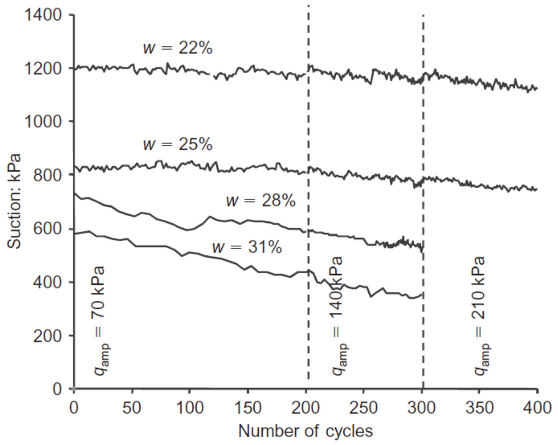


Figure 8. Suction changes during cyclic loading at different compaction water contents.

Nishimura & Habasimbi (2018) investigated liquefaction behaviour of an unsaturated silty soil having various water contents and therefore having different matric suctions. The authors employed the microporous membrane to control and measure low matric suctions. The samples prepared at different water contents were subjected to cyclic loading at different loading frequencies, with the pore air being vented to atmospheric pressure. The study concludes that cyclic loading induces excess positive pore water pressure and continuous axial strain which in general agrees with the findings reported by Sivakumar et al. (2011). As pointed out above the suction in the soil can influence the dynamic properties.

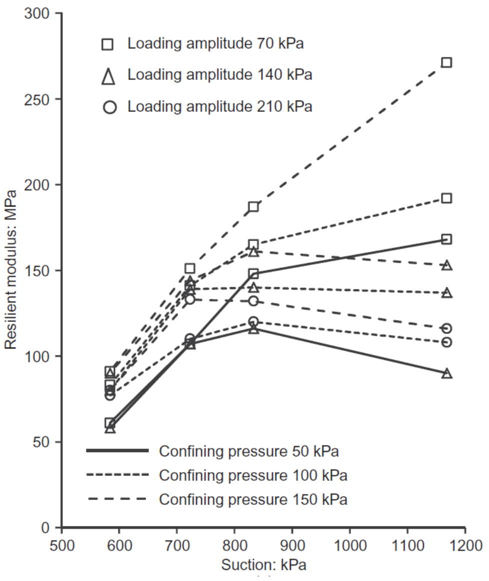


Figure 9. Resilient modulus at different initial suction and loading amplitude under various confining pressures.

Mirshekari & Ghayoomi (2018) examined the characteristics of a fine sand in saturated and unsaturated state in a complex centrifuge seismic test set-up. The level of saturation was controlled during the experiments by implementing the steady state infiltration technique. Selected earthquake motions (Northridge 0.3g and Kobe 0.2g) were applied to the samples to evaluate the influence of partial saturation on the response under motions. The results showed higher intensity amplification in unsaturated sand layers than those captured in dry sand, under both input motions.

7 HYDRAULIC PROPERTIES OF UNSATURATED SOILS

Permeability or hydraulic conductivity is a widely varying parameter that is highly dependent on soil structure and greatly influences the behaviour of soils. Clay soils can be expected to change volume on a change in the water content, and thus suction, depending on the availability of water; while fines can be washed from coarse granular materials. Soil fabric significantly influences the mechanical and hydro-mechanical bahaviour (Casagrande, 1932; Lambe, 1951; Mitchell, 1993; Leroueil & Vaughan, 1990). Structure is particularly important in fine-grained clayey soils, which comprise an abundance of fine, plate-like particles. Though also influential in coarser-grained sands and gravels, the effects are less pronounced. The presence of mass discontinuities such as fissures, laminations and bedding planes form part of the macro-fabric of a soil and are a consequence of deposition and past stress history. Such characteristics significantly influence the soil behaviour in the field, not least the permeability (Leroueil et al., 1992; Little et al., 1992; Hossain, 1992). In fine-grained soils, surface tension forces resist the filling of air-filled void spaces during wetting and resist the emptying of water-filled void spaces during drying resulting in hysteresis effects. The chemistry of the groundwater can also be a significant factor in soil behaviour and a notable example would be in landfill engineering where leachate influences clay linings.

The Impact of pore fluid salinity on the progressive volume change behaviour of kaolin is addressed in the paper by Mishra et al. (2018). Electrolytes present in the pore fluid phase of the clay are considered to alter the force balance of the soil system and thus affect its behaviour characteristics. The authors have demonstrated marked alterations in drying and volume change behaviour of kaolin having NaCl solution at 0.2 and 1.0 molality as the pore fluid. This has been recorded in drying and linear and volumetric shrinkage tests from a highly saturated state. Increase in concentration of pore fluid reduced the overall drying rate, minimal void ratio at the end of the shrinkage tests and the one-dimensional linear shrinkage. It also resulted in higher dry densities at the end of the shrinkage tests. Length of the moulds also impacted linear shrinkage behaviour; at the same concentration of pore fluid samples a short mould yielded high linear shrinkage. The authors rightly point out the need to ascertain field behaviour from laboratory tests with pore fluid of chemistry similar to field conditions.

An interesting hydraulic problem is presented by Kwa et al. (2018). They draw attention to the significant loss of shipping and lives as a result of the instability due to liquefaction of moist iron ore and other metallic ores carried as cargo. They report on studies currently being carried and a model under development to investigate the cyclic unsaturated soil behaviour of such materials. They comment on moisture movements that occur during liquefaction and that are likely to arise by wave rocking motions. They present some of the hydraulic properties necessary in developing a constitutive model that captures the hydro-mechanical response of these materials when subjected to unsaturated cyclic loading conditions. The hydraulic properties, including the permeabilities and SWCCs, of materials similar in grading to the ores, containing a range of particle sizes less than 9.5mm and fines (<75μm) contents of 18, 28 and 60% are presented. The SWCCs were used in a one dimensional elastic analysis on a column of material and it was found that the fines content had a significant effect on the resulting varying degrees of saturation with depth. The implications of the measured properties on the likelihood of cargo liquefaction are also discussed.

8 TEMPARETAURE EFFECTS

Heat flow and its effects on the engineering behaviour soils has been a subject of research since several decades. High temperature studies are relevant in the case of nuclear waste disposal, whereas ground source heat pumps, buried power cables, energy piles etc are other areas where significant developments have occurred. Numerous models have been developed to predict the thermal behaviour of unsaturated soils (Thomas & He 1999). Under nonisothermal conditions, the heat generated within porous media may dissipate due to various processes, such as radiation, conduction, and convection. The thermal properties of surrounding medium that acts as an insulation, the magnitudes of temperature and water pressure, density and water content may influence the distribution of water and development of stresses within soil systems. Water vapour flow under temperature gradient and liquid water flow due to suction gradient are some of the phenomena that have been able to explain chemical and contaminant transport within unsaturated soils (Tripathy et al., 2014(a), 2014(b), 2015, 2017(a); 2017(b)).

Some of the soil properties that are of paramount importance while analysing the heat flow in unsaturated soils are: dry density, water content, mineralogy, and texture. Determination of thermal conductivity as influenced by the degree of saturation is prerequisite to characterize the behaviour of unsaturated soil systems (Likos, 2014; Barry-Macaulay et al., 2015). The heat flow through soil systems is complex due to the fact that the thermal conductivity of soil increases with an increase in the dry density, decreases with an increase in the porosity, and increases with an increase in the water content and degree of saturation (Farouki, 1981).

Samarakoon et al. (2018) presents a nonisothermal apparent thermal conductivity function as applicable to silts and sands. The thermal conductivity function combines the effects of conduction, convection, and phase change in unsaturated soils into a single term that varies with the initial degree of saturation. The shape of the nonisothermal soil-water retention curve and the amount of phase change and convection have been considered to develop the simplified thermal conductivity function. The proposed function is shown to provide reasonable results when compared with the experimental data. The limitations of the work in case of coupled heat transfer and water flow analyses are discussed. The range of temperature considered by the authors were between 30 to 80°C.

The effects of suction on the thermal properties of compacted kaolin is presented by Cardoso et al. (2018). Suction was applied by vapour equilibrium technique while establishing the drying and wetting paths at a temperature of 30 °C. Compacted samples having the same water content are tested at different void ratios to achieve different structures. A thermal probe was used to derive the volumetric heat capacity, thermal diffusivity and thermal conductivity. The test results are analysed both in thermal conductivity-degree of saturation and suction-thermal conductivity plots to emphasize the role of degree of saturation on thermal conductivity.

Nishimura & Matsuato (2018) have conducted unconfined compression tests on compacted bentonite and bentonite-sand samples at isothermal conditions of 20 and 80°C using a modified triaxial compression apparatus to bring out the influence of elevated temperature on strength of these materials. The impact of shearing rate and heating load at various times (24 hr and 30 days) are discussed.

Cheng et al. (2018) presented an experimental study of the collapse potential of a loess at temperatures of 5, 23 and 50°C. Such a study is novel and embraces the climate change effects on behaviour of unsaturated soils. Laboratory suction- and temperature-controlled tests were carried out by the researchers on compacted specimens by using a double-cell triaxial apparatus. The axis-translation technique was used for imposing suction, whereas the temperature of the measuring system was controlled by a heating/cooling unit. The authors concluded that an increase in the temperature causes a dramatic increase in the collapse strain due to the wetting-induced softening of the material. The wetting-induced softening is associated with a decrease in the interparticle normal force as the temperature increases.

9 CONCLUSIONS

The behaviour of unsaturated soils is influenced by several factors including structure, frequency of loading, temperature, pore water chemistry and mineralogy. These factors would have a profound influence on strength, volumetric and hydraulic properties of unsaturated soils. This conference had been successful platform in collating and presenting some very interesting information on these topics. This paper provided an overall commentary of the key findings presented in some selected papers combined with the authors' own experiences on a wider perspective of unsaturated soil behaviour.

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