Modelling Unsaturated Soil Behaviour in Net Stress – Moisture Ratio Space

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ABSTRACT: It is now globally accepted that the fundamental principles of soil mechanics must cover both saturated and unsaturated soils. Since the early developments in unsaturated soil mechanics significant contributions have been made to advance the understanding and modelling of unsaturated soil behaviour and by now there are a number of different constitutive models capable of predicting unsaturated soil behaviour. However, despite these significant advances, the capability to predict unsaturated soil behaviour in Engineering practice is still far from being entirely satisfactory since the gap between research and practice has widened considerably as the models have become more and more complex. In addition, the use of suction as one of the stress state variables in modelling unsaturated soil behaviour is hindered due to the difficulty in measuring suction accurately in the field. In this context, the current paper reviews the literature of modelling mechanical behaviour of unsaturated soils with a special attention for the selection of constitutive variables.

1 INTRODUCTION

Originally, geotechnical engineering developed as a branch of Civil Engineering in temperate climates of the world where the soil is fully or nearly saturated with positive pore water pressures. Therefore, the primary focus of research was on the volume change, shear strength and seepage of saturated soils. The introduction of effective stress principle by Karl Terzaghi in 1936 for saturated soils, which is considered as one of the greatest discovery in classical soil mechanics history, contributed to an outstanding progression of geotechnical engineering as a science that is readily applicable in engineering practice around the world. By now this science has expanded to embrace a larger number of engineering problems encountered in routine engineering practice.

However, more than one third of the earth's surface is in arid or semi-arid condition where the soils near the ground surface are in dry condition exhibiting varying characteristics in comparison to saturated soils. This condition of soil is usually referred to as unsaturated where soil particles, air and water coexist in one system. This coexistence of air and water as a mixture in void spaces makes both the mechanical and hydraulic behaviour of unsaturated soils relatively complex and difficult to be addressed by classical saturated soil mechanics principles. However, due to this intricate nature of unsaturated soil behaviour under the influence of the varying local climate conditions there has been relatively slow advancement of unsaturated soil mechanics as a branch in geotechnical engineering.

Commonly in current practice, unsaturated zone above the water table is considered as a saturated material and, in many cases, this assumption can lead to conservative results. However, this is not always the case, and ignoring the possible complex behaviour of unsaturated soils coupled with climatic influence can lead to inaccurate assessment of the performance of geotechnical structures and, in some cases, to premature failure.(Tarantino and El Mountassir, 2013) One such example is the collapse settlement of Beliche dam in Portugal due to reservoir impounding and direct action of rainfall. (Alonso et al., 2005). Also there are a number of case histories in literature where natural and artificial slopes have failed as a result of rainfall events due to loss of soil shear strength. These different types of engineering problems encountered as a result of soil being unsaturated can be summarized under four behavioural patterns, immediate settlement due to the undrained compressibility, heave due to swelling of soil on wetting, further settlement due to collapse of soil on wetting and loss of shear strength upon suction reduction.

Over the last few decades considerable improvements in understanding the behaviour of unsaturated soils has been achieved with developments in experimental, constitutive modelling, numerical and analytical techniques and by now there are a number of constitutive models capable of predicting the unsaturated soil behaviour reasonably satisfactorily. However, the application of these models in engineering practice is still problematic. Therefore, an alternative approach which can bridge the existing gap between research and practice would be more beneficial to advance the engineering practice.

In this context this paper reviews the modelling of mechanical behaviour of unsaturated soil in different constitutive modelling spaces.

2 CONSTITUTIVE VARIABLES FOR UNSATURATED SOILS

All the variables that are used to define the mechanical behaviour of unsaturated soils are known as constitutive variables and the behaviour is described in the form of constitutive relations in different stress spaces. The selection of constitutive variables plays a crucial role in describing the unsaturated soil behaviour. With reference to the progression of unsaturated soil mechanics, selection of constitutive variables can be categorized into two, namely, the use of single constitutive variable and dual constitutive variables (Zhou, 2011).

2.1 *Single constitutive variable*

Early attempts to describe the behaviour of unsaturated soils was focussed on finding a single constitutive variable that is capable of defining mechanical behaviour of unsaturated soils and the best known attempts made the assumption that the well-defined principle of effective stress for saturated soils introduced by Terzaghi (1936) is still applicable and that the mechanical behaviour can be fully described in the conventional (q,p′) stress space. Bishop (1959) extended the Terzaghi's effective stress equation for unsaturated soils as follows, well known as Bishop's effective stress equation.

$$\sigma' = \sigma - u_a + \chi\left(u_a - u_w\right) \tag{1}$$

Where σ' is the effective stress and σ is the net normal stress. u_a and u_w are pore air and pore water pressures respectively. χ is a parameter which was assumed to be dependent upon the degree of saturation.

Many researchers (Aitchison, 1960, Bishop and Donald, 1961) tried to evaluate the applicability of the above equation in unsaturated soils and Jennings and Burland (1962) demonstrated that this equation did not account for the behaviour of many soils below a critical degree of saturation. Also it was found that parameter χ could not be directly obtained for volume change behaviour and with the presence of structural effects it was hard to achieve a good agreement between the experimental and predicted results. This questioned the validity of above effective stress equation particularly for volume change even though it seemed to be applicable for shear strength behaviour. (Bishop and Blight, 1963) As noted by Matyas and Radhakrishna (1968) this is because volume change data are normally analysed on an incremental basis in a continuous process of deformation whereas shear strength data are analysed at the failure state.

In addition if the concept of effective stress is valid for unsaturated soils, then the behaviour of an unsaturated soil sample at a given value of effective stress should be identical to the behaviour of a saturated sample of the same soil subjected to same value of effective stress and with a similar stress history. However, it is impossible to satisfy this condition in unsaturated soils particularly for volume change behaviour of unsaturated soils. For instance, wetting induced swelling or collapse depends on the initial state in addition to the Bishop's effective stress. This is because the inter granular structure and forces arising either from applied stresses or from suction have different effects on the deformation of soil structure and those effects do not appear to be able to be combined into one single expression.

More recently, however, Khalili and co-workers (Loret and Khalili, 2002) revived the use of effective stress principle providing experimental evidence that incorporating non-unique volumetric behaviour with respect to a certain effective stress could be used to predict the unsaturated soils behaviour. Nevertheless, difficulties still exist extending this approach to cover behaviour of soils especially under significantly drier states.

2.2 *Dual constitutive variables*

Due to the difficulties encountered with the use of the effective stress concept in unsaturated soil, subsequent research was focused on adopting two constitutive variables to describe the mechanical behaviour of unsaturated soils. Bishop and Blight (1963) was among the first researchers to suggest the use of net stress (σ-u_a) and matric suction (u_a-u_w) as the constitutive variables in modelling unsaturated soil behaviour. Since the suggested two variables do not include any material state parameters, they are usually referred to as independent stress state variables. Fredlund and Morgenstern (1977) showed that the mechanical behaviour of unsaturated soils can be uniquely explained by two independent state variables selected from (σ-u_a), (σ-u_w) and (u_a-u_w). The two normally selected are the net stress (σ-u_a) and matric suction (u_a-u_w), because the pore air pressure, u_a is usually zero under field conditions, and therefore, the net stress and suction simplify to the total stress and negative pore water pressure respectively.

The first effort to capture the mechanical behaviour of unsaturated soils in net stress – matric suction stress space was in the form of unique elastic state surfaces. However, with the realisation that unsaturated soil behaviour was not fully elastic even when considered non-linear, it was concluded that the state surface approach would not be appropriate in defining unsaturated soil behaviour. To account for this irrecoverable behavioural pattern, elasto-plastic constitutive models for unsaturated soils were then introduced. The first elasto-plastic constitutive model introduced to unsaturated soil mechanics was developed in the same net stress – matric suction space by Alonso et al. (1990), considered as one of the greatest milestones in the evolution of unsaturated soil mechanics. A number of constitutive models in the same stress space then followed, such as Wheeler and Sivakumar (1995), and by now it is globally accepted that elasto-plastic constitutive modelling is the most appropriate method to define mechanical behaviour of unsaturated soils.

However, there are limitations with the use of this pair of constitutive variables in modelling unsaturated soil behaviour such as the discontinuity between saturated and unsaturated states and the difficulty in handling the coupled hydro-mechanical behaviour of unsaturated soils. These shortcomings led to new investigations of the constitutive variables which resulted in describing behaviour of unsaturated soil through alternative pairs of state variables and incorporating degree of saturation (Bolzon et al., 1996, Zhou et al., 2011) In most of these models one state variable was selected to be Bishop's effective stress whereas for the second state variable suction was implicitly or explicitly introduced. Even though the alternative pairs of stress state variables were able to overcome the above mentioned shortcomings, the proposed models were usually complicated due to the dependency of one state variable over the other. For example in the model proposed by Zhou. (2011), the constitutive variables are Bishop's effective stress and effective degree of saturation where Bishop's effective stress has been defined using effective degree of saturation.

3 A NEW PRACTICAL FRAMEWORK

Despite all these significant advances, the capability in predicting unsaturated soil behaviour is far from entirely satisfactory. One major issue is the gap between unsaturated soils research and practice due to the intricate nature of the proposed constitutive models and the associated complications of the chosen constitutive variables. Although suction is moisture potential, the use of suction as one of the constitutive variables in most of the well-defined constitutive models has hindered their direct application in engineering practice due to the complications of suction such as presence of hysteresis during measurements of void ratio and water content with respect to suction, inability of taking accurate measurements of suction in the field even with the high-tech equipment and the use of suction as a variable over the entire moisture range where suction can theoretically change from 0 to 1,000,000 kPa. Even under the laboratory conditions suction controlled laboratory testing is time consuming and requires specific experimental set ups and expertise. On the other hand, attempted more precise capturing of unsaturated soil behaviour with the use of increased number of variables in more recent constitutive models, specifically the models in alternative stress spaces, have made difficult the application in engineering practice as a result of the increased complexity.

Motivated by practical needs, Kodikara (2012) introduced a new framework (MPK framework) to model compacted unsaturated soils in net stress – moisture ratio space. Although suction is a more appropriate stress state variable, traditional choice of suction has been replaced by moisture ratio which is the product of gravimetric moisture content and the specific gravity (giving the ratio of volume of water divided by volume of solids). This new choice of moisture ratio as an independent constitutive variable instead of suction is theoretically sound as the moisture ratio is energy conjugate of suction. Since moisture content is an easily measurable, commonly used parameter in engineering practice, it is believed that this new framework will be more beneficial in bridging the existing gap between unsaturated soils research and practice.

4 MPK FRAMEWORK FOR VOLUMETRIC BEHAVIOUR OF COMPACTED UNSATURATED SOILS

The basic concept in MPK volumetric framework is that there exists a state boundary surface for loosest states of compacted soils which can be constructed by a family of compaction curves obtained at different compaction stresses. This boundary surface in void ratio (e), moisture ratio (e_w) and net stress (p) space is referred to as Loading Wetting State Boundary Surface (LWSBS), which is capable in explaining unsaturated soil behaviour resulted from loading and (or) wetting paths and is depicted in Fig 1.

The LOO (Line of Optimums) shown in Fig. 1 is the line joining the optimums corresponding to each compaction curve. Constant pressure (net stress) contours indicate the compaction curves. For the wet side of the LOO, the curves corresponding to drained paths have been used. The intersection of LWSBS with the saturation plane ($e=e_w$ plane) depicts the normally consolidated line (NCL) for saturated soils. It is postulated that in the dry side of the LOO, air phase is continuous whereas in the wet side of the LOO, the air is discontinuous. Therefore, LOO provides the boundary where the air is free to drain during loading and wetting. Also, in this framework it is considered that the effective stress principle is applicable in the region between the LOO and the NCL where Equation 1 can be used with the degree of saturation as the χ parameter.

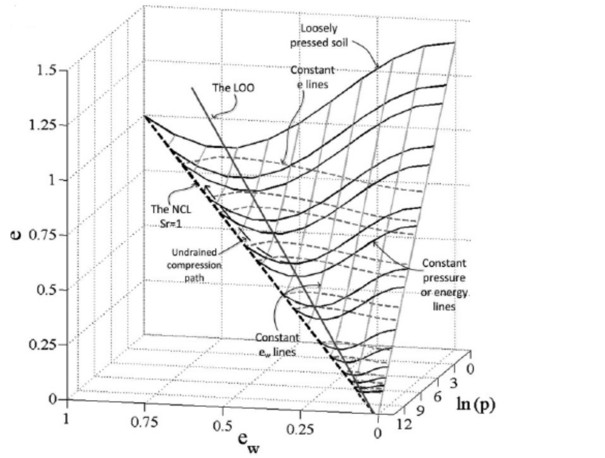

Fig 1. The LWSBS in $e-e_w-\ln(p)$ (adapted from Kodikara et al., 2012)

MPK framework for volumetric behaviour has shown promising signs so far indicating that unsaturated compacted soil behaviour can be defined in net stress – moisture ratio space. Results presented in Islam (2015) confirms the capability of MPK framework in describing volumetric behaviour of unsaturated soils under different state paths including yielding under loading, collapse under wetting, swelling pressure development and change in yield pressure due to wetting. Currently, the work is in progress to extend the framework to define how the suction changes on and within the LWSBS and to predict shear behaviour.

5 CONCLUSIONS

This paper presents a brief review on modelling unsaturated soils in different stress spaces. Net stress and suction can be identified as the most commonly used constitutive variables in modelling unsaturated soil behaviour. However, it is important to consider the implications of the chosen constitutive variables, particularly their limitations when applying sound theoretical models in routine engineering practice. Hence, the models that help bridge the existing gap between unsaturated soils research and practice would be beneficial for geotechnical engineering design.

It has been shown that the traditional choice of suction can be replaced with moisture ratio, one of common parameters measured in field for solving a range of practical cases. With the evidence of future research, it is expected that net stress – moisture ratio space will significantly simplifies the modelling of complicated unsaturated soil behaviour.

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