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# Prediction of wetting-induced volume change behaviour of compacted unsaturated soils in the context of the MPK framework

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**Abstract.** Compacted unsaturated soils show distinct behavioural patterns when compared with their saturated counterparts, and these behavioural patterns become more and more complex when soil is subjected to wetting, such as swelling or collapse and loss of shear strength. Ignoring these possible complex behaviours of unsaturated soils coupled with varying climatic conditions can lead to inaccurate assessment of the performance of geotechnical structures. Therefore, the accurate prediction of the wetting-induced volume change behaviour of compacted unsaturated soils is a key step in understanding and modelling unsaturated soil behaviour. Of the different constitutive models introduced to date which can define the wetting-induced volume change behaviour of compacted unsaturated soils reasonably satisfactorily, the MPK framework for the volumetric constitutive behaviour of compacted unsaturated soils proposed by Kodikara (2012) has shown favourable results with its direct relationship to moisture variation. This approach provides a practical approach, where reliance is placed on the variations in the moisture or degree of saturation as input. From this perspective, this study evaluates the volumetric behaviour of compacted unsaturated soils due to various wetting state paths, and the results are compared with the predictions of the MPK framework. The results show that the MPK framework is capable of predicting wetting-induced volume change behaviour, including the wetting-induced yielding of compacted unsaturated soils.

## 1 Introduction

The volume change behaviour of unsaturated soils has been a topic of debate among researchers for many years. This is due to the co-existence of air and water in void spaces, which complicates the mechanical behaviour of unsaturated soils in contrast to the principles of saturated soil mechanics. Over the last few decades considerable progress has been made into understanding and modelling unsaturated soil behaviour and there are now a number of models that can define unsaturated soil behaviour reasonably satisfactorily. (Alonso et al. [1], Wheeler and Sivakumar [2], Gallipoli et al. [3], Sun et al. [4]) Among them, the models capable of explaining compacted unsaturated soil behaviour are of significant practical concern, as the occurrence of unsaturated soils as a result of compaction is common in engineering practice in the form of embankments, earth dams and backfilling for other geo-structures.

Although compacted unsaturated soils characteristically have high strength and low compressibility, they may undergo large deformations and loss of shear strength as a result of being subjected to varying environmental loading conditions. One example is the collapse settlement of a compacted sandy clay fill under its own weight several years after construction as a result of being subjected to strong increase in surface infiltration, as reported by Brandon et al. [5]. This is due to the potential for swelling or collapse upon wetting depending on the confining stress, which is one of the key volumetric behavioural patterns of compacted unsaturated soils. Therefore, the accurate prediction of the wetting-induced volume change behaviour of compacted unsaturated soils is an important step in understanding and modelling compacted unsaturated soil behaviour.

The common practice in modelling the volumetric behaviour of unsaturated soils is in terms of two independent state variables: mean net stress and matric suction, and wetting-induced volume change behaviour is associated with the variation of suction. The very first model was proposed by Alonso et al. [1] in the net stress-suction space, known as the Barcelona Basic Model (BBM), which was then followed by many other researchers, including Wheeler and Sivakumar [2], who utilised the same stress space to model the mechanical behaviour of compacted unsaturated soils. Some other researchers have tried to deviate from the traditional choice of state variables, employing alternative pairs such as effective stress-suction, and the net stress-moisture ratio. One such model is the MPK framework introduced by Kodikara [6] to model compacted unsaturated soil behaviour in the net stress-moisture ratio space.

The MPK framework for the volumetric behaviour of compacted unsaturated soils utilises the net stress and moisture ratio, which is the product of gravimetric

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moisture content and the specific gravity (giving the ratio of volume of water divided by volume of solids). This model has shown favourable results to date, as reported by Islam [7], Islam and Kodikara [8] and Kodikara et al. [9]. More importantly, with its direct relationship to moisture variation, wetting-induced volume change behaviour, including wetting-induced yielding, can be defined in a relatively straightforward manner in the context of this framework. In this perspective, the present paper examines the application of the MPK framework to the interpretation of the wetting- induced volume change behaviour of compacted unsaturated soils.

## 2 MPK Framework

The basic concept of the MPK framework is that there exists a state boundary surface in void ratio (e), moisture ratio (*$e_w$*) and net stress (*p*) space, referred to as the Loading Wetting State Boundary Surface (LWSBS). The LWSBS represents the loosest states that compacted unsaturated soil can obtain from loading and (or) wetting paths and it can be produced by a family of compaction curves at different compaction stresses. The LWSBS as presented by Kodikara [6] is shown in Figure 1.

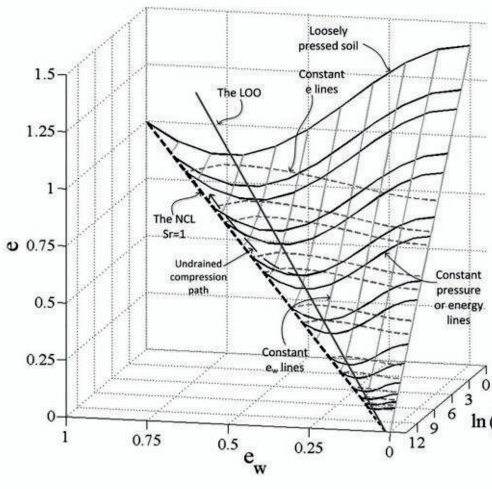


**Figure 1**. The LWSBS in *$e – e_w – ln(p)$* (adapted from Kodikara,[6])

One of the striking features of the LWSBS as shown in Figure 1 is the Line of Optimums (LOO), marked by the line joining the optima of each compaction curve, which defines the boundary for the continuous air phase of compacted unsaturated soils. According to the LWSBS concept, on the dry side of LOO, the air phase is postulated to be continuous with air free to drain during loading and wetting, while on the wet side of LOO air is trapped within the water menisci. Compaction curves represent the constant net stress contours of the LWSBS. However, when constructing the LWSBS for the wet side of LOO, curves corresponding to drained paths have been used as the compaction curves symbolize the (water) undrained compression paths where achievement of full saturation is difficult. The normally-consolidated line (NCL) for saturated soils (from the loosely compacted state) marks the intersection of the LWSBS with the saturation plane, where constant net stress contours are generally pinned.

In the MPK framework this state boundary surface is used to define the loosest states of compacted soil governing various volume change behavioural patterns of compacted unsaturated soils under loading and/or wetting, including yielding due to loading at constant moisture content, collapse and/or swelling due to wetting at constant operational stress, dependence of collapse potential on the operational stress, and change of yield pressure during wetting. It could be considered analogous to the extension of the saturated normally-consolidated line into unsaturated space. For example, a loading of a loose soil at constant moisture content state path should follow the constant moisture ratio contour on the LWSBS from a nominal stress to a certain net compressive stress. If that soil is wetted at that compressive stress, the soil should collapse following the current net stress contour of the LWSBS to the final moisture content.

## 3 Experimental Work

### 3.1 Materials and methods

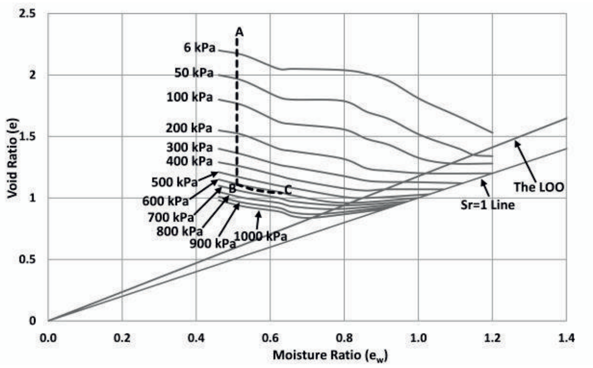
Commercially-available kaolin, known by the trade name of Eckalite 1, was used throughout the experimental program. Kaolin is white-coloured lightly reactive clay which has been widely used in unsaturated soil modelling for many years. The kaolin used in the present research program had a clay content of 75% with liquid and plastic limits of 60.5% and 27.9% respectively.

A number of laboratory experiments were carried out on kaolin soil under isotropic compression using the GCTS unsaturated soils tri-axial test system to develop the LWSBS and to validate it under independent state paths. The GCTS unsaturated soils tri-axial test system is an electro-pneumatic system with closed-loop digital servo control capable of performing fully automated tri-axial tests on saturated or unsaturated test specimens. The LWSBS was generated through constant moisture content isotropic compression tests in tri-axial test system performed on samples prepared as loosely as possible at different moisture contents. Validation tests were performed independently employing various loading/unloading, wetting or combination state paths with non-decreasing degrees of saturation.

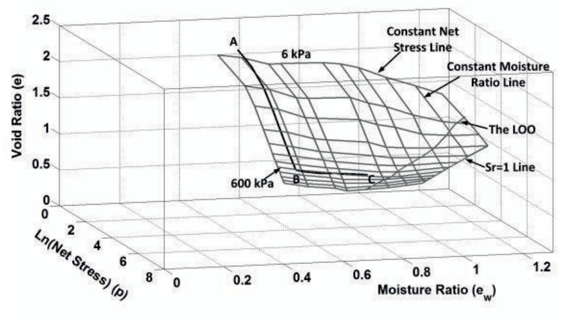
Two validation experimental results, a loading/wetting state path validation test and a loading/unloading/wetting/loading state path validation test are presented here, giving emphasis to the wetting state paths. The loading/wetting state path test was performed by initially mixing dry powder kaolin with water to a moisture content of 19.2% ($e_w$ = 0.51), compacting in five layers at a vertical compaction stress of 50 kPa to prepare the test specimen, then isotropically compressing the test specimen to a maximum of net stress of 600 kPa in tri-axial test system at constant moisture content under the loading stage and finally wetting to a moisture content of 28.3% ($e_w$ = 0.75) at constant net stress of 600 kPa under the wetting stage. For the loading/unloading/wetting/loading state path test the procedure was similar until the first loading stage to a net stress of 700 kPa. Thereafter, the soil was unloaded to a net stress of 400 kPa at constant moisture content of 17.1% ($e_w = 0.45$) before wetting to a moisture content of 33.6% ($e_w = 0.88$) at constant net stress, followed by a second loading stage.

### 3.2 Results and discussion

Figures 2(a) and 3(a) show the results of the two validation experimental tests described above in $e - e_w$ plane while Figures 2(b) and 3(b) show their three-dimensional representations in $e - e_w - p$ space respectively.



**(a)** In $e - e_w$ plane

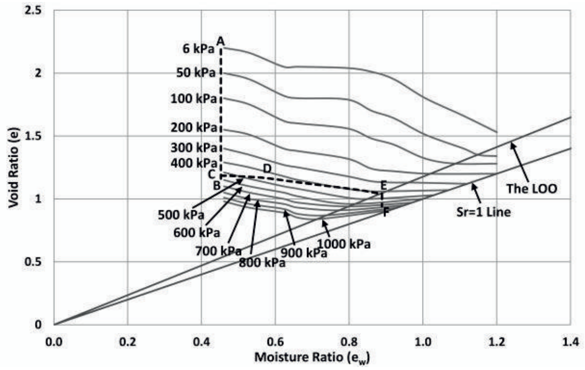


**(b)** In $e - e_w - lnp$ space

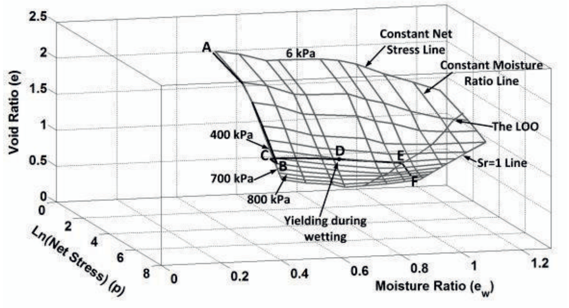
**Figure 2**. Loading – wetting state path test

As shown in Figures 2(a) and 3(a), the void ratio decreased during isotropic loading at the respective constant moisture content and during unloading the void ratio increased. During wetting the void ratio continually decreased in Figure 2(a) where as in Figure 3(a) the void ratio slightly increased until point D and thereafter the void ratio decreased.

According to the MPK framework, the loading/wetting state path test should follow the LWSBS, and it is clear in Figure 2 that the soil compressed following the constant moisture ratio contour of the LWSBS during loading (the AB line in Figure 2) and the constant net stress contour of the LWSBS during wetting (the BC line in Figure 2). Similarly, as explained in Abeyrathne et al. [10], it is evident in Figure 3 that for the loading/unloading/wetting/loading test the soil also followed the LWSBS, thus confirming the state boundary concept of the MPK framework. Since soil has moved into the unloading space of LWSBS during unloading, the soil swelled until it reached the LWSBS at D, indicating a volume increase during subsequent wetting. It is important to note here that wetting-induced volume change behaviour can take two forms: either swelling or collapse, depending on the position of soil with respect to the LWSBS, as is evident in Figures 2 and 3. If the soil has already yielded on the LWSBS, the soil will continue to collapse during wetting (the BC line in Figure 2). However, if the soil has previously yielded and has moved into the unloading space inside the LWSBS during unloading, the soil could swell until it intercepts the corresponding net stress contour of the LWSBS (the CD line in Figure 3). Wetting beyond that would lead to collapse following the LWSBS.



**(a)** In $e - e_w$ plane



**(b)** In $e - e_w - lnp$ space

**Figure 3**. Loading – unloading – wetting – loading state path test

Another important feature of the LWSBS concept is its ability to explain yielding of compacted unsaturated soils during loading and/or wetting. The traditional approach to defining yielding of unsaturated soils is in the form of yield curves, where the loading-collapse (LC) yield curve is specifically used in volumetric space. The LWSBS of the MPK framework acts as a yield surface for compacted unsaturated soils in volumetric space and the soil will start yielding and generate plastic volumetric strains once it reaches the LWSBS. Therefore, the yielding of compacted unsaturated soils during wetting state paths can be easily captured by the LWSBS. For example, the wetting path CE in Figure 3 will yield at D when it reaches the corresponding net stress contour of LWSBS during swelling.

If the LC curve for the MPK framework is plotted in the moisture ratio-net stress space, which can be approximated to the projection of LWSBS into that stress space, the two yield points B and D would lie on two different LC curves, indicating the yielding of compacted unsaturated soils during wetting from an unloaded position, as shown in Figure 4. $P_B$ and $P_D$ are the yield stresses of 700 kPa and 400 kPa respectively. This is in contrast to one of the key assumptions of the LC curve model in the BBM that any soil behaviour inside the LC curve is elastic. This has been pointed out by some other researchers, including

Zakaria [11]. The path DE is also marked in Figure 4, where subsequent collapse deformation has increased the yield point again at the LOO, as shown.

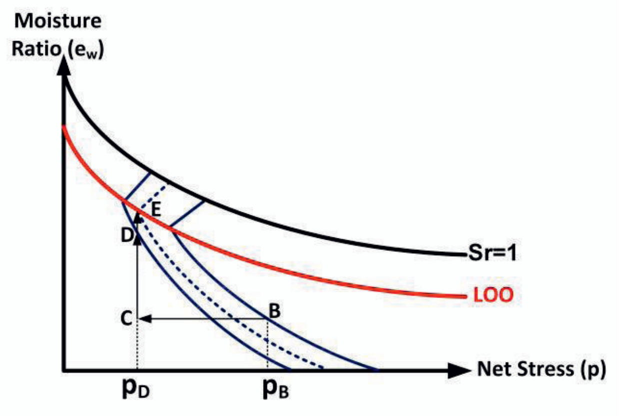


**Figure 4**. Loading-collapse yield curves for CE wetting path of Figure 3

## 4 Conclusion

The applicability of the LWSBS concept of the MPK framework in predicting the wetting-induced volume change behaviour of compacted unsaturated soils was evaluated using loading/unloading, wetting or combination state paths with non-decreasing degrees of saturation. The results prove that wetting-induced volume change behaviour, including wetting-induced yielding, is well captured by the LWSBS of the MPK framework.

The major advantage of the model is its reliance on relatively simple constant moisture content compaction testing in constructing the LWSBS (or the compaction surface). Furthermore, its direct relationship with moisture content facilitates the straightforward prediction of wetting-induced volume change behaviour, in contrast to suction-based models where change in suction due to wetting is measured.

On the basis of current progress in modelling compacted unsaturated soil behaviour in the context of the MPK framework, the framework may be used to answer a range of state paths applicable to field applications.

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