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Interpretation of the loading/wetting behaviour of compacted soils within the MPK framework:**Part I Static compaction**

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Abstract

Depending on the state paths, loading/wetting of compacted unsaturated soils can exhibit complex volumetric behaviour such as swelling, collapse, collapse followed by swelling, swelling followed by collapse, and swelling pressure development. Microscopically, these behaviours arise from complex interactions among applied stresses, air-water pressure deficit or suction at the water menisci, moisture content or degree of saturation in the voids and the nature of the micro- and macro-soil aggregates of compacted soils that depend on the level of suction (Alonso et al. 1999). While significant advances have been made in modelling the hydromechanical behaviour of compacted unsaturated soils taking these interactions into account, input parameter determination requires advanced testing equipment and the testing processes can be very time-consuming. Recently, a relatively simple and practical framework within the void ratio-moisture ratio (volume of water/volume of solids)-net stress space (referred to as the MPK framework) was proposed by Kodikara (2012) to explain/predict these state paths. A desirable feature of this framework is that it identifies a direct link between the well-known compaction curve and the compacted soil constitutive behaviour. The current paper presents a comprehensive series of tests on statically-compacted soils, the results of which are in close agreement with this framework. Two soil types, namely lightly reactive kaolin and more reactive clay, referred to as Merri Creek soil, were used in the testing. The soils were prepared with different moisture contents from the dry state and statically compacted at constant water content to obtain void ratio-moisture ratio-net stress constitutive surfaces, as well as soil specimens for state path tests. The state path test results of yielding under loading, collapse under wetting, swelling pressure development and change in yield pressure due to wetting are explained within this framework. In addition, some published data on a silty soil mixture were also analysed, highlighting that the framework is valid, regardless of the degree of reactivity of the soil. Suction was not measured in the authors' experiments, as it was not required to explain the above state paths according to this framework. However, it is recognised that suction is the conjugate state variable to the moisture content. Therefore, in future experiments, suction will be measured and its role will be fully explained within the framework, adding more generality.

Key Words: compacted soils, MPK framework, unsaturated soils, collapse, swelling pressure

Introduction

For the last half a century, modelling of the hydromechanical behaviour of unsaturated soils has been a frontier in soil mechanics research, with many significant advances (e.g., Bishop 1959; Matays and Radhakrishna 1968; Fredlund and Morgenstern 1976; Alonso et al. 1990; 1999; Fredlund and Rahardjo 1993; Khalili et al. 2000; Sivakumar and Wheeler 2000; Loret and Khalili 2002; Wheeler et al. 2003; Gallipoli et al. 2003; Tarantino and De Col 2008; Sheng et al. 2008, 2011). Generally, in soil constitutive modelling, the overall behaviour is normally considered in two parts: volumetric behaviour that leads to bulk volume change such as compression/compaction or swelling, and deviatoric behaviour that leads to shearing within the soil. It is recognised that the volumetric behaviour of compacted soils is particularly complex, featuring behaviours such as swelling and collapse and is the most difficult to model (Sheng et al. 2008). In most models, the volumetric behaviour is explained in void ratio-net stress-suction space, where the void ratio represents the variable signifying the soil volume change. In some models, an effective stress is defined to replace the net stress (e.g., Khalili et al. 2000). It is well accepted that 'matric' suction, defined as the pressure deficit between air and water pressure at the water meniscus, has a direct stress-like influence on soil behaviour. Therefore, it is quite fitting that it is incorporated as either an independent or component stress variable in unsaturated soil constitutive modelling. However, it has been recognized recently that to explain unsaturated soil behaviour, suction alone is not generally adequate, but the soil water content or its surrogate, such as the soil's degree of saturation, needs to be incorporated in the constitutive modelling, commonly referred to as hydromechanical coupling (e.g., Wheeler et al. 2003). However, suction-controlled measurements such as those needed for determining input parameters generally require advanced equipment and can be very time-consuming, especially for practical applications.

Kodikara (2012) presented a framework (referred to as the MPK framework) to explain the volumetric behaviour of unsaturated compacted soils using void ratio (e), net stress (p) (under 1-D conditions, p refers to net vertical stress and under 3-D conditions mean net stress) and soil moisture ratio ($e_w = wG_s$), where w is the soil gravimetric moisture content and G_s is the specific gravity of

soil particles. This gives the volume of voids divided by the volume of solids and is equal to the void ratio at saturation, $S_r = e_w/e$, also referred to as the compaction space. A novel feature of this framework is the establishment of a direct relationship between the traditional compaction curve and the soil constitutive behaviour. In the framework, soil suction is presented as the fourth variable that is required to explain volumetric soil constitutive behaviour in full, but it has been shown that suction is not essential for explaining most state paths that are relevant to practice, such as soil deformation under (a) loading/unloading; (b) wetting under constant (net) stress; (c) collapse potential evaluation; (d) swelling pressure development under constrained volume; (e), shrinkage cracking during drying; and (f) likely soil 'environmental' stabilisation behaviour under wet-dry cycling (see Kodikara et al. 2014). If only the compaction space is used to explain soil behaviour, the limitation is that the field questions can only be answered with respect to variations in water content or the degree of saturation (for instance, what would the deformation be if the soil moisture content or the degree of saturation increases from one value to the other?), but not with respect to variations in suction.

In the MPK framework, the Loading Wetting State Boundary Surface (LWSBS) is defined as the compaction surface depicting the loosest states compacted soil can attain under loading or wetting or a combination of these paths. Kodikara (2012) developed the LWSBS by combining compaction curves produced at different net stresses, starting from that corresponding to a nominal stress such as 10 kPa, which represents the loosest state that soil would take when water is mixed from the dry state. Figure 1 shows a picture of this surface both in e - e_w -net stress space and the traditional compaction space of dry density- e_w -net stress. Since the inverted parabolic shape of the compaction curve is common to all clayey soils (and coarse-grained materials), the concept is suggested as being relevant for all compacted soils, independent of their volume reactivity. In addition, a distinct difference in behaviour was highlighted for compacted and slurry soils, especially with reference to their respective initial virgin states. In contrast to previous models for compacted soils, a striking feature of the LWSBS is that it features the line of optimums (LOO), which has an enduring controlling effect on the behaviour of compacted soils as the demarcation boundary where air is free to move (dry of the LOO) and air is trapped (wet of the LOO). It should be noted that, although suction is not selected as

one of the axes as in previous models, it is a congruent part of soil behaviour and plays a role in the e - e_w -net stress space, as outlined by Kodikara (2012). In the current paper, the emphasis is placed on compaction space only and its use to explain soil behaviour.

Kodikara (2012) provided a qualitative validation of the MPK framework on the basis of typical experimental data and the behaviour of compacted soils reported in the research literature. The present paper presents direct validation on the basis of a targeted experimental program, using some additional data from the literature. The experiments were undertaken using statically-compacted soil specimens under oedometric conditions. Two soils were used: slightly reactive (shrinking/swelling or expansive due to moisture change) commercially available kaolin and reactive (natural) Merri Creek soil from Melbourne, Australia. Static compaction has been commonly used to prepare soil specimens for laboratory testing in previous constitutive model development. The experimental data are analysed in state paths (a), (b), (c) and (d) noted previously. The companion paper in this journal by Kodikara et al. (2016) deals with the behaviour of dynamically compacted soils within the MPK framework.

Figure 1: Three-dimensional view of the LWSBS (a) in compaction space and (b) in e - e_w - p space (Kodikara, 2012)

Experimental Work

Materials

Two types of soils were used in the experimentation, namely kaolin, known by the trade name Ecalite, and Merri Creek soil. Ecalite is a commercially available white coloured (china) lightly reactive clay, manufactured at Granville, New South Wales, Australia. Merri Creek soil is a grey/black reactive natural soil sourced from Merri Creek, located in north-east Melbourne. Merri Creek soil is a residual soil weathered from basalt which has subsequently mixed with alluvium from the creek (Joyce 1992). Because of its sticky nature, it is commonly used for the preparation of cricket pitches around Melbourne. While the kaolin was available in dry form in bags, the preparation of Merri Creek soil

involved drying, grinding, and subsequently sieving to remove any deleterious material. The Merri Creek clay featured 50% clay, 43% silt and 7% sand content (Islam, 2015). Gallage et al. (2012) reported that Merri Creek clay mineralogy primarily comprised smectite (51%) and quartz (41%) and other minor mineral constituents. A summary of the basic geotechnical properties obtained is shown in Table 1.

Table 1: *A summary of geotechnical properties of kaolin and Merri Creek soil*

Methods

Soil with (gravimetric) moisture content of 0 to 50% was prepared for both samples. In order to prepare homogeneously wetted soil from the dry state, soil was sieved onto a tray to make a layer of uniform thickness of around 5 mm and the tray of soil was then placed in a high humidity room (100% humidity) to achieve the targeted moisture content. Next, the soil was thoroughly mixed and placed in sealed plastic bags until further testing, within not less than 48 hours. The soil was statically compacted into a steel mould of 63 mm internal diameter and 50 mm high, using a Loadtrac II compression set-up manufactured by Geocomp. Lubricating grease was applied to the walls of the mould prior to adding the soil to reduce any friction. The initial condition was that the loading cap (weighing 2.12 kg) was loosely placed, providing 7 kPa initial stress. A filter medium between the soil and the loading cap was provided for any possible drainage from the top, but the bottom was sealed. For tests dry of the line of optimums (LOO), a higher loading rate of 20 kPa per minute was used up to about 2000 kPa and a higher loading rate of 100 kPa per minute above 2000 kPa. From the dynamic compaction tests, guidance for the occurrence of the LOO was obtained at a degree of saturation (S_r) of 86% for kaolin and 82% for Merri Creek soil. The dynamic compaction curves for kaolin and Merri Creek soil are shown in Figure 2. Once the soil approached the LOO during loading, a much lower loading rate (i.e., 0.1 kPa/min) was used. Typical load-deformation curves obtained for kaolin are shown in Figure 3, and show the characteristic strain hardening behaviour of 1-D compression. A number of tests repeated under identical conditions indicated that the results are well reproducible.

Figure 2: Dynamic compaction curves for; (a) kaolin; (b) Merri Creek soil

Figure 3: Typical load vs. deformation curves for kaolin with different moisture contents

Loading Wetting State Boundary Surface (LWSBS)

In the current test program, the LWSBSs for the two soils were developed using the compression curves produced under 1-D compression, as described in the previous section. As highlighted by Kodikara (2012), under 1-D conditions energy input to soil due to external stress is characterised by the vertical net stress and vertical strain. Therefore, in the following descriptions, “net stress” refers to the vertical net stress. It should also be noted that LWSBS is developed through constant water compression curves as relevant to virgin compression, in contrast to the compaction curves for a certain net stress, as given in the original paper of Kodikara (2012).

LWSBS for Ecalite

Figure 4 shows the development of the LWSBS for kaolin. Different moisture content soil specimens were compressed using the Loadtrac II. The static compression stress applied on the soil specimens ranged between nominal stress (7 kPa) to a high stress (5000 kPa). Figure 4(a) presents the measured compression curves in traditional e versus $\log(p)$ relationships at the dry side of the LOO. Subsequently, $e - e_w$ contours were plotted using this result for different net stresses at the dry states of the LOO. Figure 4(b) shows some compression paths plotted on $e - e_w$ space with some respective stress levels guiding the development of the LWSBS contours. Air is generally free to drain even under faster rates of loading at the dry side of the LOO. Therefore, it can be assumed that air pressure did not build up from the atmospheric level during compression and therefore the net stress is the same as the applied stress. Figure 4(b) presents the developed LWSBS at the dry side of the LOO. On the other hand, when soil passed the LOO, slow loading rates were used to establish the drained states without allowing the air pressure to build up. Therefore, it is assumed that air pressure did not build up from atmospheric level during compression, meaning that the applied total stress is equal to the net stress. Figure 4(c) presents the development of 1000 kPa constant net stress contour between

the LOO and saturation line (NCL), which was obtained by compression of the loose saturated soil. It is apparent that to develop a 1000 kPa drained constant net stress contour, three different moisture content soil specimens were compressed. Once the soil specimens approached close to the LOO, a much slower loading rate was used, as explained earlier. The development of other constant net stress contours between the LOO and saturation line is presented in Islam (2015). Figure 4(d) shows the complete (dry and wet states of the LOO together) compression curves in $e - \log(p)$ plot, while Figure 4(e) presents the complete LWSBS. Figure 5(a) shows the LWSBS for kaolin soil presented in the form of compaction contours corresponding to net stress values. Figure 5(b) shows a 3-D view of the LWSBS generated.

Figure 4: Development of the Loading Wetting State Boundary Surface for kaolin

Figure 5: Loading Wetting State Boundary Surface for kaolin: (a) in the form of compaction contours; (b) 3-D surface

LWSBS for Merri Creek Soil

Figure 6 shows the development of the LWSBS for Merri Creek soil. Similar to the kaolin soil, different moisture content soil specimens were compressed statically from nominal stress (7 kPa) to a high stress (5000 kPa). Figure 6(a) presents the measured compression curves in traditional e versus $\log(p)$ relationships at the dry side of the LOO. Subsequently, using this result, $e - e_w$ contours were plotted for different net stresses at the dry states of the LOO. Figure 6(b) presents some compression paths plotted on $e - e_w$ space with some respective stress levels guiding the development of the LWSBS contours. Figure 6(b) also shows the developed LWSBS at the dry side of the LOO. On the other hand, similar to the kaolin soil, constant net stress contours between the LOO and saturation line were produced using a much slower loading rate once the soil specimens approached close to the LOO. Figure 6(c) presents the development of the 700 kPa constant net stress contour between the LOO and saturation line. It is apparent that to develop the 700 kPa drained constant net stress contour, three different moisture content soil specimens were compressed. The other constant net stress

contours between the LOO and saturation line are presented in Islam (2015). Figure 6(d) shows the complete (dry and wet states of the LOO together) compression curves in $e - \log(p)$ plot, while Figure 6(e) presents the complete LWSBS. Figure 7(a) shows the LWSBS for Merri Creek soil presented in the form of the compaction contours corresponding to net stress values. Figure 7(b) shows a 3-D view of the LWSBS generated. From the figure, it is apparent that the compression curves reach the LOO and then display a flatter curve towards the NCL. A similar shape was presented by Kodikara (2012).

Figure 6: *Development of the Loading Wetting State Boundary Surface for Merri Creek soil*

Figure 7: *Loading Wetting State Boundary Surface for Merri Creek soil: (a) in the form of compaction contours; (b) 3-D surface*

State Path Tests for Kaolin

Once the LWSBS was established using compression tests, a series of state path tests was undertaken to examine the validity of the concepts proposed by the MPK framework. To facilitate wetting tests, the top loading cap was modified to allow injection of water into the soil specimen under loading. Figure 8 shows the loading assembly and the top and bottom configurations of the top loading cap. As this figure shows, in order to supply water to the soil specimen, four 3 mm diameter holes were provided in the top cap. A controlled amount of moisture was added through these holes equally using a syringe to increase the moisture content of the soil specimen to a targeted value. This simple testing mechanism, which was used to wet the soil specimens under stress, was developed based on the confidence obtained from the trial tests. It was found from the trial tests that if the initial heights of the soil specimens under nominal stress are kept at approximately 15 mm for kaolin soil, after each 2% to 5% moisture increment, the soil specimens would take 6 to 12 hours to reach equilibrium at the dry side of the LOO. After reaching equilibrium, stress was removed and the soil specimens were tested for moisture contents from at least five different locations of the 63 mm diameter test mould. It was found that these moisture contents ranged around an average $\pm 0.50\%$ in all cases. Moreover,

moisture contents were measured from different locations of the 63 mm diameter test mould at the end of the original tests, and the results also showed that the deviation of moisture contents for any specific test was less than $\pm 0.50\%$. Therefore, it was concluded that this experimental procedure would provide water consistently into the soil and moisture uniformity could be achieved throughout the entire soil specimen. Usually, one single wetting event took place in 4 to 6 steps, depending on the requirement of the number of points to draw the state path in $e - e_w$ plane. Moisture contents could not be measured after every step of moisture injection in these tests. However, the moisture contents of the soil specimens after each step of water application were calculated from the known initial moisture content and the amount of moisture input into the soil during that step. This is how a single wetting event was performed during different state path validation tests. Apart from the modifications to the top cap, the other test set-up features were the same as for the compression tests. The state path tests performed on kaolin soil are listed in Table 2.

Figure 8: (a) Experimental set-up of state path tests; (b) Top view of the loading cap; (c) Bottom view of the loading cap

Table 2: A summary of state path tests presented on kaolin soil

State paths involving a combination of loading and wetting

A series of tests was undertaken in which the soil was mixed to certain water contents from the dry state as for the compression tests, compressed to certain a stress level and then wetted at that stress level. During wetting under constant net stress (p), sufficient time (i.e., 24 to 48 hours) was provided to facilitate adequate drainage conditions at the wet side of the LOO. The soil specimen was inspected after 24 hours of water injection. If the deformation was less than 0.0025mm/2 hours or remained the same, it was considered that the soil specimen had reached equilibrium. However, at the dry side of the LOO, 6 to 12 hours of time was sufficient for the soil specimen to reach equilibrium after each water injection, as the presence of adequate drainage conditions is not a major issue. These test results are shown in Figures 9(a), 9(b), 9(c) and 9(d), 9(e) and 9(f). Figures 9(a), 9(b) and 9(c) show a dry

soil specimen that was loaded to 100 kPa and then wetted to 29.70% moisture content ($e_w = 0.787$). It is clear that the state path generally follows the stress contour for 100 kPa of the LWSBS. Figures 9(d), 9(e) and 9(f) show a soil specimen at 11.69% moisture content ($e_w = 0.310$) loaded to 20 kPa stress and then wetted to 31.25% moisture content ($e_w = 0.828$). It is apparent that the state path follows the LWSBS up to 20 kPa stress and then follows that contour to the final moisture content. It is also apparent that when the soils were wetted at a particular stress level, they underwent collapse (or compression), as depicted by the LWSBS. Figures 9(g), 9(h), 9(i) and 9(j), 9(k) and 9(l) show tests where the soil specimens were loaded to a particular stress level, wetted to a certain moisture content and then loaded again to a higher stress level. It is evident that the state paths follow the path dictated by the LWSBS, in agreement with the MPK framework. It should also be noted that in these tests, the soil was totally on the LWSBS, initially, during both loading and wetting.

The relevance of the finding that the loading/wetting paths follow the LWSBS is that it is possible to predict the final void ratios and therefore deformations in 1-D field scenarios under such state paths. Figures 9(b), 9(e), 9(h) and 9(k) highlight the measured and likely predicted paths in compression curves and also in respective 3-D plots. For example, with reference to Figures 9(d) and 9(e), for a soil compacted at 11.69% and wetted to 31.25% moisture content, the reduction in void ratio due to wetting collapse was predicted as 0.84 whereas the actual change is 0.80.

Figure 9: Loading/wetting state path tests for kaolin

State paths involving loading, unloading and wetting

A series of tests was undertaken in which the soil was mixed to a certain water content from the dry state and then subjected to a combination of loading, unloading and wetting. These test results are shown in Figures 10(a), 10(b), 10(c) and 10(d), 10(e) and 10(f). Figures 10(a), 10(b) and 10(c) show a soil specimen at 4.04% moisture content ($e_w = 0.107$) which was loaded to 1000 kPa, unloaded to 20 kPa wetted to 23.70% moisture content ($e_w = 0.628$), and finally loaded to 2000 kPa. It is clear

that the state path follows the LWSBS up to 1000 kPa stress and then moves inside the LWSBS due to unloading. Then, during wetting, it swells towards the stress contour for 20 kPa of the LWSBS. The position of the stress path is still inside the LWSBS at the end of the wetting stage. Finally, during loading at 23.70% moisture content ($e_w = 0.628$), it moves towards the LWSBS and follows the LWSBS up to 2000 kPa stress after intercepting the LWSBS. Figures 10(d), 10(e) and 10(f) show a soil specimen at 8.96% moisture content ($e_w = 0.237$) loaded to 1000 kPa stress, unloaded to 100 kPa, subsequently wetted to 28.30% moisture content ($e_w = 0.750$), and finally loaded to 2000 kPa. It is apparent that the state path follows the LWSBS up to 1000 kPa stress and then moves inside the LWSBS due to unloading. During subsequent wetting, it swells towards the stress contour for 100 kPa of the LWSBS. The position of the state path is still inside the LWSBS at the end of the wetting stage. Finally, during loading at 28.30% moisture content ($e_w = 0.750$), it moves towards the LWSBS and follows the LWSBS up to 2000 kPa stress after intercepting the LWSBS. Figures 10(g), 10(h) and 10(i) show the results of a test where the soil specimen was loaded to 1000 kPa, unloaded to 700 kPa, and then wetted to a certain moisture content. An interesting feature of this test result is that the state path intercepted the LWSBS (at point D on the stress contour of 700 kPa) and was subsequently controlled by the LWSBS, where it underwent collapse. Figures 10(j), 10(k) and 10(l) show a test in which a soil specimen loaded to 300 kPa was unloaded and wetted twice under particular stress levels. The unloaded stress levels (200 and 100 kPa) for wetting paths were strategically chosen to examine the control of the LWSBS when the wetting paths intercepted it. The test results show that the state paths followed the paths dictated by the LWSBS during the two interceptions. As explained earlier, observed conformance to the proposed framework could be used to make predictions for such state paths.

Figure 10: Loading/unloading/wetting state path tests for kaolin

Collapse potential tests

While the tests presented above show the collapse behaviour of compacted kaolin, a series of tests was undertaken to examine the variation of collapse potential with the stress level. Soil specimens

were prepared with 15.77% moisture content ($e_w = 0.420$) and then compressed to 500 kPa stress. There were a total of six soil specimens. Subsequently, different soil specimens were wetted to saturation in controlled steps of moisture ingress at different stress levels (e.g., 50, 100, 500, 1000, 2000, and 4000 kPa), which were kept constant throughout the wetting events. The results are similar to those presented in Figures 9 and 10, and, for brevity, are not presented here. Instead, the collapse potential (given as the reduction in void ratio) is presented in Figure 11. It is clear that collapse potential increases with increasing stress up to the compaction stress and then decreases for higher stress levels, as expounded in the MPK framework. This behaviour is consistent with the typical behaviour reported on the collapse potential of soils (e.g., Sun et al. 2004). Figure 11 also shows the prediction made using the LWSBS, highlighting the predictive capability of the framework.

Figure 11: Collapse potential given as reduction of void ratio for kaolin specimen with initial $e_{wo} = 0.420$ and $e_o = 1.177$ and a compaction stress of 500 kPa [Test Identity => Combination of SC – EK – CPT – 1 to 6]

State paths of constant volume or swelling pressure development

A series of tests was undertaken to examine the swelling pressure development for constant volume (constrained) wetting of kaolin soil. The tests were undertaken by locking the soil specimen against volumetric deformation but measuring the applied stress variation when the specimen was wetted. The same mould and set-up were used in this test program. Figure 12 shows the results of some of the tests undertaken. Figures 12(a) and 12(b) show the state path of a soil specimen prepared at 10.69% moisture content ($e_w = 0.283$) loaded to 500 kPa (path AB), unloaded to 100 kPa (path BC) and then wetted at constant volume (i.e., e constant) to saturation (path CDEF). It is clear that the unloaded position at 100 kPa is below the LWSBS (point C), and during wetting the swelling pressure builds up to D (around 180 kPa), at which the state reaches the LWSBS. Subsequently, the path DE is on the LWSBS (at constant initial void ratio = 1.366) reducing the swelling pressure until the LOO is intercepted at point E. Further wetting causes the soil to increase swelling pressure again towards saturation, as shown by path EF. This behaviour is consistent with the MPK framework and with test

results reported in the past (Kodikara, 2012). Figures 12(c), 12(d), 12(e) and 12(f) show similar behaviours for two more state paths for initial moisture contents of 10.69% and 19.88% respectively. It is evident that, as the compaction stress increases (or initial void ratio decreases), the maximum swelling pressure increases. Similarly, if the moisture content is increased with all other conditions kept constant, the swelling pressure appears to decrease. In comparison to Figures 12(a) and 12(b) and Figures 12(c) and 12(d), Figures 12(g) and 12(h) show a soil specimen loaded to 2000 kPa (path AB) then unloaded to 100 kPa (path BC) at the 10.69% moisture content, and then wetted (path CD). It is evident that this soil specimen did not reach the LWSBS, and swelling pressure continued to increase with wetting. It seems that it was too far below the LWSBS initially at 100 kPa stress (due to increased compaction stress of 2000 kPa), and this led to the observed result. At point D, S_r is equal to 0.975, but the position of D is well away from the NCL. This is because it has reached close to the saturation plane corresponding to the constant void ratio of 0.82 well below the NCL. The projected $S_r = 1$ line is shown in Figure 12(g). The other test results (not reported in the present paper) (see Islam, 2015) indicate that similar behaviour can arise for lower compaction stresses if the initial moisture content is higher due to changes in the relative positions of the LWSBS. Figure 12 also shows the swelling state path predicted from the LWSBS as it was intersected during wetting.

Figure 12: Constant volume wetting state path tests for kaolin

State Path Tests for Merri Creek Soil

A series of state path tests was undertaken on Merri Creek soil to examine the validity of the concepts proposed by the MPK framework. The trial tests, which were also performed on the Merri Creek soil, showed that at the dry side of the LOO, if the initial heights of the soil specimens under nominal stress are kept at approximately 10 mm for Merri Creek soil, after each 2% to 5% moisture increment, the soil specimens would take 6 to 12 hours to reach equilibrium. From moisture content measurements, it was also found that moisture uniformity could be achieved throughout the entire soil specimen during the period of equilibrium. Therefore, similar soil sample preparation techniques and

test procedures to those used for kaolin presented earlier were used for Merri Creek soil. The state path tests which were performed on Merri Creek soil are listed in Table 3.

Table 3: *A summary of state path tests presented on Merri Creek soil*

State paths involving a combination of loading, unloading and wetting

The results of four state path tests involving a combination of loading, unloading and wetting undertaken on Merri Creek soil are shown in Figure 13. Figures 13(a), 13(b) and 13(c) show a soil specimen with moisture content 10.35% ($e_w = 0.271$) loaded to 500 kPa (path AB), and wetted to 28.38% moisture content ($e_w = 0.743$) (path BC). Since there was no unloading, the entire path is on the LWSBS and it appears that the path depicted by LWSBS is followed. Figures 13(d), 13(e) and 13(f) show a soil specimen with 10.35% moisture content ($e_w = 0.271$) loaded 200 kPa (path AB), and wetted to 27.95% moisture content ($e_w = 0.743$) (path BC). In contrast to the previous result, the 200 kPa contour (and the LWSBS) has an upward trend followed by a typical downward trend during wetting. It is evident that under such conditions, the state path does not appear to follow the upward trend (swelling) but when it eventually intersects with the LWSBS, the soil starts to follow it again, as in other tests. However, it appears that such situations can occur for certain soils that display a rise in density (or reduction in void ratio) at dry of optimum or multiple peaks in compaction curves and when the soil is wetted from significantly drier states. The state path test results shown in Figures 13(g), 13(h) and 13(i) follow the path depicted by the LWSBS, since there is no upward trend with higher initial moisture content and higher stress level at wetting. Figures 13(j), 13(k) and 13(l) show a test with multiple loading, unloading and wetting state paths. The test was devised to examine the invocation of the influence of the LWSBS during such state paths, similar to the respective tests on kaolin. It is clear that the state path reaches the LWSBS corresponding to both stress contours of 300 kPa and 200 kPa, and subsequently follows the LWSBS during the wetting process. As explained earlier, observed conformance to the proposed framework could be used to make predictions for such state paths.

Figure 13: Loading/unloading/wetting state path tests for Merri Creek soil

Collapse potential tests

While the tests presented above also show the collapse behaviour of compacted Merri Creek soil, a series of tests was undertaken to examine the variation of collapse potential with stress level. Soil specimens were prepared with 16.06% moisture content ($e_w = 0.421$) and then compressed to 500 kPa stress. There were a total of six soil specimens. Subsequently, different soil specimens were wetted to saturation in controlled steps of moisture ingress at different stress levels (e.g., 40, 100, 500, 700, 1000, and 2000 kPa), which were kept constant throughout the wetting events. Since the results are similar to those presented in Figure 13, for brevity, they are not presented in detail here. Instead, the collapse potential (presented as the reduction in void ratio) results are presented in Figure 14. It is clear that collapse potential increases with increasing stress up to the compaction stress and then decreases for higher stress levels, as expounded in the MPK framework. This behaviour is consistent with the typical behaviour reported on the collapse potential of soils (e.g., Sun et al. 2004). Figure 14 also shows the prediction made using the LWSBS, highlighting the predictive capability of the framework.

Figure 14: Collapse potential given as reduction of void ratio for Merri Creek soil specimen with initial $e_{w0} = 0.421$ and $e_o = 0.914$ and a compaction stress of 500 kPa [Test Identity => Combination of SC – MC – CPT – 1 to 6]

State paths of constant volume or swelling pressure development

As for the kaolin soil, a series of tests was undertaken to examine the swelling pressure development for constant volume (constrained) wetting of Merri Creek soil. Figures 15(a) and 15(b) show the state paths of three soil specimens prepared at 8.69% moisture content ($e_w = 0.228$) individually loaded to 500, 1000 and 2000 kPa, unloaded to 200 kPa and then wetted at constant volume (i.e., e constant) to saturation (paths $C_{1,2,3}D_{1,2,3}E_{1,2,3}F_{1,2,3}$). Similar to kaolin soil, it is clear that all soil specimens show the characteristic swelling pressure increase until the LWSBS, the subsequent decrease to the LOO and

the final increase towards saturation. Similar to the behaviour of kaolin, these results indicate that the swelling pressure increases with the compaction stress (with initial density) when all other variables are kept constant. Similar behaviour has been reported in the literature (e.g., Imbert et al. 2006; Kassiff and Shalom 1971). Figures 15(c) and 15(d) show two test results demonstrating the influence of initial moisture contents of 8.69% and 14.87%. The soil specimens were prepared by loading to 500 kPa, unloading to 200 kPa and then wetting at constant void ratio. It is evident that the swelling pressure decreases with increasing initial moisture content, in agreement with published results (e.g., Lee et al. 1999; Kassiff and Shalom 1971). As per the MPK framework, the intersection with the LWSBS is also evident from the shape of the state paths and 3-D plots. Figures 15(e) and 15(f) show the effect of compaction stress (500 and 1000 kPa) on the swelling state paths for soil specimens prepared with the higher moisture content of 14.87%. It is evident that, while the soil specimen compacted to 500 kPa intercepts the LWSBS, that compacted to 1000 kPa does not. The latter continues to develop swelling pressure with wetting below the LWSBS towards the saturation plane (the final degree of saturation is 0.968). This also shows the difficulty of achieving full saturation during wetting due to air entrapment at later stages, perhaps after reaching the plane depicting the LOO.

Figure 15: Constant volume wetting state path tests for Merri Creek soil

Interpretation of data reported by Jotisankasa (2005)

Published data were also examined for analysis. Unfortunately, most test results were not directly usable since the tests were not carried out with the MPK framework in mind. However, the following section examines the data reported by Jotisankasa (2005) within this framework.

Materials and methods

The results of a number of suction-monitored oedometer tests are presented by Jotisankasa (2005) and Jotisankasa et al. (2007a). Soil A, a mixture of 70% silt, 20% kaolin and 10% London clay, was used for these tests. The soil preparation technique is described by Jotisankasa et al. (2007a, 2009), who

also noted that the final soil mixture was of low plasticity ($LL = 28\%$, $PL = 18\%$) and contained a large proportion of silt (clay content = 26%, silt content = 52%, and sand content = 22%) with a specific gravity of 2.64.

All test specimens were prepared by static compaction at the beginning. Three series of test specimens were prepared, namely 7 – 10 (void ratio ≈ 0.7 and moisture content $\approx 10\%$), 5 – 10 (void ratio ≈ 0.5 and moisture content $\approx 10\%$) and 7 – 13 (void ratio ≈ 0.7 and moisture content $\approx 13\%$). Different types of suction-monitored oedometer tests were performed on these soil specimens, including: (1) wetting at first and then loading and finally unloading; (2) drying at first and then loading and finally unloading; and (3) loading at first and then wetting and then loading again and finally unloading. As the present paper deals with loading/wetting, the drying test results are not presented here.

LWSBS

The compaction characteristics of Soil A presented by Jotisankasa (2005) are shown in Figure 16. Four compaction curves, namely, static compaction curves at 400 kPa and 800 kPa stress levels and those corresponding to heavy and light compactions according to BS1377 – Part 4 (1990), are shown in the figure. Also shown in this figure are the initial positions of the three test series undertaken. Figure 17 shows the approximate development of the LWSBS from these compaction curves. The black lines show the void ratio vs moisture ratio plot of the compaction curves shown in Figure 16. The other parts of the LWSBS were developed by considering a linear relationship between the void ratio and logarithmic stress along the LOO and yield and post-yield data available from different oedometer tests. This construction was necessary because Jotisankasa (2005) did not perform the tests to develop the full LWSBS. This construction was based on the observations from the kaolin and Merri Creek soil experimental data. It was found that on the LOO, e and $\ln(p)$ are related by a linear relationship. The data points available from Jotisankasa (2005) also fitted this relationship and based on this, the LWSBS was constructed. It was also found that the constant stress contours are reasonably parallel in $e - e_w$ plane. The light and heavy compactions approximately represent the 1000 and 7000 kPa constant stress lines. The dashed lines are extrapolations of the test results performed

subjectively. Figure 18(a) shows the LWSBS of Soil A presented in the form of the compaction contours corresponding to the net stress values generated from the compression data. Figure 18(b) shows a 3-D view of the LWSBS generated.

Figure 16: *Compaction characteristics of Soil A (Jotisankasa, 2005)*

Figure 17: *Development of the Loading Wetting State Boundary Surface for Soil A from the compaction curves*

Figure 18: *Loading Wetting State Boundary Surface for Soil A: (a) in the form of compaction contours; (b) 3-D surface*

Interpretation of state path tests involving wetting and loading or loading, wetting and loading

Test results are presented by Jotisankasa (2005) and Jotisankasa et al. (2007a), who wetted statically compacted soil specimens at the beginning of the test, compressed the samples to a certain stress level and then unloaded to a lower stress level. Selected test results are shown in Figures 19(a), 19(b), 19(c); 19(d), 19(e), 19(f), and 19(g), 19(h) and 19(i). Figures 19(a), 19(b) and 19(c) show a soil specimen of 0.51 initial void ratio and 9.80% moisture content ($e_w = 0.260$), wetted to 13.50% moisture content ($e_w = 0.360$) at 0 kPa pressure, loaded to 3220 kPa and finally unloaded to 54 kPa at constant moisture content. It is clear that the initial position of the soil is inside the LWSBS (point A). During wetting, it swells towards the stress contour for 0 kPa (1 kPa is used here) of the LWSBS. The position of the stress path is still inside the LWSBS at the end of the wetting stage (path AB). Next, during loading at 13.50% moisture content ($e_w = 0.360$), it moves toward the LWSBS and follows the LWSBS up to 3220 kPa stress (point C) after intercepting the LWSBS around 1150 kPa (point H). Finally, it moves inside the LWSBS during unloading to 54 kPa stage. Figures 19(d), 19(e) and 19(f) show a soil specimen of 0.69 initial void ratio (point A) and 10.20% moisture content ($e_w = 0.270$), wetted to 13.50% moisture content ($e_w = 0.360$) (point B) at 0 kPa pressure and then loaded to 3220 kPa (point C), and finally unloaded to 54 kPa (point D) at that moisture content.

Again, point H (around 380 kPa) shows the interception of the LWSBS and the path HC is on the LWSBS. Figures 19(g), 19(h) and 19(i) show a soil specimen of 0.49 initial void ratio and 9.90% moisture content ($e_w = 0.260$) (point A) wetted to 10.90% moisture content ($e_w = 0.290$) at 0 kPa pressure (point B) and then loaded to 3238 kPa (point C) and finally unloaded to 54 kPa (point D) at that moisture content. Again, point H (around 2000 kPa) shows the interception of the LWSBS and the path HC is on the LWSBS. It is apparent that in both of the tests, the soil specimens respond in similar ways, as expected according to the MPK framework.

Jotisankasa (2005) and Jotisankasa et al. (2007a) also present a series of test results in which statically compacted soil specimens were compressed to certain stress levels at as-compacted moisture content, wetted to a certain suction level and then loaded to a certain stress level and finally unloaded to a certain lower stress level. These test results are shown in Figures 19(j), 19(k), 19(l); 19(m), 19(n), 19(o); and 19(p), 19(q), 19(r). Figures 19(j), 19(k) and 19(l) show a soil specimen of 0.71 initial void ratio and 10.30% moisture content ($e_w = 0.270$), loaded to 430 kPa at as-compacted moisture content (path AB), then wetted to suction of 130 kPa ($e_w = 0.370$) at 430 kPa pressure (path BCD) and finally loaded to 3220 kPa (path DE) at constant moisture content. From the specific volume, v , versus $\log p$ graph presented in Jotisankasa (2005) and Jotisankasa et al. (2007a), it was found that $\Delta v (= \Delta e)$ between point B and D is 0.06 (collapse). As the moisture content data are not presented during wetting in Jotisankasa (2005) and Jotisankasa et al. (2007a), the value of the moisture ratio ($e_w = 0.37$) at point D was found by plotting D point on the LWSBS as the net stress (p) and the void ratio (e) are known. Finally, during loading at constant moisture content, the state path follows the LWSBS up to 3220 kPa. Figures 19(m), 19(n) and 19(o) show a soil specimen of 0.73 initial void ratio and 10.10% moisture content ($e_w = 0.270$) loaded to 215 kPa at as-compacted moisture content (path AB), then wetted to suction of 140 kPa at 215 kPa pressure (path BC) and finally loaded to 3220 kPa (path CD) at constant moisture content. An analysis of the v versus $\log p$ graph presented in Jotisankasa (2005) and Jotisankasa et al. (2007a), found that $\Delta v (= \Delta e)$ between point B and C is ≈ 0 , which means the position of the state path is still inside the LWSBS at the end of the wetting stage. Finally, during loading at constant moisture content, the state path intercepts the LWSBS around 400 kPa (point H)

and follows the LWSBS up to 3220 kPa. Figures 19(p), 19(q) and 19(r) show the results of tests performed on a soil specimen of 0.5 initial void ratio and 10.0% moisture content ($e_w = 0.260$), loaded to 1184 kPa at as-compacted moisture content (path AB) and then wetted to suction of 0 kPa at 1184 kPa pressure (path BD). It was found from the v versus $\log p$ graph presented in Jotisankasa (2005) and Jotisankasa et al. (2007a) that $\Delta v (= \Delta e)$ between point B and D is 0.01 (collapse). Point D is located on the saturation line ($S_r = 1.0$) as the value of suction is zero. According to the MPK framework, during wetting, the state path swells from point B towards the stress contour for 1184 kPa of the LWSBS, intercepts the LWSBS at point C and then follows the 1184 kPa constant net stress contour on the LWSBS to the saturation line at point D. Figures 19(b), 19(e), 19(h), 19(k), 19(n) and 19(q) highlight the measured and likely predicted paths in compression curves and also in respective 3-D plots.

Figure 19: *Wetting and loading or loading, wetting and loading state path tests for soil A*

Discussion

A large number of experiments were performed on statically compacted lightly reactive kaolin and reactive Merri Creek clay under constant water content testing. Despite the difference in their degree of reactivity, both soils followed the concepts of the MPK framework reasonably closely. This highlights that the macroscopic behaviour of compacted soil in general can be presented within this framework. In the following discussion, some of the specific features observed are examined. Overall, it was demonstrated that a host of loading/wetting state paths could be predicted through the framework once the LWSBS is developed.

Kodikara (2012) showed that one major difference between slurry soils and compacted clay may be that the void ratio for virgin compaction states (i.e., on the LWSBS) increases with decreasing moisture ratio (the strictly dry side of the LOO), whereas the void decreases for slurry soils when they are dried from saturated states. For slurry clay these states may be derived by drying from the slurry state and this would lead to reduction in void ratio as the moisture ratio is decreased. Experimental

results obtained for both kaolin (Figure 5(a)) and Merri Creek soil (Figure 7(a)) show that due to the macroscopic structure build-up, the void ratio increases with decreasing moisture ratio, but at very low moisture contents, the void ratio can decrease again. This feature is more prominent for Merri Creek soil. However, the effect appears to decrease and eventually vanishes at higher net stress levels. The occurrence of this feature is similar to having compaction curves with multiple peaks (e.g., Olson 1963; Lee 1976; Nawari and Schetelig 1991; El Mountassir et al. 2014), and appears to be related to the weakening of the effect of suction to form stronger contacts among aggregates that give larger macro void space (El Mountassir et al. 2014). The results of limited tests undertaken indicate that when wetted from a position on the LWSBS located at a very low moisture ratio, the wetting path may not follow the exact shape of the LWSBS, but the soil will swell until the LWSBS is intercepted, after which it may undergo collapse (c.f., Figure 13(d)). This aspect may need further examination in future tests. However, in practice it is not significant, since operational moisture contents may normally be over 50% degree of saturation. However, the following explanation may be given for this behaviour. Figure 20 shows a section of the LWSBS which features a downward limb towards the drier moisture states (or an upward limb in the compaction curve with dry density). The dotted line shows the respective curve that would occur if the impedance to compaction due to suction continued as the compaction moisture content is decreased. This increased impedance caused by suction is the reason for the traditional shape of the compaction curve. The reason that the measured curve shows a downward limb (Figure 20) is because the suction impedance has reduced and better compaction has occurred due to loading. It was noted in the Introduction that the LWSBS is the loosest state soil can achieve during loading/wetting. Therefore, when soil is wetted from a position like A in contrast to a position like B, it can swell rather than collapsing. However, some collapse may take place during swelling, which appears to cause the state path to deviate from the exact LWSBS. This behaviour is somewhat similar to an unloaded compacted specimen which undergoes swelling while some internal collapse takes place, but overall providing swelling strains or increase in void ratio (e.g., Figures 10(j) and 13(j)) (also see Kodikara et al. 2014). However, this deviation does not violate the definition of the LWSBS that it represents the loosest states for a compacted soil.

Figure 20: A constant net stress contour in e - e_w plane featuring downward limb towards the drier moisture state

In addition, changes in compressibility with moisture content are observed (as depicted by the gradient $\lambda(e_w)$ of e versus $\log(p)$ curve) with respect to Figure 4(d) for kaolin and Figure 6(d) for Merri Creek soil. For example, for kaolin when $S_r >$ approximately 8% (shown in Figure 4(b)), the compressibility increases as moisture content decreases. However, when $S_r <$ approximately 8%, the reverse happens where the compressibility decreases as moisture content decreases. For Merri Creek soil, this phenomenon occurs in a more pronounced way (see Figure 6(d)) for the reasons noted above and occurs around a S_r of approximately 40% as shown in Figure 6(b). In this regard, some passing observations could be made in relation to the reported compressibility behaviour with respect to suction in suction-controlled tests. For instance, Alonso et al. (1990) indicated that the compressibility ($\lambda(s)$) decreases with the increase of suction for some soils, whereas Wheeler and Sivakumar (1995) and several others (e.g., Sharma 1998) indicated that $\lambda(s)$ increases with suction. Assuming a direct correspondence between suction and water content in an approximate sense, it could be argued that the above demarcation of behaviour (with respect to the degree of saturation) highlights the deferring response that could be observed for compacted soil compressibility change with moisture content or suction. Similar observations could be made in relation to the void ratio (or specific volume) at nominal stress, which corresponds to the N parameter in volumetric compression of compacted soils.

Another feature worth observing is the cross-validity and uniqueness of the compression curves at constant moisture ratio to represent the LWSBS across moisture ratios, as embedded in the MPK framework. This is highlighted by the validated ability of the LWSBS to predict the behaviour of soil state paths during wetting and loading (or a combination) when the LWSBS is intercepted (e.g., Figure 10(e), Figure 10(j)). Alonso et al. (1987) also noted that if a state path does not decrease the degree of saturation, the resulting volumetric deformation is mostly path-independent. The existence

of such a unique surface in the non-decreasing degree of saturation paths was also noted by Tarantino and Tombolato (2005) with respect to the void ratio-suction-degree of saturation space.

An important feature of the MPK framework is the introduction of the influence of the LOO on soil behaviour, which demarcates the boundary for dry and wet of optimum. The LOO is defined as the boundary where the air phase moves from a continuous phase on the dry side to a discontinuous phase on the wet side. Along with this, the all-round influence of suction becomes prominent on the wet side and this gives rise to the increase of void ratio with increasing moisture ratio (or vice versa). This behaviour gives the canyon-like feature in the LWSBS, with the LOO at its bottom associated with the minimum void ratio (or maximum dry density). The wetting tests that followed the LWSBS showed the existence of this feature (c.f., Figure 13(a)). Similarly, constrained swelling tests also clearly demonstrated the influence of the LOO on the LWSBS. For instance, the swelling pressure increased to a peak until the state path intercepted the LWSBS and then followed it, and subsequently the swelling pressure decreased to the LOO and then increased again towards full saturation (c.f., Figure 15(c)). Another important validation is the confirmation of the characteristic behaviour of collapse potential, where the peak collapse occurred at the compaction stress.

Concluding Remarks

The present paper has presented experimental results for statically compacted lightly reactive kaolin soil and reactive Merri Creek clay under combinations of loading, wetting and unloading state paths subject to different boundary and initial conditions. The results are consistent with the MPK framework proposed by Kodikara (2012). Some tests on silty clay mixture undertaken by Jotisankasa (2005) and Jotisankasa et al. (2007a) were also successfully interpreted within the framework. The results indicate that void ratio-moisture ratio-net stress space along with the Loading Wetting State Boundary Surface (LWSBS) can be used to explain/predict the behaviour of statically compacted soil under hydro-mechanical state paths of non-decreasing degrees of saturation. The LWSBS can be established by constant moisture content compression tests and assuming cross-validity in the increasing direction of moisture content. Since constant moisture content tests do not require the

specialised test equipment necessary for suction control tests, this approach greatly simplifies the test method and reduces testing time.

Suction was not measured in the authors' experiments, as it is not essential to explain most volumetric behaviour as per the MPK framework. However, it would be prudent to measure suction in future experiments so that its role can be fully explained within the framework. In particular, the dependency of water retention characteristics on the state position within and on the LWSBS should be studied. Furthermore, the tests did not include any drying within the state paths. Future experiments could examine the influence of drying and, in general, the influence of wet/dry cycles and the possible environmental stabilisation of soils. In a companion paper, the application of the MPK framework to dynamically compacted soils is presented.

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Notations

e = void ratio

p = net pressure

e_w = moisture ratio ($= G_s * w$, where G_s specific gravity and w , moisture content)

Δe = change of void ratio

e_0 = initial void ratio

e_{w0} = initial moisture ratio

v = specific volume

Δv = change of specific volume

S_r = degree of saturation

s = suction

γ = soil density

γ_d = dry density

$\lambda(e_w)$ = compressibility in constant moisture content

$\lambda(s)$ = compressibility in constant suction

N = void ratio (or specific volume) at nominal stress

Tables

Table 1: A summary of geotechnical properties of kaolin and Merri Creek soil

Soil Properties	Kaolin Ecalite 1	Merri Creek Soil
Colour	White	Grey / Black
Swelling / Non-swelling	Non-swelling	Swelling
Liquid Limit, LL (%)	60.5	72.4
Plastic Limit, PL (%)	27.9	32.5
Plasticity Index, PI (%)	32.6	39.9
Linear Shrinkage (%)	9.3	13.5
Shrinkage Limit (%)	24.2	11.9
Specific Gravity, G_s	2.65	2.62
Clay Proportion (%)	75	50
Silt Proportion (%)	25	44
Sand Proportion (%)	0	6
Soil Classification		
Unified Soil Classification System	CH	CH / OH
United States Department of Agriculture	Clay	Silty Clay
Standard Proctor Compaction		
Maximum Dry Density (gm/cm^3)	1.374	1.4
Optimum Moisture Content (%)	30.2	27.3
Modified Proctor Compaction		
Maximum Dry Density (gm/cm^3)	1.51	1.65
Optimum Moisture Content (%)	25.3	19.2
Saturated Consolidation Parameters		
Compression Index, c_c	0.58	0.66
Compressibility Parameter, λ	0.2513	0.289
Unloading-reloading parameter, κ	0.045	0.0454
Coefficient of consolidation, c_v (m^2/sec)	1.3×10^{-7}	3.2×10^{-8}
Permeability, k (m/s)	2×10^{-9}	4.4×10^{-10}
Coefficient of volume change, m_v (kPa^{-1}) (at 50 – 100 kPa step)	0.0016	0.0014
Secondary compression, c_α	0.0058	0.056

Table 2: A summary of state path tests presented on kaolin soil

Test Identity	Description of the Test
Loading – Wetting Tests	
SC – EK – LW – 2	0% moisture content ($e_w = 0$) loaded to 100 KPa and then wetted to 29.66% moisture content ($e_w = 0.786$)
SC – EK – LW – 3	11.69% moisture content ($e_w = 0.310$) loaded to 20 KPa and then wetted to 31.25% moisture content ($e_w = 0.828$)
Loading – Wetting – Loading Tests	
SC – EK – LWL – 1	0% moisture content ($e_w = 0$) loaded to 1000 KPa and then wetted to 21.52% moisture content ($e_w = 0.570$) and then loaded to 2000 KPa
SC – EK – LWL – 2	8.96% moisture content ($e_w = 0.237$) loaded to 50 KPa and then wetted to 27.35% moisture content ($e_w = 0.725$) and then loaded to 2000 KPa
Loading – Unloading – Wetting – Loading Tests	
SC – EK – LUWL – 1	4.04% moisture content ($e_w = 0.107$) loaded to 1000 KPa and then unloaded to 20 KPa and then wetted to 23.67% moisture content ($e_w = 0.627$) and then loaded to 2000 KPa
SC – EK – LUWL – 2	8.96% moisture content ($e_w = 0.237$) loaded to 1000 KPa and then unloaded to 100 KPa and then wetted to 28.30% moisture content ($e_w = 0.750$) and then loaded to 2000 KPa
Loading – Unloading – Wetting Tests	
SC – EK – LUW – 3	15.85% moisture content ($e_w = 0.420$) loaded to 1000 KPa and then unloaded to 700 KPa and then wetted to 32.77% moisture content ($e_w = 0.868$)
Loading – Unloading – Wetting – Unloading – Wetting Tests	
SC – EK – LUWUW – 4	11.69% moisture content ($e_w = 0.310$) loaded to 300 KPa and then unloaded to 200 KPa and then wetted to 25.80% moisture content ($e_w = 0.684$) and then unloaded to 100 KPa and then wetted to 38.56% moisture content ($e_w = 1.022$)
Collapse Potential Tests	
Combination of SC – EK – CPT – 1 to 6	15.77% moisture content ($e_w = 0.420$) soil specimens loaded to 500 kPa and then wetted under the operation stresses of 50, 100, 500, 1000, 2000 and 4000 kPa. A “Reduction of Void Ratio – Net Stress” graph shows the results obtained from Collapse Potential Tests (1 – 6)
Swelling Pressure Tests	
SC – EK – SPT – 1	10.69% moisture content ($e_w = 0.283$) loaded to 500 kPa and then unloaded to 100 kPa and then wetted to 50.90% moisture content ($e_w = 1.350$) (Degree of Saturation = 0.988 and $e_0 = 1.366$) in constant volume
SC – EK – SPT – 2	10.69% moisture content ($e_w = 0.283$) loaded to 1000 kPa and then unloaded to 100 kPa and then wetted to 43.40% moisture content ($e_w = 1.150$) (Degree of Saturation = 0.975 and $e_0 = 1.179$) in constant volume
SC – EK – SPT – 4	19.88% moisture content ($e_w = 0.527$) loaded to 500 kPa and then unloaded to 100 kPa and then wetted to 42.30% moisture content ($e_w = 1.120$) (Degree of Saturation = 0.968 and $e_0 = 1.156$) in constant volume
SC – EK – SPT – 6	19.88% moisture content ($e_w = 0.527$) loaded to 2000 kPa and then unloaded to 100 kPa and then wetted to 30.20% moisture content ($e_w = 0.800$) (Degree of Saturation = 0.976 and $e_0 = 0.82$) in constant volume

SC => Static Compaction, EK => Ecalite Kaolin, LW => Loading – Wetting, LWL => Loading – Wetting – Loading, LUWL => Loading – Unloading – Wetting – Loading, LUW => Loading – Unloading – Wetting, LUWUW => Loading – Unloading – Wetting – Unloading – Wetting, CPT => Collapse Potential Test, SPT => Swelling Pressure Test.

Table 3: A summary of state path tests presented on Merri Creek soil

Test Identity	Description of the Test
Loading – Wetting Tests	
SC – MC – LW – 1	10.35% moisture content ($e_w = 0.271$) loaded to 500 kPa and then wetted to 28.38% moisture content ($e_w = 0.743$)
SC – MC – LW – 2	10.35% moisture content ($e_w = 0.271$) loaded to 200 and then wetted to 27.95% moisture content ($e_w = 0.732$)
Loading – Wetting – Loading Tests	
SC – MC – LWL – 1	15.0% moisture content ($e_w = 0.393$) loaded to 1000 kPa and then wetted to 20.24% moisture content ($e_w = 0.530$) and then loaded to 2000 kPa
Loading – Unloading – Wetting – Unloading – Wetting Tests	
SC – MC – LUWUW – 3	15.0 % moisture content ($e_w = 0.393$) loaded to 400 kPa and then unloaded to 300 kPa and then wetted to 20.78% moisture content ($e_w = 0.544$) and then unloaded to 200 kPa and then wetted to 27.35% moisture content ($e_w = 0.717$)
Collapse Potential Tests	
Combination of SC – MC – CPT – 1 to 6	16.06% moisture content ($e_w = 0.421$) soil specimens loaded to 500 kPa and then wetted under the operation stresses of 40, 100, 500, 700, 1000 and 2000 kPa. A “Reduction of Void Ratio – Net Stress” graph shows the results obtained from Collapse Potential Tests (1 – 6)
Swelling Pressure Tests	
SC – MC – SPT – 1	8.69% moisture content ($e_w = 0.228$) loaded to 500 kPa and then unloaded to 200 kPa and then wetted to 36.26% moisture content ($e_w = 0.950$) (Degree of Saturation = 0.972 and $e_0 = 0.977$) in constant volume
SC – MC – SPT – 2	8.69% moisture content ($e_w = 0.228$) loaded to 1000 kPa and then unloaded to 200 kPa and then wetted to 32.06% moisture content ($e_w = 0.840$) (Degree of Saturation = 0.966 and $e_0 = 0.87$) in constant volume
SC – MC – SPT – 3	8.69% moisture content ($e_w = 0.228$) loaded to 2000 kPa and then unloaded to 200 kPa and then wetted to 27.48% moisture content ($e_w = 0.720$) (Degree of Saturation = 0.968 and $e_0 = 0.744$) in constant volume
SC – MC – SPT – 4	14.87% moisture content ($e_w = 0.390$) loaded to 500 kPa and then unloaded to 200 kPa and then wetted to 35.50% moisture content ($e_w = 0.930$) (Degree of Saturation = 0.969 and $e_0 = 0.96$) in constant volume
SC – MC – SPT – 5	14.87% moisture content ($e_w = 0.390$) loaded to 1000 kPa and then unloaded to 200 kPa and then wetted to 28.63% moisture content ($e_w = 0.750$) (Degree of Saturation = 0.968 and $e_0 = 0.775$) in constant volume

SC => Static Compaction, MC => Merri Creek Soil, LW => Loading – Wetting, LWL => Loading – Wetting – Loading, LUWL => Loading – Unloading – Wetting – Loading, LUW => Loading – Unloading – Wetting, LUWUW => Loading – Unloading – Wetting – Unloading – Wetting, CPT => Collapse Potential Test, SPT => Swelling Pressure Test.

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Figure 7: Loading Wetting State Boundary Surface for Merri Creek soil: **(a)** in the form of compaction contours; **(b)** 3-D surface

(a)

(b)

(c)

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(a) Loading at 0% moisture content ($e_w = 0$) to 100 kPa stress and then wetted to 29.66% moisture content ($e_w = 0.786$) [Test Identity => SC – EK – LW – 2]

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(b) $e - \log p$ plot of state path test (a)

(c) 3-D view of state path test (a)

(d) Loading at 8.96% moisture content ($e_w = 0.237$) to 1000 kPa, unloaded to 100 kPa, wetted to 28.30% moisture content ($e_w = 0.750$), and loaded to 2000 kPa [Test Identity => SC – EK – LUWL – 2]

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(h) $e - \log p$ plot of state path test (g)

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(b) 3-D view of state path test (a)

(c) Specimen of 10.69% moisture content ($e_w = 0.283$) loaded to 1000 kPa and then unloaded to 100 kPa and then wetted to 43.40% moisture content ($e_w = 1.150$) (Degree of Saturation = 0.975) in constant volume [Test Identity => SC – EK – SPT –2]

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(e) Specimen of 19.88% moisture content ($e_w = 0.527$) loaded to 500 kPa and then unloaded to 100 kPa and then wetted to 42.30% moisture content ($e_w = 1.120$) (Degree of Saturation = 0.968) in constant volume [Test Identity => SC – EK – SPT –4]

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(b) $e - \log p$ plot of state path test (a)

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(j) Loading at 15.0 % moisture content ($e_w = 0.393$) to 400 kPa, unloaded to 300 kPa, wetted to 20.78% moisture content ($e_w = 0.544$), unloaded to 200 kPa and then wetted to 27.35% moisture content ($e_w = 0.717$) [Test Identity => SC – MC – LUWUW – 3]

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(a) Specimens of 8.69% moisture content ($e_w = 0.228$) loaded to 500, 1000 and 2000 kPa and then unloaded to 200 kPa and then wetted to 36.26% moisture content ($e_w = 0.950$) (Degree of Saturation = 0.972), 32.06% moisture content ($e_w = 0.840$) (Degree of Saturation = 0.966) and 27.48% moisture content ($e_w = 0.720$) (Degree of Saturation = 0.968) respectively in constant volume [Test Identity => SC – MC – SPT – 1, 2 & 3]

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Figure 17: Development of the Loading Wetting State Boundary Surface for Soil A from the compaction curves

(a)

(b)

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(a) Test 5 – 10 – B (initial void ratio = 0.51 and moisture content = 9.80% ($e_w = 0.260$)) – firstly, soil specimen was wetted to 13.50% moisture content ($e_w = 0.360$) at 0 kPa stress and then loaded to 3220 kPa stress and then unloaded to 54 kPa stress

(b) $e - \log p$ plot of state path test (a)

(c) 3-D view of state path test (a)

(d) Test 7 – 10 – H (initial void ratio = 0.69 and moisture content = 10.20% ($e_w = 0.270$)) – firstly, soil specimen was wetted to 13.50% moisture content ($e_w = 0.360$) at 0 kPa stress and then loaded to 3220 kPa stress and then unloaded to 54 kPa stress

(e) $e - \log p$ plot of state path test (d)

(f) 3-D view of state path test (d)

(g) Test 5 – 10 – F (initial void ratio = 0.49 and moisture content = 9.90% ($e_w = 0.260$)) – firstly, soil specimen was wetted to 10.90% moisture content ($e_w = 0.290$) at 0 kPa stress and then loaded to 3238 kPa stress and then unloaded to 54 kPa stress

(h) $e - \log p$ plot of state path test (g)

(i) 3-D view of state path test (g)

(j) Test 7 – 10 – I (initial void ratio = 0.71 and moisture content = 10.30% ($e_w = 0.270$)) – firstly, soil specimen was loaded to 430 kPa stress at as-compacted moisture content and then wetted to suction of 130 kPa at 430 kPa stress and then loaded to 3220 kPa stress

(k) e – log p plot of state path test (j)

(l) 3-D view of state path test (j)

(m) Test 7 – 10 – L (initial void ratio = 0.73 and moisture content = 10.10% ($e_w = 0.270$)) – firstly, soil specimen was loaded to 215 kPa stress at as-compacted moisture content and then wetted to suction of 140 kPa at 215 kPa stress and then loaded to 3220 kPa stress

(n) $e - \log p$ plot of state path test (m)

(o) 3-D view of state path test (m)

(p) Test 5 – 10 – D (initial void ratio = 0.5 and moisture content = 10.0% ($e_w = 0.260$)) – firstly, soil specimen was loaded to 1184 kPa stress at as-compacted moisture content and then wetted to suction of 0 kPa at 1184 kPa stress

(q) $e - \log p$ plot of state path test (p)

(r) 3-D view of state path test (p)

Figure 19: Wetting and loading or loading, wetting and loading state path tests for soil A

Figure 20: A constant net stress contour in e - e_w plane featuring downward limb towards the drier moisture state