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Complete List of Authors:	Kodikara, Jayantha; Monash University, Civil Engineering Islam, Tanvirul; Monash University, Civil Engineering Rajeev, Pathmanathan; Swinburne University of Technology, Civil and Construction Engineering
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Interpretation of the loading/wetting behaviour of compacted soils within the MPK framework:

Part II Dynamic compaction

By

Dr. Jayantha Kodikara (Corresponding author)

Professor

Department of Civil Engineering

Monash University

Victoria, Australia 3800.

Email: Jayantha.Kodikara@monash.edu

Phone: +613 99054963

Fax: +613 99054944

Tanvirul Islam

PhD Scholar

Department of Civil Engineering

Monash University

Victoria, Australia 3800.

Email: Tanvirul.Islam@monash.edu

Phone: +613 99055549

Fax: +613 99054944

And

Dr. Pathmanathan Rajeev

Senior Lecturer

Department of Civil and Construction Engineering

Swinburne University of Technology

Victoria, Australia 3122.

Email: prajeev@swin.edu.au

Phone: +613 92144942

Abstract

Dynamic compaction is commonly used to construct structural fills for various geo-infrastructures. Current practice is to specify a minimum dry density and moisture content criterion to be used in the field on the basis of Proctor compaction carried out in the laboratory. Nonetheless, we still do not have practical methods for predicting the compacted clay behaviour under expected mechanical and environmental loadings. Current theories are difficult to apply in practice due to difficulty in determining the necessary parameters. In this paper, the recently developed MPK framework is extended to cover dynamically compacted soils, with significant supporting experimental evidence. Two types of soils are used; lightly reactive kaolin and reactive Merri Creek clay. Since the compaction stress was unknown for dynamic compaction, recompression of soil specimens from compacted soil was used to establish the Loading Wetting State Boundary Surface (LWSBS). Independent tests showed that the framework can predict well the behaviour of compacted soils under loading/unloading and yielding, collapse during wetting, change of loading yield stress after wetting, and swelling pressure development during constrained wetting. The value of the approach is that the testing methods are straight-forward, do not require specialised equipment and the testing times are much shorter. In addition, the uncertainty that laboratory dynamic compaction may not relate directly to field roller compaction can be addressed with the developed framework. Soil specimens obtained from field soil pads compacted by actual rollers can be used to establish the LWSBS. This information will allow the prediction of the likely behaviour of field compacted fills under expected environmental and mechanical loadings under one-dimensional conditions. Extension to triaxial conditions would require further experimental work and theoretical modelling.

Key Words

Dynamic compaction, wetting collapse, Proctor test, MPK framework, compacted fills

Introduction

Dynamic compaction is commonly used to undertake earthworks in civil engineering. It is carried out in the field using various forms of rollers to impart mechanical energy into soil to achieve a competent engineered fill for an intended purpose, such as to support a structural foundation. Typically, the compaction specification is based on the laboratory Proctor test, which characterises the relationship between the water content and dry density for a given energy level. This test was originally developed by Proctor in 1933 to simulate field compaction in the laboratory. Commonly Standard Proctor, which imparts a gross energy density of 560 kJ/m^3 (AS1289.5.1.1), is used when moderately heavy machinery is used for compaction. In situations where heavier machinery is used, Modified Proctor energy of 2550 kJ/m^3 (AS1289.5.2.1) is used. To cater for other situations, varied forms of gross energy are used, including reduced compaction energy to simulate hand-operated machinery (Daniel and Benson 1990). Compaction specification typically involves a minimum dry density (on the basis of a Proctor's maximum dry density) to be achieved and a range of moisture contents that could be used. More elaborate criteria have been developed for special applications such as clay liners, where the primary intention is to achieve a minimum hydraulic conductivity (e.g., Daniel and Benson 1990). However, it is still not clear how these compaction energy levels relate to field compaction, where rollers are commonly used. More importantly, it is still difficult at the compaction design stage to examine the likely behaviour of compacted fills under mechanical and environmental loadings that may be imposed during their field operation.

Although static compaction is preferred, dynamically compacted clay has also been used by researchers working in the unsaturated soil mechanics field to develop predictive models (e.g., Sivakumar and Wheeler 2000). However, most of this research has constructed compacted test soil specimens, not using Proctor's compaction methods but using simplified ways of manual compaction, in many cases using miniature compaction hammers. These kinds of simplifications are necessary to construct reproducible specimens for consistency of test results. It is acknowledged that different compaction methods can give rise to different clay structures (Lambe 1958), and therefore even when the density and the moisture content are the same, somewhat different behaviours under mechanical

and environmental loadings could be expected. While it is possible to extract samples from field compacted cores representing the field compaction procedures and then test them in the laboratory to develop predictive models, it is not very practical, since current suction control test methods are very tedious and time-consuming. It follows therefore that alternative approaches to address these shortcomings are useful. Building on the MPK framework proposed by Kodikara (2012), the current paper presents a series of experimental results and a methodology that may help to address these issues. The paper is a follow-up of the companion paper by Islam and Kodikara (2016).

MPK framework in unsaturated soil modelling context

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 conceptually 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 void ratio (e) – moisture ratio ($e_w = wG_s$, where G_s is specific gravity and w gravimetric moisture content) – net stress (p) space and the traditional compaction space of (dry density) $\gamma_d - e_w - p$ (Note: under 1D conditions p refers to net vertical stress and under 3D conditions it refers to mean net stress). Since the inverted parabolic shape of the compaction curve is common to all clayey soils (and also for coarse-grained materials) and various methods of compaction, the concept is suggested to be relevant for all compacted soils, independent of their volume reactivity to moisture content. In addition, a distinct difference in behaviour was highlighted for compacted and slurry soils, especially with reference to their respective initial virgin states, where the initial void ratio increases with decreasing of moisture content for compacted soils while the initial void ratio decreases with decreasing moisture content for a soil started as a slurry. 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 (s) is not selected as one

of the axes as in previous models, it is a congruent part of soil behaviour and plays its role in the $e - e_w - p$ 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) discussed the development this framework in the context of the current state-of-play in unsaturated soil mechanics. It was highlighted that most models (Alonso et al., 1990 introducing Barcelona Basic Model (BBM); Wheeler and Sivakumar, 1995; Wheeler et al., 2003; Sheng et al., 2008) uses $e - s - p$ space to define the volumetric behaviour of unsaturated soils. Some researchers also followed the use of an effective stress (p') combining net stress and suction (e.g., Khalili et al., 2000). Wheeler and Sivakumar (1995) however highlighted the importance of water content given as $v_w (=1 + e_w)$ as a state variable within the unsaturated soil behavioural framework. Recent work in unsaturated soils modelling has been on incorporating degree of saturation (S_r) (as a surrogate to moisture content or e_w), commonly described as hydromechanical coupling (e.g., Gallipoli et al., 2003; Tarantino and De Col, 2008; Zhou and Sheng, 2015). The uniqueness in MPK framework is that it uses moisture ratio e_w , in place of suction used in older models (e.g., BBM) but recognises the importance of suction as a conjugate state variable. This choice can be considered as capturing the essential aspects of hydromechanical coupling without it linking through suction. The practical benefit of this choice is that the framework can be cast in the compaction space providing a direct link to the traditional compaction curve. In addition, it overcomes the difficulties of measuring suction, especially in the field, making it amenable to practical use in many field relevant state paths. However, the limitations are that field questions can be answered only with respect to changes in water content (or degree of saturation) and net stress. The current paper presents the use of this framework under K_o loading (with the use of vertical net stress as p) as applicable to one dimensional analysis of field problems. None the less, the framework captures essential observed aspects of hydromechanical coupling such as shift in yield stress with wetting, characteristics of swelling pressure development and the variation of collapse strain with operational stress. In more recent work, Alonso et al. (2013) indicated that it is necessary to introduce a microstructural state parameter (e.g.,

microstructural void ratio divided by total void ratio) to describe the complete behaviour within a compaction plane ($e - e_w$ at certain operational p). However, they highlighted that additional complexity can arise with expansive soils with this parameter. In MPK framework, the most field state paths are explained with the help of known macroscopic state variables ($e - e_w - p$) as a practical approach to field application, directly linking the well-known compaction curve.

Figure 1: Three-dimensional view of the LWSBS (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. Kaolin Ecalite is commercially available white coloured (china) lightly reactive clay, manufactured at Granville, New South Wales, Australia. Merri Creek soil is a grey/black colour reactive natural soil sourced from Merri Creek located north-east Melbourne, Australia. Merri Creek soil is a residual soil weathered from basalt and 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 kaolin is available in dry form in bags, the preparation of Merri Creek soil involved drying, grinding, and subsequently sieving to remove any deleterious material. A summary of the basic geotechnical properties obtained is given in the companion paper (Islam and Kodikara, 2016) and in the thesis of Islam (2015).

Methods

Samples with (gravimetric) moisture content 12 to 45% were prepared for both soils. In order to prepare homogeneously wetted soil from the dry state, the soil was sieved onto a tray to make a uniform layer thickness of around 5 mm and the tray of soil was then placed in a fog room (100% humidity) to achieve the targeted moisture content. The soil was then thoroughly mixed and placed in sealed plastic bags until further testing, within not less than 48 hours. The soil was dynamically

compacted into a Standard Proctor compaction mould, which has a 105 mm internal diameter and is 115 mm in height. Soil cylinders were compacted using different compaction efforts as listed in Table 1. An automated compaction machine was used to prepare High and Intermediate compaction soil cylinders, while Moderate, Low and Very low compaction soil cylinders were prepared manually. This is because the falling height of the hammer of the automated compaction machine could only be fixed to 300 and 450 mm. As can be seen from Table 1, the falling height was kept at 150mm during the manual compaction. After compaction, soil cylinders were extruded carefully from the mould and wrapped with several layers of plastic and aluminium foil. Finally, the cylinders were placed in plastic bags and stored in a high humidity room. The dynamic compaction curves for kaolin and Merri Creek soil are shown in Figure 2. For kaolin soil, the degree of saturation (S_r) at the LOO varies between 82 to 89% depending on the compaction effort, while for Merri Creek soil, this value is around 82% for most compaction efforts.

For subsequent one-dimensional (K_0) static loading tests, soil specimens were cut from the dynamically compacted soil cylinders after removing them from the fog room. A bottomless steel mould with dimensions of 63 mm internal diameter and 50 mm height was used to cut the soil specimens from the dynamically compacted soil cylinders. Figure 3 shows the preparation procedure of soil specimens for the static compaction tests. First, the generously-greased steel mould was put upside down on top of a dynamically compacted soil cylinder and then a steel plate was put on the bottom of the steel mould. Next, load was applied on the steel plate manually using a Loadtrac II compression set-up until a soil specimen was inside the steel mould. Subsequently, the soil specimen was separated carefully from the dynamically compacted soil cylinder with the help of a knife and the top surface was made smooth. Finally as shown in Figure 3, the soil specimen was pushed down slowly to the bottom of the test mould and a steel base was attached to the bottom of the mould using duct tape. Following the procedure for static compaction similar to that explained in the companion paper, the soil specimens were compressed using the Loadtrac II compression set-up. 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 LOO, a 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 vertical stress. Air phase is continuous at the dry side of the LOO, therefore, no air pressure builds up even at faster loading rate. As a result, applied stress can be considered as net stress. However, once the soil approached the LOO, the air gets trapped and, therefore, the air phase becomes discontinuous at the wet side of optimum (Hilf 1956; Gilbert 1959; Langfelder et al. 1968; Kodikara 2012). As a result, a much lower loading rate (i.e., 0.1 kPa/min) was used not to build air pressure and provide adequate drained conditions.

Table 1: *A summary of compaction efforts used to prepare the dynamically compacted soil cylinders*

Figure 2: *Family of dynamic compaction curves for the kaolin and Merri Creek soil*

Figure 3: *Preparation of dynamically compacted soil specimen for static compaction test*

Loading Wetting State Boundary Surface (LWSBS)

The LWSBS in the MPK framework (Kodikara 2012) is defined as the surface depicting the loosest states compacted soil can attain under loading or wetting or a combination of these paths. The LWSBS for statically compacted soil is usually developed by compressing the soil specimens at different moisture content from a nominal pressure to a certain high pressure. In the companion paper, the LWSBSs of statically compacted kaolin and Merri Creek soil were constructed following this procedure. The nominal pressure on these soils was taken as 7 kPa, which represented the loosest state that the soils would take when water is mixed with soil from dry state. In contrast, in the current test program, the soil cylinders were compacted dynamically with different compaction efforts during specimen preparation. As a result, initially the soil specimens retrieved from compacted cylinders were unloaded and positioned inside the LWSBS applicable to the dynamically compacted soil. Therefore, it was necessary to establish the LWSBS for dynamically compacted soil by retesting of soil specimens to undergo yielding. It was expected that soil would deform predominantly elastically up to the LWSBS, where it would undergo yielding (i.e., yield pressure) and, for further loading,

would follow the LWSBS. On this basis, the yield point and post-yield loading state paths were used to develop the LWSBS for dynamically compacted soils. To reduce the effort required and to be relevant to typical field conditions, the LWSBS was only targeted above a degree of saturation of 50%. Obtaining test specimens with very low moisture contents could also be difficult using the established procedure, especially for sandy materials.

The LWSBS for kaolin Ecalite

Kaolin soil specimens with different moisture contents and different initial dynamic compaction efforts were compressed statically from zero to a certain high pressure to obtain deformation versus load graphs and then using this data, void ratio versus stress graphs were generated. Figures 4(a-g) show measured compression curves presented in traditional e versus $\log(p)$ plots, where p is the net vertical stress. Since the soil specimens were compacted previously, they compressed initially elastically and after yielding, followed the normal compression lines (NCLs) for the corresponding moisture contents. A number of specimens with different initial void ratios but approximately similar moisture contents were used to establish the corresponding NCLs. Solid black lines represent the NCLs at those moisture contents and the average moisture contents are noted at the right hand corner of the figures. The tests that started from the significantly dry side of the LOO were not taken past the LOO during compression even at high pressures and, therefore, the final moisture content was the same as the initial moisture content. However, the specimens with higher initial moisture contents were compressed past the LOO, and in these cases, the final moisture content measured was lower than the initial content due to moisture drainage. Since air pressure was not allowed to develop in any of the tests, the applied vertical stresses were the same as the vertical net stresses. After developing NCLs at different moisture contents, void ratio (e) versus moisture ratio (e_w) lines at different stress levels were generated. Figures 5(a) and 5(b) show how the LWSBS of dynamically compacted kaolin soil was constructed. Figure 5(a) shows the LWSBS that was constructed from the NCLs at different moisture contents obtained from Figure 4, while the dotted lines in Figure 5(b) show the complete LWSBS. Figure 6(a) shows the LWSBS presented in the form of compaction contours and Figure 6(b) shows a 3-D view of the LWSBS generated.

Figure 4: *Void Ratio vs Stress curves for the kaolin soil at different moisture contents and different initial dynamic compaction efforts to develop the LWSBS*

Figure 5: *Construction of the LWSBS for the kaolin soil by only real data & real and extrapolated data to complete the surface*

Figure 6: *The LWSBS for dynamically compacted kaolin soil*

The LWSBS for Merri Creek Soil

Figures 7(a-g) show measured compression curves for Merri Creek soil presented in traditional e versus $\log(p)$ plots. The test procedure was similar to that for kaolin presented earlier. Figures 8(a) and 8(b) show how the LWSBS of dynamically compacted Merri Creek soil was constructed. Figure 8(a) shows the LWSBS that was constructed from the NCLs at different moisture contents obtained from Figure 7, while the dotted lines in Figure 8(b) show the complete LWSBS. Figure 9(a) shows the LWSBS presented in the form of compaction contours and Figure 9(b) shows a 3-D view of the LWSBS generated.

Figure 7: *Void Ratio vs Stress curves for the Merri Creek soil at different moisture contents and different initial dynamic compaction efforts to develop the LWSBS*

Figure 8: *Construction of the LWSBS for the Merri Creek soil by only real data & real and extrapolated data to complete the surface*

Figure 9: *The LWSBS for dynamically compacted Merri Creek soil*

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. The soil specimen

preparation technique was similar to that of the compression tests presented earlier. As the soil specimens needed to be wetted during loading, a load cap was modified by having four 3 mm diameter holes to facilitate water ingress. The description, the loading assembly and the top and bottom configurations of the top loading cap are presented in the companion paper (Islam and Kodikara 2016). Compared with the compression tests, the test set-up features remained the same, with the exception of the load cap. The state path tests which were performed on kaolin soil are listed in Table 2.

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

State paths involving a combination of loading and wetting

A series of tests was undertaken in which dynamically compacted kaolin soil specimens were compressed to a certain stress level and then wetted at that stress level. These test results are shown in Figures 10a, 10b, 10c; 10d, 10e, 10f and 10g, 10h, 10i. Figures 10a, 10b and 10c show a soil specimen at Moderate compaction with 19.85 % moisture content ($e_w = 0.526$) loaded to 1000 kPa and then wetted to 29.92% moisture content ($e_w = 0.793$). As the soil specimen was compacted previously, it is clear that the state path starts from inside the LWSBS (point A) and then moves towards the LWSBS. Next, it follows the LWSBS up to 1000 kPa stress (point B) after intercepting the LWSBS (at point H) around 600 kPa stress. It can be seen from Table 2 that the pre-compaction stress (p_c) of the kaolin soil specimens for this moisture content due to Moderate compaction was found to be 600 kPa. Finally, during wetting, the state path follows the 1000 kPa constant net stress contour on the LWSBS to the final moisture content (path BC), displaying some collapse followed by some swelling. Figures 10d, 10e and 10f show a soil specimen with High compaction at 16.51% moisture content ($e_w = 0.438$) loaded to 1000 kPa and then wetted to 28.15% moisture content ($e_w = 0.746$). As can be seen from Table 2, the pre-compaction stress of the kaolin soil specimens for this moisture content due to High compaction was found to be 1500 kPa, the position of the state path is still inside the LWSBS (at point B) at the end of loading stage. Finally, during wetting, it

swells and intercepts the LWSBS (at point H) around 24.50% moisture content ($e_w = 0.650$) and then follows the 1000 kPa constant net stress contour on the LWSBS to final moisture content (path HC), displaying some collapse. Figures 10g, 10h and 10i show a soil specimen at Low compaction with 25.96% moisture content ($e_w = 0.688$) loaded to 300 kPa and then wetted to 36.87% moisture content ($e_w = 0.977$). It is clear that the state path intercepts the LWSBS around 250 kPa (at point H), which was found to be the pre-compaction stress of the kaolin soil specimens for this moisture content subjected to Low compaction as can be seen from Table 2. It then follows the LWSBS and during wetting, follows the 300 kPa constant net stress contour on the LWSBS to final moisture content (path BC). Figures 10j, 10k and 10l show a test in which a dynamically compacted Ecalite soil specimen was loaded to a particular stress level, wetted to certain moisture content and then loaded again to a higher stress level. It is evident that the state path intercepts the LWSBS (at point H) during the initial loading stage and then follows the LWSBS during wetting (path BC). Finally, during second stage loading, instead of following the moisture ratio line of ($e_w = 0.680$), it moves somewhat away from the LWSBS (path CD). This slight deviation may occur because of measurement errors. It is apparent from the loading/wetting tests that once the soil specimens intercept the LWSBS and hence are wetted, they undergo collapse (or compression), as controlled by the LWSBS. It is also evident that the state paths generally follow the path dictated by the LWSBS, in agreement with the MPK framework.

Figure 10: Loading/wetting state path tests for kaolin

State paths involving a combination of loading, unloading and wetting

Two state path tests involving loading, unloading and wetting undertaken on dynamically compacted kaolin soil are shown in Figure 11. Figures 11a, 11b and 11c show a soil specimen at Moderate compaction with 19.85 % moisture content ($e_w = 0.526$) loaded to 3000 kPa, then unloaded to 1000 kPa and finally wetted to 23.24% moisture content ($e_w = 0.616$). As the soil specimen was compacted under higher stress earlier, the state path starts from inside the LWSBS and then moves

towards the LWSBS due to initial loading (path AH). Next, it intercepts the LWSBS around 600 kPa (point H), which was found to be the pre-compaction stress of the kaolin soil specimens for this moisture content subjected to Moderate compaction as can be seen from Table 2. Subsequently, it follows the LWSBS up to 3000 kPa stress (path HB) and then moves inside the LWSBS because of unloading (path BC). Finally, during wetting at 1000 kPa, it swells towards the stress contour for 1000 kPa of the LWSBS to final moisture content but ends inside the LWSBS (path CD). Figures 11d, 11e and 11f show a soil specimen at Intermediate compaction with 19.94% moisture content ($e_w = 0.528$) loaded to 2000 kPa, then unloaded to 1000 kPa and finally wetted to 26.90% moisture content ($e_w = 0.713$). It is clear that the soil specimen behaves very much the same way as shown in the previous test, intercepts the LWSBS around 1000 kPa during initial loading (at point H), moves inside the LWSBS due to unloading (to point C) and ends inside the LWSBS after the wetting stage (path CD). It is apparent from both tests that the soil specimens stay inside the LWSBS during the wetting stage. As a result, they do not undergo any collapse (or compression) during this stage. Once again, it is evident that the state paths follow the path dictated by the LWSBS, in agreement with the MPK framework.

Figure 11: Loading/unloading/wetting state path tests for kaolin

Collapse potential tests

A series of tests was undertaken on dynamically compacted kaolin soil specimens to examine the collapse potential variation with the stress level. Specimens were prepared with 16.51% ($e_w = 0.438$) and 25.96% ($e_w = 0.688$) moisture content were subjected to High and Low compaction levels respectively. High compaction 16.51% moisture content ($e_w = 0.438$) soil specimens were loaded to 500, 1000, 1500, 2000 and 3000 kPa and then wetted at these stress levels. Low compaction 25.96% moisture content ($e_w = 0.688$) soil specimens were loaded to 100, 250, 300, 700 and 1000 kPa and then wetted at these stress levels. Since the results are similar to those presented in Figures 10 and 11, for brevity, they are not presented here. Figures 12a and 12c show the compression curves of 16.51%

moisture content ($e_w = 0.438$) High compaction and 25.96% moisture content ($e_w = 0.688$) Low compaction respectively, presented in traditional e versus $\log(p)$ plots. On the other hand, collapse potential (defined as the reduction in void ratio) vs stress graphs are presented in Figures 12b and 12d. It is clear from Figures 12a and 12c that the pre-compaction stresses of the kaolin soil specimens for those moisture contents subjected to High and Low compaction are 1500 kPa and 250 kPa respectively. According to the MPK framework, during wetting, maximum collapse is considered to occur when the operational stress becomes the same as the pre-compaction yield stress. This behaviour is also apparent from Figures 12b and 12d. It is also evident from Figures 12b and 12d that when the operational stress is higher or lower than the pre-compaction yield stress, the amount of collapse is lower than the maximum. This behaviour agrees with the typical behaviour reported on the collapse potential of soils (*e.g.*, Sun et al. 2004).

Figure 12: State path tests to determine collapse potentiality for kaolin

State paths of constant volume or swelling pressure development

While the tests presented in Figures 10 and 11 show the swelling behaviour of unloaded kaolin (the state path is located inside the LWSBS) during wetting, a series of tests was undertaken to examine swelling pressure development by constant volume (constrained) wetting for dynamically compacted kaolin soil specimens. The tests were undertaken by locking the specimen against volumetric deformation but measuring the applied stress variation when the specimen was wetted. The same mould and set-up as for the loading and wetting tests were used in this test program. Figure 13 shows the results of some of the tests undertaken. Figures 13a and 13b show the state path of a Moderate compaction 19.85% moisture content ($e_w = 0.526$) soil specimen which was loaded to 200 kPa (path AB) and then wetted in constant volume (*i.e.*, e constant) to saturation (path BCDE). As the pre-compaction stress of the kaolin soil specimens for this moisture content subjected to Moderate compaction was found to be 600 kPa, it is clear that the position of the state path after 200 kPa stress application is below the LWSBS (point B), and during wetting, the swelling pressure builds up to C (around 250 kPa), at which the state reaches the LWSBS. Subsequently, the path CD is on the

LWSBS (at constant initial void ratio = 1.16), reducing the swelling pressure until the LOO is intercepted at point D. Further wetting causes the soil to increase swelling pressure again towards saturation, as shown by path DE. This behaviour is consistent with the MPK framework and with the test results reported in the companion paper (Islam and Kodikara 2016) on statically compacted soils and in the past (Kodikara 2012). Figures 13c and 13d also show similar behaviour for the state path of a soil specimen at Intermediate compaction with 19.94% moisture content ($e_w = 0.528$) which was loaded to 300 kPa (path AB) and then wetted in constant volume to saturation (path BCDE). It is evident that, as the compaction stress increases (or initial void ratio decreases or initial density increases), the maximum swelling pressure increases. Figures 13e, 13f and Figures 13g, 13h show Intermediate compaction 27.71% moisture content ($e_w = 0.734$) and High compaction 19.27% moisture content ($e_w = 0.511$) soil specimens loaded to 500 kPa (path AB) and then wetted in constant volume to saturation (path BC). It is evident that these specimens did not reach the LWSBS and swelling pressure continued to increase with wetting. The final positions of these specimens were close to saturation as can be seen from the $S_r = 1$ line on the saturation plane projected on $e_w - p$ plane. It seems that at the beginning of wetting, both were far below the LWSBS. It can be noted that this behaviour is common for clay with higher compaction stresses. In addition, similar behaviour can arise for lower compaction stresses if the initial moisture content is sufficiently high due to changes in the relative positions of the LWSBS.

Figure 13: 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 too to examine the validity of the concepts proposed by the MPK framework. The soil specimen preparation technique and the test procedure were similar to that for kaolin presented earlier. The state path tests which were performed on Merri Creek soil are listed in Table 3.

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

State paths involving a combination of loading and wetting

Similar to the kaolin soil, a series of tests was undertaken in which dynamically compacted Merri Creek soil specimens were compressed to a certain stress level and then wetted at that stress level. Four test results are presented in Figures 14a, 14b, 14c; 14d, 14e, 14f; 14g, 14h, 14i and 14j, 14k, 14l. As the soil specimens were compacted previously, it is clear that the state paths started from inside the LWSBS (point A) and then moved towards the LWSBS during the loading stage. If the applied stress is less than pre-compaction stress, the position of the state paths are still inside the LWSBS (point B) at the end of this stage (see Figures 14a, 14b, 14c; 14d, 14e, 14f and 14g, 14h, 14i), while the position of the state paths are on the LWSBS (point B) if the applied stress is higher than pre-compaction stress (see Figures 14j, 14k and 14l). Finally, during wetting, depending on the position of the state path, it either swells until intercepting the LWSBS (see Figures 14a, 14b, 14c and 14g, 14h, 14i) or collapses following the LWSBS (see Figures 14j, 14k and 14l). However, the state path may reach close to the saturation without intercepting the LWSBS during wetting, displaying only swelling (see Figures 14d, 14e and 14f).

Figures 14m, 14n, 14o and 14p, 14q, 14r show two test results in which dynamically compacted Merri Creek soil specimens were loaded to a particular stress level, wetted to a certain moisture content and then loaded again to a higher stress level. Similar to the kaolin soil, it is evident from both of the tests that the state paths intercept the LWSBS (at point H) during the initial loading stage and then follow the LWSBS during wetting (path BC). Finally, during second stage loading, they follow the corresponding constant moisture ratio contours on the LWSBS to the final stress (point D).

Similar to the kaolin soil, it is apparent from the loading/wetting tests that once the soil specimens intercept the LWSBS, they undergo collapse (or compression), as depicted by the LWSBS due to wetting. It is also evident that the LWSBS takes control of the state path when it reaches the LWSBS. Once the path is on the LWSBS, the volumetric behaviour of a soil specimen can be predicted by it unless the state path leaves the LWSBS again due to unloading.

Figure 14: Loading/wetting state path tests for Merri Creek soil

State paths involving a combination of loading, unloading and wetting

The results of two state path tests involving loading, unloading and wetting undertaken on dynamically compacted Merri Creek soil are shown in Figure 15. Similar to the kaolin soil, it is evident from both of the tests that the state paths intercept the LWSBS (at point H) during the initial loading stage and then move inside the LWSBS (point C) because of unloading. Finally, during wetting, they reach close to the saturation without intercepting the LWSBS, displaying only swelling. It is apparent from these tests that the state paths follow the path dictated by the LWSBS, consistent with the MPK framework.

Figure 15: Loading/unloading/wetting state path tests for Merri Creek soil

Collapse potential tests

While the tests presented above also showed the collapse behaviour of dynamically compacted Merri Creek soil, a series of tests was undertaken to examine the variation of collapse potential with the stress level. Specimens prepared with 15.52% ($e_w = 0.407$) and 20.52% ($e_w = 0.538$) moisture contents were subjected to Intermediate and Moderate compaction respectively. Soil specimens with Intermediate compaction and at 15.52% moisture content ($e_w = 0.407$) were then loaded to 100, 500, 1000, 2000 and 3000 kPa and wetted, while Moderate compaction at 20.52% moisture content ($e_w = 0.538$) specimens were loaded to 100, 300, 500, 700 and 1000 kPa and then wetted. The results are similar to those shown in Figures 14 and 15, and, therefore for brevity, compression curves of the soil specimens and reduction of void ratio during wetting with operational net stresses are presented in Figures 16. It is apparent that similar to the kaolin soil, maximum collapse is occurred when the operational stress becomes the same as the compaction yield stress. It is also evident that when the operational stress is higher or lower than the compaction yield stress, the amount of collapse is lower than maximum. This behaviour agrees with the typical behaviour reported on the collapse potential of soils (e.g., Sun et al. 2004).

Figure 16: State path tests to determine collapse potentiality for Merri Creek soil

State paths of constant volume or swelling pressure development

Similar to the kaolin soil, a series of tests was undertaken to examine the swelling pressure development for constant volume (constrained) wetting of dynamically compacted Merri Creek soil. Figures 17a and 17b present three test results showing the influence of initial moisture contents of 15.52% ($e_w = 0.407$), 18.16% ($e_w = 0.476$) and 19.89% ($e_w = 0.521$). The specimens were prepared by Intermediate compaction at the beginning, loaded to 500 kPa and then wetted at constant volume (*i.e.*, e constant) to saturation (paths $B_{1,2,3}C_{1,2,3}D_1E_1$). It is clear that during wetting, the state path of 15.52% ($e_w = 0.407$) initial moisture content soil specimen intercepts the LWSBS due to swelling pressure development and then follows constant void ratio ($e = 0.70$) contour on the LWSBS, while other two state paths did not reach the LWSBS and swelling pressure continued to increase with wetting. It is also evident that the swelling pressure decreases with increasing initial moisture content, a finding which is consistent with published results (e.g., Lee et al. 1999; Kassiff and Shalom 1971). As per the MPK framework, the interception with the LWSBS is also evident from the shape of the state paths and 3-D plots.

Figures 17c and 17d show the effect of compaction effort (High and Intermediate compaction) on the swelling state paths for specimens prepared at the initial moisture contents of 15.93% ($e_w = 0.417$) and 15.52% ($e_w = 0.407$) respectively. It is apparent that the specimen compacted by Intermediate compaction intercepted the LWSBS, while the High compaction specimen did not. The latter continued to develop swelling pressure with wetting below the LWSBS towards the saturation plane (final degree of saturation is 0.983). In addition, these results indicate that the swelling pressure increases with the compaction effort (with initial density) when all other variables are kept constant. Similar behaviour has been reported in the research literature (e.g., Imbert et al. 2006; Kassiff and Shalom 1971).

Figure 17: *Constant volume wetting state path tests for Merri Creek soil*

Discussion

A large number of experiments were performed on dynamically 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 closely. This highlights that the macroscopic behaviour of compacted soil in general can be presented within this framework. It should, however, be recognised that manifestation of the observed macroscopic behaviour is due to the complex interaction between the micro and macro void and associated structural elements, which are inherent to initially compacted soils (Alonso et al. 1999; Alonso et al. 2013). In the following discussion, some of the specific features observed are examined. The following points are considered noteworthy.

- (i) Similar to statically compacted soils, the influence of the LOO is clearly evident from the experimental results. The cross-validity (validity of using test results of constant moisture content loading in predicting state paths of wetting under constant net stress loading) and the uniqueness of the LWSBS have been established by a large number of state paths involving a combination of loading, unloading and wetting.
- (ii) The capability for the LWSBS to predict the change in yield point under loading for state paths that undergo wetting from an initial compaction state with certain void ratio and initial moisture content at constant stress has been verified. This issue has been raised by Wheeler et al. (2003) and has implications to the current practice of the development of Loading/Collapse curves that need to be examined further (e.g., Wheeler and Sivakumar 1995).
- (iii) Another important validation is the confirmation of the characteristic behaviour of collapse potential, where the peak collapse appears to occur at the compaction (yield) stress, similar to the

behaviour displayed for statically compacted soils. A physical explanation of this process is presented below.

Figure 18a shows schematically the decomposition of the void ratio into microscopic (e_m) and macroscopic (e_M) components (Alonso et al., 2013). As can be seen, an initial loose state is given by Point 0 and the soil is compacted on the LWSBS to a certain pre-compaction stress as depicted by Point 1. Predominantly macroscopic voids have reduced during this process and there may be a slight reduction of microscopic voids as well ($\Delta e = \Delta e_m + \Delta e_M$). If the soil is wetted from this position at this operational stress (p_o), then soil aggregates would experience predominantly slippage at the contacts since it is already at and following the loosest states for this operational stress that is the current yield stress. The collapse predominantly manifests from the reduction of the macroscopic voids. The final collapse is expected to complete at Point 2. If the soil is unloaded from the pre-compaction stress (Point 1) to a smaller operational stress (p_o) depicted by Point 3, then during wetting it can undergo both aggregate swelling and slippage between the aggregates. A possible reason for the occurrence of less aggregate slippage in this instance is that the shear stresses applied at aggregate contacts are less (lower operational stress) and the shear strength at the aggregate contacts may be even higher (higher suction during unloading from Point 1 to 2, see Tarantino and De Col, 2008). Since aggregate swelling dominates over slippage, markedly for expansive soils, soil will display an overall swelling giving a positive hydric coefficient ($\alpha = \left(\frac{\partial e}{\partial e_w} \right)_{p_o}$). If this process continues until the LWSBS is intercepted for example at Point 4, then it has reached the loosest possible state for that operational stress and subsequent wetting would only lead to soil collapse due to domination of the aggregate slippage up to Point 5. Note that at low operational stresses, it is possible that a state path like Points 3,4,5 may not intersect the LWSBS at all, wherein the soil would not experience any collapse but only swelling. On the other hand, if the soil was further loaded to higher pre-compaction stress (either from Point 1 or 3 or 0) to Point 6, then it would again be at a loosest state for that high stress and would therefore experience macroscopically collapse during wetting (up to a Point 7). The amount of collapse at this state path is less than the path for Points 1 to

2 because the macroscopic voids at Point 1 is larger than that at Point 6. It is clear from Figure 18a, the maximum collapse therefore occurs at the pre-compaction stress. Figure 18b shows schematically the likely changes in the micro/macro voids during loading/unloading and wetting. It should be noted that this representation is only a simplified view without taking into account the possible interaction of aggregate clusters working as single units.

Figure 18: Schematic decomposition of the void ratio into macroscopic and microscopic components during loading/wetting state paths

(iv) The constrained swelling tests also clearly demonstrate the influence of the LOO on the LWSBS. For instance, similar to statically compacted soils, the swelling pressure increases to a peak until the state path intercepts the LWSBS and then follows it, the swelling pressure subsequently decreasing to the LOO and then increasing again towards full saturation (e.g., Figure 13a), as observed by other researchers (e.g., Imbert et al. 2006; Kassiff and Shalom 1971).

The similar micro/macro void interaction could be used to explain this observed behaviour. When a soil is wetted at constrain volume from an unloaded position (e.g., Point 3), it would first try swell predominantly which translates to an increase of stress due to constant volume constraining. When the state path reaches the LWSBS, however, it has reached the relevant loosest state and therefore would experience predominantly collapse, which translates to a reduction in swelling pressure at constant volume. Once the collapse is mostly complete at the LOO, it would further experience aggregate swelling towards saturation, which would translate to an increase in swelling pressure.

(v) Figure 19 shows 2-D and 3-D comparisons of the LWSBSs of statically and dynamically compacted kaolin and Merri Creek soils. The LWSBS contours and surfaces for two types of compaction are markedly similar for both soils. This result corroborates the similarity in the observed phenomenological behaviour of the two soil types under the two types of compaction processes. Nonetheless, for kaolin soil, static compaction appears to produce lower void ratio or higher density at

the same compaction stress, especially at lower stress levels. For the more reactive Merri Creek soil, the reverse behaviour seems to be operative, where the lower void ratios are produced for dynamic compaction, especially at lower stress levels. For both soils, at higher stress levels this difference seems to diminish. It is unclear why these differences arise, but despite the similar initial state, considering dynamic compaction involves repetitive loading, where soil is progressively compacted, such differences are not surprising.

Figure 19: Comparisons of the LWSBSs for the statically and dynamically compacted kaolin and Merri Creek soils

Within this qualification, most significant application of these findings to practice is that, with the proposed framework, it now appears possible to directly evaluate compacted clay performance at field scale. The shape of the compaction curves found for field compactions are also similar (inverted parabolic shape). Hence it is expected that laboratory observed behaviour would be applicable. However, further research is needed to verify this. For instance, it is possible to obtain cores from field pads, where compaction is conducted using rollers to be used in the field. These cores can then be used to establish the LWSBS for compacted soils and then analyses can be undertaken to predict the performance under expected field environmental and external loadings. As noted previously, constant moisture content testing is very straightforward and, furthermore, it is only necessary to develop the relevant section of the LWSBS that is considered operative for a given field application.

Concluding Remarks

Significant experimental results have been presented in support of the MPK framework for dynamically compacted soils. Since the compaction stress was unknown for dynamic compaction, recompression of soil specimens from compacted soil was used to establish the LWSBS. Independent tests undertaken showed that the framework can predict well the behaviour of compacted soils under loading/unloading and yielding, collapse during wetting, change of loading yield stress after wetting, and swelling pressure development during constrained wetting. The value of the approach is that the

testing methods are straight-forward, do not require specialised equipment and the testing times are short. In addition, the uncertainty that laboratory dynamic compaction may not relate directly to field roller compaction may also be addressed with the developed framework. It is argued that soil specimens obtained from field soil pads compacted by actual rollers may be used to establish the LWSBS. Such knowledge would allow the prediction of the likely behaviour of field-compacted fills under expected environmental and external loadings under one-dimensional conditions. Extension to triaxial conditions would require further experimental work and theoretical modelling.

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Notations

e = Void ratio

e_w = Moisture ratio; ($e_w = wG_s$, where G_s is specific gravity and w gravimetric moisture content)

p = Net stress

γ_d = Dry density

s = Suction

p' = Effective stress

v_w = Specific water volume; ($v_w (=1 + e_w)$)

S_r = Degree of saturation

K_o = 1-D loading

e_m = Microvoids

e_M = Macrovoids

p_c = Pre-compaction stress

Δe = Change of void ratio; ($\Delta e = \Delta e_m + \Delta e_M$)

p_o = Operational stress

α = Hydric coefficient; ($\alpha = (\frac{\partial e}{\partial e_w})_{p_o}$)

Tables

Table 1: A summary of compaction efforts used to prepare the dynamically compacted soil cylinders

Compaction Name	Mould volume (cm ³)	No. of layers	No. of blows each layer	Hammer weight (lb/kg)	Hammer falling height (inch/mm)	Total energy input (kN-m/m ³)	Kaolin Soil		Merri Creek Soil	
							Maximum dry density (kN/m ³)	Optimum moisture content (%)	Maximum dry density (kN/m ³)	Optimum moisture content (%)
Modified Proctor	≈1000	5	25	10/4.545	18/450	2548	14.8	25.4	16.2	19.2
High compaction	≈1000	5	25	10/4.545	12/300	1669	14.4	27.1	15.4	20.5
Intermediate compaction	≈1000	5	25	5.5/2.5	12/300	934	13.9	29.1	14.3	24.8
Standard Proctor	≈1000	3	25	5.5/2.5	12/300	560	13.5	30.4	13.8	27.1
Moderate compaction	≈1000	5	25	5.5/2.5	6/150	467	13.2	31.5	13.0	30.6
Low compaction	≈1000	5	12	5.5/2.5	6/150	224	12.4	33.9	12.4	33.3
Very low compaction	≈1000	5	6	5.5/2.5	6/150	112	11.5	36.8	11.0	41.4

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

Test Identity	Description of the Test
Loading – Wetting Tests	
DC – EK – LW – 2	Moderate compaction 19.85 % moisture content ($e_w = 0.526$) soil specimen (Pre-compaction stress = 600 kPa) loaded to 1000 kPa and then wetted to 29.92% moisture content ($e_w = 0.793$)
Loading – Unloading – Wetting Tests	
DC – EK – LUW – 1	Moderate compaction 19.85 % moisture content ($e_w = 0.526$) soil specimen (Pre-compaction stress = 600 kPa) loaded to 3000 kPa and then unloaded to 1000 kPa and then wetted to 23.24% moisture content ($e_w = 0.616$)
DC – EK – LUW – 2	Intermediate compaction 19.94% moisture content ($e_w = 0.528$) soil specimen (Pre-compaction stress = 1000 kPa) loaded to 2000 kPa and then unloaded to 1000 kPa and then wetted to 26.90% moisture content ($e_w = 0.713$)
Loading – Wetting – Loading Tests	
DC – EK – LWL – 1	Intermediate compaction 19.94% moisture content ($e_w = 0.528$) soil specimen (Pre-compaction stress = 1000 kPa) loaded to 1000 kPa and then wetted to 25.66% moisture content ($e_w = 0.680$) and then loaded to 2000 kPa
Collapse Potential Tests	
DC – EK – CPT – 3 or DC – EK – LW – 5	High compaction 16.51% moisture content ($e_w = 0.438$) soil specimen (Pre-compaction stress = 1500 kPa) loaded to 1000 kPa and then wetted to 28.15% moisture content ($e_w = 0.746$)
Combination of DC – EK – CPT – 1 to 5	High compaction 16.51% moisture content ($e_w = 0.438$) soil specimens (Pre-compaction stress = 1500 kPa) wetted under the operation stresses of 500, 1000, 1500, 2000 and 3000 kPa A “Reduction of Void Ratio – Net Stress” graph shows the results obtained from Collapse Potential Tests (1 – 5)
DC – EK – CPT – 6 or DC – EK – LW – 8	Low compaction 25.96% moisture content ($e_w = 0.688$) soil specimen (Pre-compaction stress = 250 kPa) loaded to 300 kPa and then wetted to 36.87% moisture content ($e_w = 0.977$)
Combination of DC – EK – CPT – 6 to 10	Low compaction 25.96% moisture content ($e_w = 0.688$) soil specimens (Pre-compaction stress = 250 kPa) wetted under the operation stresses of 100, 250, 300, 700 and 1000 kPa A “Reduction of Void Ratio – Net Stress” graph shows the results obtained from Collapse Potential Tests (6 – 10)
Swelling Pressure Tests	
DC – EK – SPT – 1	Moderate compaction 19.85% moisture content ($e_w = 0.526$) soil specimen loaded to 200 kPa and then wetted to 43.40% moisture content ($e_w = 1.150$) ($S_r = 0.991$ and $e_0 = 1.16$) in constant volume
DC – EK – SPT – 3	Intermediate compaction 19.94% moisture content ($e_w = 0.528$) soil specimen loaded to 300 kPa and then wetted to 36.60% moisture content ($e_w = 0.970$) ($S_r = 0.99$ and $e_0 = 0.98$) in constant volume

DC – EK – SPT – 4	Intermediate compaction 27.71% moisture content ($e_w = 0.734$) soil specimen loaded to 500 kPa and then wetted to 32.08% moisture content ($e_w = 0.850$) ($S_r = 0.975$ and $e_0 = 0.872$) in constant volume
DC – EK – SPT – 5	High compaction 19.27% moisture content ($e_w = 0.511$) soil specimen loaded to 500 kPa and then wetted to 30.20% moisture content ($e_w = 0.800$) ($S_r = 0.96$ and $e_0 = 0.835$) in constant volume

DC => Dynamic Compaction, EK => Ecalite Kaolin, LW => Loading – Wetting, LUW => Loading – Unloading – Wetting, LWL => Loading – Wetting – Loading, CPT => Collapse Potential Test, SPT => Swelling Pressure Test.

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

Test Identity	Description of the Test
Loading – Wetting Tests	
DC – MC – LW – 1	High compaction 15.70% moisture content ($e_w = 0.411$) soil specimen loaded to 1000 kPa and then wetted to 22.33% moisture content ($e_w = 0.585$)
DC – MC – LW – 2	Low compaction 23.38% moisture content ($e_w = 0.613$) soil specimen (Pre-compaction stress = 300 kPa) loaded to 400 kPa and then wetted to 28.62% moisture content ($e_w = 0.750$)
Loading – Unloading – Wetting Tests	
DC – MC – LUW – 1	Intermediate compaction 15.52% moisture content ($e_w = 0.407$) soil specimen (Pre-compaction stress = 980 kPa) loaded to 2000 kPa and then unloaded to 1000 kPa and then wetted to 20.52% moisture content ($e_w = 0.538$)
DC – MC – LUW – 2	Low compaction 23.38% moisture content ($e_w = 0.613$) soil specimen (Pre-compaction stress = 300 kPa) loaded to 500 kPa and then unloaded to 400 kPa and then wetted to 27.86% moisture content ($e_w = 0.730$)
Loading – Wetting – Loading Tests	
DC – MC – LWL – 1	High compaction 15.93% moisture content ($e_w = 0.417$) soil specimen (Pre-compaction stress = 1700 kPa) loaded to 2000 kPa and then wetted to 17.27% moisture content ($e_w = 0.452$) and then loaded to 3000 kPa
DC – MC – LWL – 2	Moderate compaction 20.52% moisture content ($e_w = 0.538$) soil specimen (Pre-compaction stress = 505 kPa) loaded to 700 kPa and then wetted to 22.76% moisture content ($e_w = 0.596$) and then loaded to 1000 kPa
Collapse Potential Tests	
DC – MC – CPT – 2 or DC – MC – LW – 4	Intermediate compaction 15.52% moisture content ($e_w = 0.407$) soil specimen loaded to 500 kPa and then wetted to 27.30% moisture content ($e_w = 0.715$)
Combination of DC – MC – CPT – 1 to 5	Intermediate compaction 15.52% moisture content ($e_w = 0.407$) soil specimens (Pre-compaction stress = 1000 kPa) wetted under the operation stresses of 100, 500, 1000, 2000 and 3000 kPa A “Reduction of Void Ratio – Net Stress” graph shows the results obtained from Collapse Potential Tests (1 – 5)
DC – MC – CPT – 6 or DC – MC – LW – 8	Moderate compaction 20.52% moisture content ($e_w = 0.538$) soil specimen loaded to 100 kPa and then wetted to 33.80% moisture content ($e_w = 0.886$)
Combination of DC – MC – CPT – 6 to 10	Moderate compaction 20.52% moisture content ($e_w = 0.538$) soil specimens (Pre-compaction stress = 500 kPa) wetted under the operation stresses of 100, 300, 500, 700 and 1000 kPa A “Reduction of Void Ratio – Net Stress” graph shows the results obtained from Collapse Potential Tests (6 – 10)

Swelling Pressure Tests	
DC – MC – SPT – 1	High compaction 15.93% moisture content ($e_w = 0.417$) soil specimen loaded to 500 kPa and then wetted to 21.56% moisture content ($e_w = 0.565$) ($S_r = 0.983$ and $e_0 = 0.575$) in constant volume
DC – MC – SPT – 2	Intermediate compaction 15.52% moisture content ($e_w = 0.407$) soil specimen loaded to 500 kPa and then wetted to 26.27% moisture content ($e_w = 0.688$) ($S_r = 0.983$ and $e_0 = 0.7$) in constant volume
DC – MC – SPT – 3	Intermediate compaction 18.16% moisture content ($e_w = 0.476$) soil specimen loaded to 500 kPa and then wetted to 23.33% moisture content ($e_w = 0.611$) ($S_r = 0.983$ and $e_0 = 0.622$) in constant volume
DC – MC – SPT – 4	Intermediate compaction 19.89% moisture content ($e_w = 0.521$) soil specimen loaded to 500 kPa and then wetted to 22.26% moisture content ($e_w = 0.583$) ($S_r = 0.984$ and $e_0 = 0.593$) in constant volume

DC => Dynamic Compaction, MC => Merri Creek Soil, LW => Loading – Wetting, LUW => Loading – Unloading – Wetting, LWL => Loading – Wetting – Loading, CPT => Collapse Potential Test, SPT => Swelling Pressure Test.

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Figure 19: *Comparisons of the LWSBSs for the statically and dynamically compacted kaolin and Merri Creek soils*

(a) In compaction space

(b) In e - e_w - p space**Figure 1:** Three-dimensional view of the LWSBS (Kodikara, 2012)

(a) Dynamic compaction curves for the kaolin soil

(b) Dynamic compaction curves for the Merri Creek soil

Figure 2: Family of dynamic compaction curves for the kaolin and Merri Creek soil

Figure 3: Preparation of dynamically compacted soil specimen for static compaction test

(a) 19.70% moisture content ($e_w = 0.522$)

(b) 23.30% moisture content ($e_w = 0.617$)

(c) 25.60% moisture content ($e_w = 0.678$) (d) 27.70% moisture content ($e_w = 0.734$)

(e) 30.0% moisture content ($e_w = 0.795$)

(f) 32.80% moisture content ($e_w = 0.869$)

(g) 34.70% moisture content ($e_w = 0.920$)

Figure 4: Void Ratio vs Stress curves for the kaolin soil at different moisture contents and different initial dynamic compaction efforts to develop the LWSBS

(a) In $e - e_w$ plane (only real data)

(b) In $e - e_w$ plane (real and extrapolated data)

Figure 5: Construction of the LWSBS for the kaolin soil by only real data & real and extrapolated data to complete the surface

(a) In $e - e_w$ plane (b) In $e - e_w - p$ space**Figure 6:** The LWSBS for dynamically compacted kaolin soil

(a) 15.70% moisture content ($e_w = 0.411$)

(b) 18.30% moisture content ($e_w = 0.479$)

(c) 20.20% moisture content ($e_w = 0.529$) (d) 23.30% moisture content ($e_w = 0.610$)

(e) 26.20% moisture content ($e_w = 0.686$)

(f) 30.30% moisture content ($e_w = 0.794$)

(g) 33.30% moisture content ($e_w = 0.872$)

Figure 7: Void Ratio vs Stress curves for the Merri Creek soil at different moisture contents and different initial dynamic compaction efforts to develop the LWSBS

(a) In $e - e_w$ plane (only real data)

(b) In $e - e_w$ plane (real and extrapolated data)

Figure 8: Construction of the LWSBS for the Merri Creek soil by only real data & real and extrapolated data to complete the surface

(a) In $e - e_w$ plane (b) In $e - e_w - p$ space**Figure 9:** The LWSBS for dynamically compacted Merri Creek soil

(a) Moderate compaction 19.85 % moisture content ($e_w = 0.526$) soil specimen (Pre-compaction stress = 600 kPa) loaded to 1000 kPa and then wetted to 29.92% moisture content ($e_w = 0.793$) [Test Identity => DC – EK – LW – 2]

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

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

(d) High compaction 16.51% moisture content ($e_w = 0.438$) soil specimen loaded to 1000 kPa and then wetted to 28.15% moisture content ($e_w = 0.746$) [Test Identity => DC – EK – CPT – 3 or DC – EK – LW – 5]

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

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

(g) Low compaction 25.96% moisture content ($e_w = 0.688$) soil specimen (Pre-compaction stress = 250 kPa) loaded to 300 kPa and then wetted to 36.87% moisture content ($e_w = 0.977$) [Test Identity => DC – EK – CPT – 6 or DC – EK – LW – 8]

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

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

(j) Intermediate compaction 19.94% moisture content ($e_w = 0.528$) soil specimen (Pre-compaction stress = 1000 kPa) loaded to 1000 kPa and then wetted to 25.66% moisture content ($e_w = 0.680$) and then loaded to 2000 kPa [Test Identity => DC – EK – LWL – 1]

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

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

Figure 10: Loading/wetting state path tests for kaolin

(a) Moderate compaction 19.85 % moisture content ($e_w = 0.526$) soil specimen (Pre-compaction stress = 600 kPa) loaded to 3000 kPa and then unloaded to 1000 kPa and then wetted to 23.24% moisture content ($e_w = 0.616$) [Test Identity => DC – EK – LUW – 1]

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

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

(d) Intermediate compaction 19.94% moisture content ($e_w = 0.528$) soil specimen (Pre-compaction stress = 1000 kPa) loaded to 2000 kPa and then unloaded to 1000 kPa and then wetted to 26.90% moisture content ($e_w = 0.713$) [Test Identity => DC – EK – LUW – 2]

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

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

Figure 11: Loading/unloading/wetting state path tests for kaolin

(a) Void Ratio versus Net Stress compression for High compaction kaolin specimen with initial $e_{wo} = 0.438$

(b) Reduction of void ratio versus Operational Net Stress

(a) & (b) Collapse potential given as reduction of void ratio for High compaction (Pre-compaction stress = 1500 kPa) kaolin specimen with initial $e_{wo} = 0.438$ and unloaded to zero stress $e_o = 0.97$ [Test Identity => Combination of DC – EK – CPT – 1 to 5]

(c) Void Ratio versus Net Stress compression for Low compaction kaolin specimen with initial $e_{w0} = 0.688$

(d) Reduction of void ratio versus Operational Net Stress

(c) & (d) Collapse potential given as reduction of void ratio for Low compaction (Pre-compaction stress = 250 kPa) kaolin specimen with initial $e_{w0} = 0.688$ and unloaded to zero stress $e_o = 1.337$ [Test Identity => Combination of DC – EK – CPT – 6 to 10]

Figure 12: State path tests to determine collapse potentiality for kaolin

(a) Moderate compaction 19.85% moisture content ($e_w = 0.526$) soil specimen loaded to 200 kPa and then wetted to 43.40% moisture content ($e_w = 1.150$) ($S_r = 0.991$ and $e_0 = 1.16$) in constant volume [Test Identity => DC – EK – SPT – 1]

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

(c) Intermediate compaction 19.94% moisture content ($e_w = 0.528$) soil specimen loaded to 300 kPa and then wetted to 36.60% moisture content ($e_w = 0.970$) ($S_r = 0.99$ and $e_0 = 0.98$) in constant volume [Test Identity => DC – EK – SPT – 3]

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

(e) Intermediate compaction 27.71% moisture content ($e_w = 0.734$) soil specimen loaded to 500 kPa and then wetted to 32.08% moisture content ($e_w = 0.850$) ($S_r = 0.975$ and $e_0 = 0.872$) in constant volume [Test Identity => DC – EK – SPT – 4]

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

(g) High compaction 19.27% moisture content ($e_w = 0.511$) soil specimen loaded to 500 kPa and then wetted to 30.20% moisture content ($e_w = 0.800$) ($S_r = 0.96$ and $e_0 = 0.835$) in constant volume [Test Identity => DC – EK – SPT – 5]

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

Figure 13: Constant volume wetting state path tests for kaolin

(a) Intermediate compaction 15.52% moisture content ($e_w = 0.407$) soil specimen loaded to 500 kPa and then wetted to 27.30% moisture content ($e_w = 0.715$) [Test Identity => DC – MC – CPT – 2 or DC – MC – LW – 4]

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

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

(d) Moderate compaction 20.52% moisture content ($e_w = 0.538$) soil specimen loaded to 100 kPa and then wetted to 33.80% moisture content ($e_w = 0.886$) [Test Identity $\Rightarrow$ DC – MC – CPT – 6 or DC – MC – LW – 8]

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

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

(g) High compaction 15.70% moisture content ($e_w = 0.411$) soil specimen loaded to 1000 kPa and then wetted to 22.33% moisture content ($e_w = 0.585$) [Test Identity => DC – MC – LW – 1]

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

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

(j) Low compaction 23.38% moisture content ($e_w = 0.613$) soil specimen (Pre-compaction stress = 300 kPa) loaded to 400 kPa and then wetted to 28.62% moisture content ($e_w = 0.750$) [Test Identity => DC – MC – LW – 2]

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

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

(m) High compaction 15.93% moisture content ($e_w = 0.417$) soil specimen (Pre-compaction stress = 1700 kPa) loaded to 2000 kPa and then wetted to 17.27% moisture content ($e_w = 0.452$) and then loaded to 3000 kPa [Test Identity => DC – MC – LWL – 1]

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

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

(p) Moderate compaction 20.52% moisture content ($e_w = 0.538$) soil specimen (Pre-compaction stress = 505 kPa) loaded to 700 kPa and then wetted to 22.76% moisture content ($e_w = 0.596$) and then loaded to 1000 kPa [Test Identity => DC – MC – LWL – 2]

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

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

Figure 14: Loading/wetting state path tests for Merri Creek soil

(a) Intermediate compaction 15.52% moisture content ($e_w = 0.407$) soil specimen (Pre-compaction stress = 980 kPa) loaded to 2000 kPa and then unloaded to 1000 kPa and then wetted to 20.52% moisture content ($e_w = 0.538$) [Test Identity => DC – MC – LUW – 1]

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

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

(d) Low compaction 23.38% moisture content ($e_w = 0.613$) soil specimen (Pre-compaction stress = 300 kPa) loaded to 500 kPa and then unloaded to 400 kPa and then wetted to 27.86% moisture content ($e_w = 0.730$) [Test Identity => DC – MC – LUW – 2]

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

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

Figure 15: Loading/unloading/wetting state path tests for Merri Creek soil

(a) Void Ratio versus Net Stress compression for Intermediate compaction Merri Creek soil specimen with initial $e_{wo} = 0.407$

(b) Reduction of void ratio versus Operational Net Stress

(a) & (b) Collapse potential given as reduction of void ratio for Intermediate compaction (Pre-compaction stress = 1000 kPa) Merri Creek soil specimen with initial $e_{wo} = 0.407$ and unloaded to zero stress $e_o = 0.842$ [Test Identity => Combination of DC – MC – CPT – 1 to 5]

(c) Void Ratio versus Net Stress compression for Moderate compaction Merri Creek soil specimen with initial $e_{wo} = 0.538$

(d) Reduction of void ratio versus Operational Net Stress

(c) & (d) Collapse potential given as reduction of void ratio for Moderate compaction (Pre-compaction stress = 500 kPa) Merri Creek soil specimen with initial $e_{wo} = 0.538$ and unloaded to zero stress $e_o = 1.064$ [Test Identity => Combination of DC – MC – CPT – 6 to 10]

Figure 16: State path tests to determine collapse potentiality for Merri Creek soil

(a) Intermediate compaction 15.52% moisture content ($e_w = 0.407$), 18.16% moisture content ($e_w = 0.476$) and 19.89% moisture content ($e_w = 0.521$) soil specimens loaded to 500 kPa and then wetted to 26.27% moisture content ($e_w = 0.688$) ($S_r = 0.983$ and $e_0 = 0.7$), 23.33% moisture content ($e_w = 0.611$) ($S_r = 0.983$ and $e_0 = 0.622$) and 22.26% moisture content ($e_w = 0.583$) ($S_r = 0.984$ and $e_0 = 0.593$) respectively in constant volume [Test Identity => DC – MC – SPT – 2, 3 & 4]

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

(c) High compaction 15.93% moisture content ($e_w = 0.417$) and Intermediate compaction 15.52% moisture content ($e_w = 0.407$) soil specimens loaded to 500 kPa and then wetted to 21.56% moisture content ($e_w = 0.565$) ($S_r = 0.983$ and $e_0 = 0.575$) and 26.27% moisture content ($e_w = 0.688$) ($S_r = 0.983$ and $e_0 = 0.7$) respectively in constant volume [Test Identity => DC – MC – SPT – 1 & 2]

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

Figure 17: Constant volume wetting state path tests for Merri Creek soil

(a) Macro and micro voids during loading/wetting and loading/unloading/wetting

(b) Interaction of soil aggregates during loading/wetting and loading/unloading/wetting

Figure 18: Schematic decomposition of the void ratio into macroscopic and microscopic components during loading/wetting state paths

(a) The LWSBSs for the kaolin soil in $e - e_w$ plane

(b) The LWSBSs for the kaolin soil in $e - e_w - p$ space

(c) The LWSBSs for the Merri Creek soil in $e - e_w$ plane

(d) The LWSBSs for the Merri Creek soil in $e - e_w - p$ space

Figure 19: Comparisons of the LWSBSs for the statically and dynamically compacted kaolin and Merri Creek soils