The mechanical behaviour of an unsaturated compacted silty clay

A. JOTISANKASA*, M. COOP† and A. RIDLEY‡

A comprehensive experimental study has been carried out to investigate the volumetric and shear strength behaviour of a compacted silty clay, which exhibited collapse-on-wetting behaviour. The experiments consisted mainly of suction-monitored triaxial tests, carried out in a new apparatus. The test results are interpreted on the basis of an elasto-plastic framework using the conventional stress variable approach (net stress and suction) as well as an approach that takes into account the degree of saturation within two modified stress variables. The evidence for critical states was examined, based on the stress–dilatancy relationships. It was found that a critical state was observed experimentally in cases where the samples contracted over much of their stress paths, but was not truly established in other cases. Relationships between the shear strength and specific volume at the ultimate state were established for samples over a wide range of degrees of saturation (from fully saturated to the air-dried state).

KEYWORDS: collapsed settlement; compaction; laboratory tests; partial saturation; shear strength; suction

On a effectué une étude expérimentale complète afin d'examiner le comportement volumétrique et la résistance au cisaillement d'argiles silteuses, qui présentaient un comportement d'écrouissage au mouillage. Les expériences effectuées consistaient, pour la plupart, en essais triaxiaux contrôlés par aspiration, effectués dans un nouvel appareil. Les résultats des essais sont interprétés sur la base d'un cadran élasto-plastique, en adoptant la méthode traditionnelle des variables de contraintes (contrainte et aspiration nettes), ainsi qu'une méthode tenant compte du degré de saturation au sein de deux variables de contraintes modifiées. On a examiné les relevés pour les états critiques, sur la base des rapports contraintes-dilatance, et on a établi expérimentalement la présence d'un état critique dans certains cas où les échantillons s'étaient contracté sur la majeure partie de leur chemin de contrainte, sans toutefois pouvoir établir véritablement dans d'autres cas. On a établi les rapports entre la résistance au cisaillement et le volume spécifique à l'état limite pour des échantillons sur une vaste gamme de degrés de saturation (de l'état à saturation intégrale à l'état séché à l'air).

INTRODUCTION

Much of the understanding of non-expansive unsaturated soil behaviour has evolved around the elasto-plastic framework proposed by Alonso et al. (1987) and further developed by subsequent researchers such as Alonso et al. (1990), Wheeler & Sivakumar (1995), Mautouk et al. (1995) and Cui & Delage (1996). The central idea of the framework lies in the existence of the loading-collapse (LC) yield surface, which can be identified as a series of normal compression lines at constant suction, in the three-dimensional space of specific volume, net mean stress and suction. A fundamental assumption associated with the LC yield surface is that the plastic compression due to collapse on wetting and that due to loading are similar processes and thus can be described by a single unique surface. Jotisankasa et al. (2007a) validated this assumption of a unique yield surface in the net vertical stress-suction-specific volume space, based on the results of suction-monitored oedometer tests on a compacted silty clay.

The importance of the degree of saturation for the mechanical behaviour of unsaturated soils has long been appreciated, and was taken into account in the effective stress equation by Bishop (1959). Studies by Toll (1990) and Toll & Ong (2003) also led to an appreciation of the dependence on the degree of saturation of the critical state parameters in terms of the volume change of the unsaturated soils. More recent frameworks (e.g. Jonni, 2000; Karube & Kawai, 2001; Gallipoli et al., 2003; Wheeler et al., 2003) employ a stress variable that takes into account the degree of saturation by using the Bishop equation as well as another independent variable that represents the bonding factor due to meniscal water lenses around idealised soil particles. Despite this progress, test results for collapsible soils remain relatively scarce and are still required to validate many aspects of these models.

This paper is aimed at presenting the experimental results of a comprehensive set of tests on a compacted silty clay, which has a collapse-on-wetting nature. The interpretation of the results was intended to explore some key aspects of the existing models, and, where possible, to suggest some improvements. The experiments consisted of compression, wetting and shearing tests in a new triaxial apparatus. More experimental results from suction-monitored oedometer tests and unconfined wetting/drying on the same material have been reported by Jotisankasa et al. (2007a).

THE COMPACTED SILTY CLAY

The material used was a mixture of 70% silt, 20% kaolin and 10% London clay. The silt was of a pure silica type (manufacturer's grade HPF4), consisting primarily of angular quartz grains (see Zdravkovic & Jardine, 1997). The three constituents were initially mixed as a reconstituted slurry at a water content of 1.5 times the liquid limit of the soil. This slurry was subsequently dried in an oven at 70°C, ground into a powder, and passed through a No. 40 (425 μm) sieve. The powder was then slowly mixed with de-ionised water until it reached the desired water content. The mixture was subsequently stored within three layers of airtight bags for at least one week to hydrate. The final powder was of low plasticity (LL = 28%, PI = 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.

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This hydrated mixture was statically compacted to form the specimens, which had average values of water content $w$ of 10.1% (standard deviation 0.2%), void ratio $e$ of 0.706 (standard deviation 0.013) and degree of saturation $S_e$ of 38% (standard deviation 1.2%). For the triaxial samples, compaction was carried out in nine layers, each at the rate of 1.5 mm/min and to a maximum vertical pressure of about 800 kPa; the diameter was 50 mm and height 100 mm. Between each layer, its surface was scarified to ensure good contact with the next layer. The samples compacted in this condition were drier and looser than those at the optimum value of the standard compaction (BS 1377), and thus they exhibited an open structure and consequently collapse-on-wetting.

Soil-water retention surface

The results from the suction-monitored oedometer tests, unconfined wetting and drying by hanging water column tests, and filter paper tests, as described in Jotisankasa (2005) and Jotisankasa et al. (2007a), were used to prepare the main boundary wetting surface at different void ratios, as shown in Fig. 1. As tests were not performed at constant void ratio, contouring software was used in the data processing, as explained in the Appendix. In preparing the data for processing, the results from tests that involved initial drying were excluded, since the sample would have followed the scanning surface as opposed to the main wetting surface. A degree of hysteresis is evident for all the retention curves. The degree of saturation at the transition between macro- and microstructural levels increases with decreasing void ratio. The curve-fitting for these contours was carried out using the functions proposed by Gititana & Fredlund (2004). The input parameters for the fitting curves, summarised in Table 1, were derived by trial and error, based on visual observation of the accuracy of fit of the curves. The sharpness of the transition at the bending points on the retention curve is defined by parameter $a$, while $\psi_b$ represents the blow-through suction, $\psi_{res}$ the residual suction, $S_{res}$ the degree of saturation at the residual point and $S_e$ the degree of saturation at the second blow-through value. The subscripts 1 and 2 represent the macro- and microstructural levels respectively.

**Experiments and testing programme**

**Suction-controlled triaxial apparatus**

Details of the suction-controlled triaxial apparatus are given in Jotisankasa et al. (2007b). The apparatus incorporated the Imperial College tensiometers, the so-called suction probe (Ridley & Burland, 1993, 1999) for independent suction measurement of the soil samples. A new suction control technique was developed and incorporated into a Bishop & Wesley (1975) stress path triaxial apparatus, which consisted of two subsystems, one each for drying and wetting. The drying system was a development based on the air circulation system of Cunningham et al. (2003), which essentially employed a flow of dry air across the base porous disc in order to dry the sample. The rate of drying was controlled by opening and closing the circulation valve, based on suction measurements at the bottom and top of the sample, so as to avoid too high a suction gradient across it. The new development involved incorporating a relative humidity sensor into the air-out line, the readings from which were used to estimate the amount of water loss from the sample during drying. The water mass transfer during suction-controlled tests could therefore be calculated. Jotisankasa et al. (2007b) explain in detail the method used for the estimation and its underlying assumptions. The rate of drying was controlled in terms of the changes in suction using a feedback loop from the measurements of the suction probes attached at the side of the soil sample and an air-flow valve connected to a control system.

The wetting system incorporated in the triaxial apparatus is shown in Fig. 2. It employs the circulation of water and air across the top surface of the sample via a flexible tube using a peristaltic pump. During the circulation, water was gradually absorbed into the soil sample. A plastic woven mesh and a piece of filter paper were placed between the top surface of the sample and the top cap in order to ensure that wetting occurred evenly over the surface of the sample. The amount of water within the tube before and after the circulation was measured, and other parts of the system were checked after circulation to ensure that all of the water was accounted for. The amount of water absorbed by the sample could therefore be calculated for each wetting, and the water mass transfer and soil water content are known during suction-controlled tests. The wetting was carried out incrementally, and after each increment the readings of both suction and the local strains were allowed to stabilise, prior to the next stage. As will be explained later, the wetting system was used only in tests involving wetting stages, namely Tests TC25, TC26, TC27 and TC28.

To estimate the total volume change of the sample, local axial and radial strain measurements were used. The axial strain of the sample was measured using a pair of inclinometer-type local strain devices (Burland & Symes, 1982), and the radial strain was monitored at the mid-height of the sample.

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**Fig. 1. Contours of main wetting surface**

**Table 1. Summary of curve-fitting parameters for the main wetting surface**

<table>
<thead>
<tr>
<th>$e$</th>
<th>$a$</th>
<th>$\psi_{b1}$: kPa</th>
<th>$\psi_{res1}$: kPa</th>
<th>$S_{res1}$</th>
<th>$\psi_{b2}$: kPa</th>
<th>$S_e$</th>
<th>$\psi_{res2}$: kPa</th>
<th>$S_{res2}$</th>
</tr>
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<tbody>
<tr>
<td>0.77</td>
<td>0.05</td>
<td>3.5</td>
<td>40</td>
<td>0.50</td>
<td>1300</td>
<td>0.33</td>
<td>4500</td>
<td>0.06</td>
</tr>
<tr>
<td>0.70</td>
<td>0.05</td>
<td>4.5</td>
<td>35</td>
<td>0.56</td>
<td>1200</td>
<td>0.35</td>
<td>4500</td>
<td>0.06</td>
</tr>
<tr>
<td>0.60</td>
<td>0.05</td>
<td>5.5</td>
<td>25</td>
<td>0.68</td>
<td>800</td>
<td>0.43</td>
<td>4500</td>
<td>0.06</td>
</tr>
<tr>
<td>0.50</td>
<td>0.05</td>
<td>6.5</td>
<td>22.5</td>
<td>0.78</td>
<td>700</td>
<td>0.52</td>
<td>4500</td>
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</tr>
<tr>
<td>0.40</td>
<td>0.05</td>
<td>6.5</td>
<td>15</td>
<td>0.85</td>
<td>150</td>
<td>0.86</td>
<td>4500</td>
<td>0.06</td>
</tr>
<tr>
<td>0.35</td>
<td>0.05</td>
<td>6.5</td>
<td>12</td>
<td>0.86</td>
<td>150</td>
<td>0.9</td>
<td>4500</td>
<td>0.06</td>
</tr>
</tbody>
</table>
using a single linear variable displacement transducer (LVDT) strain belt. When the sample was sheared and failed with a barrelled shape, an approach similar to that used by Klots & Coop (2002) was adopted to estimate the global volume change, based on the local strain measurements. Otherwise, a right cylinder assumption was employed for estimating the volume change. Tables 2 and 3 describe the details of tests performed in the suction-controlled triaxial apparatus.

_Fully saturated triaxial tests_

Only two tests, TC1 and TC2 (Group s), were performed in the conventional stress path triaxial cell on saturated samples. The two samples were brought to full saturation by means of back-pressure at a small effective stress (20 kPa) and then isotropically compressed to a mean effective stress $p'$ of 200 kPa prior to shearing. Fig. 3 shows the results during compression as well as the shearing stages. Sample TC1 was sheared drained and Sample TC2 undrained. They seem to define a critical state line (CSL) that is parallel to the normal compression line (NCL) and the CSL for reconstituted samples of the same material, details of which are discussed in Jotisankasa (2005). Nevertheless, the position of the CSL, plotted in $p' - u$ space, for the compacted samples appears to be below that of the reconstituted samples. This is believed to be due to the different fabrics induced by the static compaction process and reconstitution at a water content of 1-5 times the liquid limit.

In order to fit the curvature of the compression paths better, a fitting curve using a power law expression (e.g. Butterfield, 1979) has been used, and a power law CSL has been drawn parallel to it, passing close to the two critical state points. It has been assumed that, as a result of the compaction-induced fabric, the compression paths of the two tests lie above even the power law NCL for mean effective stresses less than about 100 kPa. The power-law fitting curves for the NCL and CSL are those used for further data interpretation, based on the assumption that both samples (TC1 and TC2), although compacted at different water contents, have the same saturated NCL and CSL.

**VOLUMETRIC BEHAVIOUR**

The volumetric behaviour was investigated for samples following two main types of stress path: constant water-content loading (Groups 1, 2 and 3 in Table 2) and constant net-stress wetting (Group 4 in Table 2). This scheme was chosen with the aim of checking the uniqueness of the loading-collapse yield curve, as described previously. The samples from Groups 1, 2 and 3 were compressed at different water contents, while their initial water contents and void ratios after compaction were approximately equal. Table 2 also shows the water contents after modification either by drying or wetting, prior to testing for each sample. The Group 1 tests were performed under an isotropic stress, whereas tests from Groups 2 and 3 were carried out under $K_0$ conditions and with a constant $q/p$ of 0-5 respectively, where $q$ is the deviatoric stress and $p$ is the net mean stress. Fig. 4 shows typical results from the constant-water content loading tests of Group 1, in terms of changes in specific volume and suction with net mean stress. It can be seen that, as the suction increases, the normal compression line dislocates to higher net stresses, as does the yield stress, which has been estimated using the Casagrande (1936) method and is shown as an arrow in Fig. 4(a). Based on the results of the Group 1 tests, the contours of the normal compression lines at suction of 150, 300 and 600 kPa were estimated using contouring software, as explained in the Appendix, and are included in Fig. 4(a).

Also included in Fig. 4 are the results of some wetting tests from Group 4, which were carried out under isotropic stress conditions (Tests TC25 and 26). The tests of this group involved wetting the sample incrementally by means of the water circulation system shown in Fig. 2, while monitoring the suction and water mass transfer to the soil sample. Fig. 4(c) shows the variation of specific volume with suction during wetting for both tests. The yield points are estimated in the figure, and are also included in Fig. 4(b). It can be seen that the onset of yield due both to an increase in net stress and to a decrease in suction can be approximated using the same loading-collapse curve in $s - p$ space.

The results of all the tests from Groups 2, 3 and 4 were interpreted in a similar manner, and the yield points from these tests are plotted together with those of Group 1 in Fig. 5 in terms of deviatoric stress and net mean stress. Also plotted in Fig. 5 are the estimated yield loci at constant suction. The yield loci are skewed, reflecting the anisotropic structure of the compacted soil, which is likely to have been induced during the formation of the samples. This skewed shape of the yield loci has also been observed by other researchers (e.g. Cui & Delage, 1996) for an unsaturated silt prepared by one-dimensional compaction. The yield points
Table 2. Programme of suction-controlled triaxial tests: Groups 1–4, tests primarily investigating compression

<table>
<thead>
<tr>
<th>Group</th>
<th>Test</th>
<th>As-compacte</th>
<th>Prior to testing</th>
<th>Pre-shearing stages</th>
<th>Shearing</th>
<th>Final w: %</th>
<th>Test duration: days</th>
</tr>
</thead>
<tbody>
<tr>
<td>s</td>
<td>TC1</td>
<td>13-0 0-689 49-8</td>
<td>13-0 0-689 49-8</td>
<td>Saturation; isotropic compression to 200 kPa $p'$; saturation; isotropic compression to 200 kPa $p'$</td>
<td>Drained</td>
<td>14-5</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>TC2</td>
<td>10-1 0-694 38-3</td>
<td>10-1 0-694 38-3</td>
<td>Constant $w%$; isotropic compression to 800 kPa; constant $w%$, isotropic compression to 800 kPa</td>
<td>Undrained</td>
<td>18-1</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>TC16</td>
<td>9-8 0-702 36-9</td>
<td>12-9 0-714 47-8</td>
<td>Constant $w%$; isotropic compression to 800 kPa</td>
<td>Constant water content/800 kPa $\sigma_3$</td>
<td>12-4</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>TC18</td>
<td>10-1 0-726 38-6</td>
<td>11-7 0-733 42-2</td>
<td>Constant $w%$; isotropic compression to 800 kPa; constant $w%$, isotropic swelling to 200 kPa</td>
<td>Constant water content/800 kPa $\sigma_3$</td>
<td>11-1</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>TC29</td>
<td>10-1 0-712 37-3</td>
<td>10-6 0-712 39-2</td>
<td>Constant $w%$, isotropic compression to 50 kPa; drying to 1000 kPa suction; constant $w%$, isotropic compression to 800 kPa</td>
<td>Constant water content/200 kPa $\sigma_3$</td>
<td>8-7</td>
<td>19</td>
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<tr>
<td>2</td>
<td>TC14</td>
<td>10-0 0-705 36-8</td>
<td>13-0 0-720 47-1</td>
<td>Constant $w%$, isotropic compression to 20 kPa; constant $w%$, $K_0$-compression to 1093 kPa $p$</td>
<td>Successful (pump reached its stress limit)</td>
<td>—</td>
<td>18</td>
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<tr>
<td></td>
<td>TC15</td>
<td>9-9 0-709 36-9</td>
<td>11-4 0-708 42-7</td>
<td>Constant $w%$, isotropic compression to 20 kPa; constant $w%$, $K_0$-compression to 800 kPa $p$</td>
<td>Constant water content/200 kPa $\sigma_3$</td>
<td>10-8</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>TC30</td>
<td>10-0 0-707 37-3</td>
<td>10-5 0-708 39-2</td>
<td>Constant $w%$, isotropic compression to 50 kPa; drying to 1000 kPa suction; $K_0$-compression to 1400 kPa $p$; Leakage problem</td>
<td>Constant water content/200 kPa $\sigma_3$</td>
<td>—</td>
<td>34</td>
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<tr>
<td>3</td>
<td>TC19</td>
<td>10-1 0-719 37-2</td>
<td>13-2 0-726 48-1</td>
<td>Constant $w%$, isotropic compression to 16 kPa; constant $w%$, anisotropic compression to 960 kPa $p$; constant $w%$, unloaded to 200 kPa $\sigma_3$</td>
<td>Constant water content/200 kPa $\sigma_3$</td>
<td>11-9</td>
<td>26</td>
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<tr>
<td></td>
<td>TC20</td>
<td>10-0 0-709 37-2</td>
<td>11-6 0-715 42-7</td>
<td>Constant $w%$, isotropic compression to 12 kPa; constant $w%$, anisotropic compression to 960 kPa $p$; constant $w%$, unloaded to 200 kPa $\sigma_3$</td>
<td>Constant water content/200 kPa $\sigma_3$</td>
<td>10-8</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>TC25</td>
<td>10-2 0-718 37-3</td>
<td>11-6 0-723 42-4</td>
<td>Constant $w%$, isotropic compression to 200 kPa; wetted at constant stress to 90 kPa succion</td>
<td>Constant water content/200 kPa $\sigma_3$</td>
<td>15-4</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>TC26</td>
<td>10-3 0-714 38-0</td>
<td>11-9 0-716 43-8</td>
<td>Constant $w%$, isotropic compression to 100 kPa; wetted at constant stress to 25 kPa succion</td>
<td>—</td>
<td>20-5</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>TC27</td>
<td>10-2 0-711 37-9</td>
<td>11-8 0-717 43-6</td>
<td>Constant $w%$, isotropic compression to 15 kPa; constant $w%$, anisotropic compression to 220 kPa $p$; wetted at constant stress 20 kPa succion</td>
<td>—</td>
<td>17-6</td>
<td>27</td>
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<tr>
<td></td>
<td>TC28</td>
<td>10-1 0-690 38-7</td>
<td>11-6 0-697 43-9</td>
<td>Constant $w%$, isotropic compression to 20 kPa; constant $w%$, $K_0$-compression to 175 kPa $p$; wetted at constant stresses to 180 kPa succion; constant $w%$ and $q$, loading to 891 kPa $p$; wetted at constant stresses to 0 kPa succion</td>
<td>—</td>
<td>15-4</td>
<td>42</td>
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<td>Group</td>
<td>Test</td>
<td>As-compacte</td>
<td>Prior to testing</td>
<td>Pre-shearing stages</td>
<td>Shearing</td>
<td>Final w: %</td>
<td>Test duration: days</td>
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<tr>
<td></td>
<td>w: %</td>
<td>e</td>
<td>$S_i$: %</td>
<td>w: %</td>
<td>$S_i$: %</td>
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</tr>
<tr>
<td>5</td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>TC7</td>
<td>10-6</td>
<td>0.680</td>
<td>41.3</td>
<td>13.5</td>
<td>0.691</td>
<td>51.5</td>
<td>Constant water content/50 kPa $\sigma_1$</td>
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<tr>
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<td>10-2</td>
<td>0.710</td>
<td>37.9</td>
<td>11.7</td>
<td>0.719</td>
<td>43.1</td>
<td>Constant water content/50 kPa $\sigma_1$</td>
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<td>TC9</td>
<td>10-0</td>
<td>0.718</td>
<td>36.8</td>
<td>10.5</td>
<td>0.712</td>
<td>39.0</td>
<td>Constant water content/50 kPa $\sigma_1$</td>
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<td>TC10</td>
<td>10-0</td>
<td>0.720</td>
<td>36.7</td>
<td>10.2</td>
<td>0.720</td>
<td>37.3</td>
<td>Constant water content/50 kPa $\sigma_1$</td>
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<td>TC21</td>
<td>10-0</td>
<td>0.711</td>
<td>37.0</td>
<td>10.6</td>
<td>0.711</td>
<td>39.2</td>
<td>Constant water content/50 kPa $\sigma_1$; drying to 850 kPa suction</td>
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<td>10-4</td>
<td>0.711</td>
<td>38.4</td>
<td>10.8</td>
<td>0.705</td>
<td>40.6</td>
<td>Constant water content/50 kPa $\sigma_1$; drying to 1000 kPa suction</td>
</tr>
<tr>
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<td>37.7</td>
<td>12.9</td>
<td>0.702</td>
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<td>38.4</td>
<td>10.8</td>
<td>0.702</td>
<td>40.7</td>
<td>Constant water content/200 kPa $\sigma_3$</td>
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<td>0.719</td>
<td>36.4</td>
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<td>0.724</td>
<td>42.03</td>
<td>Constant water content/200 kPa $\sigma_3$</td>
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<td>9-5</td>
<td>0.697</td>
<td>36.0</td>
<td>0.73</td>
<td>0.699</td>
<td>2.8</td>
<td>Constant water content/200 kPa $\sigma_3$</td>
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<td>TC4</td>
<td>10-3</td>
<td>0.685</td>
<td>39.8</td>
<td>0.79</td>
<td>0.676</td>
<td>3.1</td>
<td>Constant water content/50 kPa $\sigma_3$</td>
</tr>
<tr>
<td>TC12</td>
<td>10-1</td>
<td>0.677</td>
<td>39.3</td>
<td>0.68</td>
<td>0.676</td>
<td>2.7</td>
<td>Constant water content/100 kPa $\sigma_3$</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TC19</td>
<td>10-1</td>
<td>0.719</td>
<td>37.2</td>
<td>13.2</td>
<td>0.726</td>
<td>48.1</td>
<td>Constant water content/200 kPa $\sigma_3$</td>
</tr>
<tr>
<td>TC20</td>
<td>10-0</td>
<td>0.709</td>
<td>37.2</td>
<td>11.6</td>
<td>0.715</td>
<td>42.7</td>
<td>Constant water content/200 kPa $\sigma_3$</td>
</tr>
<tr>
<td>TC25</td>
<td>10-2</td>
<td>0.718</td>
<td>37.3</td>
<td>11.6</td>
<td>0.723</td>
<td>42.4</td>
<td>Constant water content/200 kPa $\sigma_3$; wetted at constant stress to 90 kPa suction</td>
</tr>
<tr>
<td>TC29</td>
<td>10-1</td>
<td>0.712</td>
<td>37.3</td>
<td>10.6</td>
<td>0.712</td>
<td>39.2</td>
<td>Constant water content/200 kPa $\sigma_3$; drying to 1000 kPa suction; constant w%, isotropic compression to 800 kPa; constant w%, isotropic swelling to 200 kPa</td>
</tr>
</tbody>
</table>
from both wetting and loading tests correspond to the same set of contours, which is again in agreement with the assumption of a unique loading-collapse surface.

Figure 6 shows the NCLs at different stress ratios for suction of 150, 250 and 600 kPa respectively. The NCLs shown have again been estimated using contouring software, and are based on the post-yield data points from the tests in Groups 1, 2, 3 and 4. The actual stress paths followed by samples from these groups are omitted in the plot for clarity. The trends of the paths are, however, similar to those observed in Fig. 4. The NCL for isotropic compression lies significantly below those for anisotropic states at a suction of 150 kPa. As the suction increases, the NCLs for all stress ratios become closer. Within the limited range of net stresses investigated in the triaxial apparatus, the NCLs were found to be linear in a $v$–$\log p$ plot. If the stress ranges were larger, the NCLs would be likely to be curved, as observed in the oedometer test results (Jotisankasa et al., 2007a). For net mean stresses below about 850 kPa, the NCLs can be characterised using the conventional formulation

$$v = N(s) - \lambda(s) \cdot \ln p$$

(1)

**Fig. 4.** Compression and wetting tests under isotropic loading conditions: (a) $v$–$\log p$; (b) $s$–$\log p$; (c) $v$–$\log s$

**Fig. 3.** Results of triaxial tests on fully saturated samples: (a) $v$–$\log p'$; (b) $p'$ – $\gamma$

**Shearing Behaviour**

Four groups of shearing tests have been performed (Groups 5–8). The details of each test are summarised in Table 3. The aim of the Group 5 tests was to investigate the shearing behaviour at a cell pressure of 50 kPa for samples at different suctions. The shearing tests from Group 6 were carried out at a cell pressure of 200 kPa. The tests from these groups were performed on samples at different suctions and with various stress histories. The shearing was carried out under a constant water content condition in all tests except for Test 23 (Group 5), during which the suction was kept approximately constant during shearing, using the air-circulation system. The Group 7 tests were carried out on air-dried samples at various cell pressures. The Group 8 tests followed a variety of stress paths, involving overconsolidating the samples in different manners, as explained in Table 3. Samples TC19, TC20 and TC29 were well inside the loading-collapse surface before shearing, whereas Sample TC25 had been collapsed by wetting before shearing. All four samples were sheared at a cell pressure of 200 kPa.

The results for shearing of the Group 5 tests are shown in Fig. 7. Prior to shearing, each sample was isotropically compressed to a cell pressure of 50 kPa. After the initial compression it was observed that each sample was still well inside the yield surface on an $s$–$p$–$v$ plot. Creep was allowed until the rate of change in the volumetric strain fell below 0.05%/day, before shearing was started. For the volumetric strains a correction was applied, where necessary, for the barrelled shape of the sample, as described by Klotz & Coop (2002). This correction assumed the deformed shape of the sample to be an arc in its vertical profile, with the ends fixed. The volumetric strains calculated using the right cylinder assumption are also included in the figures for comparison. The barrelled correction was applied only from
the point where the diameter of the sample calculated using the right cylinder assumption corresponded to the smallest diameter measured along the sample's height after the completion of each test. The details of these calculations are explained by Jotisankasa (2005). In tests where two suction probes were used, both readings are shown in the figure.

Table 4 summarises the failure modes observed in all of the samples during shearing. It can be seen that, as the suction increases, the failure mode changes progressively from barrelling without a shear plane, to barrelling with a shear plane, and finally non-barrelling with a shear plane. From Figs 7(a) and 7(b) it is evident that, as the initial suction increases, the samples become stiffer, and reach a higher peak deviatoric stress at a lower strain. For Tests TC21 and 23 the deviatoric stresses reached peak values, prior to reducing rapidly after the formation of failure planes. These observations correspond to the failure modes, as shown in Table 4. Regarding the change in suction during constant water content shearing, Fig. 7(b) suggests that the reduction in suction on loading becomes greater as the initial suction increases and as the degree of saturation decreases. This trend is similar to that observed in the constant water content loading tests illustrated in Fig. 4.

### Table 4. Failure mode (Barrelling, Non-Barrelling/Shear plane, No Shear plane)

<table>
<thead>
<tr>
<th>Group 5</th>
<th>Group 6</th>
<th>Group 7</th>
<th>Group 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC7</td>
<td>B/NS</td>
<td>TC13</td>
<td>B/NS</td>
</tr>
<tr>
<td>TC8</td>
<td>B/S</td>
<td>TC22</td>
<td>B/NS</td>
</tr>
<tr>
<td>TC9</td>
<td>B/S</td>
<td>TC24</td>
<td>B/NS</td>
</tr>
<tr>
<td>TC10</td>
<td>NB/S</td>
<td>TC12</td>
<td>NB/S</td>
</tr>
<tr>
<td>TC21</td>
<td>NB/S</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TC23</td>
<td>NB/S</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 5. Yield loci at different suction from Groups 1, 2, 3 and 4 triaxial tests. Suction value indicated adjacent to data point for each test.

Fig. 6. Normal compression lines for isotropic, constant $q/p$, and $K_0$ compression tests at constant suction of 150, 250 and 600 kPa.

Fig. 7. Results for shearing of Group 5 triaxial tests: (a) $q$-axial strain; (b) $u_w$-axial strain; (c) volumetric strain-axial strain.
Of particular interest is the result of Test TC23, in which the suction was maintained constant during shearing. The drying system was controlled using the suction measurement near the base, closer to the drying surface. The suction at the top of the sample was within about 10% of the base reading at the start of the shearing phase. However, after about 4% axial strain the sample sheared along a discrete plane, and the relative movement of the two blocks caused the membrane to stretch, resulting in a shear test probe losing contact with the soil. This loss in contact brought about a steady increase of the top suction measurement, as shown in Fig. 7(b).

The changes in volumetric strain during shearing are shown in Fig. 7(c). All of the samples, regardless of their suction, initially reduced in volume upon shearing, up to an axial strain of around 0.5–1.5% (dilation is plotted here as negative). The samples with lower initial suctions tended to compress more, and did so up to a higher strain. After continued shearing the samples started to dilate. The general trend is that the higher the suction, the greater was the dilation. The arrows indicate the points at which the barrel-ling correction was started in Tests TC7, TC8 and TC9. With the assumption of the barrelled shape, the dilation becomes less than that which was calculated based on the right cylinder assumption. The representative volumetric strains of the samples are likely to have values between those based on the two assumptions. From Fig. 7(c), none of the samples showed clearly that a constant-volume condition was achieved, although the volumetric strain in Test TC7 was probably reaching a constant value towards the end of the test. The degrees of saturation were also calculated, although they are not shown here. For all tests, the degree of saturation appeared to reduce slightly upon completion of shearing.

Influence of overconsolidation on shearing behaviour

Figure 8 shows the results during shearing for tests from Groups 6 and 7. Samples TC13, TC22 and TC24 were initially isotropically compressed to a cell pressure of 200 kPa at different constant water contents, prior to shearing, whereas Sample TC25 was first compressed to a cell pressure of 200 kPa, and then wetted and collapsed to a suction of about 70 kPa. From the observation of the behaviour of these samples on an s–p–v plot, Samples TC13, TC24 and TC25 were at the onset of yielding on the loading-collapse surface at the start of shearing, whereas Sample TC22 was still within the yield surface.

For the three samples from Group 8 (Tests TC19, 20 and 29), the stress histories prior to shearing were different from those from Group 6, as described in Table 3. These three samples were initially compressed at constant water contents to a net mean stress in excess of 800 kPa before being unloaded to a cell pressure of 200 kPa. Tests TC19 and TC20 also involved anisotropic compression of the sample. Their states prior to shearing were therefore those of overconsolidated samples, and far inside the loading-collapse surface when plotted in s–p–v space.

The plot of deviatoric stress against axial strain in Fig. 8(a) shows a strain-hardening mode of failure for all samples except TC29. The general trend for the results of Tests TC13, TC22, TC24 and TC25 is that the samples with higher initial suctions were stiffer, they reached higher ultimate deviatoric stresses, and their volumetric strains were less compressive during shearing. As indicated in Table 4, all four samples (TC13, TC22, TC24 and TC25) failed in a barrelled mode without any formation of failure planes. Nevertheless, none of the samples appeared to reach a constant-volume state within the working range of the radial strain transducer. This is considered to be an important limitation of the instrumentation, which made it impossible to continue the tests to larger strains. However, the deviatoric stresses and the pore water pressures appeared to be reaching constant values at larger strains. It is therefore likely that at axial strains above 20% all samples would probably have reached a critical state.

The more highly overconsolidated samples of Group 8 (TC19, TC20 and TC29) appear to be more dilatant (Fig. 8(c)), yet are showing overall a strain-hardening behaviour in Fig. 8(a) except Sample T29. Despite the difference in the initial suctions of Samples T19 and TC20, the values of the ultimate deviatoric stresses and the stress paths followed were very similar. It was thus believed that other factors, such as void ratio and degree of saturation, had come into play, as will be discussed later. The failure modes of the three samples, as shown in Table 4, were barrelled, combined with the development of a slip plane. From a comparison of Tests TC22 and TC21 (Figs 7 and 8), despite having similar final suctions of about 700 kPa, Sample TC22 failed in a barrelled mode, as opposed to the slip-plane formation for TC21. This was due to the higher confining pressure used for Test TC22. It can be concluded that the failure mode of the sample depends not only on the suction, but also on the relative distance of the sample state from the yield surface in p–q–s stress space.

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Fig. 8. Results for shearing of Groups 6 and 7 triaxial tests: (a) q-axial strain; (b) μ-axial strain; (c) volumetric strain–axial strain
Failure envelopes

The failure envelopes corresponding to the peak and ultimate deviatoric stresses from shearing tests at cell pressures of 50 and 200 kPa are shown on a $q$–$p$ plot in Fig. 9. The points corresponding to zero suction were estimated using the fully saturated failure envelope, determined from a series of fully saturated shearing tests, details of which are given by Jotisankasa (2005). The envelopes are clearly non-linear, and within the suction range investigated (up to 1000 kPa) may be characterised as approximately bilinear. Test TC25 was stopped prematurely owing to the limitation of the travel distance of the axial loading system. The deviatoric stress at the critical (or ultimate) state of Test TC25 shown in Fig. 9 was therefore estimated from Fig. 8 to be between 500 and 550 kPa. This estimated stress at the ultimate state falls close to the same trend as those from other tests of Group 6, as shown in Fig. 9. At a lower cell pressure of 50 kPa the strain-softening behaviour of samples with suction higher than about 400 kPa means that the peak and ultimate failure envelopes are not the same.

Being only slightly overconsolidated before shearing, Sample TC29 had a barrelled shape with a slip plane upon failure. The stress state of the sample at the peak deviatoric stress is also plotted in Fig. 9 and is found to lie close to the same trend as the failure envelope of the Group 6 tests. For Tests TC19 and 20, however, the samples were heavily overconsolidated. From Fig. 8, it could be assumed that both samples had reached the critical state upon shearing, as suggested by the constant deviatoric stress and pore water pressure, and the trend of the volumetric strain towards a constant value. The stress states at failure of the two tests, when plotted in Fig. 9, however, lie significantly above the failure envelope of the Group 6 and Test 29, probably because of the overconsolidation.

Air-dried shearing tests

This group of tests (Group 7) was carried out with the aim of identifying the boundary of the failure envelope on a $q$–$p$ plot at the maximum suction. As described in Table 3, three tests were performed, namely TC4, TC12 and TC3, in which air-dried samples were sheared at a constant water content and cell pressures of 50, 100 and 200 kPa respectively. Each sample was dried by being exposed to air in the laboratory until the water content remained unchanged. Upon air-drying, the samples’ void ratios remained practically unchanged owing to the low plasticity of the soils and hence its low expansiveness. The samples were then compressed to a desired cell pressure, and creep was allowed until the rate of change of volumetric strain fell below 0.05%/day (normally for a period of around 1–2 days) before shearing started. However, no suction measurements were performed on these samples during the tests, because the levels of suction were beyond the range of the instrumentation.

The changes in volume during compression prior to the shearing stage were very small, owing to the high suctions. The results during shearing are shown in Fig. 10. The failure mode of all samples was non-barrelling with a distinct shear plane. The stress–strain plots for the three samples show a very brittle behaviour, as would be expected for samples with very high suctions. The peak deviatoric stresses are plotted against the mean net stress in Fig. 11, together with the failure envelope from the fully saturated tests. From these data it could be assumed that the peak failure envelope for the air-dried samples has a similar gradient to that of the fully saturated soil. Also included in Fig. 11 are the stress

![Fig. 9. Failure envelopes](image)

![Fig. 10. Results from triaxial tests on air-dried samples: (a) $q$-axial strain; (b) volumetric strain-axial strain](image)

![Fig. 11. Failure envelopes for air-dried samples](image)
states at the end of the tests. The failure envelope at the completion of the air-dried tests is significantly higher than that of the critical state at zero suction. The suctions of the three samples were not directly measured, but were estimated from the soil water retention curves described in Jotisankasa et al. (2007a) to be around 30 MPa if they are assumed to be unaffected by shearing.

EVIDENCE FOR CRITICAL STATES

Shearing behaviour

An approach similar to that of Toll (1990) and Toll & Ong (2003) has been used to model the data from the triaxial shearing tests. Fig. 12 shows the variations of the parameters $M_s$ and $M_b$ with the degree of saturation at the critical state,

$$ q = M_s(p - u_s) + M_b(u_b - u_w) $$

(2)

where $M_s$ and $M_b$ are parameters that are analogous to the gradient $M_s$ of the critical state line of the saturated soil in $q:p'$ space, but define components of strength arising from net mean stress and suction respectively. The values of $M_s$ at a degree of saturation of 100% (i.e. $M_s$) and at the air-dried state ($S_r \approx 3\%$) are taken directly from the test results shown in Fig. 11. The end-of-test states were assumed to be the critical states for the air-dried samples, despite the effects of the strain localisation. A linear variation of $M_s$ with $S_r$ was initially assumed, and the values of $M_b$ were calculated from the test results. The variations of $M_s$ and $M_b$ at different values of $S_r$ were then adjusted iteratively until smooth variations were obtained with compatible values of the two parameters. The fitting curve for $M_b$ in the figure was derived from

$$ M_s = M_s \quad \text{for} \quad S_r > S_{1a} $$

$$ M_b = M_b \quad \text{for} \quad S_r > S_{1b} $$

$$ M_s = \left( \frac{M_s}{M_s} \right)_{\text{max}} - \left( \frac{M_s}{M_s} \right)_{\text{min}} - \left( S_r - S_m \right) \cdot \frac{k_s}{S_{1a} - S_{1b}} $$

for $S_{1a} < S_r < S_{1a}$

$$ M_b = \left( \frac{M_b}{M_b} \right)_{\text{min}} - \left( \frac{M_b}{M_b} \right)_{\text{min}} - \left( S_r - S_m \right) \cdot \frac{k_b}{S_{1b} - S_{1b}} $$

for $S_{1b} < S_r < S_{1b}$

$$ M_b = \left( \frac{M_b}{M_b} \right)_{\text{min}} \cdot M_b \quad \text{for} \quad S_r < S_{1b} $$

(3)

These equations are similar to those proposed by Toll & Ong (2003), with a difference in the variation of $M_b$. The minimum value of $M_b$ is specified directly from the test results of air-dried samples, as opposed to the value of zero used by Toll (1990).

The reference degrees of saturation, $S_{1a}$ and $S_{1b}$, for the parameters $M_s$ and $M_b$ are specified independently and do not necessarily have the same values, as indicated by the additional subscripts a and b. Nevertheless, the values of $S_{1a}$ and $S_{1b}$ were found to be the same and equal to 100%. This trend is similar to the suggestion by Vanapalli et al. (1996) that $S_{1a}$ represents full saturation (100%), and $S_{1b}$ represents the degree of saturation at the residual state. However, the values of $S_{1a}$ and $S_{1b}$ were determined based on the data at degrees of saturation between 30% and 60% and on some results at air-dried and fully saturated states. More test results at degrees of saturation greater than 60% are needed before any relationships can be established for the strength in that range. The data points included in Fig. 12 are only from the tests in which the samples appeared more likely to have reached critical states (Tests TC7, TC8, TC9, TC10, TC22, TC19 and TC20). Table 5 summarises the parameters for the two fitting curves.

Another approach that includes the degree of saturation within the stress variable is that proposed by Tarantini & Tombolato (2005). Based on the Bishop's stress approach, they suggested that the degree of saturation that is effective in controlling the mechanical behaviour of the aggregate fabric is the degree of saturation of the macropores, $S_m = \frac{e_w - e_{wm}}{e - e_{wm}}$. The term $e_w$ is called the water ratio. It is the ratio of water volume over solid volume: that is, $e_w = S_r \cdot e$. The term $e_{wm}$ is the microstructural water ratio, originally defined by Romero & Vaunat (2000) as the value of $e_w$ at which the retention curves of the same material with different densities converge. For the soil studied, Jotisankasa (2005) found that the convergence occurred at a gravimetric water content of about 3%, corresponding to a value of $e_{wm}$ of 0.0792. The shear strength can then be expressed in the same way as for fully saturated soils, as

$$ q = M_s(p + s S_m) $$

(4)

where $(p + s S_m)$ is similar to the effective stress. The values of $q$ at the critical state were predicted using this approach and are shown in Fig. 13, compared with the experimental values. A good agreement is evident between the predicted and the experimental values. The results from the tests on air-dried samples are excluded from this figure, since these samples were at moisture contents less than the microstructural value. The ultimate shear strength of the air-dried samples, however, is far greater than the value calculated from equation (4) with the value of $S_m$ set to zero. It can then be suggested that for the samples drier than those at the microstructural state, the contribution from the water menisci, or the bonding factor, to the ultimate shear strength becomes significant, and obviously a change to the modified stress approach is required to predict the behaviour of samples accurately in this condition.

Table 5. Parameters for the variations of $M_s$ and $M_b$

<table>
<thead>
<tr>
<th></th>
<th>$M_s$</th>
<th>$S_{1a}$</th>
<th>$S_{1b}$</th>
<th>$k_s$</th>
<th>$(M_b/M_b)_{\text{max}}$</th>
<th>$S_m$</th>
<th>$k_b$</th>
<th>$(M_b/M_b)_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_s$</td>
<td>1.32</td>
<td>100</td>
<td>100</td>
<td>0</td>
<td>0.5</td>
<td>1.5</td>
<td>1.5</td>
<td>0.00452</td>
</tr>
</tbody>
</table>

Fig. 12. Variations of $M_s$ and $M_b$ with degree of saturation
Stress–dilatancy relationships

In Fig. 14 an attempt has been made to examine the relationship between the rate of dilation and the mobilised stress ratio for the tests on the partially saturated samples. The rate of dilation \( \frac{d \varepsilon_d}{d \varepsilon_s} \) is used as usual, where \( \varepsilon_s \) is the shear strain, calculated as \( \varepsilon_s = \varepsilon_a - \varepsilon_v/3 \), in which \( \varepsilon_a \) is the axial strain. In this calculation the average of the volumetric strains assuming the barrelling and right cylinder corrections has been used. In place of the ratio of invariants \( q/p^* \) that would be used for saturated soils, here a mobilised \( M_s \) has been calculated as \( (q - sM_s) \). The term \( sM_s \) represents the additional shear strength mobilised by the suction, and takes account of the current degree of saturation by using the current \( M_s \) from Fig. 12 for the current \( S_s \) at any stage of the test. Also plotted are estimated critical state values of \( M_s \) based on the projected \( S_s \) at the end of the test.

Test TC13 was on a sample that was sheared at a cell pressure of 200 kPa, which was a static on the yield surface, and so its stress–dilatancy behaviour is similar to that of a normally consolidated saturated clay and is compressive throughout. Because of limitations to the axial strains that could be applied, a true critical state could not be reached. Nevertheless, it is clear that the trend is towards the value of \( M_s \) calculated independently from Fig. 12.

Critical state in terms of volume change

For the tests that reached a reasonably constant volume, the critical state points have been plotted in terms of volume in Fig. 15. The maximum and minimum values in the error bars represent the critical state values of the specific volume that resulted respectively from the right cylinder and the barrelling corrections. Critical state lines have been estimated for two values of suction, again using contouring as for the isotropic normal compression lines in Fig. 4. These are compared with the NCLSs from Fig. 4 and the CSL and NCL for the saturated soil, although for the latter an NCL has been shown that is steeper than that shown in Fig. 3, as it has been fitted to a longer portion of the post-yield compression paths of the two saturated tests. In conventional soil mechanics the CSL and NCL would be expected to be parallel, which is clearly not the case here. Toll & Ong (2003) assumed that the parameters that defined the NCL or CSL would be unique for a given degree of saturation, but here the values of \( S_s \) are changing along each line.

From Fig. 4, it appears that over a wider range of stresses the isotropic NCL for the saturated compacted soil is not straight, and so, rather than using the conventional equation (1), the power law assumption of Butterfield (1979) has been adopted, and the equations of Toll (1990) have been modified accordingly.

Fig. 13. Comparison between predicted and experimental deviatoric stresses at critical state using Tarantino & Tombolato (2005) approach

Fig. 14. Typical stress–dilatancy relationships

Fig. 15. Critical state lines and isotropic normal compression lines at constant suctions
\[ \ln v = \ln v_b + b_s \ln p \] for NCL or CSL when \( s = 0 \)
\[ \ln v = \ln v_{ob} + b_a \ln p - b_b \ln s \] for NCL or CSL when \( s \neq 0 \)
\[ v_{ob} = 1 + \frac{e_{ob} \ln s}{S_i} \]

(5)

where \( v_b \) and \( b_s \) are the fitting parameters for the NCL or CSL at zero suction, and the values \( b_a \) and \( b_b \) are equal to \( b_s \) at \( S_i = 1 \). To calculate values of \( b_a \) and \( b_b \) the method of Toll (1990) was adopted, and \( b_b \) was assumed to vary linearly with \( S_i \) and was chosen by multiple regression analysis. The values of \( b_a \) were then calculated directly at each value of \( S_i \).

The data plotted in Fig. 16 include \( b_a \) and \( b_b \) values for all the critical states, isotropic compression data and those for wetting tests as well as anisotropic compression (both constant \( q/p \) and \( K_0 \) conditions). Apart from slightly higher values of \( b_b \) for the wetting tests at lower degrees of saturation, there is very good agreement, showing that \( b_a \) and \( b_b \), which are analogous to \( \lambda_a \) and \( \lambda_b \) used by Toll & Ong (2003), are indeed unique for a given \( S_i \) and are the same for the isotropic NCL, the CSL, and any constant \( q/p \) path in between, so that all of these lines are parallel for a given \( S_i \) as assumed by Toll & Ong (2003). In this case the value of \( b_a \) is negative at lower \( S_i \) values, whereas Toll & Ong (2003) reported only positive values. This is believed to be the result of the collapsible nature of this soil: that is, a decrease in suction could induce a reduction in soil volume, instead of swelling, especially when the soil is of a low degree of saturation.

The volumetric response of the soil during compression and shearing has also been compared with that predicted using the modified stress model of Gallipoli et al. (2003). In this approach the average skeleton stress \( p^* \) is expressed by

\[ p^* = p + S_i S \]

(6)

A bonding factor \( \xi \) is then defined by

\[ \xi = f(s)(1 - S_i) \]

(7)

The function \( f(s) \) is based on an analysis of the stabilising forces at the contact between particles, and the term \( (1 - S_i) \) is assumed to be related to the number of menisci per unit volume of solids. The underlying assumption of the model is that the ratio between the current void ratio and that at the same average skeleton stress for the saturated soil, \( e_s \), should be a unique function of the bonding factor \( \xi \). Gallipoli et al. (2003) suggested that this could be represented by an equation of the form

\[ e = \frac{1}{\xi} [1 - \exp (h \xi)] \]

(8)

where \( a \) and \( b \) are empirical curve-fitting factors. From oedometer tests on the same soil as tested here, Jotisankasa et al. (2007a) found that this form of expression was valid for values of \( \xi \) up to about 0.8, but that for soils in a very dry state it was less successful, as Gallipoli et al. (2003) had expected, and for \( \xi > 1 \) the value of \( e/\xi \) levelled off. Jotisankasa et al. (2007a) also showed that the values of \( a \) and \( b \) depended on the initial fabric of the soil created by compaction under different conditions.

The data from the triaxial tests are shown in Fig. 17, in which the power-law relationship of Butterfield (1979) has again been used to describe the NCL and CSL at zero suction. Because no anisotropic compression tests were carried out on saturated samples, the isotropic NCL has been used to calculate \( e_s \), not only for the isotropic tests on partially saturated samples, but also for the constant \( q/p \) and \( K_0 \) paths and for the wetting tests. Despite this, and given some scatter in the data, the agreement between the various test types is again fairly good up to the maximum \( \xi \) of about 0.8 for the triaxial tests, and can be modelled with equation (8). For the critical states the \( e_s \) values were initially calculated using the saturated CSL, but this was found to lead to the data falling on a distinctly different curve from the compression paths. In the second interpretation of the critical states in Fig. 17, the saturated isotropic NCL has been again used to calculate the \( e_s \) values, in which case the critical state data plot on the same line as the compression paths for the various stress ratios. The values of \( e_s \) would be different in the first and second interpretations for the same skeleton stress, owing to the two different assumptions involved.

CONCLUSIONS

A new suction-controlled triaxial apparatus has been developed and used to test a compacted silty clay that exhibited collapse-on-wetting behaviour. The uniqueness of the loading-collapse (or normal compression) surface has been demonstrated using the new triaxial apparatus for tests involving monotonic loading and wetting paths. Because of the \( K_0 \) condition imposed on the samples during compaction, the behaviour observed in the triaxial tests shows strong anisotropy with a skewed yield surface.

From the shearing tests, stress–dilatancy relationships were plotted in terms of \( \Delta\varepsilon_\alpha/\Delta\varepsilon_\gamma \) against \( (q-\sigma_\delta) \), which provided an indication of the critical state at the end of the tests. The critical state appeared to be reached in the cases

![Fig. 16. Relationships between \( b_a \) and \( b_b \) and degree of saturation for CSLs and NCLs](image1)

![Fig. 17. Relationship between \( e/\xi \) and bonding factor \( \xi \)](image2)
where the samples showed contractant behaviour over much of their stress paths, and at relatively low suction. The samples with relatively high suctions or at low cell pressures failed along a distinct failure plane, and the critical state for these samples did not appear to be reached at the end of the test. An approach similar to that of Tolf (1990) has been satisfactorily used to model the shearing data at the ‘critical state’ for samples with a wide range of degree of saturation.

The estimated critical state parameters in terms of volumetric behaviour were identified, based on the Tolf (1990) model with some modification for the collapse-on-wetting nature of the soil. The relationship between these parameters and the degree of saturation is consistent with those for the normal compression surfaces identified from a variety of stress paths, although the same uncertainties still exist for tests in which critical states were not clearly reached.

A unique relationship between $e_s$ and the bonding factor $\xi$ from the Gallipoli et al. (2003) model was found to exist for a variety of stress paths, including the ‘critical states’. However, the saturated isotropic NCL has to be used to calculate the $e_s$ values, in which case the critical state data plot on the same line as the compression paths for various stress ratios.

**APPENDIX**

Since the experimental results obtained directly from the tests did not usually consist of data at a constant value of one variable (e.g. suction or void ratio), a contouring technique was used in the interpretation of these data. The grid function in a software that was originally designed for geographical contouring purposes was employed, in which the coordinates $x$, $y$ and $z$ needed to be within a similar order of magnitude. Consequently, the grid function was performed on the dataset of $\log p$ (for $x$), $10e$ (for $y$) and $\log s$ (for $z$) as shown in Figs 4a, 6 and 15. The specified volume $v$ was multiplied by 10 to give it a similar order of magnitude to $\log p$ and $\log s$: which is a mathematical transformation necessary to obtain good contouring results. The Kriging method and other default settings were used in this function. The resulting grid data file was imported into a spreadsheet and converted into $p$, $v$ and $s$. Then the data at constant values of suction were sorted. These datasets were then used for further curve-fitting and for the identification of the mathematical expressions for the isotropic, anisotropic and $K_0$-compression lines. The reliability of this method can be seen in Fig. 4(a), where the estimated contour lines are plotted with the actual measurements. This technique was also used to identify the main wetting surface in Fig. 1. However, in this case, the grid function was performed on the dataset of $S_{s}/10$ (for $x$), $\log s$ (for $y$) and $10e$ (for $z$).

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**NOTATION**

- $a$ parameter for sharpness of transition at bending points on retention curve from Gitirana & Fredlund (2004)
- $a$, $b$ parameters for variation of $e_s$ with $\xi$ in equation (7)
- $b_n$, $b_v$ components of gradient of NCL or CSL in volume plane relating to mean net stress (equation (4))
- $b_n$ gradient of NCL or CSL in volume plane for $s = 0$ (equation (4))
- $c_v$ void ratio
- $e_s$ void ratio in saturated condition
- $K_0$ one-dimensional
- $M_v$ gradient of CSL related to mean net stress (equation (2))
- $M_s$ gradient of CSL related to suction (equation (2))
- $M_s$ gradient of CSL for saturated soil (equation (3)), $M_s = M$
- $N$ intercept of NCL at $p' = 1$ kPa
- $p'$ mean total stress, equal to mean net stress if $u_a = 0$
- $p''$ mean effective stress
- $p'$ average skeleton stress
- $p - t_v$ mean net stress
- $q$ deviatoric stress
- $S_{r}$ degree of saturation at second blow-through value
- $S_{t}$ degree of saturation
- $S_{res1}$, $S_{res2}$ degree of saturation at residual point for macro- and microstructural levels
- $S_{ref1}$, $S_{ref2}$ reference degrees of saturation in equation (3)
- $s$ suction = $u_a - u_p$
- $u_a$ pore air pressure
- $u_p$ pore water pressure
- $v$ specific volume
- $v_0$ fitting parameter for NCL or CSL at $s = 0$ (equation (5))
- $w$ water content
- $e_s$ axial strain
- $e_s$ deviatoric strain ($= e_s - e_v/3$)
- $e_v$ radial strain
- $e_v$ volumetric strain
- $\lambda$ gradient of NCL and CSL in $v' - \ln p'$ space
- $\xi$ bonding variable (equation (6))
- $\Psi_{bl}$, $\Psi_{bc}$ blow-through suction for macro- and microstructural levels
- $\Psi_{res1}$, $\Psi_{res2}$ degree of saturation at residual point for macro- and microstructural levels

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