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Parameter variability of undrained shear strength and strain using a database of reconstituted soil tests

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Parameter variability of undrained shear strength and strain using a database of reconstituted soil tests

M. E. W. Beesley and P. J. Vardanega

ABSTRACT

During construction, the mobilisation of undrained shear strength must be limited to avoid soil failure. Soil strains must be controlled to avoid compromising structural serviceability. To assess foundation performance by strength mobilisation, an understanding of soil strains at various levels of strength mobilisation is required. In practice, ground investigation data is often limited, and assessment of the expected variation of stress-strain and undrained shear strength is improved with empirical correlations calibrated with a database. The new database RFG/TXCU-278 contains data of 278 consolidated-undrained triaxial tests on reconstituted fine-grained soil samples compiled from the literature. Analysis of the database to evaluate the variability of undrained strength ratio \( \frac{c_u}{\sigma'_w} \) and a reference shear strain with shear mode is undertaken in this paper. The new database provides evidence that shear strain (like undrained shear strength) is sensitive to the consolidation (isotropic or \( K_0 \)) and shear mode (triaxial compression or extension) applied in the test. For the materials included in the database, the strength mobilisation parameters obtained from a triaxial compression test can be used to predict the corresponding triaxial extension parameters to a reasonable accuracy.

Keywords: Databases, Stress-strain, Fine-grained soils

INTRODUCTION

Prediction of soil strains at increments of stress ratio or mobilisation level (cf. BSI, 1994) allows engineers to better evaluate foundation performance. For this purpose, the Mobilisation Strain Framework (MSF) is a convenient model for characterising nonlinear stress-strain from undrained shear test data (Vardanega and Bolton 2011; Vardanega et al. 2012). Whether a simple hand calculation or a more advanced numerical model is used, checking the possible range of ground movements at any mobilisation level requires the selection of representative design parameters which are often determined by experiment. If a test is representative of the site, \( \gamma_{ref} \) (a reference strain parameter) controls undrained foundation settlement at 50% mobilisation. This important question of whether the soil test is...
representative can only be answered if the possible variation of $\gamma_{ref}$ within the displacement mechanism is known.

**Understanding parameter variability by database analysis**

Variability of a soil test parameter arises from an incomplete knowledge of its variation with different test conditions together with the contribution of natural geological variation. Database analysis is an essential tool for characterising geotechnical variability (e.g., Kulhawy and Mayne 1990; Mayne 1980; Phoon and Kulhawy 1999a,b; Ching and Phoon 2013, 2014a) and many empirical correlations between measured parameters are available in the literature. A decision to use general parameter trends for design depends largely upon the availability of data from the ground investigation. For example, to measure the anisotropy of undrained shear strength ($c_u$) at a ground investigation site advanced testing apparatus such as the hollow cylinder could be used to shear soil specimens to peak failure following different complex stress paths (e.g. Brosse et al. 2017). Alternatively, a variety of soil tests can be employed to assess the effect of shear mode on $c_u$ variation (e.g., Low et al. 2011; Ratananikom et al. 2015). In practice, projects often have limited scope for detailed ground investigation and advanced experimental work. When project test data is scarce, predicting the variation in $c_u/\sigma'_{vo}$ or $\gamma$ must necessarily be estimated from any available test information. Databases such as RFG/TXCU-278 can also be used to establish prior estimates of relevant statistical parameters for subsequent Bayesian analysis as has been done for standard geotechnical parameters in the works of Cao and Wang (2014), Cao et al. (2016) and Wang et al. (2016).

**Variation of Undrained Strength Ratio**

It is well established that $c_u$ is sensitive to its method of measurement. For example, differences have been observed from comparisons of test specimens that were either unconsolidated or reconsolidated (Chen and Kulhawy 1993), isotropically or anisotropically consolidated (Mayne 1985), sheared in different directions (Mayne and Holtz 1985) and at various strain rates (Sheahan et al. 1996; Kulhawy and Mayne 1990). Undrained shear strength is also known to vary with stress history (Ladd et al. 1977; Mayne 1980; Jamiolkowski et al. 1985; Chandler 1988; Ladd 1991). Ladd et al. (1977) proposed a
framework for clays exhibiting ‘normalized behaviour’ that enables the prediction of $c_u$ if in-situ
effective vertical stress and OCR are known (Equation 1):

$$\left( \frac{c_u}{\sigma'_{v0}} \right)_{OC} = OCR^A$$

Where, $A =$ fitted exponent; $\sigma'_{v0} =$ present vertical effective consolidation stress; $(c_u / \sigma'_{v0})_{OC} =$ normalised
strength of an overconsolidated material; $(c_u / \sigma'_{v0})_{NC} =$ normalised strength of a normally consolidated
material; and $OCR =$ ratio of maximum past vertical effective consolidation stress to present vertical
effective consolidation stress.

Using large databases of soil tests, Mayne (1988) and Ching and Phoon (2014b) showed that
the fitted regression coefficient $A$ was sensitive to the consolidation type (isotropic or anisotropic) and
mode of shear (triaxial compression or extension). Following the framework proposed by Kulhawy and
Mayne (1990), Ching and Phoon (2013) developed a data-driven method to standardise $c_u / \sigma'_{v0}$ using
modification factors to capture the effects of different test mode, OCR, strain rate and plasticity index.

**Variation of Mobilised Strain**

While much research effort has focussed on understanding $c_u$ variability, less information is available
to quantify the variability of shear strains. The Mobilisation Strain Framework (MSF) has been
developed to incorporate undrained strength mobilisation parameters in a framework suitable for
reliability-based design style approaches (Vardanega and Bolton 2016a) by employing a simple power-
law model. Equation (2) can be fitted to shear stress-strain data if the peak failure stress is known
(Vardanega and Bolton 2011) and can be expressed as:

$$\frac{1}{M} = \frac{\tau_{mob}}{c_u} = 0.5 \left( \frac{\gamma}{\gamma_{50, CIU}} \right)^{b_{CIU}}$$

Where, $M =$ mobilisation factor (which is akin to a reduction factor on undrained shear strength);
$\tau_{mob} =$ the mobilised shear strength; $\gamma =$ shear strain; $\gamma_{50, CIU} =$ shear strain to mobilise 0.5$c_u$ under
isotropically-consolidated undrained conditions (denoted in previous works as $\gamma_{50, O}$ and for compression
and extension tests the notation $\gamma_{50, CIUC}$ and $\gamma_{50, CIUE}$ is respectively used in this paper); and $b_{CIU}$ is an
exponent to describe non-linearity (ductility): for compression and extension tests the notation $b_{CIUC}$ and $b_{CIUE}$ is respectively used in this paper.

Equation (2) is similar to models used in classic p-y curve work for offshore structures which often assume a set ‘$b$’ value and thus imply a constant soil ductility (Matlock 1970; Zhang and Anderson 2017). A variant of Equation (2) has been incorporated in the AUS constitutive model recently presented in Krabbenhøft et al. (2019).

Vardanega and Bolton (2016b) when discussing the work of Casey et al. (2016) did acknowledge that a modification of Equation (2) is needed when considering $K_0$-tests (shown here in the form of Equation 3) making use of the $B$ parameter which was proposed in Casey et al. (2016) and Vardanega (2012). Equation 3 reduces to Equation 2 if $\tau_0 = 0$ (isotropic stress conditions).

$$\frac{\tau_{mob} - \tau_0}{c_u - \tau_0} = B = 0.5\left(\frac{\gamma}{\gamma_{50\ CKU}}\right)^{b_{CKU}} \quad 0.2 \leq \frac{\tau_{mob} - \tau_0}{c_u - \tau_0} \leq 0.8$$

(3)

Where, $\tau_0$ = initial shear stress; $\gamma_{50\ CKU} = \gamma_{ref}$ shear strain to mobilise 0.5$(c_u - \tau_0)$ (denoted in previous works as $\gamma_{ref}$ and for compression and extension tests the notation $\gamma_{50\ CKUC}$ and $\gamma_{50\ CKUE}$ is used in this paper); and $b_{CKU}$ is an exponent that describes soil non-linearity (ductility): for compression and extension tests the notation $b_{CKUC}$ and $b_{CKUE}$ is respectively used in this paper.

The importance of shear mode was highlighted by P. W. Mayne when discussing Vardanega et al. (2012) (Vardanega et al. 2013): ‘[one] must take care in the mixing and matching of different strength modes’. Klar and Klein (2014) also pointed out that the experimental stress-strain function used in a model prediction should be based on tests simulating the appropriate stress path (for instance, triaxial extension was selected for their study of volume losses with tunnel advancement). Casey (2016) observed that a large difference in reference strain measured in triaxial compression may occur as a result of using an isotropic or $K_0$ consolidation stress path and recommended Equation 4 to describe the variation of reference strain with OCR for CKUC tests:

$$\gamma_{50\ CKUC} = 0.0004(OCR)^{1.57}$$

(4)

By extending the application of the MSF framework to different triaxial stress paths, the key contribution of this paper is in demonstrating the likely variation in stress-strain response with consolidation type (CIU or CKU) and shear mode (triaxial compression or extension).
Comparing shear modes to estimate parameter variation

The mobilisation strain parameters can be used in any serviceability design method that requires a characteristic nonlinear stress-strain curve in the moderate to high strain range (e.g., Lam and Bolton 2011, McMahon et al. 2014). Procedures of settlement prediction which rely upon the assumption of similarity between the load-settlement relationship and the experimental stress-strain curve (e.g., Skempton 1951; Bolton et al. 1990; Osman and Bolton 2005; Klar and Klein 2014) require the selection of an ‘average’ characteristic curve. When ground investigations are limited, a method to quantify the variation of deformation parameters due to changing shear modes is valuable when evaluating the sensitivity of such parameters. As a first step we examine the effect of shear mode and stress history (OCR) on the MSF parameters in absence of the effects of soil structure. To this end a large database of reconstituted soils tests was compiled.

DATABASE: RFG/TXCU-278

The new database RFG/TXCU-278 is analysed of to examine the influence of applied shear mode on $c_u / \sigma_v^0$, $\gamma_{50}$, $\gamma_{90}$, $b_{CIU}$ and $b_{CKU}$ for reconstituted soils. Two shear modes are investigated: triaxial compression and triaxial extension. Table 1 lists the sources of data in the database compiled from experiments on 23 fine-grained soils from 21 publications. Shear stress-strain data from 278 consolidated undrained triaxial tests were digitised or acquired from the authors’ tabulated data where available. The selection criteria for the database were:

(i) Multiple experiments using reconstituted samples of natural fine-grained soil,
(ii) consolidated at different overconsolidation ratios (OCR), under isotropic or $K_0$ conditions,
(iii) and subsequently sheared in triaxial compression or extension up to peak failure to examine the effect of applied shear mode. (Several datasets included samples sheared in compression only, to increase the range of soil types studied – see Table 1).

Strain rate corrections were not applied to the digitised test data as a universal modification factor for strain measurements was not available. Previous studies have shown that $c_u$ increases by 10 to 20% per log cycle of increased strain rate (Kulhawy and Mayne 1990). The number of digitised data-points for each triaxial test ranged from 3 to around 200 with a mean of 24. Therefore, for consistency the model
parameters were derived by applying either Equation 2 or 3 as appropriate to the digitised test data and then using the fitted equation to calculate them (e.g., $\gamma_{50\ CIUC}$ and $b_{CIUC}$).

**Classification of database samples**

Classification of the 23 experimental soils indicate a wide range of plasticity (Figure S1), with about 70% of materials classified as inorganic and medium-high plasticity. Materials classified outside of this range include the processed kaolin clays, which cluster close to the A-line, and a low plasticity glacial till investigated by Gens (1982). With exception of the kaolin materials, all soils included in RFG/TXCU-278 were sampled from natural deposits.

**ANALYSIS**

The power-law model (Equation 2 or 3) was fitted to the data points of 271 tests with a range of $0.779 \leq R^2 \leq 0.9999$ and $0.0017 \leq S.E. \leq 0.0925$. Seven tests provided only peak stress data. The collected test database is presented in sub-databases of specimen consolidation type (isotropic or $K_0$) and shear mode (triaxial compression or triaxial extension) which are identified by test mode i.e. CIUC, CIUE, CKUC and CKUE. Undrained strength data from a triaxial test database (number of tests = 70) of natural clays, digitised from Mayne and Holtz (1985), are also presented for comparison: about 75% of each sub-database consists of normally consolidated specimens, with $OCR$ ranging from 1 to 25 for CIU tests and 1 to 20 for CKU tests.

Empirical correlations (or transformation models) of the test parameters were investigated using linear regression analysis and standard errors were calculated to describe scatter in the data. An alternative description of parameter variability using predicted vs. measured plots and bandwidths of prediction error is valuable (Koutsoftas et al. 2017; Kootahi and Mayne 2017), particularly when evaluating the variability of different parameters (or the uncertainty of different transformation models). All factor errors quoted in this paper refer to a region that encompasses 80% of the data points and may be viewed in graphical form in the Online Supplement.
Correlation between triaxial extension and compression parameters

The undrained strength (Figure 1) and strain parameters obtained for each digitised test are presented by comparing extension and compression modes. Pairs of tests (i.e. extension and compression) on the same material with identical OCR (±0.1) and strain rate were selected from each published series of experiments. Linear regression analysis indicates that a significant relationship exists between $c_u/\sigma'_{v0}$ measured in compression and in extension for samples consolidated under either isotropic or K0 stresses, with a high coefficient of determination and $p<0.001$ (see Figure 1). K0-consolidated specimens appear to have greater strength anisotropy and less scatter (standard error). The intact soils show similar ranges in $c_u/\sigma'_{v0}$ to the reconstituted soils and produce close best-fit lines between normalised compression and extension strengths. On average, intact soils demonstrate to some extent greater strength anisotropy and more variability than reconstituted soils. A comparison of predicted vs. measured reconstituted soil data shows the factor error of the regression to be 1.3 to 1.4 depending on consolidation type (Figure S2).

Significant correlations also exist between the reference strains measured in triaxial extension and compression, although only reconstituted soil data are available. Figure 2 shows that the reference strains are less sensitive to shear mode if tested from an isotropic stress state: the slope regression coefficient for CKU tests is five times the slope for CIU tests. Reference strains mobilised in CKUE, in some cases, are one order of magnitude greater than the strains mobilised in CKUC; considerable scatter of the strain anisotropy (Figure S3) warrants further investigation. No correlation to describe the shear mode effect was found for $b_{CKU}$ or $b_{CIU}$ (see Table 2 for average means and standard deviations) although the CKU tests analysed here show more disparity between compression and extension (see Figure S4). Using the framework presented in this paper, a designer could possibly justify the likely variation of reference strain from a single triaxial compression test with no prior information about the material or in-situ conditions. From this database, the prediction of triaxial extension reference strain includes a factor error of 1.7 to 2.2 (dependent on CIU or CKU test conditions), which can be incorporated into sensitivity analyses.
Estimation of OCR

Using only 2 measurements of $c_u/\sigma'_o$ at different depths, the SHANSEP framework (Ladd et al. 1977; Mayne 1988) can be adopted to assess OCR of the soil using Equation (1). Table 3 shows the values of $(c_u/\sigma'_o)_{NC}$ and $\Lambda$ by shear mode for the sub-databases presented here and in other studies (see also Mayne et al. 2009 for values of $(c_u/\sigma'_o)_{NC}$ by test mode). The reference strain data in Figure 3 suggest that a similar approach can be used with measurements of $\gamma$. The new transformation models given by Equations 5 to 8 identify positive correlations between the reference strain and OCR in all four test modes. Hence, with knowledge of a reference strain from a triaxial test OCR may be estimated (using an analogous approach to that shown in Mayne 1988 with $c_u$).

Using Equations 5 to 8 (Figure 3), OCR can be approximated with a factor error of 1.5 to 2.7 for the selected consolidation-shear mode. Adopting the SHANSEP framework (Equations 9 to 12, given in Table 3) to estimate OCR produces a factor error of 1.3 to 1.8. Perhaps as expected soil mobilisation strains are a poorer predictor of OCR than undrained shear strength (i.e. the correlations have lower $R^2$ values). Figures S7 and S8 show that for Equations 5 to 8 around 80% of the data plots within a bandwidth of 1.7 to 2.1 factor error (about the predicted = measured line). Equation 6 is of similar form to Equation 4 and this may be partly explained by some shared data from Abdulhadi (2009).

\[
\begin{align*}
\gamma_{50 \text{CU}} &= 0.0010(OCR) + 0.0074 \quad [n = 114, R^2 = 0.51, S.E. = 0.0051, p<0.001] \quad (5) \\
\gamma_{50 \text{CE}} &= 0.0013(OCR) + 0.0042 \quad [n = 55, R^2 = 0.65, S.E. = 0.0033, p<0.001] \quad (6)
\end{align*}
\]

\[
\log_{10}(\gamma_{50 \text{CU}}) = 1.35\log_{10}(OCR) - 3.31 \quad [n = 67, R^2 = 0.79, S.E. = 0.234, p<0.001] \quad (7a)
\]

which can be rearranged as:

\[
\gamma_{50 \text{CU}} = 0.00049(OCR)^{1.35} \quad (7b)
\]

\[
\gamma_{50 \text{CE}} = 0.0038(OCR) \quad [n = 30, R^2 = 0.45, S.E. = 0.0086, p<0.001] \quad (8)
\]
SUMMARY

RFG/TXCU-278 is a large database of triaxial tests on reconstituted soil samples that has been analysed by consolidation mode (isotropic or \(K_0\)) and shear mode (compression or extension) to quantify the variability of shear strength and strain. Undrained strength ratio \((c_u/\sigma'_v)\) and MSF parameters \(\gamma_{50\,CIU}\), \(\gamma_{50\,CKU}\), \(b_{CIU}\) and \(b_{CKU}\) were chosen to study the influences of shear-mode anisotropy and OCR on parameter variability. The correlations presented for quantifying the variability of the undrained strength and strain parameters in this study may not be representative of intact materials, but the general trends are useful for those wishing to assess the effects of OCR (less reported for studies on intact soils) and shear mode. Factor errors of the new transformation models provide a useful indication of parameter variability related to the uncertain effects of different experimental procedures and the material variability of reconstituted soils.

ACKNOWLEDGEMENTS

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DATA AVAILABILITY STATEMENT

This research has not generated new experimental data.

NOTATION

The following notation is used in this paper:

\[ b_{CIU} = \text{fitted exponent (Equation 2) in power-law regression of normalised shear strain } (\gamma/\gamma_{50\,CIU}) \text{ and stress ratio } (\tau_{mob}/c_u); \]

\[ b_{CKU} = \text{fitted exponent (Equation 3) in power-law regression of normalised shear strain } (\gamma/\gamma_{50\,CKU}) \text{ and stress ratio } (\tau_{mob} - \tau_0)/(c_u - \tau_0); \]

\[ B = \text{stress ratio for tests sheared from anisotropic conditions (with initial shear stress)} \]

\[ c_u = \text{undrained shear strength}; \]

\[ c_u/\sigma'_v = \text{normalised undrained strength, or undrained strength ratio}; \]

\[ (c_u/\sigma'_v)_{NC} = \text{normalised strength of a normally consolidated material}; \]
(c_u/σ'v_0)_{OC} = normalised strength of an overconsolidated material;

I_P = Plasticity index;

K_0 = ratio of horizontal to vertical stress with zero lateral strain;

M = mobilisation factor (which is akin to a reduction factor on undrained shear strength);

n = number of data points;

OCR = overconsolidation ratio (maximum past consolidation stress to present consolidation stress);

p = calculated probability of finding the observed value to be at least as extreme as the test statistic when the null hypothesis H_0 is true;

R^2 = coefficient of correlation;

S.E. = standard error;

w_L = liquid limit;

w_P = plastic limit;

γ = shear strain;

γ_{50 CIU} = reference shear strain to mobilise 0.5c_u in a consolidated undrained isotropic test;

γ_{50 CKU} = reference shear strain to mobilise 0.5(c_u – τ_0) in a consolidated undrained K_0 test;

γ_{ref} = a reference shear strain;

A = fitted exponent in power-law regression of normalised undrained strength and OCR;

σ'_{v_0} = current vertical consolidation stress;

τ = shear stress

τ_{mob} = increment of mobilised shear strength;

τ_0 = initial shear stress;

CAU = Anisotropically-consolidated undrained test of any shear mode;

CIU = Isotropically-consolidated undrained test of any shear mode;

CKU = K_0-consolidated undrained test of any shear mode;

CAUC = Anisotropically-consolidated undrained triaxial compression;

CAUE = Anisotropically-consolidated undrained triaxial extension;

CIUC = Isotropically-consolidated undrained triaxial compression
CIUE = Isotropically-consolidated undrained triaxial extension;
CKUC = $K_0$-consolidated undrained triaxial compression;
CKUE = $K_0$-consolidated undrained triaxial extension;
MSF = Mobilisation Strain Framework;
SHANSEP = Stress History and Normalized Soil Engineering Properties.

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[https://doi.org/10.1139/t00-054](https://doi.org/10.1139/t00-054)
### Table 1: Sources of experimental data in RFG/TXCU-278

<table>
<thead>
<tr>
<th>Reference</th>
<th>Test Material</th>
<th>$w_L$ (%)</th>
<th>$w_P$ (%)</th>
<th>Test modes</th>
<th>OCR Range</th>
<th>Excluded test data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parry (1956, 1960)</td>
<td>Wreahl Clay (n=8)</td>
<td>43</td>
<td>25</td>
<td>CIUC (n=6)</td>
<td>1-12</td>
<td>8 undrained tests available for digitisation (drained tests excluded)</td>
</tr>
<tr>
<td>Gasparre (2005)</td>
<td>London Clay (n=7)</td>
<td>63-67</td>
<td>35-41</td>
<td>CIUC (n=7)</td>
<td>1-12</td>
<td>6 tests excluded from digitisation due to poor resolution</td>
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<tr>
<td>Gens (1982)</td>
<td>Lower Cromer Till (n=10)</td>
<td>25</td>
<td>12</td>
<td>CIUC (n=5)</td>
<td>1-10</td>
<td>All undrained tests included (drained tests excluded)</td>
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<tr>
<td>Loudon (1967)</td>
<td>Kaolin (n=8)</td>
<td>74</td>
<td>32</td>
<td>CIUC (n=8)</td>
<td>1-8.1</td>
<td></td>
</tr>
<tr>
<td>Liu (2004)</td>
<td>Kaolin (n=22)</td>
<td>56</td>
<td>24</td>
<td>CIUC (n=11)</td>
<td>1-8</td>
<td>3 tests excluded from digitisation due to poor resolution</td>
</tr>
<tr>
<td>Sachan &amp; Penumadu (2007)</td>
<td>Kaolin (n=12)</td>
<td>62</td>
<td>30</td>
<td>CIUC (n=6)</td>
<td>1-10</td>
<td>6 tests on 'Flocculated' samples included; 6 tests on 'Dispersed' samples excluded</td>
</tr>
<tr>
<td>Conn (1988)</td>
<td>Keuper Marl (n=20)</td>
<td>36</td>
<td>17</td>
<td>CIUC (n=9)</td>
<td>1-10</td>
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</tr>
<tr>
<td>Valls-Marquez (2009)</td>
<td>Kaolin (n=11)</td>
<td>65</td>
<td>32</td>
<td>CIUC (n=7)</td>
<td>1-5.1</td>
<td></td>
</tr>
<tr>
<td>Braathen (1966)</td>
<td>Boston Blue Clay (n=3)</td>
<td>45.5</td>
<td>22.3</td>
<td>CIUC (n=3)</td>
<td>1-8.1</td>
<td>4 cyclic tests and 7 anisotropically consolidated tests excluded from digitisation as per selection criteria; 1 CIUC test (OCR=2) excluded due to possible seating/bedding error</td>
</tr>
<tr>
<td>Fayad (1986)</td>
<td>Boston Blue Clay (n=1)</td>
<td>42</td>
<td>21</td>
<td>CIUC (n=1)</td>
<td>7.5</td>
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<tr>
<td>Chu and Yin (2000)</td>
<td>Hong Kong Marine Clay (n=24)</td>
<td>60</td>
<td>32</td>
<td>CIUC (n=12)</td>
<td>1-8</td>
<td></td>
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<tr>
<td>Atkinson &amp; Little (1988)</td>
<td>Ware Lodgement Till (n=7)</td>
<td>40</td>
<td>22</td>
<td>CIUC (n=7)</td>
<td>1-32</td>
<td>10 'tubed' (intact) samples excluded</td>
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<td>Kamal (2012)</td>
<td>Oxford Clay (n=5)</td>
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<td>32</td>
<td>CIUC (n=5)</td>
<td>1-10</td>
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<td>Kamal (2012)</td>
<td>Gauld Clay (n=3)</td>
<td>74</td>
<td>46</td>
<td>CIUC (n=3)</td>
<td>1-5</td>
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<td>Kamal (2012)</td>
<td>Kimmeridge Clay (n=3)</td>
<td>49</td>
<td>26</td>
<td>CIUC (n=3)</td>
<td>1-5</td>
<td></td>
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<tr>
<td>Vardanega et al. (2012) c</td>
<td>Kaolin (n=18)</td>
<td>62.6</td>
<td>33</td>
<td>CIUC (n=18)</td>
<td>1-20</td>
<td></td>
</tr>
<tr>
<td>Parry &amp; Nadarajah (1974)</td>
<td>Kaolin (n=8)</td>
<td>72</td>
<td>32</td>
<td>CIUC (n=4)</td>
<td>1-2.3</td>
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<td>K0-consolidated undrained triaxial shear tests</td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Fayad (1986)</td>
<td>Boston Blue Clay (n=7)</td>
<td>42</td>
<td>21</td>
<td>CKUC (n=4)</td>
<td>1-8.2</td>
<td>1 cyclic test excluded</td>
</tr>
<tr>
<td>Gens (1982)</td>
<td>Lower Cromer Till (n=10)</td>
<td>42</td>
<td>21</td>
<td>CKUC (n=6)</td>
<td>1-10</td>
<td>All undrained tests included (drained tests excluded)</td>
</tr>
<tr>
<td>Valis-Marquez (2009)</td>
<td>Kaolin (n=2)</td>
<td>65</td>
<td>32</td>
<td>CKUC (n=1)</td>
<td>1-7</td>
<td></td>
</tr>
<tr>
<td>Abdulhadi (2009)</td>
<td>Boston Blue Clay (n=22)</td>
<td>46.5</td>
<td>22.7</td>
<td>CKUC (n=19)</td>
<td>1-4.2</td>
<td>1 CKUC test excluded from digitisation due to poor resolution</td>
</tr>
<tr>
<td>Kamei &amp; Nakase (1989)</td>
<td>Kawasaki Clay (n=8)</td>
<td>55.3</td>
<td>29.4</td>
<td>CKUE (n=4)</td>
<td>1-9.6</td>
<td></td>
</tr>
<tr>
<td>Hight et al. (1985)</td>
<td>London Clay (n=7)</td>
<td>75</td>
<td>37</td>
<td>CKUE (n=4)</td>
<td>1-7</td>
<td></td>
</tr>
<tr>
<td>Hight et al. (1985)</td>
<td>North Sea Clay (n=8)</td>
<td>32</td>
<td>17</td>
<td>CKUE (n=5)</td>
<td>2-8</td>
<td></td>
</tr>
<tr>
<td>Sheahan (1991)</td>
<td>Boston Blue Clay (n=37)</td>
<td>45.1-45.8</td>
<td>23-25.5</td>
<td>CKUE (n=28)</td>
<td>1-8</td>
<td></td>
</tr>
<tr>
<td>Parry &amp; Nadarajah (1974)</td>
<td>Kaolin (n=7)</td>
<td>72</td>
<td>32</td>
<td>CKUE (n=3)</td>
<td>1-2.6</td>
<td>1 CKUC test excluded from digitisation due to poor resolution</td>
</tr>
</tbody>
</table>

Notes: Digitised peak deviator stress and shear strain $\gamma = 1.5$ times axial strain have been used to develop all the correlations in this paper.

- Liquid limit ($w_L$) and plastic limit ($w_P$) were measured using the standard methods (BSI 1990) of fall cone penetrometer and thread-rolling. In two studies (Gasparre 2005 and Sheahan 1991) the authors identify $w_L$ and $w_P$ values for the block sample associated with each reconstituted specimen, while the other studies indicate a single ‘best estimate’ value for the set of specimens.

- $n$ = number of tests.

- Experimental data of the triaxial tests published by Vardanega et al. (2012) were reanalysed and re-filtered from the original data source for this paper.
Table 2: Distribution of non-linearity parameter from undrained triaxial compression and extension tests sorted by test mode

<table>
<thead>
<tr>
<th>Sample type</th>
<th>OCR</th>
<th>Test mode</th>
<th>mean</th>
<th>standard deviation</th>
<th>n</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstituted</td>
<td>1-32</td>
<td>b_{CIUC}</td>
<td>0.459</td>
<td>0.143</td>
<td>114</td>
<td>This study</td>
</tr>
<tr>
<td>Reconstituted</td>
<td>1-12</td>
<td>b_{CIUE}</td>
<td>0.399</td>
<td>0.082</td>
<td>55</td>
<td>Vardanega &amp; Bolton (2011)</td>
</tr>
<tr>
<td>Reconstituted</td>
<td>1-10</td>
<td>b_{CIUC}</td>
<td>0.581</td>
<td>0.167</td>
<td>68</td>
<td>Vardanega &amp; Bolton (2011)</td>
</tr>
<tr>
<td>Reconstituted</td>
<td>1-17</td>
<td>b_{CIUE}</td>
<td>0.350</td>
<td>0.100</td>
<td>34</td>
<td>Vardanega &amp; Bolton (2011)</td>
</tr>
<tr>
<td>Intact</td>
<td>Unknown</td>
<td>b_{CIU}</td>
<td>0.608</td>
<td>0.158</td>
<td>92</td>
<td>Vardanega &amp; Bolton (2011)</td>
</tr>
</tbody>
</table>
Table 3: Correlations between $OCR$ and $(c_u/\sigma' v_0)$ from undrained triaxial compression and extension tests sorted by test mode

<table>
<thead>
<tr>
<th>Sample type</th>
<th>Database Reference</th>
<th>OCR</th>
<th>Test mode</th>
<th>$(c_u/\sigma' v_0)_{he}$</th>
<th>$\Lambda$ (slope regression coefficient)</th>
<th>(Equation number)/Equation</th>
<th>n</th>
<th>R²</th>
<th>S.E.</th>
<th>p-value</th>
<th>Data within error bounds</th>
<th>Factor Error</th>
<th>Figure in Online Supplement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstituted</td>
<td>This study</td>
<td>1-32</td>
<td>CIUC</td>
<td>0.288</td>
<td>0.653</td>
<td>(9) $\log_{10}(c_u/\sigma' v_0)=0.653\log_{10}(OCR)-0.541$</td>
<td>115</td>
<td>0.86</td>
<td>0.114</td>
<td>&lt;0.001</td>
<td>80%</td>
<td>1.45</td>
<td>S5</td>
</tr>
<tr>
<td>Intact</td>
<td>Mayne 1988</td>
<td>1-20</td>
<td>CIUC</td>
<td>0.25</td>
<td>0.7</td>
<td></td>
<td>115</td>
<td>0.86</td>
<td>0.114</td>
<td>&lt;0.001</td>
<td>80%</td>
<td>1.45</td>
<td>S5</td>
</tr>
<tr>
<td>Intact</td>
<td>Mayne 1988</td>
<td>1-20</td>
<td>CIUC</td>
<td>0.55</td>
<td>0.7</td>
<td></td>
<td>115</td>
<td>0.86</td>
<td>0.114</td>
<td>&lt;0.001</td>
<td>80%</td>
<td>1.45</td>
<td>S5</td>
</tr>
<tr>
<td>Intact</td>
<td>Ching &amp; Phoon 2014b</td>
<td>1-6</td>
<td>CIUC</td>
<td>0.397</td>
<td>0.71</td>
<td></td>
<td>115</td>
<td>0.86</td>
<td>0.114</td>
<td>&lt;0.001</td>
<td>80%</td>
<td>1.45</td>
<td>S5</td>
</tr>
<tr>
<td>Reconstituted</td>
<td>This study</td>
<td>1-12</td>
<td>CIUE</td>
<td>0.267</td>
<td>0.729</td>
<td>(10) $\log_{10}(c_u/\sigma' v_0)=0.729\log_{10}(OCR)-0.574$</td>
<td>55</td>
<td>0.92</td>
<td>0.083</td>
<td>&lt;0.001</td>
<td>80%</td>
<td>1.30</td>
<td>S5</td>
</tr>
<tr>
<td>Intact</td>
<td>Mayne 1988</td>
<td>1-20</td>
<td>CIUE</td>
<td>0.20</td>
<td>0.58</td>
<td></td>
<td>55</td>
<td>0.92</td>
<td>0.083</td>
<td>&lt;0.001</td>
<td>80%</td>
<td>1.30</td>
<td>S5</td>
</tr>
<tr>
<td>Intact</td>
<td>Mayne 1988</td>
<td>1-20</td>
<td>CIUE</td>
<td>0.60</td>
<td>0.58</td>
<td></td>
<td>55</td>
<td>0.92</td>
<td>0.083</td>
<td>&lt;0.001</td>
<td>80%</td>
<td>1.30</td>
<td>S5</td>
</tr>
<tr>
<td>Reconstituted</td>
<td>This study</td>
<td>1-10</td>
<td>CKUC</td>
<td>0.300</td>
<td>0.790</td>
<td>(11) $\log_{10}(c_u/\sigma' v_0)=0.790 \log_{10}(OCR)-0.522$</td>
<td>74</td>
<td>0.94</td>
<td>0.066</td>
<td>&lt;0.001</td>
<td>80%</td>
<td>1.2</td>
<td>S6</td>
</tr>
<tr>
<td>Intact</td>
<td>Mayne 1988</td>
<td>1-20</td>
<td>CAUC</td>
<td>0.20</td>
<td>0.78</td>
<td></td>
<td>74</td>
<td>0.94</td>
<td>0.066</td>
<td>&lt;0.001</td>
<td>80%</td>
<td>1.2</td>
<td>S6</td>
</tr>
<tr>
<td>Intact</td>
<td>Mayne 1988</td>
<td>1-20</td>
<td>CAUC</td>
<td>0.45</td>
<td>0.78</td>
<td></td>
<td>74</td>
<td>0.94</td>
<td>0.066</td>
<td>&lt;0.001</td>
<td>80%</td>
<td>1.2</td>
<td>S6</td>
</tr>
<tr>
<td>Intact</td>
<td>Ching &amp; Phoon 2014b</td>
<td>1-6</td>
<td>CKUC</td>
<td>0.328</td>
<td>0.736</td>
<td></td>
<td>74</td>
<td>0.94</td>
<td>0.066</td>
<td>&lt;0.001</td>
<td>80%</td>
<td>1.2</td>
<td>S6</td>
</tr>
<tr>
<td>Reconstituted</td>
<td>This study</td>
<td>1-10</td>
<td>CKUE</td>
<td>0.165</td>
<td>0.952</td>
<td>(12) $\log_{10}(c_u/\sigma' v_0)=0.952 \log_{10}(OCR)-0.782$</td>
<td>34</td>
<td>0.94</td>
<td>0.087</td>
<td>&lt;0.001</td>
<td>79%</td>
<td>1.30</td>
<td>S6</td>
</tr>
<tr>
<td>Intact</td>
<td>Mayne 1988</td>
<td>1-20</td>
<td>CAUE</td>
<td>0.12</td>
<td>0.85</td>
<td></td>
<td>34</td>
<td>0.94</td>
<td>0.087</td>
<td>&lt;0.001</td>
<td>79%</td>
<td>1.30</td>
<td>S6</td>
</tr>
<tr>
<td>Intact</td>
<td>Mayne 1988</td>
<td>1-20</td>
<td>CAUE</td>
<td>0.25</td>
<td>0.85</td>
<td></td>
<td>34</td>
<td>0.94</td>
<td>0.087</td>
<td>&lt;0.001</td>
<td>79%</td>
<td>1.30</td>
<td>S6</td>
</tr>
<tr>
<td>Intact</td>
<td>Ching &amp; Phoon 2014b</td>
<td>1-6</td>
<td>CKUE</td>
<td>0.146</td>
<td>1.009</td>
<td></td>
<td>34</td>
<td>0.94</td>
<td>0.087</td>
<td>&lt;0.001</td>
<td>79%</td>
<td>1.30</td>
<td>S6</td>
</tr>
</tbody>
</table>
Figure 1. Comparison of $c_u / \sigma'_v$ CIU and $c_u / \sigma'_v$ CKU from triaxial extension and compression tests on two similarly reconstituted specimens (a) for CIU tests and (b) for CKU tests.
Figure 2. Comparison of $\gamma_{50 \text{ CIU}}$ and $\gamma_{50 \text{ CKU}}$ from triaxial extension and compression tests on two similarly reconstituted specimens (a) for CIU tests and (b) for CKU tests.
Figure 3 (a) Variation of $\gamma_{50 \text{ CIU}}$ with OCR for all CIUC and CIUE tests in the database and 3 (b) Variation of $\gamma_{50 \text{ CKU}}$ with OCR for all CKUC and CKUE tests in the database. Previously reported trend $\gamma_{50 \text{ CKUC}} = 0.0004 \cdot \text{OCR}^{1.35}$ (Casey 2016) (Equation 4) is shown for comparison.