

Shear mode and OCR effects on the mobilised shear strains of a laboratory Kaolin and Bothkennar Clay

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ABSTRACT: In this work, an experimental dataset of triaxial tests on reconstituted Kaolin and intact and reconstituted Bothkennar Clay was used to investigate the applicability of using a simple non-linear model to simulate variations in stress-strain behaviour of fine-grained soils. An experimental programme of consolidated undrained triaxial tests with displacement-control loading was designed to evaluate the sensitivity of the mobilisation strain framework (MSF) parameters to different shear modes (compression and extension), *OCR* (in the range of 1 to 8), composition, and to the reconstituted and intact material states. The experimental methods are presented and discussed including commentary on the design of the extension cap and its suitability for routine testing. The observed behaviours in the tests were reviewed by calibration with the MSF and by comparison with published tests that adopt similar materials and procedures. Results of the experiments provide evidence to support the conclusion from earlier database analyses that mobilised shear strains vary with material composition and *OCR*. A brief background to the mobilisation strain framework providing context of the research is also included.

KEYWORDS: clay soil, laboratory testing, triaxial compression and extension.

1 INTRODUCTION

Whether undertaking tasks such as: ‘assessing ground performance risk across miles of long linear infrastructure’, or ‘designing a foundation’, geotechnical engineers need to think about the variability of soil behaviour. Characterising the variability of undrained shear strength, c_u , from soil test databases has been researched extensively (e.g., Mayne 1980, Mayne 1985, Mayne & Holtz 1985, Chen & Kulhawy 1993, Mayne et al. 2009, Ching & Phoon 2013, 2014). More recently, the study of the variability of undrained pre-failure deformation has also adopted database analysis of soil tests. To adopt such an approach, a simple constitutive model is employed to simulate nonlinear behaviour in the moderate strain range (Vardanega & Bolton 2011, Vardanega & Bolton 2016, Casey 2016, Beesley & Vardanega 2020, Beesley et al. 2024a, 2024b). This paper continues the investigation of the use of simple non-linear models (e.g. mobilisation strain framework) for predicting stress-strain behaviour of fine-grained soils, by analysing a recent experimental programme of triaxial tests.

1.1 Background to the mobilisation strain framework (MSF)

The MSF allows engineers to employ a simple model for strength mobilisation for use in design work. For a more detailed recent review of the developments of the MSF the reader is directed to Beesley et al. (2024a, 2024b).

Hollomon (1945) proposed the use of a power-law for deformation response of metal. Matlock (1970) used a power-law expression for soil stress-strain response in a p-y curve framework for offshore structures (the power-law exponent was taken as a fixed value in this early p-y curve work: see also the discussion in Zhang & Andersen (2017)).

Bolton & Sun (1991) proposed an equation of the form shown as Equation (1) for shear strength mobilisation in clays:

$$\frac{\tau_{mob}}{c_u} = \left(\frac{\gamma}{\gamma_u}\right)^b \quad (1)$$

where τ_{mob} = mobilised shear strength at shear strain γ ; c_u is the undrained shear strength of the clay; γ_u is the predicted γ at $\tau_{mob}/c_u = 1$ and b is an exponent. Bolton et al. (2010) and Lam & Bolton (2011) used a similar expression to Equation (1) but

took the soil strength mobilisation response to be parabolic (i.e. for Equation (1) this is done by setting b equal to 0.5).

There are two concerns with Equation (1): (i) b can vary considerably when a large database of soil tests is examined (cf. the paper of Vardanega & Bolton (2011) on natural clays and silts and more recently the paper of Beesley & Vardanega (2020) on reconstituted soils); (ii) γ_u is an artefact of the power-curve fitting to the test data and cannot be directly measured. This is because the power-law has been observed not to fit the test data well close to c_u (especially for overconsolidated clays i.e. clays with significant ‘peakiness’ in their stress-strain response) or at low levels of strength mobilisation (see Vardanega & Bolton 2011).

Vardanega & Bolton (2011) proposed an expression of the form shown as Equation (2):

$$\frac{\tau_{mob}}{c_u} = 0.5 \left(\frac{\gamma}{\gamma_{50}}\right)^b \quad 0.2 \leq \frac{\tau_{mob}}{c_u} \leq 0.8 \quad (2)$$

where γ_{50} is the shear strain to mobilise $0.5c_u$ (termed $\gamma_{M=2}$ in Vardanega & Bolton (2011)). The moderate strain range is defined as $0.2 \leq \tau_{mob}/c_u \leq 0.8$. The limits of τ_{mob}/c_u are only approximate and were originally assigned using judgement. (A similar concept of using strain at 0.5 times the maximum stress was used in the Matlock (1970) framework; though it should be noted that Matlock (1970) appeared to utilise the power curve up to $c_u = 1$). Importantly, Equation (2) allows for b to vary. As an aside, initially Vardanega & Bolton (2011) and later publications by Casey et al. (2016), Vardanega & Bolton (2016) and Casey (2016) discussed how Equation (2) could be adjusted for K_0 conditions: essentially an initial shear stress term needs to be added to the formulation.

A key question following the proposition of Equation (2) is whether γ_{50} or b can be predicted using more fundamental (basic) soil mechanics parameters?

1.2 b-parameter

Vardanega & Bolton (2011) set $b = 0.6$ when investigating the applicability of Equation (2) using a database of over 100 laboratory tests on natural clays. Vardanega et al. (2012) found a reasonable correlation linking b with *OCR* for a series of tests conducted on a laboratory kaolin. This finding was supported

to some extent by the laboratory findings presented in Beesley et al. (2019).

1.3 γ_{50} -parameter

Vardanega & Bolton (2011) presented the results of a multi-linear regression analysis and found for the natural clays studied that γ_{50} was predicted by a function of plasticity index, undrained shear strength and mean effective stress; however, the coefficient of determination was only around 0.4. Vardanega et al. (2012) found a reasonably strong correlation linking γ_{50} and OCR but again only for a single laboratory kaolin – although this finding was also supported to some extent by the laboratory findings presented in Beesley et al. (2019).

Mayne (when discussing Vardanega et al. (2012)) advised against lumping together tests conducted using various shear modes (as was done in Vardanega & Bolton (2011) where most tests in the database were CIU) (see Vardanega et al. (2013)) as c_u is strongly dependent on shear mode (cf. e.g. Mayne et al. 2009). Beesley & Vardanega (2020) showed that the correlations linking OCR to γ_{50} do change for varying shear modes, and this work was further extended in Beesley et al. (2024a).

1.4 γ_{70} -parameter

Beesley et al. (2024a) explored if γ_{30} or γ_{70} (both within the range of the power-law function: Equation (2)) may be better normalisers of γ than γ_{50} – as there is no physical reason why γ_{50} should be superior. For the database of reconstituted soils outlined in Beesley & Vardanega (2020), Beesley et al. (2024a) showed that γ_{70} was statistically better correlated with OCR , initial void ratio and liquid limit than γ_{50} . This finding will be explored further in this work.

1.5 Research aims

An experimental programme was carried out to investigate the effects of reconstitution, material composition, OCR , and shear mode on the MSF model deformation parameters. Use of conventional testing equipment for both triaxial compression and triaxial extension tests was an important requirement, so that the results can be applicable to routine ground investigation interpretation procedures. To achieve this objective, the experimental work included the design of a new axial unloading extension cap for routine triaxial testing, which is presented and discussed in this paper. The reconstituted soil experiments presented here have also been used to evaluate the parameter correlations determined by analysis of the published database RFG/TXCU-278 (see Beesley & Vardanega 2020 for further details on the database), as discussed in Beesley et al. (2024a).

2 EXPERIMENTAL PROGRAMME

2.1 Materials

One batch of powdered Speswhite Kaolin from a UK supplier was selected as the primary test material. Kaolin was chosen due to its availability and reasonably fast consolidation rate (with a measured coefficient of consolidation of $4\text{cm}^2/\text{s}$). Also, 88 of the 278 triaxial tests in RFG/TXCU-278 were from experiments using Kaolin samples.

The Bothkennar Clay was taken from the remainder of a block sample that had also been used in the experimental work of Sukolrat (2007). The sample had been resealed with wax and clingfilm. The block sample (from 5.4m depth) was extracted from the site in 1997 using a Sherbrooke sampler at 5.4m depth and with an assessed in-situ OCR of 1.5; see Beesley (2019) for further details.

The Kaolin was found to have 66% to 73% silt with the remainder clay and a liquid limit (w_L) of 66%. The Bothkennar Clay comprised 96% silt, 2% clay, and 2% sand; the w_L of the Bothkennar Clay (77%) is higher than the maximum w_L of the test materials included in RFG/TXCU-278 (75%). Further material properties, such as plastic limit, w_P , and specific gravity, G_s , are listed in Table 1. In Table 1, n represents the number of tests in the corresponding experimental investigation; in Table 2, n represents the number of database tests.

2.2 Test equipment

A tall floating-ring consolidometer of 50mm diameter was used to reconstitute individual samples of the Kaolin and the Bothkennar Clay. To consolidate the slurry, the compressions were monitored and the shaft friction regularly broken by displacing the floating ring. Shaft friction should be minimised to avoid nonuniform void distribution within the sample when extruded. Despite these extra measures, initial effective stresses measured immediately after extrusion indicated shaft friction losses of 50% to 58% in the Kaolin samples; Sukolrat (2007) measured shaft friction losses of 35% to 55% in the Bothkennar Clay samples reconstituted using a similar consolidometer of 75mm diameter. Procedures involving tall consolidometers to reconstitute individual samples had been adopted in one-third of the soil tests in database RFG/TXCU-278; 47% were reconstituted in batches inside a large diameter consolidation tank; the remaining tests were reported with little information reported about the sample reconstitution.

Table 1. Parameter values/ranges of soils in the CU test programme (n = number of CU triaxial tests performed) (data from Beesley (2019))

	Kaolin		Bothkennar Clay	
	CIUC $n = 4$	CIUE $n = 4$	CIUC $n = 2$	CIUE $n = 1$
w_L	0.66	0.66	0.77	0.77
w_P	0.35	0.35	0.39	0.39
G_s	2.60	2.60	2.70	2.70
σ'_{v0}	50-403	49-402	29 * 99 **	28 *
K_θ	1.00	1.00	1.00	1.00
OCR	1, 2 or 8	1, 2 or 8	1.5	1.5
e_0	1.10-1.24	1.16-1.28	1.94 * 1.41 **	1.94 *

* Intact Bothkennar Clay; ** Reconstituted Bothkennar Clay

Table 2. Parameter values/ranges of the tests included in RFG/TXCU-278 (curve fitted tests only) (n = number of tests) (adapted from Beesley et al. (2024a))

	CIUC		CIUE	
	n	value(s)	n	value(s)
w_L	114	0.25-0.74	55	0.25-0.72
w_P	114	0.13-0.42	55	0.13-0.40
I_P	114	0.12-0.46	55	0.12-0.32
G_s	114	2.46-2.79	55	2.60-2.74
σ'_{v0}	114	9.0-2900	55	20.7-2900
K_θ	114	1.00	55	1.00
OCR	114	1-32	55	1-12
e_0	98	0.38-1.50	43	0.43-1.31

The CU triaxial test apparatus included a hydrostatic cell pressure system, back pressure/drainage system including top and base drain connection pressure transducers, displacement control loading frame, internal load cell, a flat load cap (CIUC tests), a vacuum-connection extension cap (CIUE tests), an external linear displacement transducer (LDS), and two internal linear variable displacement transducers (LVDTs) between the end platens (Beesley 2019). For the soil tests in the RFG/TXCU-278 database around three quarters used displacement measurements external to the confinement cell, about 7% were equipped with local to the sample axial displacement measurements, and the remainder were reported without information about the strain measurement system. It is noted that 114 of the 278 tests in the database were reported to have lubricated end platens; no anti-frictional end platen systems were used in the laboratory investigation reported in this paper.

2.3 Test procedures and programme

The CU test procedures explained in detail in Beesley (2019) are summarised as follows:

Intact sample preparation – Due to the limited volume of intact material in the block sample, only two triaxial specimens of the Bothkennar Clay were trimmed to 50mm x 100mm.

Reconstitution – Reconstituted Kaolin samples were formed by hand mixing deaired deionized water with the powdered Kaolin to achieve a slurry of water content approximately equal to $1.95w_L$ and compressed in three increments up to σ'_v of 120kPa to create reconstituted samples of 96-103mm (and one outlier of 114mm) height on extrusion. The slurry water content was chosen following preliminary trials of the reconstitution procedure. For consistency, the trimmings from the intact Bothkennar Clay sample were also reconstituted using deaired deionized water added by hand mixing to form a slurry with water content approximately equal to $1.95w_L$. The slurry was compressed in three increments up to σ'_v of 100kPa in the consolidometer to create a reconstituted sample of 102mm height on extrusion.

Consolidation – Intact Bothkennar Clay samples were reconsolidated to the estimated in-situ stress. The maximum isotropic consolidation stress applied to the reconstituted Bothkennar Clay in the triaxial cell (150kPa) was 1.5 times the maximum pressure applied in the consolidometer (100kPa). Likewise, a minimum factor of 1.6 between the consolidometer and isotropic stresses was applied to the Kaolin samples. Each sample was isotropically consolidated to the target OCR (see Table 1) in the triaxial cell at 5 to 8kPa/hour (Kaolin) or 1kPa/hour (Bothkennar Clay) to minimise excess pore pressures.

Shearing – All specimens were subjected to undrained shearing at rates of 0.002%/minute (Kaolin) or 0.0013%/minute (Bothkennar Clay). Compression tests were performed using a flat load cap; extension tests first included vacuum connection between the specimen and load cell via the extension cap (this is discussed further in section 3). Table 1 presents the sample and test conditions for both reconstituted Kaolin and intact and reconstituted Bothkennar Clay samples. σ'_{v0} and e_0 are the vertical effective stress and void ratio, respectively, after consolidation (pre-shear).

3 FEASIBILITY OF A 'ROUTINE' CIUE TEST

With reference to the experimental studies reviewed and selected to compile RFG/TXCU-278, suction or vacuum-connection extension caps are a popular choice for undertaking Isotropically Consolidated Undrained triaxial Extension (CIUE) tests on reconstituted fine-grained soils though rigid

threaded bar and bayonet connections have also been used (see Beesley 2019). Vacuum-connection was used in this case to facilitate a connection procedure that could be completed rapidly (successfully demonstrated under 10 minutes) between the consolidation and shear stages of the triaxial test, without draining the cell or altering confinement. The compromise of some initial axial displacement between the top and base platens during the connection procedure was judged to be acceptable. This compromise was deemed acceptable as the specific objective of the test was to measure soil stress-strain behaviour in the moderate strain range (however, small-strain stiffness measurements would not be feasible).

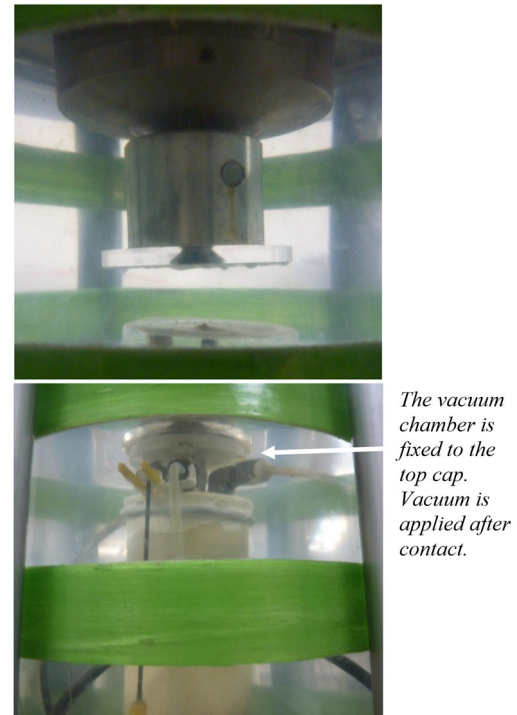


Figure 1 Extension test setup inside conventional isotropic triaxial cell (photographs taken by MB)

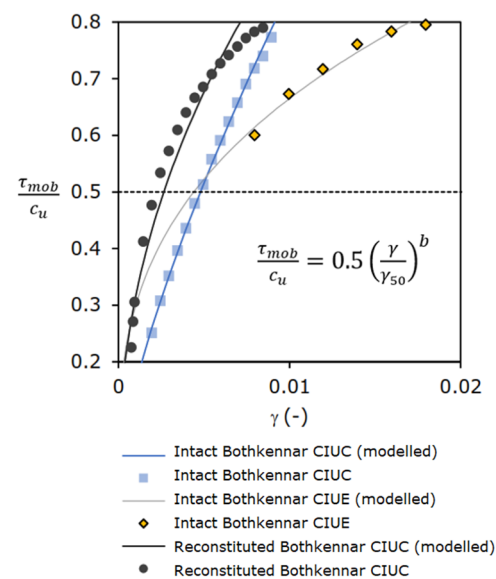


Figure 2 Measured and modelled stress-strain curves for intact and reconstituted Bothkennar Clay

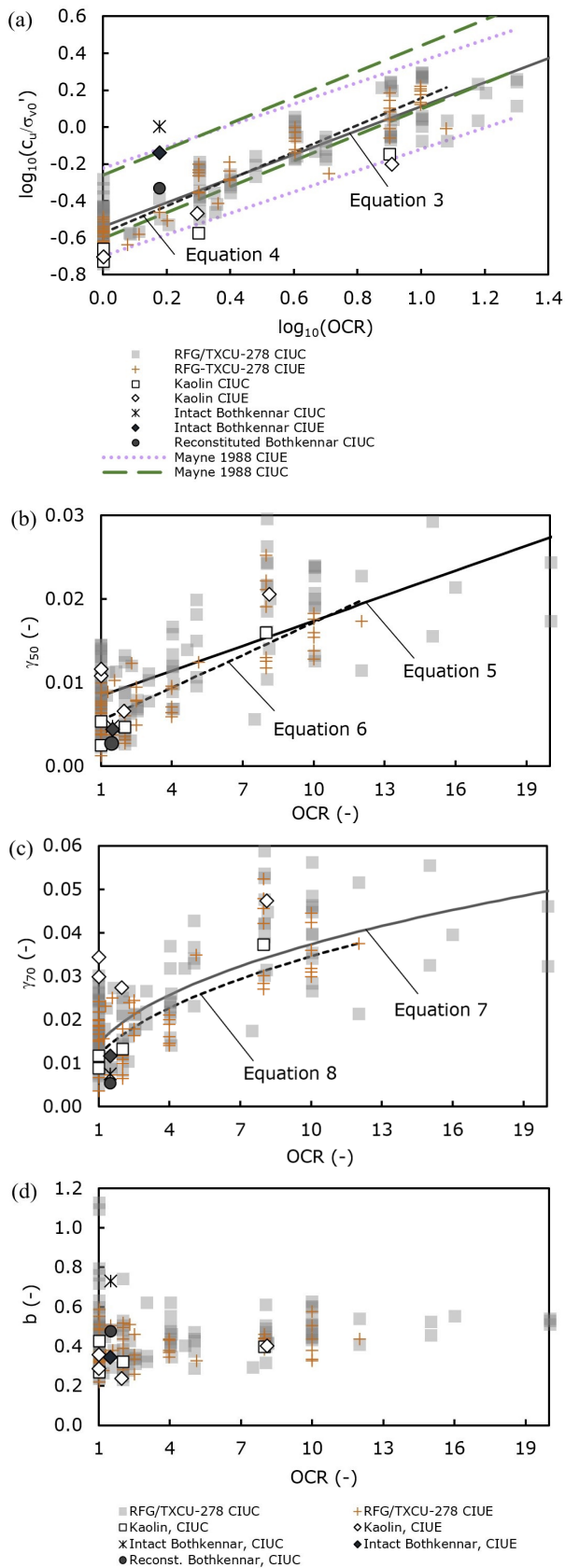


Figure 3 Normalised undrained shear strength c_u/σ'_{v0} and deformation model parameters γ_{50} , γ_{70} and b measured in the CIU experimental programme compared with published database values and correlations

The extension cap design consisted of two parts (see Figure 1): an upper load cap connection fixed to the load cell and a lower vacuum chamber fixed to the top cap. Rotational flexibility of the load cap connection was incorporated into the design to accommodate the tilt observed in preliminary Kaolin tests resulting from the shaft friction of the sample consolidometer and to minimise the compression load on initial contact before applying vacuum. This solution resulted in a successful vacuum seal being achieved during contact alignment. A minimal seating load of 6 to 9kPa and axial strain of 0.01% (in compression) was observed. However, the subsequent vacuum connection resulted in an axial strain (in extension) of 0.14%. As a result, the extension cap is only useful for testing softer soil samples in the moderate strain range, and further design improvement to reduce axial displacement during connection is recommended for future work.

4 RESULTS

A comparison of stress-strain behaviours of the reconstituted and intact Bothkennar Clay in CIUC shear mode is shown in Figure 2 by plotting the stress ratio, τ_{mob}/c_u , against shear strain, γ . The undrained shear stress-strain measurements are curve-fitted with the MSF model proposed by Vardanega & Bolton (2011), using Equation (2). Compared with the intact soil behaviour, smaller shear strains and more non-linearity (lower b value) are observed in the reconstituted sample. Normalised undrained shear strength is lower in the reconstituted sample (see Figure 3a). The difference in shear strains is explained by the lower initial void ratio and greater pre-shear consolidation stress resulting from the sample reconstitution procedure (see Table 1). A lower value of b appears to be related to destructuration of the material; Beesley et al. (2021) found that lower b values were associated with sampling disturbance and SHANSEP test procedures on Bothkennar Clay after analysing CU triaxial test data reported by SERC (1989).

The anticipated model fitting error of Equation (2) is also visible in Figure 2; by inspection, the power-law function fits the intact CIUC measurements apparently well but is unable to simulate the full stress-strain curve of the reconstituted sample which shows more non-linearity than the fitted curve. Beesley et al. (2024b) quantified the model fitting error of all stress-strain increments in RFG/TXCU-278 and discussed the model choice justification where the modelling objective is to simulate continuous non-linear stress-strain measurements for variability characterisation studies (albeit in a limited range for engineering purposes). The impact of the initial axial displacement caused by the extension connection in the CIUE test is also demonstrated in Figure 2 by the absence of measurements of the initial part of the undrained stress-strain curve. The axial displacement mobilised 60% of the peak stress for the intact stiffer samples (during connection to the sample) thus creating a challenge with characterisation of the moderate strain range.

To review the differences in stress-strain behaviours observed in the CU test programme compared with those of the reconstituted soils in RFG/TXCU-278, the model parameters of Equation (2) have been plotted in Figure 3. Reference strains γ_{50} and γ_{70} , defined as the shear strain to respectively mobilise $0.5c_u$ and $0.7c_u$, and b , the non-linearity parameter, are derived from the curve fitted to the data of each triaxial test. Figure 3 also shows the previously reported linear regressions between $\log_{10}(c_u/\sigma'_{v0})$ and $\log_{10}(OCR)$ (Equation (3) and (4)) (Beesley & Vardanega 2020), γ_{50} and OCR (Equation (5) and (6)) (Beesley & Vardanega 2020), and $\log_{10}(\gamma_{70})$ and $\log_{10}(OCR)$ (Equation (7) and (8)) (Beesley et al. 2024a), which indicate the expected

or average trends for the range of reconstituted soils summarised in Table 2 (RFG/TXCU-278, noting one test result for $OCR = 32$ is not shown, and shear mode is indicated by subscripts CIUC and CIUE in Equations (5) to (8)).

$$\log_{10} \left(\frac{c_u^{CIUC}}{\sigma'_{v0}} \right) = 0.653 \log_{10}(OCR) - 0.541 \quad (3)$$

$$[R^2 = 0.86, n = 115, p < 0.001]$$

$$\log_{10} \left(\frac{c_u^{CIUE}}{\sigma'_{v0}} \right) = 0.729 \log_{10}(OCR) - 0.574 \quad (4)$$

$$[R^2 = 0.92, n = 55, p < 0.001]$$

Note that Equations (3) and (4), previously reported by Beesley and Vardanega (2020), are of the form from Ladd et al. (1977) and Mayne (1980). For comparison with the parameters of intact Bothkennar Clay, Figure 3a also includes the upper and lower bound regression equations reported by Mayne (1988).

Figure 3a shows that, as expected, the normalised undrained shear strength of the Kaolin CIUC and CIUE tests increases with OCR . Based on the previously published empirical equations, the c_u/σ'_{v0} values of the reconstituted Kaolin are lower than expected whilst, conversely, the normalised strength of the intact and reconstituted Bothkennar Clay samples are higher than expected. The Kaolin samples were sheared at a lower strain rate than the majority of tests on Kaolin in RFG/TXCU-278 (with rates reported from 0.002%/min to 0.063%/min), which may explain the lower strength measurements (e.g., Kulhawy and Mayne 1990). Interestingly, the measured extension strengths of the Kaolin are also in the lower range, despite the rapidly applied initial strain caused by vacuum connection. A high content of silt grade material in the reconstituted Bothkennar Clay possibly caused more dilative behaviour and higher c_u/σ'_{v0} compared with the Kaolin; sedimentation and age of the intact sample increase the normalised strength further.

The results in Figures 3b and 3c indicate that both γ_{50} and γ_{70} increases with OCR for both CIUC and CIUE shear modes for the Kaolin. γ_{50}^{CIUC} and γ_{70}^{CIUC} tend to increase with OCR more than would be suggested by Equations (5) and (7). Whereas the observed variation of γ_{50}^{CIUE} and γ_{70}^{CIUE} with OCR does not appear to follow a clear trend. According to Equations (5) to (8) (from Beesley et al. 2024a), on average where $OCR \leq 10$ the reference shear strains are expected to be smaller in extension than in compression; however, the opposite is observed in the Kaolin test results ($OCR = 1, 2, \text{ and } 8$). These results are likely to have been significantly influenced by the mechanical effects of the vacuum connection procedure, resulting in higher shear strains in extension than might be expected from many of the earlier studies compiled in RFG/TXCU-278.

$$\gamma_{50}^{CIUC} = 0.0010(OCR) + 0.0074 \quad (5)$$

$$[R^2 = 0.51, n = 114, p < 0.001]$$

$$\gamma_{50}^{CIUE} = 0.0013(OCR) + 0.0042 \quad (6)$$

$$[R^2 = 0.65, n = 55, p < 0.001]$$

$$\gamma_{70}^{CIUC} = 0.0015(OCR)^{0.41} \quad (7)$$

$$[R^2 = 0.55, n = 114, p < 0.001]$$

$$\gamma_{70}^{CIUE} = 0.0012(OCR)^{0.46} \quad (8)$$

$$[R^2 = 0.50, n = 55, p < 0.001]$$

The model parameters in Figures 3b, 3c and 3d indicate that the studied Bothkennar Clay is a stiffer material with less non-linearity in the moderate strain range than the Kaolin. No correlation exists between b and OCR for the studied CIUC tests probably due to increased scatter around values at $OCR=1$

(Vardanega et al. 2012 did show a weak correlation between b and OCR) – see Figure 3d. For Kaolin, b values in extension are generally less than the values in compression (up to 0.1 difference).

5 SUMMARY & CONCLUSIONS

Results of the experiments presented in this paper provide evidence to support the observations of earlier studies that mobilised shear strains vary with shear mode and OCR . CIUE tests are less reported in the literature than CIUC tests and further work is needed to develop an improved triaxial extension procedure for load cap connection that could be used for routine triaxial tests. Some value was demonstrated in the exercise of comparing the strength (c_u/σ'_{v0}) and deformation (γ_{50}, γ_{70}) parameters of the new tests with the average predictions of each parameter using OCR that had been found from earlier analyses of soil test databases, as the deviations could be explained by the material composition and adopted test procedures.

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