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Stress path testing on intact and reconstituted Bolders Bank till

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ABSTRACT: Large areas of North Eastern UK and the North Sea are underlain by stiff, often overconsolidated glacial tills. Detailed evaluation of their properties is particularly important to offshore engineering. Studies that compare the behaviour of natural and reconstituted tills can provide valuable information on the effects of natural structure on the glacial sediments. This paper presents a systematic investigation of reconstituted and natural Bolders Bank till tested in triaxial stress path cells. The specimens were sampled at the PISA project Cowden test site near Hull in NE England. The intact and reconstituted samples showed common shear strength, stiffness and critical state behaviours, provided they were consolidated to similar OCRs.

RÉSUMÉ: De vastes zones du nord-est du Royaume-Uni et de la mer du Nord reposent sur des tills glaciaires raides, souvent surconsolidés. Une évaluation détaillée de leurs propriétés est particulièrement importante pour l'ingénierie offshore. Des études comparant le comportement de tills naturels et reconstitués peuvent fournir des informations précieuses sur les effets de la structure naturelle sur les sédiments glaciaires. Cet article présente une étude systématique de la Bolders Bank reconstituée et naturelle testée dans des cellules à trajet de contrainte triaxial. Les échantillons ont été échantillonnés sur le site d'essai Cowden du projet PISA, près de Hull, dans le nord-est de l'Angleterre. Les échantillons intacts et reconstitués ont montré des comportements communs en matière de résistance au cisaillement, de rigidité et d'état critique, à condition qu'ils soient consolidés en OCR similaires.

Keywords: Glacial-till; intrinsic and natural properties; stress-path laboratory tests

1 INTRODUCTION

Geotechnical projects in the North of the UK often encounter variable glacial tills. This paper reports a study performed on the Bolders Bank till at Cowden that supported the PISA research project into offshore monopiles, as described by Byrne *et al.* (2017) and Zdravkovic *et al.* (2018).

Although there exists a considerable volume of historic laboratory data for the stony and fissured Cowden till (see for example Powell and Butcher 2003), a comprehensive comparison between intact and reconstituted material behaviour remained to be undertaken. Drawing on earlier studies on the low plasticity Lower Cromer and Magnus tills by Gens (1982) and Jardine (1985), it was appreciated that experiments on reconstituted specimens can provide valuable information on the shear strength and stiffness properties of tills.

This paper reports stress path testing undertaken on reconstituted till samples. One group was K_0 consolidated to OCRs=1, 2 and 10 before undrained shearing in compression or extension, while others were isotropically consolidated and swelled before shearing from OCR=1 and 10. Additional 1-D compression tests were also performed. The results were combined with parallel stress path and oedometer tests on high quality intact specimens.

2 SITE CONDITIONS AND SAMPLING

Ushev (2018) and Ushev and Jardine (2018) report the detailed properties of the Bolders Bank till at Cowden. High quality sampling, including both block and 100mm diameter Geobor-S wireline rotary techniques, show that site has 40m of stiff glacial clay till (including isolated sand layers) which overlies chalk. Figure 1 shows the site profiles of bulk density, water content, liquid and plastic limits to 12m. The till is weathered down to 4.8m where the colour changes. This paper reports tests on samples from 3.0 to 3.5m depth where the till consists of around 30% clay, 40% silt, 20% sand and 10% gravel. The grain specific gravity ≈2.71 and organic and carbonate contents were around 1% and 3.5%. The till has plastic and liquid limits of 16.5 and 35.5% at this depth, giving a plasticity index of 19%. Natural samples were trimmed from rotary cores. Oedometer and triaxial tests indicate a Yield Stress Ratio (YSR, or apparent OCR) ≈12 at this depth. Ushev (2018) shows that the deeper unweathered tills show generally similar behaviour, but lower YSRs.

The reconstituted specimens were trimmed from a 'cake' prepared from flaked, dried natural soil. Following Burland's (1990) procedure, soil was wetted to 1.5 the Liquid Limit, sieved through a 2mm sieve (that retained 8% of the mass) and consolidated one dimensionally under 200kPa vertical stress in a 229mm diameter consolidometer to form clay 'cakes'.

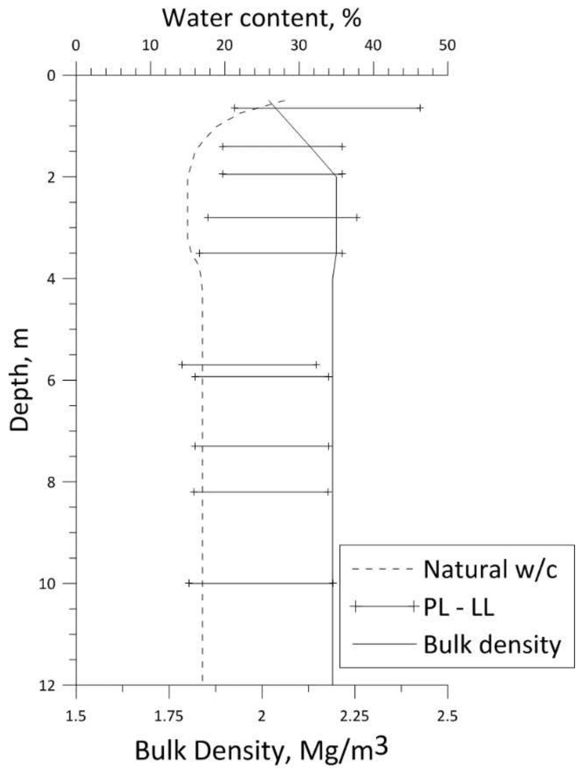

Figure 1. Profiles of bulk density, water content, liquid and plastic limits (Ushev and Jardine 2018)

3 COMPRESSION BEHAVIOUR

The 1-D compression behaviour of reconstituted and intact Cowden till sampled from 3.0 to 3.5m depth, loaded up to 10MPa, is shown in Figure 2. The intrinsic curves shown by the four reconstituted samples have similar shapes and form a relatively narrow band. The average intrinsic compression and swelling slopes from the oedometer tests at this depth give C_c=0.23 and C_s=0.052.

The intact specimen show only gradual yielding without revealing any distinct yield point and tend to cross the intrinsic K_0 normal compression lines without converging towards the same final gradient. A dense and insensitive initial fabric was imparted to the till by its glacial origin, which cannot be removed or modified easily by oedometer compression. The natural

Cowden till sample's final C_c and C_s values were 0.154 and 0.035 respectively.

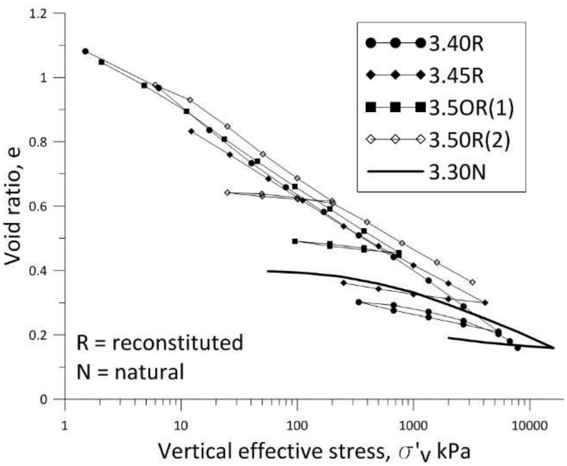

Figure 2. One-dimensional compression behaviour of reconstituted and natural Cowden till at 3.5m depth

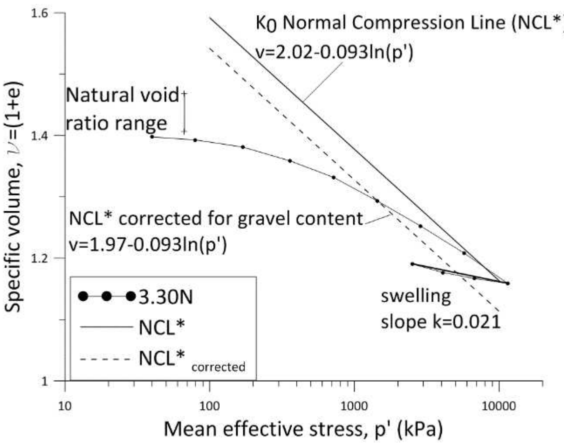

*Figure 3. One-dimensional compression behaviour of natural Cowden till with NCLs**

Intrinsic K_0 Normal Compression (NCL*) and Critical State (CSL) parameters λ*, κ* and v_1* (v=specific volume=1+e) were found from the oedometer data in Figure 2 by applying the Equation 1 K_0-OCR relationship, and treating the first loading stages as having OCR=1.

$$K_0 = (1 - sin\varphi')OCR^{sin\varphi'} \quad (1)$$

The results are presented in v-ln(p') space in Figure 3. Removing the 8% gravel (>2mm) fraction affected the location of the NCL*, as noted by Gens and Hight (1979). Corrections were made by applying:

$$w_{corr} = \frac{M_w}{M_{s(<2mm)}+0.08M_{s(<2mm)}} = \frac{w}{1.08} \quad (2)$$

Where M_s and M_w are the masses of water and solids.

$$e_{corr} = \frac{wG}{1.08} = \frac{e}{1.08} \quad (3)$$

4 SHEARING BEHAVIOUR

Computer controlled Bishop and Wesley (1975) triaxial stress path cells utilising local axial and radial strain gauges were employed for all shear testing. The reconstituted specimens were consolidated either isotropically (to OCR 1 and 10) or under K_0 conditions (to OCRs 1, 2 and 10). The natural specimens were consolidated to their estimated in-situ (K_0) stresses following the pore pressure and K_0 profiles described by Zdravkovic *et al.* (2018) before undrained compression or extension tests were conducted to failure.

4.1 Undrained compression tests

The reconstituted samples failed in compression without developing any clear strain localisation. They developed barrel-shapes after large strains, reaching well-defined plateaux in terms of deviatoric stress and excess pore pressure after 10% to 15% axial strain (ε) (refer to Figure 4). Note that under undrained triaxial conditions the axial strain is identical to the shear strain invariant ($\varepsilon=\varepsilon_s$). The isotropically consolidated specimens IUC1 (OCR=1) and IUC10 (OCR=10) exhibited ductile strain hardening behaviour while the K_0 consolidated samples tested at low OCR (KUC1 (OCR=1) and KUC2 (OCR=2)) strain softened markedly after reaching peak q at small strain.

The corresponding effective stress paths (ESP) shown in Figure 5 confirm "contractive" behaviour for specimens tested at OCR=1 and 2 that switches to "dilative" at higher OCR.

The high YSR natural Cowden till responds to shearing in compression in a fully ductile manner, as illustrated by the four tests reported in Figure 6. All samples bulged as they approached failure and axial strains generally exceeded 25% before reaching well defined deviatoric stress plateaux. In some cases the pore pressures kept decreasing (and p' rising) at large strains, although at clearly decreasing rates. Only semi-stable final conditions were reached in these tests.

The stress ratios (q/p') mobilised over the full axial strain (ε) ranges are plotted in Figure 7. The effective stress paths in Figures 5 and 8 tend towards critial states with $M_{reconstituted}^{TXC}$=q/p'=0.96, (corresponding to φ'_{cs}=24.4º) and M_{intact}^{TXC}=q/p'=1.0 (or φ'_{cs}=25.4º).

The natural soil exhibited slightly higher critical state M values than the reconstituted samples. While the reconstituted tests' peak q/p' ratios varied with OCR, the OCR=10 specimen revealed almost identical behaviour to the natural specimens (which had YSR≈12) from 3.0 to 4.0m depth.

4.2 Undrained extension tests

Samples sheared to failure in extension underwent substantial losses of shear resistance once non-uniform necking bands appeared, which usually developed from around ε=-9%. The apparent losses of resistance became more pronounced with OCR. The effective stress paths (Figures 5b) developed in extension revealed increasingly dilative behaviour at higher OCRs. The final effective stress ratio q/p'=0.62 seen in extension corresponds to a nominal φ' angle equal to 20.2º.

The compression and extension S_u/σ'_{v0} ratios of reconstituted specimens vary with OCR according to Equation (4) with the best fitting values of parameters A and *b* being 0.28 and 0.75 in compression and 0.18 and 0.92 in extension respectively.

$$\frac{S_u}{\sigma'_{v0}} = A[OCR]^b \tag{4}$$

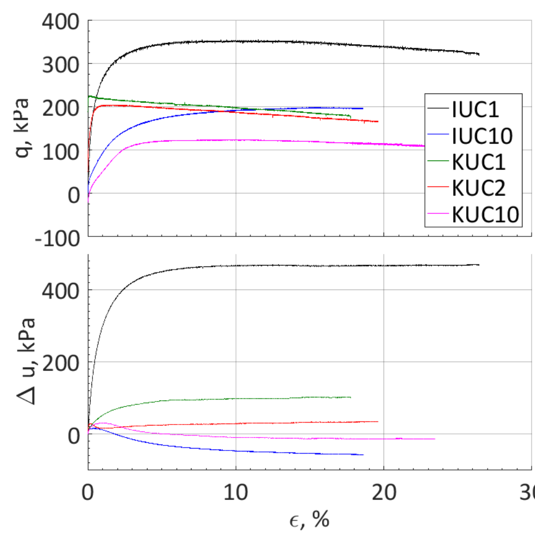

Figure 4. Stress-strain and pore pressure response during shearing in TXC for isotropic (IUC) and K_0 consolidated (KUC) reconstituted samples

5 CRITICAL STATE AND STATE BOUNDARY SURFACE

The ultimate critical states expressed in v-p' space shown by the five reconstituted and four intact samples sheared in compression are presented in Figure 9. Due to the tentative nature of their ultimate failure points, the extension tests are not considered. Also shown on the plot is the isotropic intrinsic normal compression line, NCL*.

The v-p' points applying at the end of shearing indicate the intrinsic Critical state line (CSL*), which lies below and is parallel to the isotropic NCL*. In v-ln(p') space the CSL* has a slope N*=0.093 and intersects the specific volume axis at unit pressure, Γ*=2.035. Removing the gravel fraction (>2mm) during sample preparation changes the location of the reconstituted critical state points as shown in Figure 9. The corrected intrinsic critical state points and their best fit line (with $N^*_{corrected}$=0.093 and $\Gamma^*_{corrected}$=1.995), which are also plotted in Figure 9, bring the intact and reconstituted points closer to one another.

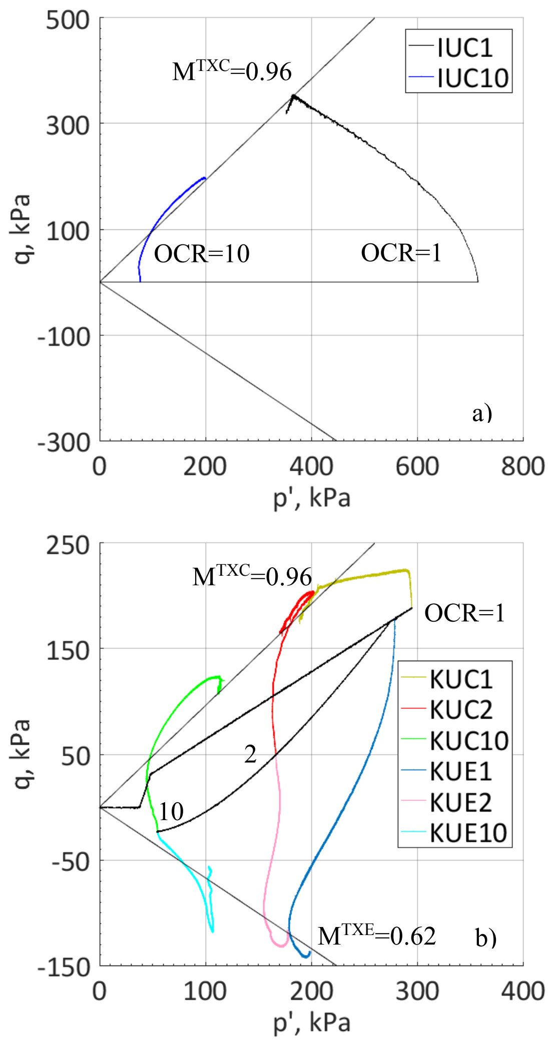

Figure 5. Effective stress paths for reconstituted a) isotropic (IUC) and b) K_0 consolidated (KUC) Cowden samples

The effective stress paths of the undrained reconstituted tests are shown in Figure 10, normalised by the Hvorslev equivalent p' pressure defined on the NCL*. The Local Boundary Surfaces (LBS*) traced by the isotropic and K_0 consolidated samples differ considerably, as expected by Gens (1982) and Jardine *et al.* (2004). However, all reconstituted compression tests appear to travel towards a single Critical State (CS) point in compression, which is located between p'/p'_e=0.5 and 0.6. On the extension side, the non-uniform failure conditions lead to a wider spread of final values.

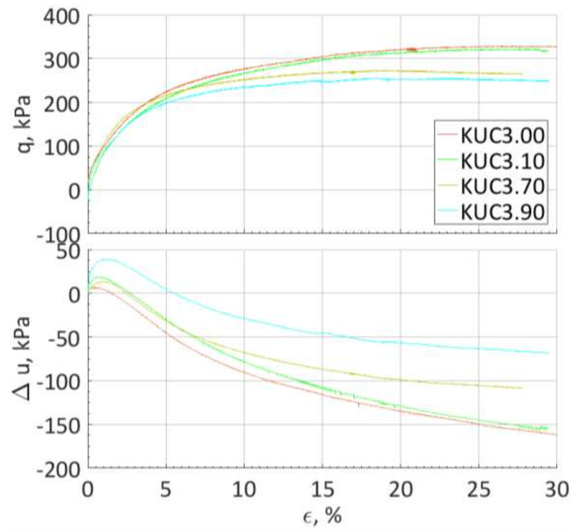

Figure 6. Stress-strain and pore pressure response during shearing in TXC for natural specimens

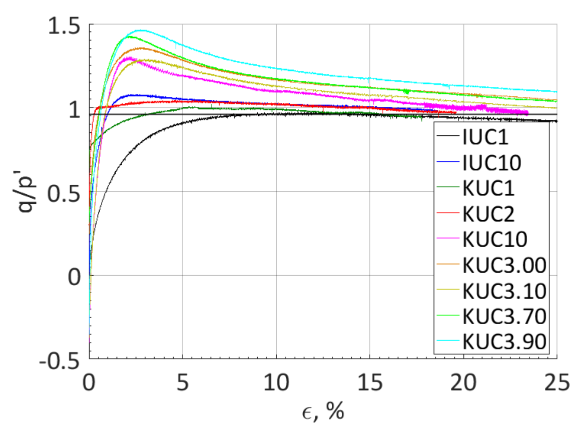

Figure 7. Stress ratio (q/p') vs axial strain (ε) for reconstituted and natural Cowden till in TXC

Considering the effective stress paths in Figure 8 and normalising the end of shearing point by the equivalent pressure p'_e to allow for differences in void ratios, a SBS can be identified on the dry side of critical state (the Hvorslev surface) for the 3.0 to 4.0m depth range, as shown in Figure 11. The State Boundary Surfaces (SBS) identified from intact and reconstituted Cowden till show similar slopes and locations on the dry side.

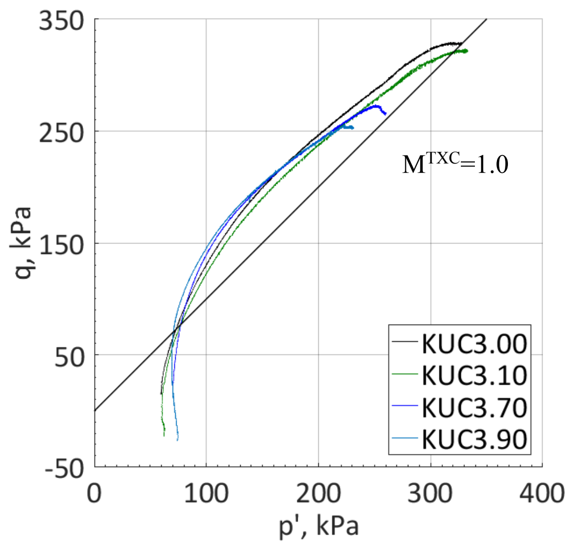

Figure 8. Effective stress paths for intact Cowden till samples at 3.0 to 4.0m depth

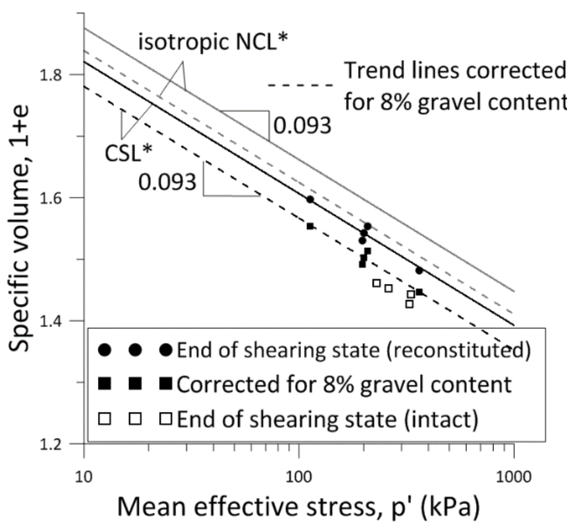

Figure 9. Normal compression and Critical state lines for reconstituted and intact Cowden till

6 STIFFNESS CHARACTERISTICS

The secant undrained vertical Young's moduli measured in the triaxial compression tests varied with axial strain, as shown in Figure 12 for the reconstituted till tests, while the equivalent intact specimens' results are summarised in Figure 13. In both cases, the initial quasi-elastic ranges appear to extend to between 0.003 and 0.004% and 0.001 and 0.003% axial strain for the reconstituted and natural specimens, followed by highly non-linear stiffness degradation once the first (Y_1) kinematic yield surface is engaged, as expected by Jardine (1992).

The natural specimens' stiffnesses plot in a narrow 130 to 160MPa range. The initial OCR has a marked effect on the stiffness behaviour of the reconstituted soil, reducing the absolute stiffnesses and also promoting a more gradual stiffness degradation.

It was shown earlier that Cowden till is not a sensitive or cemented soil. However, it might be expected that the glacial genesis of the Cowden till affects its shear stiffness behaviour. To examine this possibility the secant stiffness trends from reconstituted and natural specimens are compared in Figure 14.

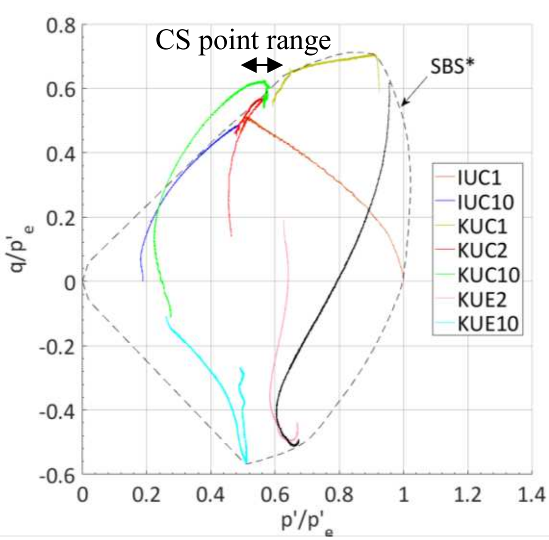

Figure 10. State bounding surface for reconstituted Cowden till

Following Ushev (2018), normalisation of mean effective stress to a fractional power ($p'^{0.5}$) is applied and allowance made for void ratio variations by dividing stiffness by the void ratio function $f(e)=e^{-1.3}$. Plotted in this way the reconstituted and natural tills show closely comparable behaviour when tested from similar overconsolidated conditions.

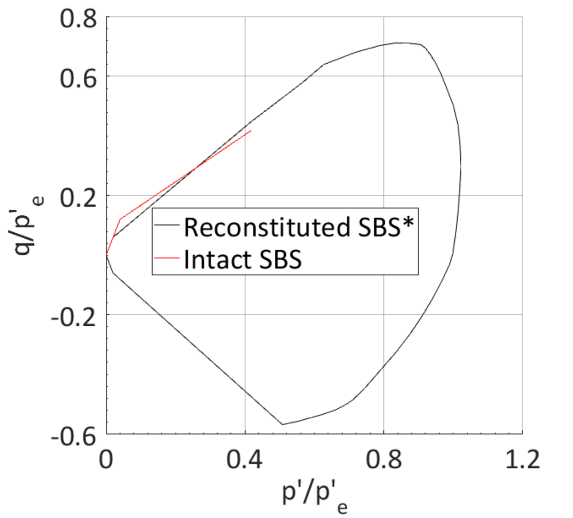

Figure 11. State bounding surface for reconstituted and intact (dry side only) Cowden till

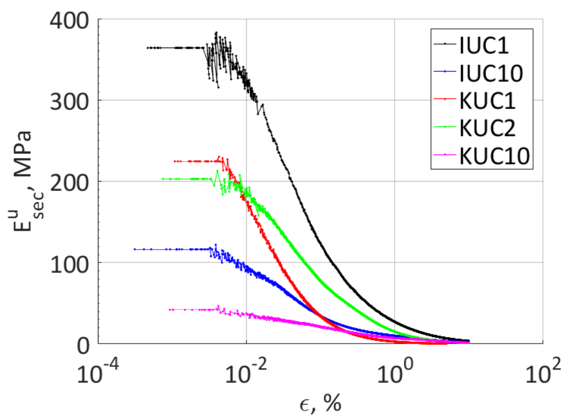

Figure 12. Secant stiffness trends from reconstituted triaxial compression tests

7 SUMMARY AND CONCLUSIONS

The experiments presented in this paper indicate that intact and reconstituted specimens of low plasticity Cowden Bolders Bank till sampled from the same depth possess common features in terms of shear strength, undrained stiffness and critical state parameters, provided that comparable OCRs are considered and the data are normalised appropriately. The findings have implications for site characterisation and may be helpful in overcoming the difficulties associated with high quality sampling in stony and fissured tills.

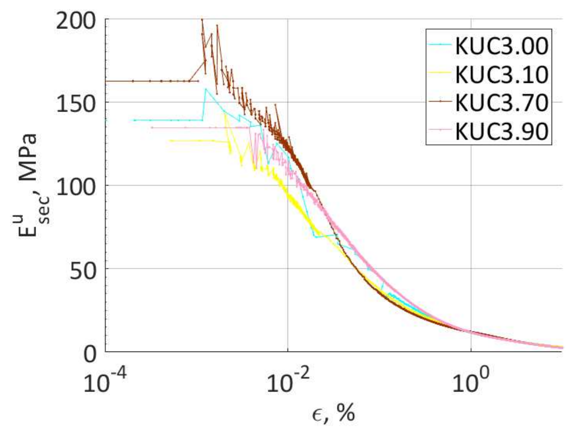

Figure 13 Secant stiffness trends for intact TXC specimens

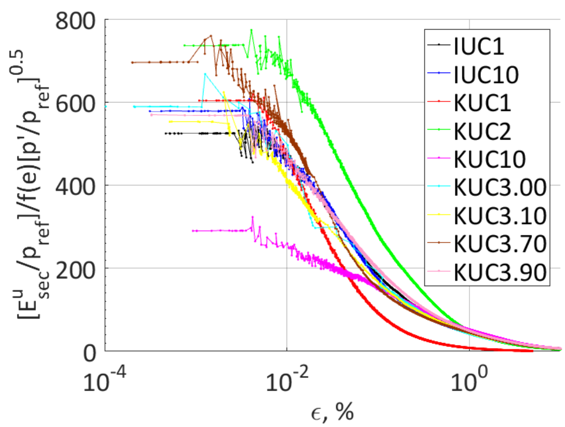

Figure 14 Normalised secant stiffness $[E^u_{tan}/p_{ref}]/[p'/p_{ref}]^{0.5}$ for intact and reconstituted till

The key points observed were:

- The reconstituted Cowden till's effective stress and stress-strain responses varied markedly with OCR.
- K_0 consolidated samples tested at low OCR failed after relatively small strains in compression and manifested brittleness before developing their critical states.
- Careful sampling and testing of the Cowden Bolders bank till shows that the deposit is neither sensitive nor cemented. Furthermore, it possesses a robust fabric, owing to its deposition under glacial conditions, which cannot be removed by simple 1-D consolidation.
- Notwithstanding the previous point, laboratory testing of intact samples retrieved from 3.0 to 4.0m depth shared many common behavioural attributes with the experiments on high OCR reconstituted till.
- After normalisation by equivalent pressure (p'_e) to allow for the effect of variable void ratios the reconstituted till's Critical State Line and State Boundary Surfaces were compatible with those of the intact Cowden till.
- Comparison of intact and reconstituted shear stiffness data also identified similar stiffness trends, provided the data are normalised for void ratio, OCR and p' in appropriate manner.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

Bishop, A.W. & Wesley, L.D. (1975) A hydraulic triaxial apparatus for controlled stress path testing. *Géotechnique*. 25 (4), 657–670.

Burland, J.B. (1990) On the compressibility and shear strength of natural clays. *Géotechnique*. 40 (3), 329–378.

Byrne, B.W., McAdam, R.A., Burd, H.J., Houlsby, G.T., et al. (2017) PISA: New Design Methods for Offshore Wind Turbine Monopiles. In: *Proceedings of the 8th International Conference on Offshore Site Investigation and Geotechnics*. 2017 London. pp. 142–161.

Gens, A. (1982) *Stress-strain and strength of a low plasticity clay*. PhD Thesis, Imperial College London.

Gens, A. & Hight, D.W. (1979) The laboratory measurement of design parameters for a glacial till. In: *Proceedings of the 7th European Conference on Soil Mechanics and Foundation Engineering*. 1979 Brighton. pp. 57–65.

Jardine, R.J. (1985) *Investigations of pile-soil behaviour, with special reference to the foundations of offshore structures*. PhD Thesis, Imperial College London.

Jardine, R.J. (1992) Some observations on the kinematic nature of soil stiffness. *Soils and Foundations*. 32 (2), 111–124.

Jardine, R.J., Gens, A., Hight, D.W. & Coop, M.R. (2004) Developments in understanding soil behaviour. In: *Advances in geotechnical engineering, Proceedings of the Skempton Conference*. 2004 London, Thomas Telford. pp. 103–206.

Powell, J.J.M. & Butcher, A.P. (2003) Characterisation of a glacial till at Cowden, Humberside T S Tan, K K Phoon, D W Hight, & S Cerark (eds.). *Proceedings of the International Workshop on Characterisation and Engineering Properties of Natural Soils*.2 pp.983–1020.

Ushev, E. (2018) *Laboratory Investigation of the Mechanical Properties of Cowden Till Under Static and Cyclic Conditions*. PhD thesis, Imperial College London.

Ushev, E.R. & Jardine, R.J. (2018) The behaviour of Bolders Bank glacial till under undrained cyclic loading. Submitted.

Zdravkovic, L., Jardine, R., Taborda, D.M.G., Abadias, D., et al. (2018) Ground characterisation for PISA pile testing and analysis. *Geotechnique*, Accepted.