The behaviour of Bolders Bank glacial till under undrained cyclic loading

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E. Ushev

Arup, formerly Department of Civil and Environmental Engineering, Imperial College London, SW7 2BU

R. J. Jardine

Department of Civil and Environmental Engineering, Imperial College London, SW7 2BU

Abstract

Analysis of foundation behaviour under repeated loading can be important to the design of offshore facilities, towers, bridges, wind-turbines and other structures. While detailed guidance is available on how some geomaterials behave under cycling, few such studies have been reported on the glacial formations that are widespread across parts of northern Europe and under the North and Baltic Seas. This paper presents a cyclic laboratory investigation involving block samples of Bolders bank till, which is one of the most extensive North Sea glacial formations. Static and cyclic triaxial tests are reported on nominally identical, low plasticity, high OCR, specimens from Cowden, near Hull in the UK. Twenty-three cyclic tests are reported on specimens that were re-consolidated to K_0 stresses before experiencing up to 3500 undrained cycles involving a range of mean and cyclic shear stress combinations. The impacts of cycling on effective stress paths and strain development, cyclic stiffness and damping ratios are reported and interpreted with respect to parallel index, oedometer and monotonic triaxial compression and extension tests. Stable, metastable and unstable patterns of behaviour are identified, along with different cyclic failure modes. The styles of cyclic response are related to the till's static yielding behaviour. While the till can only manifest quasi-elastic behaviour within a very small (Y_1) Kinematic Yield Surface (KYS), a larger second (Y_2) KYS is identified within which repeated loading leads to a non-linear yet stable response, with negligible mean effective stress drifts or stiffness degradation with low and stabilising strain accumulation rates. Cyclic paths that engage and relocate the Y_2 surface lead to greater permanent strains, mean effective stress drifts and stiffness decays that become progressively more marked as the magnitudes of the cyclic stress perturbation and the number of cycles increase. While cycling under stable or metastable conditions increased the ultimate undrained strength of specimens that did not develop excessive strains, most cyclic paths that exceeded and climbed the till's Hvorslev surface were unstable and eventually failed. The experiments identified the key factors that affect the till's response to repeated loading and provide a basis for developing, testing and calibrating cyclic constitutive models and establishing simplified design procedures for comparable tills.

Key words: Glacial-till; cyclic loading; stress-path laboratory tests.

Introduction

Assessing how foundations respond to cyclic loading can be important in foundation design, especially with offshore structures; see for example Andersen (2009) or Jardine *et al.* (2012). Stress-path laboratory tests on site-specific, or regionally typical, soil types offer an element-level approach for studying how regular cycling influences soil behaviour. The soil response is tracked as cycling progresses in terms of permanent strain development, cyclic stiffness and damping ratio changes and, if undrained, mean effective stress or pore pressure drifts; the number of cycles at which any cyclic failure develops is also a key outcome. Multiple testing programmes involving wide ranges of cyclic conditions have been reported for sands (see for example Wichtmann *et al.* (2005)) and low-to-medium OCR clay sediments; see for example Andersen (2015).

Offshore Gravity Based Structure (GBS) designers routinely employ such testing to assess directly how severe storms may affect safety and performance. While the designers of offshore piled foundations often neglect the effects of axial load cycling, Aghakouchak *et al.* (2015), Aghakouchak (2015) and Jardine (2020) applied cyclic triaxial and hollow cylinder apparatus (HCA) tests directly to assess its impact on piles driven in sands, matching successfully the cyclic field tests described by Jardine and Standing (2012) and model tests reported by Tsuha *et al.* (2012). Jardine (2020) also reports several offshore projects where design has been guided by site-specific cyclic simple shear testing and cyclic tests on piles driven at representative sites.

Load cycling often has its most critical impact under undrained conditions and interpretive constitutive frameworks of varying complexity have been developed to simulate the responses observed in undrained cyclic laboratory tests. Simple non-linear cyclic models can capture shear modulus degradation and hysteresis by defining a backbone curve to determine the monotonic stress–strain response, combined with sets of unloading and reloading rules, see: Ramberg & Osgood (1943), Pyke (1979), Puzrin and Shiran (2000) or Taborda and Zdravkovic (2012). These models' predictive capabilities are limited by the implicit decoupling of the stress-strain response from the generation of excess pore water pressures, or changes in mean effective stress. More advanced effective stress-based elastic-plastic constitutive laws can simulate more completely the cyclic responses of clays. One class of models, originating from Dafalias (1986), considers anisotropic extensions of the Modified Cam Clay model. Dafalias *et al.*'s (2006) SANICLAY framework accounts for the softening responses seen in soft clays and the de-structuration under loading of natural sensitive clays. Seidalinov and Taiebat (2014) proposed a versatile modification of the framework that accounts for de-structuration due to cyclic loading in low OCR clays. Kinematic hardening constitutive models that apply bounding surface plasticity frameworks through extensions of Modified Cam Clay include those proposed by

Rouania and Muir Wood (2000), Kavvasdas and Amorosi (2000), Baudet and Stallebrass (2004) and Grammatikopoulou et al (2006).

While the above experimental and theoretical developments focus principally on characterising and modelling the generally contractive cyclic responses seen in experiments on low-to-medium OCR, potentially sensitive or structured, clays, far less emphasis has been given to investigating and modelling stiff, insensitive, high OCR clays. This paper presents an experimental investigation into the undrained cyclic behaviour of low plasticity, high OCR, Bolders bank glacial till. The formation is widespread under the North Sea; Davies *et al.* (2011) and similar deposits are encountered frequently in engineering projects located across northern Europe, as well offshore in the North and Baltic Seas. The experiments provide a new benchmark for the development and calibration of cyclic design frameworks and constitutive models for application in such strata.

The samples were taken from Cowden, on the Holderness peninsula near Hull in NE England where static and cyclic piling research has been conducted since the 1970s; see Ove Arup & Partners Ltd (1986), Lehane and Jardine (1994), and Karlsrud *et al.* (2014). Cowden was also one of the two test sites selected for the recent PISA monopile wind-turbine research project described by Byrne *et al.* (2017), which included cyclic lateral loading tests on tubular steel piles with outside diameters up to two metres.

Site conditions and till response to monotonic loading

Powell and Butcher (2003) and Zdravkovic *et al.* (2020) outline the key geotechnical aspects of the 40m thick, stiff and lean, Bolders Bank clay till present at Cowden, which overlies chalk and include isolated sand layers. The till's deposition is likely to have involved both drained and undrained cyclic pre-shearing stages which may have contributed to its relatively high in-situ undisturbed undrained shear strengths and low liquidity indices. More detailed descriptions of the till's properties are given by Ushev (2018) and Liu (2018), who emphasise the important impact of its coarse sand, gravel and cobble fractions and also characterised the till's anisotropic monotonic stiffness and shear strength characteristics. Ushev's tests on Geobor-S rotary samples taken to 12m depth led to the profiles given in Figure 1 of natural water contents, liquid and plastic limits while his anisotropically consolidated undrained (CAU) triaxial tests gave the undisturbed undrained shear strengths from stress-path tests, which were run from in-situ K_0 stresses at an axial strain rate of 5%/day.

The cyclic study presented in this paper tested specimens trimmed from high-quality cubical (350 x 350 x 350mm) block samples taken at 3.00–3.50m depth in a closely supported excavation near to the Geobor-S boreholes. At this depth the till consists of approximately 30% clay, 40% silt, 20% sand and

10% gravel. A high pressure oedometer experiment on reconstituted till and monotonic undrained triaxial tests on K_0 reconsolidated natural specimens from the same depth range led to the key outcomes in Figure 2a), which identifies parallel K_0 Normal Compression and Critical State lines for the till at this depth. A typical unload-reload trace is also reported. Ushev's (2018) analysis of the oedometer and triaxial shear strength data identified Yield Stress Ratio (YSR), or apparent OCR, range of 10 to 14 within the cyclic test samples' depth range.

Considering the mean cyclic test specimen depth of 3.40m, the in-situ stresses were estimated as $\sigma'_v = 50\text{kPa}$, $\sigma'_h = 75\text{kPa}$, with $K_0 = 1.5$. Figure 2b) shows the undrained effective stress paths, where $q = (\sigma'_v - \sigma'_h)$ and $p' = [\sigma'_v + 2\sigma'_h]/3$, manifested in triaxial compression and the extension tests conducted from in-situ conditions on samples from 2.5 to 4.0m depth. Under constant volume, undrained, conditions the radial strains $\epsilon_r = -\epsilon_a/2$ and $\epsilon_a = \epsilon_s$, the shear strain invariant. The deviator stress (q) against absolute axial strain $|\epsilon|$ curves are shown in Figure 3a) while the small-strain initial response is presented at enlarged scale as $|\Delta q|$ against $|\epsilon|$ in Figure 3b). Compression tests on Cowden till reach stable plateaux after experiencing large axial strains, with the specimens failing by bulging and no shear bands forming; their final stress points are interpreted as stable critical states with ultimate $M = q/p' = 1.0$, as shown in Figure 2. Specimens tested in extension develop localised necking failures after around 6% strain which lead to apparent peak shear strengths and post-peak softening. However, the global post-peak stress-strain response is not considered representative of the local behaviour applying within the necking region and the lower extension S_u values is not representative of the till's true anisotropy, which was investigated separately in HCA tests; see Liu (2018).

The triaxial specimens were equipped with local axial and radial strain sensors, based on the systems proposed by Cuccovillo and Coop (1997) and Ackerley et al (2016), whose very high-resolution allowed the linear stress-strain behaviour manifested in Figure 3b) to be defined accurately in extension and compression along with the limits to the linear Y_1 Kinematic Yield Surface (KYS) as defined by Jardine (1992). These features cannot be resolved without employing such local strain instruments. At this depth the linear regions extended vertically in q - p' space by around $\pm 2.5\text{kPa}$ (after $\epsilon_{\text{axial}} = \epsilon_s$ increments of around 1.10^{-5}) and the mean initial elastic stiffnesses amounted to $202 \pm 36 \text{ MPa}$, as established by linear regression analysis of the initial linear test portion. While similar stiffnesses should apply in extension and compression, differences are seen that reflect the test specimens' slightly different sampling depths (3.40m and 3.45m) and a slight tendency for samples to creep very slowly in extension following the application of $K_0 > 1$. Small-strain cyclic probing tests reported by Ushev (2018) and Liu (2018) confirm that plastic straining commences once the Y_1 KYS is reached and that, once engaged, the Y_1 KYS is dragged with the current effective stress point. Multiple tests on samples at other depths show that the stiffnesses grow in proportion to in-situ $[p']^{0.5}$ and that the KYS vertical

extent in q - p' stress space grows in proportion to p' . Figure 3c) shows how the till's secant and tangent stiffness curves vary with strain after engaging the till's Y_1 KYS in plots where the undrained vertical stiffnesses is normalised by $[p']^{0.5}$; which brings the respective stiffness curves into narrow bands over the full depth profile; Ushev (2018). Note that the stress strain curves can show changes in slope on reaching Y_1 , which lead to discontinuities in the tangent stiffness curves. Other static and dynamic probing tests by Ushev (2018) and Liu (2018) following the Kuwano and Jardine (2002) procedures demonstrated that the till's stiffness is anisotropic over the full strain range and that behaviour within the Y_1 KYS under can be expressed for this depth and in-situ stress conditions by the transversely isotropic stiffness and Poisson ratios listed in Table 1. The till has remarkably high elastic bulk stiffness (K'), which far exceeds any elastic parameters that might be interpreted from the swelling portion of the oedometer curve shown in Figure 2a).

Ushev (2018) interpreted large-scale ' Y_3 yield points' (as defined by Jardine 1992) from his compression tests as the points (at $q \approx 100$ kPa) where the effective stress paths rotated from and the initial negative dp'/dq ratios (that reflect the till's elastic stiffness anisotropy) to follow paths with positive, dilative, dp'/dq directions. He also interpreted the notional Hvorslev surface shown on Figure 2b) that ran from the final critical state point back to the no-tension cut-off and encompassed the large strain undrained effective stress paths. Uncertainty regarding the ultimate conditions applying locally within the necked regions of the extension tests led to assuming similar critical states and Hvorslev surfaces to those established in compression. The monotonic framework summarised in Figures 2 and 3 is central to interpreting the cyclic tests.

Cyclic testing programme

The cyclic study presented comprised 23 triaxial experiments on a mix of 38mm and 100mm diameter specimens, as listed in Table 2. Ushev's (2018) cyclic triaxial tests were performed, under stress-control, in Bishop and Wesley (1975) type hydraulic stress path cells. Lubricated top and base sample ends were employed comprising double latex membranes incorporating radial cuts and a thin layer of silicone grease. In addition to high resolution local strain gauges, mid-height pore-pressure probes Hight (1982) were deployed. The specimens were cut from the blocks by a hand-saw, trimmed to cylinders in a soil lathe and saturated after setup by increasing the isotropic cell pressure until $B > 0.95$. Full surface drainage was employed through filter paper strips placed on the specimen exteriors. Reconsolidation was performed to the in-situ stresses estimated for 3.4m depth. The necessary effective stress changes were applied no faster than 1 kPa/h and the specimens were held under drained conditions at $q = -25$ kPa and $p' = 67$ kPa until the axial strain creep rate fell below 0.005%/day.

Multiple specimens were cycled directly from these conditions. However, larger numbers were cycled from higher mean q_m values and these were loaded, undrained, at axial stress rates to achieve the desired (pre-cycling) q_m values. In most cases 2kPa/h rates of axial stress change were employed to impose q_m , although 5kPa/h rate was employed for specimens that were cycled from $q_m = 200\text{kPa}$. All the specimens tested with $q_m > -25\text{ kPa}$ were held under undrained conditions until their axial creep rates became negligible ($<0.005\%/day$).

Regular undrained sinusoidal cyclic deviatoric stress cycles were then applied with periods (in most cases) of 5min (0.0033Hz) per cycle. As described in Appendix A, this relatively slow rate was chosen after multiple trials as giving the best compromise with the systems available between: (i) good cyclic load control, (ii) accurate and full logging of each cycle and (iii) accurate cyclic pore-pressure measurement over each individual cycle. Cyclic failure was defined as occurring when either: i) the axial strains, of either sign, exceeded 10% or ii) the strain rates became too high for the actuators to maintain the required stress paths. Ushev (2018) explored the impact of varying loading rates under monotonic conditions and confirmed that the till's response varied with strain rate. A 10-fold increase in strain rate could result in a 6% increase in undrained shear strengths and 10-14% gain in non-linear stiffnesses. Conversely, increasing the period of applied cycling can lead to larger permanent deformations developing and fewer cycles being required to reach failure.

The interactive influences of the mean q_m and cyclic q_{cyc} deviatoric stresses were explored through the combinations outlined in Figure 4, which offers parallel schemes for normalising the loading parameters. The first employs the conventional total stress $q_{cyc}/2S_u$ and $q_m/2S_u$ measures. The till's mean S_u value at this depth (averaging $\approx 130\text{ kPa}$ in triaxial compression and $\approx 120\text{ kPa}$ in extension monotonic tests) was 125kPa and the resulting S_u/σ'_{v0} ratio of 2.5 is indicative of an apparent OCR (or Yield Stress Ratio, YSR) ≈ 12 , which varies markedly with depth; Ushev (2018). Figure 4 also shows alternative 'effective-stress' normalised axes with q_{cyc}/p'_{insitu} and q_m/p'_{insitu} and distinguishes between those tests where the maximum and/or minimum q/p' inclinations exceeded the M ratio indicated by the monotonic tests. Specimens sheared monotonically to higher ratios tended to dilate as they progressed to their ultimate shear failures; see Figure 2b).

The sub-plots given in Figure 5a) to c) define the extents of the maximum and minimum deviatoric stresses q_{max} and q_{min} applied in each cyclic series (comprising of up to six q_{cyc} cases) conducted at fixed q_m values = -25kPa (the in-situ case), 50kPa, 125kPa or 200kPa. Also shown are the interpreted monotonic critical state points and Hvorslev surfaces. Five of the higher amplitude cyclic tests failed according to the adopted criteria after the indicated number (N_f) of cycles. All other specimens remained un-failed when the loading halted after 1500 to 3500 cycles. Those with accumulated axial strains $\epsilon_a < 4\%$ were sheared (after allowing 24h periods for any undrained creep to stabilise)

monotonically to compressive failure at axial strain rates of 5%/day to provide information on post-cyclic shearing behaviour.

Numbers of cycles to failure

Interpreted contours are shown in Figure 4 of the cyclic stress combinations under which the tests indicated failure after $N = 10, 100$ or 1000 cycles. The contours were established by semi-logarithmic interpolation between the experimental results, modified from Andersen's (2015) linear procedure for lower OCR clays. The failed tests' N_f values are also annotated; points marked with a '>' sign represent cases that remained un-failed at the specified total number of cycles. The nominal $N_f = 1$ contours extend from $q_{cyc}/2S_u = 0, q_m/2S_u = -1$ to $q_{cyc}/2S_u = 1, q_m/2S_u = +1$ and neglect any strain rate dependency of S_u over the ranges considered. Contours on the less populated extension side of the interactive diagram are shown as straight, dashed lines interpreted from the monotonic extension tests.

The interaction diagram may be separated into an un-failed zone and regions where failures occurred by either (i) a combination of large cyclic and average strains, as defined in Figure 6, that led to "abrupt failure" or (ii) cases where large mean strains developed without correspondingly large cyclic strains and samples tended to a "creeping failure". The abrupt failure mode is typical for specimens cycled symmetrically from in-situ stresses ($q_m = -25\text{kPa}$) with high q_{cyc} values, while the creeping failure mode applied in tests with higher initial deviatoric offsets ($q_m \geq 50\text{kPa}$).

Most of the 13 samples that did not fail under cyclic conditions developed apparently stable critical states when sheared monotonically to large compressive strains. The post-cyclic undrained shear strengths of the un-failed specimens revealed $S_u^{\text{post-cyclic}}/S_u^{\text{TXC}}$ ratios exceeding unity (one exception is the test at $q_m = 200\text{kPa}$ which had a ratio of 0.93) with an average of 1.19. Stable or metastable cyclic loading appears to lead to slightly higher undrained shear strengths at constant void ratio. As noted below, stable cyclic loading had little impact on the samples' mean effective stresses. Given also the till's very high bulk stiffness the gains in undrained shear strength exhibited by un-failed samples could not be explained by positive plastic volumetric straining. Instead, it appears to be related to the effects of the many low-level, shear strain cycles that led to a stable non-linear and principally reversible response being established after the first few load cycles.

Effective stress paths under cyclic loading

A special feature of the cyclic tests was their ability to track effective stress paths accurately throughout cycling and identify trends that varied systematically with the loading parameters, $q_m/2S_u$,

$q_{cyc}/2S_u$ or q_{cyc}/p'_{insitu} and q_m/p'_{insitu} and N . Figures 7 to 12 present, in multiple sub-plots, the paths, grouped into sets that employed the same q_{cyc} amplitudes. Also shown in each sub-plot are the no-tension lines, the Hvorslev surfaces and failure M lines identified from the static tests.

The cyclic tests all exceeded their short (± 2.5 kPa) quasi-elastic ranges, and so manifested non-linear stiffness and minor plastic straining. Nevertheless, the Figure 7 sub-plots reveal that all the $q_{cyc} = 10$ kPa tests presented relatively tight, steady and stable effective stress path loops, including tests where $q_m/p' > M$ and in the $q_m = 200$ kPa case, approached the outer Hvorslev surface established from slow monotonic tests. The paths were oriented nearly vertically in the 'in-situ' $q_m = -25$ kPa test but rotated clockwise to give positive dq/dp' slopes in the higher q_m experiments. Slight gains in p' were observed over the first 1000 cycles, followed by either stasis or slightly falling values as cycling continued. The $|\Delta p'|$ changes amounted to less than $0.05p'_0$ over the 1 to 2 weeks required to apply 2000 to 3500, 5-minute period, cycles. Figure 8 shows that the experiments involving the next largest $q_{cyc} = 25$ kPa ($q_{cyc}/2S_u = 0.1$) amplitude also exhibited broadly stable responses. Shifts can be seen again from an initially "dilative" drift trend to one indicating slightly "contractive" behaviour, but after lower numbers of cycles than in the equivalent lowest amplitude ($q_{cyc} = 10$ kPa) cases. The tests' overall $|\Delta p'/p'_0|$ changes were smaller than 5% over the 1697 to 2013 cycles applied in the $q_m = -25$ cases, while the $q_m = 125$ kPa test, which also approached the Hvorslev surface showed a 6% drift.

Overall, the $q_{cyc} = 10$ and 25 kPa experiments followed broadly stable effective stress paths over thousands of cycles. Working from tests involving far fewer cycles on other soils, Jardine (1992), (2013) and Kuwano and Jardine (2007) identified a 'Y₂' Kinematic Yielding Surface (KYS) which marked a threshold beyond which soil behaviour changed distinctly under cyclic or (drained) static loading. In the analysis that follows, we define the Y₂ threshold as corresponding to the limit to the undrained cyclic stress paths within which $|\Delta p'/p'_0|$ remains $< 5\%$ over 2000 cycles and, as discussed later, no significant loss of cyclic stiffness occurs. The $q_{cyc} = 25$ kPa, $q_m = 125$ kPa test, which showed $|\Delta p'/p'_0| = 6\%$, exceeds this criterion marginally. Tests with the same $q_{cyc} = 25$ kPa, but lower q_m , remained within their Y₂ surfaces. Pre-shearing to $q_m = 125$ kPa evidently diminished the absolute size of the current KYS, even though the undrained pre-loading path led to 'dilative' increases in p' .

The $q_{cyc} = 50$ kPa ($q_{cyc}/2S_u = 0.2$) tests conducted at $q_m = -25$ and 50 kPa developed the more extensive and broader effective stress paths shown in parts a) and b) of Figure 9. Their initially dilative trends and movements to the right were followed by more contractive shifts between $N = 100$ and 1000, that subsequently slowed and led to overall $|\Delta p'/p'_0|$ drifts $\approx 10.0\%$. The paths clearly engaged and modified the till's Y₂ surface (as defined above) but remained well within the Hvorslev surface. No failure occurred, indicating metastable outcomes. Increasing the cyclic amplitude to $q_{cyc} = 75$ kPa

($q_{cyc}/2S_u = 0.3$) in tests from $q_m = -25$ and 50 kPa led to the still more marked p' drifts seen in Figure 10, parts a) and b). In the first case, the imposed minima in q approached the Hvorslev surface interpreted from slow monotonic extension tests. However, both specimens survived the 2000 or more cycles imposed, so their behaviour was also metastable. The effective stress paths observed under cycling with $q_{cyc} = 75$ kPa amplitudes and 5min periods from $q_m = 125$ kPa appeared to cross (and so violate) the 'slow shearing' Hvorslev surface in compression (see Figures 10 part c)) provoking "dilative" behaviour over the first 100 cycles ($|\Delta p'/p'_0| > 25.0\%$) followed by a rightward drift, away from the Y_3 yield surface. The cyclic strain rate was around 40 times that applied in the monotonic test and the observed 'over-shooting' is interpreted as being due to shear strain rate effects.

The resulting q - p' loops remained relatively symmetrical and of limited width. No failure occurred. Even though significant permanent strain accumulation took place over the 2000 cycles, as detailed later, these tests also classify as being metastable.

However, the higher amplitude $q_{cyc} = 100$ and 150 kPa ($q_{cyc}/2S_u = 0.4$ and 0.6) experiments conducted from $q_m = -25$, 50 and 125 kPa all first violated the 'slow shearing' Hvorslev surface and subsequently progressed to fail within 1000 cycles; see Figures 11 and 12. Their final stages involved cyclic axial strain rates of 10 to more than 1000%/h, which were up to 200 times higher than in the reference monotonic experiments, which may explain again why they were able to occupy regions of effective stress space that were inadmissible in the slower tests. Their initial cyclic effective stress paths showed markedly dilative behaviour, which the till could not sustain for many cycles. The specimens' p' values started to fall more significantly on unloading than they rose during loading, leading to a contractive overall trend with the paths heading leftward towards the origin, developing irregular loops and broad "butterfly" shapes. As summarised in Figure 6, large permanent strains accumulated, and cyclic failures developed with maximum deviatoric stresses q_{max} as low as half the $2S_u$ limit applying to the monotonic tests, despite the cyclic tests higher axial strain rates.

The experiments demonstrate that the high YSR Cowden till's cyclic response is controlled by how the effective stress paths invoked by any given level of cycling map onto the till's kinematic 'small-strain' and outer yielding surfaces. Behaviour remains linear-elastic provided the cycles remain within the Y_1 surface whose size, although very small, increases with in-situ p' . Stable non-linear responses are seen under cycles whose q_{cyc}/p' amplitudes allow them to remain within the second Y_2 surface size. Failure develops when the loading paths' peaks or troughs attempt to exceed or climb significant distances up and along the Hvorslev surface.

Although strain-rate dependent aspects of behaviour may allow cyclic paths to exceed the 'static slow shearing' Hvorslev surface, as noted above, this is only possible when the cyclic strains are large. Any

foundation built in or on the till that experiences such cycles can be expected to exceed its serviceability criteria.

As shown in Figures 2a) and b) the ratio of $p'_{\text{critical state}}/p'_{\text{in-situ}}$ is high (≈ 4.0) for the Cowden till samples taken at 3 to 3.5m, reflecting its high YSR (≈ 12) at the depth considered. This is the key feature that leads to cyclic failures at $[q_{\text{cyc}}/S_u + q_m/S_u]$ ratios as low as 0.5. However, YSR often varies strongly with depth at glacial sites (as is true at Cowden) and as a result, the q_{cyc}/S_u , q_m/S_u combinations at which failure occurs under given numbers of cycles are likely to also vary significantly. Relating the loading limits to the till's stable Hvorslev surface provides a more direct link to the effective-stress mechanism that controls cyclic failure. In the same way, normalising the loading parameters by p' (as q_{cyc}/p' and q_m/p') should lead to criteria that are less sensitive to variations with depth in soil state or YSR.

Overall trends for mean effective stress drifting under cycling

It is important in cyclic foundation analysis to consider further details of how the soil responds to cycling. An example of the mean effective stress drifts recorded in each test during the 100th cycle is shown as functions of q_{cyc} and q_m in Figure 13. The data are presented as $\Delta p'/p_0$ percentages. As Cowden till exhibits generally "dilatant" initial behaviour, followed by "contraction" under medium and high cyclic stress amplitudes the overall p' contours rise and fall. To help identify the points at which these changes occur, contours are shown of the "incremental" dp'/p'_0 per cycle rates of change (as averaged over intervals of 20 cycles) in Figure 14, parts a) to c). The zero value contours, shown with thicker lines, represent the locus of the points where dilative behaviour gives way to contractive. The loci move progressively downwards in the q_{cyc} , q_m plots as the number of cycles increases.

Evolution of strains

Axial strain contours

The corresponding patterns of change in axial strains, which is equivalent here to shear strain invariant ϵ_s , are presented as contours of accumulated average and cyclic axial strains for the $N = 10, 100$ and 1000 cases in Figure 15, parts a) to c). The contours, which are spaced on nearly logarithmic intervals, were obtained by linear interpolation. Their intersection with the horizontal axis is defined by the axial strains accumulated during the companion monotonic compression tests. The testing programme left uncertainties on the extension side, where the contour patterns are presented as dashed lines extending to $q_{\text{cyc}}/2S_u = 0.2$ ($q_{\text{cyc}} = 50\text{kPa}$). The contours naturally become more densely packed in the lower portions of the plots as N increases. They also change in shape and inclination as N rises, showing a greater dependence on both q_m and q_{cyc} as cycling progresses.

Axial strain accumulation trends

The accumulation of average axial strains ϵ_{mean} with number of cycles (N) is examined in Figure 16 with sub-plots (part a) to c)) employing logarithmic axes and grouping the sets of tests conducted at $q_m = -25$ to 125kPa. All the experiments developed some permanent straining, although three of the four tests that sustained the lowest (10 kPa) cyclic amplitudes tended to stabilise after 100 to 1000 cycles and had rates that were often comparable to the slow residual creep rates (<0.005%/day) applying before cyclic started. The broad trends seen over the full durations of all tests that manifested stable or metastable effective stress paths, and those from the initial stages of unstable tests, appear to follow approximately power law relationships with N:

$$\epsilon = A(N)^l \quad \text{Eq. (1)}$$

The trend lines indicate an average exponent l that does not appear to vary systematically with the cyclic loading variables but falls around 0.35; most tests showed exponents within ± 0.15 of this mean. However, the parameter A varies with both q_{cyc} and q_m and Ushev (2018) showed that the empirical relationships given by Eq. (2) to Eq. (4) allow the experimental ϵ_{mean} trends to be fitted with coefficients of determination > 80%.

$$A = a \left(\frac{q_{\text{cyc}}}{p'_0} \right)^b \quad \text{Eq. (2)}$$

$$a = 0.075e^{2.34[\frac{q_m}{p'_0}]} \quad \text{Eq. (3)}$$

$$b = 2.06e^{0.21[\frac{q_m}{p'_0}]} \quad \text{Eq. (4)}$$

Cyclic stiffness

As illustrated in Figure 17 by the 50th cycle of the high-level $q_{\text{cyc}} = 150\text{kPa}$, $q_m = -25\text{kPa}$ experiment, which failed after 71 cycles, the stress and strain maxima do occur at the exactly the same time under high level cycling; the same is true of the minima. Undrained cyclic secant vertical equivalent Young's Moduli (E^u_{sec}) may therefore be defined for each cyclic loop by four alternative $\Delta q/\Delta \epsilon$ combinations; Ushev (2018) considered the average from the four possible combinations to be the most representative measure.

The trends for the average cyclic secant stiffness are presented in Figure 18, part a) to c) grouped by cases maintaining the same q_m values. The tests that manifested stable effective stress loops (and remained within the till's Y_2 kinematic yield surfaces) showed stiffness either growing slightly with N,

or falling modestly before stabilising. Cycling within the Y_2 kinematic yield surface (at constant overall volume and with little change in p') generates repetitive plastic shear strains that appear to stiffen the soil's response under the applied loading.

However, metastable and unstable tests all show significant stiffness degradation that did not stabilise within the number of applied cycles. Ushev (2018) shows that their stiffness degradation trends could be matched by exponential expressions:

$$E_{sec}^u/p' = Be^{-Cq_{cyc}/p'_0} \quad \text{Eq. (5)}$$

The coefficient B appears ≈ 1950 ($\pm 15\%$) independently of the cyclic loading variables. However, coefficient C varies with N as indicated by Eq. (6) and the coefficients c and d depend on q_m as indicated by Eq. (7) and Eq. (8).

$$C = cN^d \quad \text{Eq. (6)}$$

$$c = 1.37e^{0.3q_m/p'_0} \quad \text{Eq. (7)}$$

$$d = 0.07e^{-1.1q_m/p'_0} \quad \text{Eq. (8)}$$

Damping ratios

The variations of damping ratio D (defined as the ratio of the inscribed area of the stress-strain loop to the maximum elastic energy stored during each cycle) with N and q_{cyc} are presented in Figures 19, parts a) to c) with logarithmic axes and grouped according to the tests' q_m value ($q_m=200\text{kPa}$ single test's $m=0.12$ and is not shown). Stable and metastable tests indicated D ratios that fell as cycling continued, while unstable tests exhibited sharp rises in D as they approached failure. Ushev (2018) suggests that the trends applying before the onset of any cyclic failure can be matched by further functions as given in Eq. (9) to Eq. (11):

$$D = L(N)^{-m} \quad \text{Eq. (9)}$$

Where L appears insensitive to q_m and depends principally on cyclic amplitude ratio q_{cyc}/p'_0 as indicated in Eq. (10), while m varies mainly with q_m/p'_0 as shown by Eq. (11):

$$L = 18.1 \left(\frac{q_{cyc}}{p'_0} \right)^{0.31} \quad \text{Eq. (10)}$$

$$m = 0.035e^{0.65[q_m/p'_0]} \quad \text{Eq. (11)}$$

Ushev (2018) gives corresponding details of the energy dissipated per cycle in each test, showing that the tests whose stress paths remained within the Y_2 limits dissipated less than 1J/m^3 in each cycle. Metastable showed greater rates of energy consumption (10^{-1} to 10^{-2}kJ/m^3), while unstable tests showed very high rates ($> 1\text{kJ/m}^3$ per cycle) as they approached failure.

Tracking the evolution of the cyclic kinematic yield surfaces

As noted earlier, the cyclic responses observed in stable and metastable tests can be related to two kinematic yield surfaces that, once engaged, move with the current effective stress point. Ushev (2018) showed from monotonic stress probing tests that the first elastic, Y_1 , region is approximately elliptical in shape and has a maximum height of only about $\pm 2.5\text{kPa}$ in-situ at the 3.0 to 3.5m cyclic series' sampling depth. He could not identify any second Y_2 surface from his monotonic tests, but this KYS has been defined in this paper as the threshold limit to: i) stable effective stress conditions that involve less than 5% variation in p' over 2000 ± 500 cycles and (ii) practically constant cyclic stiffness. The experiments showed that tests that satisfy these two criteria also tended to exhibit low damping ratios and energy dissipation per cycle, as well as low and stabilising axial strain rate trends. Figure 20 marks the approximate boundaries of the Y_1 (red circles) and Y_2 (black ellipses) kinematic yield surfaces that surround each q_m point, along with the points at which large scale (Y_3) yielding developed under cyclic loading, which are shown as squares.

The plotted ellipses are shown with nominal aspect ratios of 2:1: the Y_2 surfaces were characterised through only undrained cyclic tests that established their vertical limits but gave no information on their width in q - p' space. Fully drained cyclic tests that involve only changes in p' with little or no change in q over large number of cycles are required to check the assumed Y_2 surface shapes, and these have not been attempted. Nevertheless, the Y_2 surfaces' vertical dimensions were seen to diminish as the pre-loading effective conditions approached the outer Hvorslev boundary, even though p' increased as the samples moved along this undrained loading path. While cyclic loading within the initial Y_2 KYSs does not appear deleterious, paths that engage Y_2 on each loading and unloading stages dissipate far more energy and provoke marked stiffness degradation and strain accumulation.

Summary

The experiments on Bolders bank glacial till provide comprehensive information on the cyclic response a highly significant, and yet previously hardly investigated, class of geomaterials. The low plasticity,

high YSR, dilatant clay responded to cycling in distinctly different ways to the principally contractant low OCR clays on which most previous studies have focussed. The tests offer insights into the phenomena that must be captured in representative constitutive models, as well as a benchmark against which such models may be tested. The key aspects established include the conditions under which cyclic failure can be expected to develop, as well as the impact of cycling on mean effective drifts, cyclic permanent strains, stiffness degradation, damping ratio and monotonic undrained shear strength. This previously unavailable information can also be used to guide directly engineering analyses of the cyclic response of foundations installed in comparable tills, including the PISA programme of cyclic lateral loading tests conducted at Cowden on large monopiles; Byrne *et al.* (2017).

Conclusions

1. The cyclic test outcomes can be summarised succinctly in contoured interaction diagrams that express the effects of the cyclic loading parameters on the number of cycles to failure, mean effective stress drifts, accumulated (mean) and cyclic (amplitude) strains. The diagrams can be divided into "safe" and "unsafe" zones. Failure occurred in the latter through either "abrupt" or "creeping" modes.
2. The interaction diagrams can be developed in terms of cyclic and mean shear stresses normalised by total or effective stress parameters, with the latter being more representative for the high YSR, low plasticity, Cowden till.
3. The till's cyclic behaviour can also be interpreted within a critical state framework which recognises the onset of significant changes of behaviour once carefully defined kinematic yield surfaces are engaged. Behaviour is linear elastic within the initial Y_1 kinematic yield surface, which only applies over a very limited range of q - p' stress space; which was around ± 2.5 kPa in vertical extent under in-situ stresses at the 3.4m average sampling depth considered.
4. However, cycling loading could lead to completely stable outcomes, with negligible mean effective stress drifts and stiffness degradation, provided the cyclic effective stress paths remained within a more extensive Y_2 kinematic yield surface. Repeated non-linear, and yet principally recoverable, shear straining under constant volume conditions allowed the till to grow, sustain or recover its secant stiffness and undrained shear strength. Only minor permanent strains and effective stress drifts developed, which could stabilise, while damping ratios and energy dissipation remained low.
5. The Y_2 kinematic yield surface moves with the effective stress path once it is engaged. Under stable in-situ conditions, the Y_2 "bubble" grew in height (in q - p' space) in proportion with p' indicating isotropic hardening. However, undrained pre-shearing stages that involved raising

peak q/p' above M diminish the KYS 'bubble' heights, even though such paths led to dilative responses that increased the specimens' mean effective stresses: the Y_2 surface's hardening rules also depend on q/p' .

6. Cyclic loading paths that engaged the Y_2 yield surface but remained within the outer Hvorslev surface developed more significant p' drifts, permanent strains and stiffness losses that varied systematically with the cyclic loading variables and the number of cycles imposed. Such tests could sustain 2000 or more cycles without manifesting full failure, so their responses were considered metastable.
7. The key trends of all tests could be fitted over their pre-failure ranges by empirical relationships that employed the effective stress variables q_{cyc}/p'_0 and q_m/p'_0 .
8. Cyclic loading tests that crossed the monotonic tests' outer Hvorslev surface underwent sharp effective stress path direction changes. Cyclic failure ensued in most such tests. However, in some cases positive rate effects allowed the cyclic effective stress paths to travel beyond the Hvorslev surface interpreted from relatively slow monotonic tests.

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Nomenclature

A, B, C, L, a, b, c, d	Empirical coefficients
CSL	Critical state line
D	Damping ratio
ESP	Effective stress path
E_{sec}^u	Undrained vertical secant Young's modulus
E_v', E_h'	Drained vertical and horizontal Young's moduli respectively
E_v^u, E_h^u	Undrained vertical and horizontal Young's moduli respectively
GBS	Gravity Based Structures
G_{hh}	Shear modulus in horizontal plane
G_{hv}, G_{vh}	Shear moduli in vertical plane
ICL	Intrinsic compression line
JIP	Joint industry project
K'	Effective bulk modulus
K_0	Stress ratio σ_h'/σ_v' for zero lateral strain
KYS	Kinematic Yield Surface
I	Slope of the $\epsilon_{\text{mean}}-N$ curve
LL	Liquid limit
m	Slope of the D-N curve
M	Slope of the failure (Critical state) line
N	Number of cycles
NCL	Normal compression line
N_f	Number of cycles to failure
OCR	Overconsolidation ratio
p'	Mean effective stress
p'_0	Initial mean effective stress

PISA	Pile Soil Analysis project
PL	Plastic Limit
q	Triaxial deviatoric stress
q_{cyc} , q_{cyclic}	Cyclic deviatoric stress
q_m , q_{mean}	Mean deviatoric stress
q_{min} , q_{max}	Minimum and maximum deviatoric stresses
S_u	Undrained shear strength
TXC	Triaxial compression test
TXE	Triaxial extension test
v	Specific volume
Y_1 , Y_2	Kinematic yield points
Y_3	Large scale 'gross' yield point
YSR	Yield Stress Ratio defined as $\sigma'_{vy}/\sigma'_{v0}$
ϵ_a	Axial (vertical) strain
ϵ_{cyclic}	Cyclic axial (vertical) strains recorded during cyclic loading
ϵ_{mean}	Average axial (vertical) strains recorded during cyclic loading
ϵ_r	Radial strain
ϵ_s	Shear strain
λ	Slope of the 1-D compression line
ν_{vh}' , ν_{hv}' , ν_{hh}'	Drained Poisson's ratios in the cross-anisotropic elastic model
ν_{vh}^u , ν_{hv}^u , ν_{hh}^u	Undrained Poisson's ratios in the cross-anisotropic elastic model
σ'_h	Horizontal effective stress
σ'_v	Vertical effective stress

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Appendix A

Pore-pressure distribution under cyclic loading

The rough ends of conventional triaxial apparatus' base and top platens act to resist radial soil movement at the boundaries. Total stress and consequently pore pressure non-uniformities ensue under static or cyclic loading, unless the loading is slow enough to allow full pore pressure equilibration to occur. Lubricated ends were employed to overcome such non-uniformities, although this step slowed down the base pore-pressure response.

The pore-water pressure distributions developed during cyclic loading were investigated with three trial tests equipped with lubricated ends and multiple miniature pore pressure probes. All specimens were tested in 100mm diameter cells, after reconsolidation to in-situ stresses under the same cyclic amplitude $q_{cyc} = 50\text{kPa}$. The tests are distinguished by the extensions added at the end of the test code, pwp1 to pwp3, as listed in Table 2. Test pwp1 was equipped with two pore-pressure probes mounted on the specimens while tests pwp2 and 3 had three. The results revealed:

- Good agreement could be achieved between the pore-pressures measured at the base and probes over each whole cycle with cyclic periods $T > 30\text{min}$, however this loading period is both impractical for research and far from representative of offshore storm conditions.
- Full equilibration of otherwise non-uniform pore-pressures through slow testing leads to measurements that are less representative of ideal element behaviour than those made locally under more rapid loading in the middle part of the specimen.
- The differences between individual local pore-pressure probe readings reduce to small values ($< 2\text{kPa}$) under cycling with $T = 5\text{min}$, showing that relatively uniform distributions apply over the main part of the samples under cycling at this rate.
- While the $T = 5\text{min}$ tests are still slower than anticipated in the field, this was the fastest rate at which tests could be controlled effectively.
- While peak and trough sample base measurements are not reliable for cycling with $T < 30\text{min}$, the average (mid-cycle) base pore pressures recorded in faster cyclic tests were found close to those from the pressure probes.
- The presence of lubricated ends slows down the base response but reduces the non-uniformity induced by rough platens.
- Mid-height pore-pressure probes provide the best measurements of true elemental soil behaviour over individual cycles in cyclic tests with periods less than 30min.

The effect of cyclic loading frequency on the behaviour

The shearing rate effect on the cyclic behaviour of Cowden till was investigated with additional slower experiments from in-situ stresses ($q_m = -25\text{kPa}$) with $q_{cyc} = 100$ and 150kPa ($q_{cyc}/2S_u = 0.4$ and 0.6) on 100mm diameter specimens from the 3.40m depth, cycled with periods of 120min ($1.4 \times 10^{-4}\text{Hz}$) and $T=360\text{min}$ ($4.6 \times 10^{-5}\text{Hz}$). The results indicate:

- Reducing the cyclic frequency leads to a further decrease in the average pore water pressure recorded during each cycle with broader individual effective stress cyclic loops.
- Slowing the cyclic loading leads to greater cyclic softening, energy dissipation, stiffness degradation and more marked permanent strain accumulation.
- The number of cycles to failure decreased as the cyclic frequency was reduced.

Tables

Table 1. Summary for the 3.0 to 3.5m depth range of Cowden till's anisotropic and bulk elastic stiffness components, normalised by elastic undrained vertical stiffness, and Poisson's ratios. Shown to two significant places.

E_{vh}/E_{vu}	E_v'/E_{vu}	E_h'/E_{vu}	G_{vh}/E_{vu}	G_{hh}/E_{vu}	K'/E_{vu}	μ_{vh}'	μ_{hh}'	μ_{hvu}	μ_{hhu}
2.2	0.81	2.1	1.0	1.3	4.1	0.41	-0.17	1.12	-0.12

Table 2. Programme of cyclic loading tests

No.	Test Code	q_m , kPa	q_{cyc} , kPa	γ , kN/m ³	p'_{0v} , kPa	Final void ratio
1	CB38KUC3.4_qm25qc10	-25	10	21.64	68.2	0.418
2	CB100KUC3.4_qm25qc25	-25	25	21.48	67.0	0.430
3	CB100KUC3.4_qm25qc50	-25	50	21.65	75.9	0.431
4	CB38KUC3.4_qm25qc75	-25	75	22.16	67.6	0.425
5	CB38KUC3.4_qm25qc100	-25	100	21.45	76.2	0.433
6	CB38KUC3.4_qm25qc150	-25	150	21.82	93.1	0.411
7	CB100KUC3.4_qm50qc10	50	10	21.57	65.3	0.444
8	CB38KUC3.4_qm50qc25	50	25	21.88	79.6	0.406
9	CB100KUC3.4_qm50qc50	50	50	21.76	73.7	0.407
10	CB38KUC3.4_qm50qc75	50	75	21.41	74.0	0.451
11	CB38KUC3.4_qm50qc100	50	100	21.54	77.8	0.433
12	CB38KUC3.4_qm50qc150	50	150	21.78	91.5	0.420
13	CB38KUC3.4_qm125qc10	125	10	21.77	96.4	0.438
14	CB38KUC3.4_qm125qc25	125	25	21.71	98.9	0.415
15	CB100KUC3.4_qm125qc50	125	50	21.81	97.8	0.430
16	CB38KUC3.4_qm125qc75	125	75	21.83	93.1	0.411
17	CB38KUC3.4_qm125qc100	125	100	21.28	104.8	0.468
18	CB100KUC3.4_qm200qc10	200	10	21.77	170.6	0.427
19	CB100KUC3.4_qm-25qc50_pwp1	-25	50	21.98	71.3	0.428
20	CB100KUC3.4_qm-25qc50_pwp2	-25	50	21.65	67.5	0.442
21	CB100KUC3.4_qm-25qc50_pwp3	-25	50	22.07	70.3	0.418
22	CB100KUC3.4_qm-25qc100_T	-25	100	21.53	74.7	0.431
23	CB100KUC3.4_qm-25qc150_T	-25	150	21.92	64.4	0.415

Figures

Figure 1 Profiles of natural water content, liquid and plastic limits, undrained triaxial shear strengths in compression (TXC) and extension (TXE)

Figure 2a) Typical oedometer compression and triaxial Critical State CS line from tests on samples from 3.0 to 3.5m depth.

Figure 2b) Effective stress paths developed in monotonic undrained triaxial tests with the interpreted Hvorslev surface in TXC for the 3.0 to 3.5m depth range

Figure 3a) Stress strain curves from monotonic undrained triaxial compression and extension tests from $\approx 3.4\text{m}$ depth

Figure 3b) Stress strain curves at small strains from monotonic undrained triaxial compression and extension tests from $\approx 3.4\text{m}$ depth

Figure 3c) Tangent and secant stiffness-strain curves from monotonic undrained triaxial compression and extension tests from $\approx 3.4\text{m}$ depth normalised by $[p']^{0.5}$

Figure 4 Cyclic stress space with static failure, M, surface contours and contours of number of cycles to failure as a function of $q_{cyc}/2S_u$ and $q_m/2S_u$ as well as $q_{cyc}/p'_{in-situ}$ vs $q_m/p'_{in-situ}$

Figure 5 Extent of the cyclic amplitudes in relation to the Hvorslev surfaces established in monotonic triaxial tests; $q_m =$ a) 25 and b) 50 kPa

Figure 5 Extent of the cyclic amplitudes in relation to the Hvorslev surfaces established in monotonic triaxial tests; $q_m = c)$ 125 and 200 kPa

Figure 6 Combination of mean and cyclic axial strains at end of tests. Numbers represent values as $\epsilon_{mean}/\epsilon_{cyclic}$ in %

Figure 7 Effective stress paths during cycling with $q_{cyc} = 10 \text{ kPa}$. Part a) combined plot and b) from $q_m = -25 \text{ kPa}$ (in-situ)

Figure 7 Effective stress paths during cycling with $q_{cyc} = 10 \text{ kPa}$. Part c) from $q_m = 50 \text{ kPa}$ and d) from $q_m = 125 \text{ kPa}$

Figure 7 Effective stress paths during cycling with $q_{cyc} = 10 \text{ kPa}$. Part e) from $q_m = 200 \text{ kPa}$

Figure 8 Effective stress paths during cycling with $q_{cyc} = 25 \text{ kPa}$. Part a) combined plot and b) from $q_m = -25 \text{ kPa}$ (in-situ)

Figure 8 Effective stress paths during cycling with $q_{cyc} = 25 \text{ kPa}$. Part c) from $q_m = 50 \text{ kPa}$ and d) from $q_m = 125 \text{ kPa}$

Figure 9 Effective stress paths during cycling with $q_{cyc} = 50 \text{ kPa}$. Part a) $q_m = -25 \text{ kPa}$ and b) $q_m = 50 \text{ kPa}$

Figure 9 Effective stress paths during cycling with $q_{cyc} = 50 \text{ kPa}$. Part c) $q_m = 125 \text{ kPa}$

Figure 10 Effective stress paths during cycling with $q_{cyc} = 75 \text{ kPa}$. Part a) $q_m = -25 \text{ kPa}$ and b) $q_m = 50 \text{ kPa}$

Figure 10 Effective stress paths during cycling with $q_{cyc} = 75 \text{ kPa}$. Part c) $q_m = 125 \text{ kPa}$

Figure 11 Effective stress paths during cycling with $q_{cyc} = 100 \text{ kPa}$. Part a) $q_m = -25 \text{ kPa}$ and b) $q_m = 50 \text{ kPa}$

Figure 11 Effective stress paths during cycling with $q_{cyc} = 100 \text{ kPa}$. Part c) $q_m = 125 \text{ kPa}$

Figure 12 Effective stress paths during cycling with $q_{cyc} = 150 \text{ kPa}$. Part a) $q_m = -25 \text{ kPa}$ and b) $q_m = 50 \text{ kPa}$

Figure 13 Contours of change in mean effective stress as a function of $q_{cyc}/2S_u$ and $q_m/2S_u$ as well as $q_{cyc}/p'_{in-situ}$ vs $q_m/p'_{in-situ}$; for $N = 100$

Figure 14 Contours of $[(dp'/dp'_0)/dN]$ mean effective stress changes per cycle. Part a) at $N = 10$

Figure 14 Contours of $[(dp'/dp'_0)/dN]$ mean effective stress changes per cycle. Part b) at $N = 100$

Figure 14 Contours of $[(dp'/dp'_0)/dN]$ mean effective stress changes per cycle. Part c) at $N = 1000$

Figure 15 Contours of mean and cyclic strains. Part a) at $N = 10$

Figure 15 Contours of mean and cyclic strains. Part b) at $N = 100$

Figure 15 Contours of mean and cyclic strains. Part c) at $N = 1000$

Figure 16 Variation of mean strain with number of cycles; a) $q_m = -25 \text{ kPa}$ in log-log scale

Figure 16 Variation of mean strain with number of cycles; b) $q_m = 50 \text{ kPa}$ in log-log scale

Figure 16 Variation of mean strain with number of cycles; c) $q_m = 125\text{kPa}$ in log-log scale

Figure 17 Stress-strain loop showing range of possible of maximum and minimum values of q and ϵ from which E_u can be calculated for any given cyclic loop

Figure 18 Cyclic secant stiffness against number of cycles at $q_m =$ a) -25 and b) 50 kPa

Figure 18 Cyclic secant stiffness against number of cycles at $q_m = c$) 125 and 200kPa

Figure 19 Damping ratios against number of cycles at $q_m = a) -25$ and b) 50kPa

Figure 19 Damping ratios against number of cycles at $q_m = c) 125$

Figure 20 Y_2 Kinematic Yield Surfaces and Y_3 cyclic yield points interpreted from cyclic undrained tests