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Steel interface shear behaviour of Bolders Bank till

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ABSTRACT: The design of a wide range of offshore foundation elements, including monopiles, 'jacket' piles, suction caissons buckets and pipelines requires accurate characterisation of soil-steel interface shearing behaviour. Interface shear resistances, as available after large-shear-displacement installation, govern the shaft capacities of axially loaded driven piles and suction caissons; they also affect their lateral responses and the behaviour of large diameter monopiles. Large-displacement ring shear soil-steel interface testing employing pre-shearing stages is the industry-recognised approach for characterising interface resistance, particularly when large displacements are expected. This paper reports suites of interface shear tests conducted with Bishop ring shear apparatus on onshore-sampled low-to-medium plasticity Bolders Bank till as part of the PISA JIP Cowden site characterisation. The outcomes are compared with earlier testing studies on Cowden till to identify how soil grading variations, interface characteristics (material type, surface roughness), testing conditions and normal effective stress affect interface resistance. The tests reported should aid those designing soil testing strategies and/or making preliminary design studies involving similar low-to-medium plasticity silty-sandy glacial sediments.

Keywords: Bishop ring shear; Bolders Bank till; interface friction angle; foundation design.

1 INTRODUCTION

Quaternary glacial sediments dominate much of the UK North Sea sector where many oil, gas and offshore wind structures are founded. Accurate characterisation of the interface shearing resistances available in such strata is essential when applying effective stress axial pile design procedures such as the ICP-05 (Jardine et al., 2005). It is also relevant to caissons and monopiles, whose lateral and moment loading behaviour depends on their shaft (m-θ) resistance components (Byrne et al., 2017).

This paper addresses the interface shearing behaviour of silty-sandy clays from the Bolders Bank till, one of the most extensive North Sea glacial sequences (Jardine, 2020). It reports the interface and soil-soil shearing behaviours characterised through torsional (ring) shear tests performed with Bishop et al., (1971) apparatus at Imperial College London (ICL) on low plasticity sandy and silty glacial Bolders Bank till sampled at the PISA Cowden test site. The tests were performed following the ICP-05 procedures and their outcomes are compared with earlier studies on Cowden till by Lupini (1981), Lemos (1986), Lehane (1992) and, Powell and Butcher (2003), as well as the highly instrumented field pile tests reported by Lehane and Jardine (1994). Soil grading variations, interface material and surface roughness, testing conditions and normal effective stress are all shown to affect interface resistance. The study should aid those designing soil testing strategies and making preliminary foundation design involving similar sediments.

2 EQUIPMENT

The Bishop et al. (1971) apparatus is illustrated in Figure 1. Lateral confinement is provided for annular specimens with heights of 10 mm and 20mm (for soil-steel and soil-soil interface tests respectively) by two 101.6 and 152.4 mm inside and outside diameter stainless steel rings. A porous stone is provided at the top and either a porous stone or steel interface at the base. Normal load is transmitted by a vertical shaft with ball bushings that allow vertical and rotational motions. The bottom of the assembly is bolted to a rotational table while the top reacts against two tangential load cells. A gap may be opened between the confining rings during critical shear test stages to allow the soil-steel resistance to be isolated and closed during large displacement shearing stages to minimise soil losses. Significant modifications were made for the present study including:

- A computer-controlled pressure actuating replaced the previous dead load hanger system.

- New displacement transducers and load cells.
- A function generator-controlled torsional stepper motor that allowed more precise control over a wide range of rotational shear displacement rates.

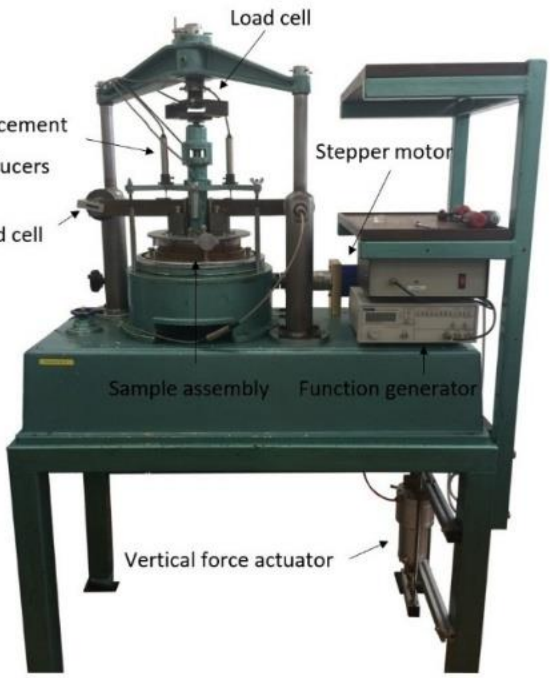

Figure 1. The Bishop ring shear apparatus.

3 TESTING PROCEDURE

The soil specimens were all sheared against mild steel interfaces which were freshly air-abraded to average centre-line roughness RCLA=8.3μm, similar to industrial driven piles (Jardine et al., 2005). As illustrated in Figure 2, the interface topography was also characterised in 3D using an interferometer. The interface tests were performed in three stages:

- Consolidation
- Fast shearing
- Slow shearing

The specimens were incrementally consolidated to vertical normal stresses of 60, 120, 240, 480 and 960 kPa. Each load increment was applied after full pore-pressure dissipation and consolidation. Fast shearing was undertaken in a series of shearing pulses at a rate of 400 to 500mm/min to a total displacement of 5m with rest periods of 10 min separating the fast shearing pulses (Jardine et al., 2005). During the fast shearing stages the gap between the interface and the confining rings were closed to minimise soil loss. As a result the steel ring was in contact with the interface and the measurements made during this stage do not represent the soil behaviour accurately. Prior to slow shearing, a gap of approximately 0.1 mm between the interface and the confining ring was opened to allow the soil-interface shear stresses to be measured.

The consolidation behaviour monitored under the last normal loading increment was used to calculate the minimum time to achieve a fully drained failure (t_f) which allowed a displacement rate of 0.016 mm/min to be employed rather than the slower default 0.005 mm/min recommended by Jardine et al., (2005) when testing clay soils.

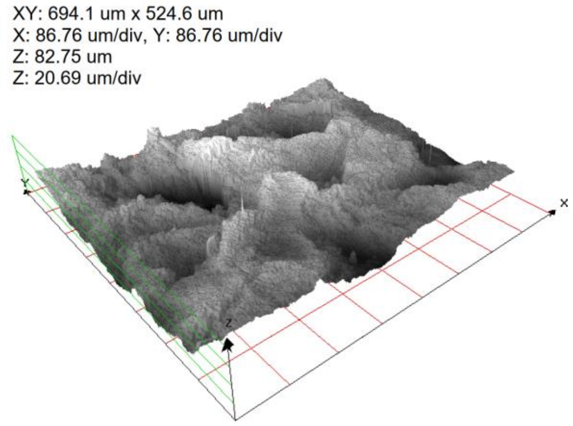

Figure 2. Typical 3D interferometer graph of a 0.7 by 0.5 mm surface patch of the mild-steel test interface.

4 COWDEN SOIL PROFILE AND SAMPLE PREPARATION

4.1 Soil profile

The Bolders Bank tills encountered at Cowden comprise stiff stony, sandy and silty clay units that under-drain into two isolated sand layers. The top 1.5 m is weathered, and seasonally influenced above an intermediate weathered section, from 2.5 to 4.8 m of stronger, desiccated, and fissured till. Despite a distinct colour change at ≈4.8 m, the intermediate layer has similar properties to the underlying unweathered till. The natural water contents, liquid and plastic limits, and bulk density profiles are shown in Figure 3. Powell and Butcher (2003), Zdravkovic et al., (2020) and Ushev and Jardine (2022a, b) give further information on the sites' CPTu and seismic profiles as well the intensive advanced laboratory testing conducted by Ushev (2018) on Bolders Bank till sampled at Cowden.

4.2 Sample preparation

Batch 1 (weathered) till specimens were derived from block samples taken at 3.0 to 3.5m depth while Batch 2 (unweathered) soil was obtained from rotary cores from 5.0 to 8.0 m. As the Cowden till contains large gravel sized particles that cannot be accommodated in ring-shear testing, the material was mechanically broken down into small fragments before being soaked in water and passed through sieves to form slurries mixed at 1.5 times the liquid limit. The slurry was one-dimensionally consolidated under 200 kPa vertical stress, σ'_v, in a 229 mm diameter consolidometer to form homogenous soil "cakes" from which specimens were cut and remoulded at their current water content.

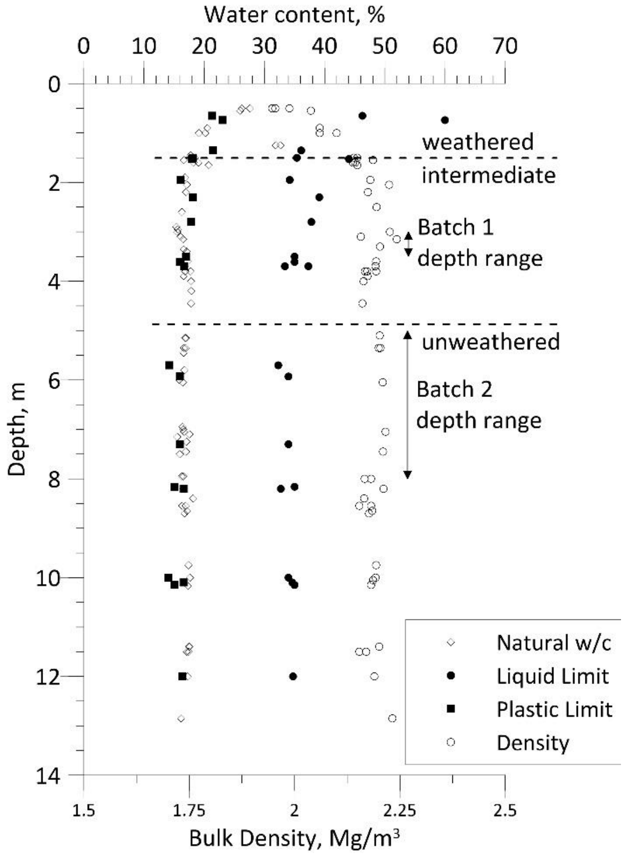

Figure 3 Profiles of natural water content, liquid and plastic limits, and bulk density.

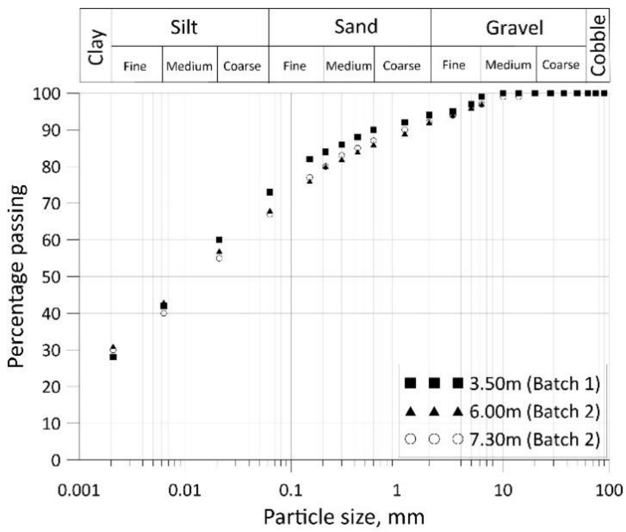

Figure 4 Particle size distribution curves.

Gravel particles were removed from the weathered Batch 1 but retained in the unweathered Batch 2. The slightly higher plasticity index (1.5-2.0%) of the Batch 1 till reflects its higher combined fraction of clay and silt content, as indicated by the particle size distribution curves in Figure 4.

5 TEST RESULTS AND DISCUSSION

5.1 Soil-steel interface tests

The steel-interface tests were performed under vertical effective stresses σ'_v of 60, 120, 240, 480 and 960 kPa. Figure 5 and 6 report the variation of mobilised interface friction angle (δ) with rotational displacement for Batch 1 and 2 tests respectively.

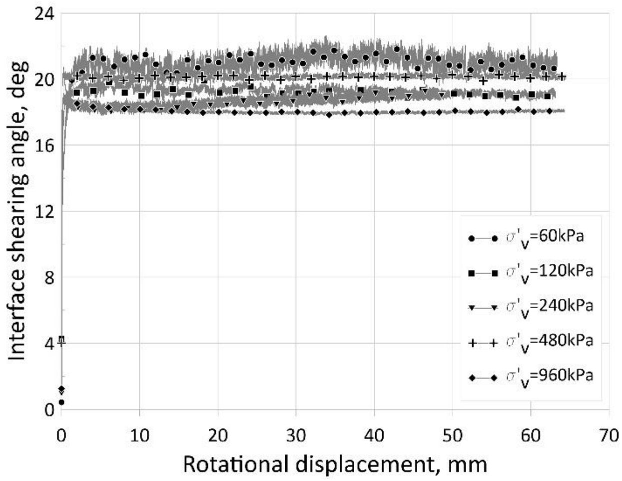

Figure 5 Mobilised interface shearing angle vs rotational displacement for weathered Batch 1 till specimens.

Brittle initial peak angles developed after relatively small displacements of 0.15 to 0.3 mm in some tests. These reduced to local minima after several mm of displacement before exhibiting angles that generally grew at diminishing rates. Table 1 lists the initial peak angles from any cases where they were observed, along with the ultimate interface angles found for all after 60mm displacements. Also listed are the test type, the stress conditions applying at failure.

The variations of residual δ with σ_v' are summarised in Figure 7. The weathered (Batch 1) till tests gave ultimate interface angles between 18.1° and 20.9°, with an average δ=19.4° and indicate no strong effect of normal effective stress level over the 60 to 960 kPa range considered. The unweathered (Batch 2) till exhibited lower ultimate interface angles at low stress levels, despite its slightly lower plasticity, although the angles gradually increase with σ_v' to similar δ values to the weathered till when $\sigma_v' \geq 400$ kPa, as illustrated Figure 7.

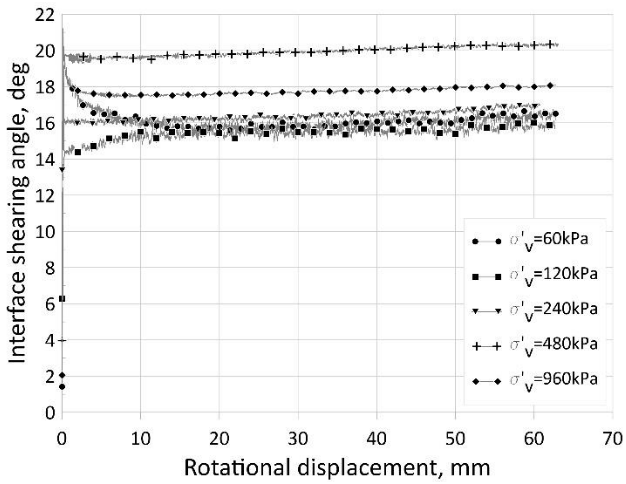

Figure 6 Interface shearing angle vs rotational shear displacement for unweathered Batch 2 till.

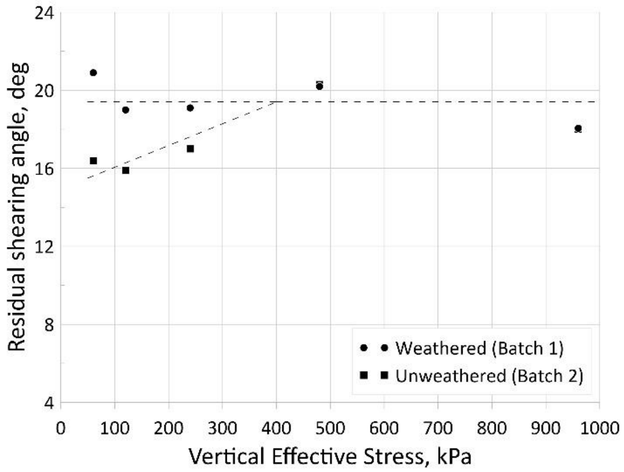

Figure 7 Summary of ultimate interface shearing angles

Large displacement shearing against the sandy till smoothed the interfaces. Post-testing roughness measurements indicated R_{CLA} reducing to 3.6 µm after shearing under σ_v' between 100 kPa and 1.0 MPa and around 5.0 µm under lower stresses. Inspection showed that the soil which had been in contact with the interface was striated and appeared to be more clay rich than the main soil mass, but without showing polished slickensides. The contact area was discoloured by the abraded steel interface particles and oxidation. A layer of highly reworked material was visible, as shown in Figure 8, suggesting that shearing had concentrated within the thin fines-rich layer between the soil and the interface, the thickness of which was approximately 0.7-0.8 mm after drying. The soil below this zone appeared less affected by the intense large displacement shearing applied.

Earlier research by Lemos (1986) emphasised the sensitivity of δ in tills to clay content, interface material, roughness and shearing rate. He had conducted ring shear tests on Cowden till against initially very smooth glass, finding slow shearing δ values that rose from initial minima as low as ≈13° to 23° ±1° and grew after applying several metres of shear displacement that gradually roughened the glass.

Lehane (1992) reported further Bishop ring shear interface tests on samples taken near to the Cowden ICP pile tests reported by Lehane and Jardine (1994). His laboratory tests employed stainless steel interfaces with 8.5µm centre-line roughness, similar to his air-abraded ICP field test pile and gave laboratory δ_{peak} values between 25° and 28° with $\delta_{residual}$ between 22° and 24°. The test pile's stainless steel Surface Stress Transducer instruments measured the field radial and shear stresses at three levels, while piezometers mounted nearby recorded the local pore pressures. These field measurements allowed pile-soil angles to be calculated, with an average peak of 18.9°, with compression tests showing higher angles than tension cases. Marginally higher angles (20.4°) were inferred from the mild steel pile sections.

The interface angles measured in the present test series, which followed the subsequently established ICP-05 procedures, agree more closely with the average field values than the laboratory tests reported by Lehane (1994). However, the spread of results emphasises the importance of even small changes in soil grading and interface conditions. Smoother interfaces generally lead to lower angles and under-estimate the capacities available to industrial piles in the field.

Figure 8 B1W specimen after dismantling.

5.2 Soil-soil interface tests

The Authors also investigated Cowden till's soil-soil mobilised friction angle (φ') at normal stresses between 120 and 480 kPa, as summarised in Table 1 which notes the test types; stresses at failure and the initial and final conditions.

Table 1. Summary of test vertical stresses, residual and peak shearing angles, initial and final water contents.

Test Type	**σ_v'**	**Rate**	**$\varphi_{ultimate}$**	**φ_{peak}**	**$wc_{initial}$**	**wc_{final}**
-	**kPa**	**mm/min**	**o**	**o**	**%**	**%**
B1W interface	60	0.016	20.9	-	20.83	23.22
B1W interface	120	0.016	19.0	-	20.6	21
B1W interface	240	0.017	19.1	-	21.1	17.99
B1W interface	480	0.016	20.2	-	20.75	17.6
B1W interface	960	0.016	18.1	20.6	20.32	18.22
B2U interface	60	0.016	16.4	21.1	19.36	20.65
B2U interface	120	0.016	15.9	-	15.98	18.76
B2U interface	240	0.016	17.0	-	21.18	17.61
B2U interface	480	0.016	20.3	-	19.28	16.92
B2U interface	960	0.016	18	19.5	20.59	15.29
B1W soil-soil	120	0.016	24.2	25.4	21.44	19.32
B1W soil-soil	240	0.016	24.5	25.2	20.27	18.24
B1W soil-soil	480	0.015	24.4	24.8	21.18	16.55
Test code: B1/2=batch number; W/U = weathered/unweathered; steel interface or soil-soil						

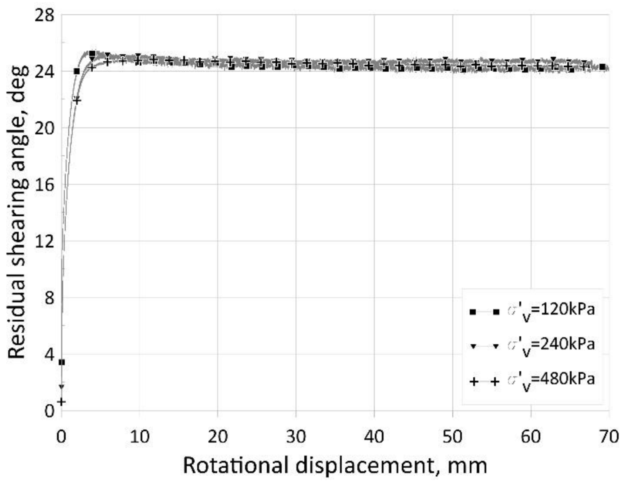

Figure 9 Mobilised φ' with displacement; Batch 1

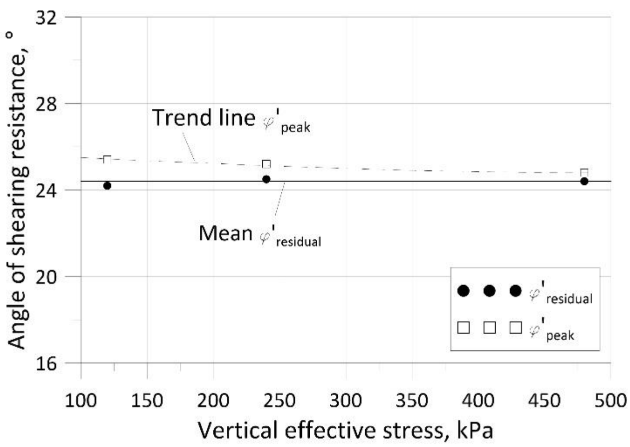

Figure 10 Variation of mobilised φ' with σ′v; Batch 1

While the peak φ' angles reduced slightly with increasing σ_v', the residual angle appeared unaffected by the stress level range. The overall $\varphi'_{residual}$=24.5° compares with the critical state φ'_{cs}=24.4° found in triaxial tests on intact and reconstituted Cowden till by Ushev and Jardine (2022a, b) and Ushev et al., (2019). Similar residual angles, between 24.5° and 26.5° were reported by Lupini (1981) and Lemos (1986) from Bishop ring shear tests on Cowden till, and by Powell and Butcher (2003) from Bromhead ring shear apparatus and shear box reversal tests.

The differences between the interface and soil-soil residual shearing angles are interpreted as being due to the shearing displacements concentrating within a thin fines-rich layer that forms between the soil and the interface as the till's coarser grains are ejected by the shearing process.

6 SUMMARY AND CONCLUSIONS

Analysis of Bishop ring shear tests on Bolders Bank till samples from the Cowden PISA JIP test site leads to eight main conclusions:

(1) The interface shear resistances of Cowden till are sensitive to small variations in soil grading, interface roughness and testing procedure.

(2) The shearing angles vary with displacement, with peaks and local minima being seen in some tests before recovering the mobilised δ

angles attained final asymptotes after approximately 50 mm.

(3) The initial average ultimate interface angle δ of unweathered till was 19.4º and showed little variation over the $60 \leq \sigma'_v \leq 960$ kPa range.

(4) The unweathered till angles were more sensitive to stress level, gradually increasing with σ'_v before reaching the same angle as the weathered soil when $\sigma'_v \geq 400$kPa.

(5) These variations are ascribed to clay and silt content differences as well as the sandy till gradually reducing the interface roughnesses through large displacement shearing.

(6) The ring shear interface tests delivered similar average δ angles to those measured in ICP field pile tests with accurate Surface Stress Transducers.

(7) The interface shear angles fall significantly below the residual φ′ values found in soil-soil tests, which fall close to the critical state angles measured in triaxial tests on intact and reconstituted Cowden till.

(8) The latter feature is due to the displacements concentrating within a thin fines-rich layer that forms between the soil and the interface as the till's coarser grains are ejected by the shearing process.

AUTHOR CONTRIBUTION STATEMENT

Emil Ushev: Original experimental analyses, Data curation, Visualisation, Writing – Original draft. **Richard Jardine**: Methodology, Supervision, Writing - Reviewing and Editing.

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