A new torsional shear device for pipeline interface shear testing

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ABSTRACT: This paper presents a new torsional shear device for interface shear testing of natural and disturbed soils, relevant to the design of hot-oil pipelines. We describe the design of the machine and present test results on samples obtained from North Sea and offshore West Africa locations. This machine is used to obtain pipeline interface strength values of very soft marine samples under axial stress conditions from 2kPa to 50kPa with shear speeds ranging from 0.0005mm/s to 0.5mm/s. Both monotonic and cyclic tests can be undertaken with cumulative shearing distance only limited by a specified test duration. The tests presented in this paper were undertaken at shear speeds of 0.001mm/s and 0.1mm/s using two interfaces of average roughness 0.3µm and 6.1µm. The results show a clear difference in interface friction between the two offshore locations, with the West African sample generating a consistently higher interface friction. All tests undertaken at the faster shear rate exhibited a well-defined peak strength before softening to a residual value. Results of macro imaging analysis and particle imaging velocimetry of sheared samples are also presented, which permit the association of the peak strength, break out behaviour and residual strength with observed micromechanical processes present during each stage of shearing.

1 INTRODUCTION

1.1 *Background*

Determination of interface friction values for the design of offshore hot-oil pipelines requires the undertaking of laboratory tests on soil samples relevant to the area of interest. The important factors that influence the interface friction value include initial soil structure, modification of soil structure during shearing, interface roughness, shear rate and applied axial stress. Previous interface testing of natural soil samples from the West coast of Africa have been undertaken by Kuo and Bolton (2014a), highlighting the importance of natural soil structure on the measured interface friction. The interface tests presented in this study consider samples taken from a different site within the Gulf of Guinea that contain a significant amount of glauconised faecal pellets. Kuo (2014a) identified similar glauconised pellets in deeper sediments (greater than 8m depth). That glauconised pellets are found in such abundance in shallow (<2m) sediments makes the samples tested in this investigation an interesting material to test. To provide a comparison with the glauconised Gulf of Guinea samples, southern North Sea samples are tested. In testing these samples, this paper introduces a new interface shear testing device called the Cam-Tor, developed at Cambridge University in collaboration with BP and Fugro (UK). This device was designed to address some of the limitations that existing interface shear devices faced, as summarised by Ganesan et al. (2014).

The key interests in completing this study are: 1) present new data from the Cam-Tor interface shear testing apparatus, 2) to provide information regarding the difference between the two soil types described above, 3) identify the role that interface roughness and shear rate have on the measured interface friction value, and 4) use imaging techniques to provide further insight into the various mechanisms present at the start and end of interface shearing.

2 METHODOLOGY

2.1 *Testing equipment*

The key features of the newly developed Cam-Tor machine (Figure 1) are given below:

- Large axial stress range from 2kPa to 50kPa
- Shear rate range from 0.0001mm/s to 1mm/s
- Ability to test both natural and reconstituted, reconsolidated soil samples
- Undertake both monotonic and cyclic tests of any cumulative shear displacement
- Flexibility in testing a range of interface roughnesses.

The Cam-Tor shears a disk of soil (either 'natural' or reconstituted) of 70mm diameter and initially, 20mm thickness after a period of one-dimensional consolidation. Loadcells measures both axial force and torque applied to the top-cap into which the interface of interest is inserted. The soil sample rotates at the required shear rate from the base and against the interface material. Analysis of the data is undertaken by considering a characteristic radius of 0.72R, where R is the radius of the sample. The factor 0.72 is determined by considering the average results of shear stress analysis under 1) plastic behaviour, 2) elastic behaviour, and 3) by assuming an 'α' strain increase each log cycle of strain.

The machine is used here to assess the behaviour of soil-structure interaction relevant to the design of hot-oil pipelines installed into shallow and ultra-deep offshore sediments.

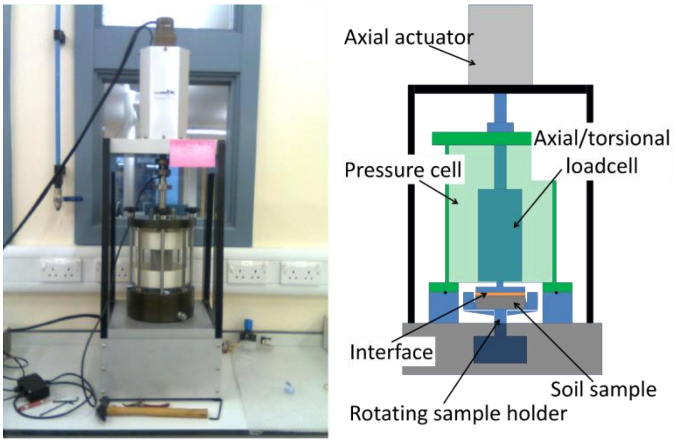

Figure 1. Photograph and schematic diagram of the Cam-Tor machine.

2.2 *Test conditions*

This paper presents the results of 8 tests undertaken using the Cam-Tor device on core samples from the southern North Sea (SNS) and the Gulf of Guinea (GOG). The key research purposes for this investigation were to:

- Characterise interface shear behaviour of low and high plasticity marine clays
- Test two shear speeds of 0.001mm/s (0.0024deg/s) and 0.1mm/s (0.24deg/s), corresponding to initially partially-drained and initially undrained conditions.
- Test one axial stress condition of 4kPa
- Test two steel interfaces of different roughness (smooth and rough).

A Taylor Hobson Precision: Form Talysurf profilometer was used to determine the interface roughness of the two interfaces used.

2.3 *Sample preparation*

Kuo and Bolton (2013) observed that marine clay samples from the Gulf of Guinea contained a significant amount of pelletised material, resulting in an increase in shear strength and grain size. It was hypothesised by Kuo and Bolton (2014a) that the presence of pelletised material could strongly influence the interface shear behaviour due to the damage caused to pellets by shearing against rough interfaces. To identify whether pellets were present in the tested samples, wet sieving following Kuo and Bolton (2013) was undertaken on natural soil samples (without prior remoulding).

Samples for interface tests were reconstituted at a water content approximately twice the liquid limit before consolidation within the Cam-Tor device. Consolidation was staged (2kPa and then 4kPa) to limit the amount of sample loss via extrusion between the interface and the sample holder. Once consolidated, a number of test stages were run (numbered 1 through 3 or 4) at both shear speeds without pauses between the two speed stages. Some tests then reverted back to the first shear speed to permit comparison of 'initial' and 'pre-sheared' behaviour. Test stage durations were determined by observing on the torque-displacement profiles, whether the samples had reached a steady-state residual condition.

2.4 *Imaging technique*

A digital single-lens reflex camera with dedicated macro lens was used to obtain videos of the shearing process of a wet-sieved GOG sample containing the material coarser than 38mm, following the method described by Kuo (2014b) and using particle image velocimetry (PIV, after White and Take, 2002). A transparent sample chamber was used in this test to permit imaging of the micromechanics associated with shearing the sample against a rough interface. Of particular interest was the identification of how the zone of shearing evolved during monotonic interface testing of these soils.

3 RESULTS

3.1 *Interface roughness and particle size distribution*

The smooth interface had an average roughness (Ra) of 0.3µm and the rough interface Ra was 6.1 µm. Particle size distributions (PSDs) based on the wet sieving for reconstituted samples are shown in Figure 2.

PSDs were limited to a minimum sieve size of 38µm and therefore it was not possible to determine the D_{50} for the SNS sample. The GOG reconstituted samples, often casually referred to as 'clay', exhibited D_{50} = 80µm. Following Oliphant and Maconochie (2007) the relative roughness, R is determined for the GOG samples of 0.076 and 0.004 for the rough and smooth interfaces, respectively.

The D_{50} was not explicitly measured for the SNS sample, and therefore, R is not found.

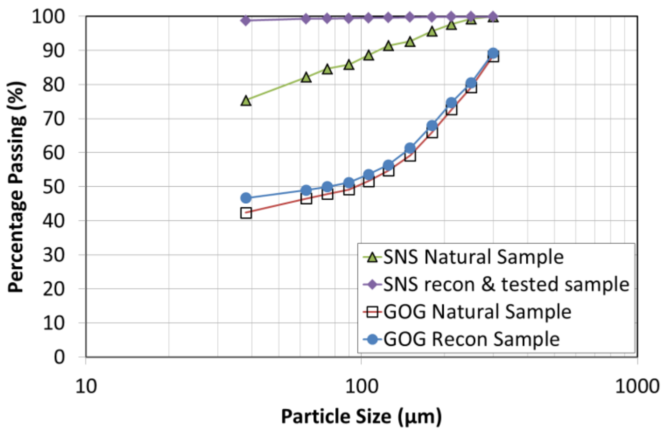

Figure 2. Particle size distribution for natural and reconstituted SNS and GOG samples.

Previous investigations with GOG samples (Ganesan et al., 2014; Thomas et al., 2005), considered soils with a smaller average particle size distribution and higher interface relative roughnesses. Based on the respective relative roughnesses for the two samples, it may be expected that the SNS sample will exhibit a larger variation in interface friction values when sheared against the ‘smooth’ and ‘rough’ interfaces.

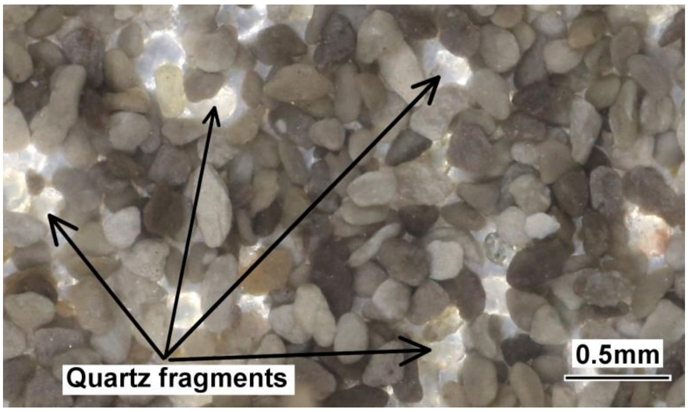

Figure 3. Wet-sieved SNS sample retained on the 125µm sieve showing clay agglomerates and quartz grains.

Imaging of the material remaining on each sieve was conducted, examples of which are shown in Figures 3 and 4. These figures show the contrast in sediment composition between the two samples. It is observed that the SNS soil predominantly comprises clayey material but with minor quartz fragments (less than 10%) as shown in Figure 3. These particles are unlikely to influence the behaviour of the interface shearing due to their apparent scarcity in the tested samples. The sample from the GOG, however, is observed to contain a significant amount of robust, glauconised faecal pellets as shown in Figure 4. These pellets range in size from larger than 300µm in diameter to 90µm in diameter. The material retained on sieves with apertures smaller than 90µm were unglauconised faecal pellets and pellet fragments. Nevertheless, these smaller pellets and fragments were still sufficiently robust to resist the remoulding and reconstitution process. Due to their robustness and abundance, it is highly likely that these glauconised and unglauconised pellets and fragments will strongly influence the measured interface friction value.

Figure 4. Wet-sieved GOG sample showing glauconised (dark grains) and unglauconised (pale grains) faecal pellets.

3.2 *Interface test results*

The interface friction value, μ is determined by Equation 1,

$$\mu = \frac{\tau}{\sigma'_0} \qquad (1)$$

where τ is the interface shear stress (determined at the characteristic radius) and σ'_0 is the initial vertical effective stress applied to the sample. Cumulative shear distances ranged from 7m to over 26m. Example tests with μ plotted against test time for SNS and GOG samples are shown in Figures 5 and 6.

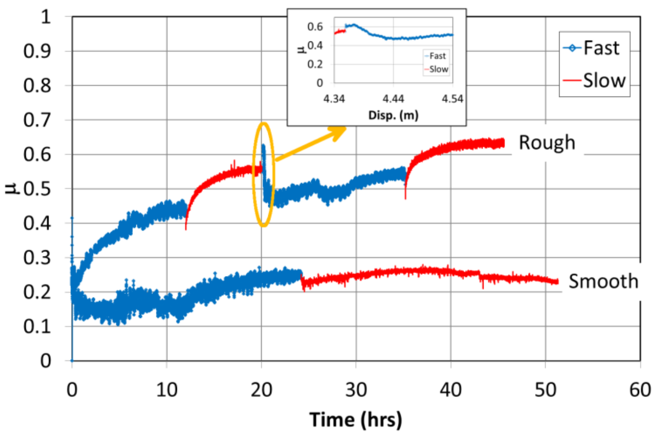

Figure 5. Example rough and smooth interface tests for SNS sample. Inset: initial fast peak plotted on semi-log axes.

From these figures, the following observations are made. A clear difference in interface friction between the rough and smooth interfaces is noted for both soil samples, where the rough interface generates a higher μ value. There appears to be a distinct rate effect for both samples when sheared against the rough interface. Fast tests generally produce lower residual values than those for the slow testes.

When sheared against the smooth interface, rate effects are observed for the GOG sample, with fast tests generating lower residual values. Rate effects are not as clear for the SNS sample sheared against the smooth interface. All transitions from slow to fast shear rates result in a sharp peak response before rapidly falling to 50% of the peak value within 30mm of shearing at the characteristic radius, as shown in the inset of Figure 5. Transitions from fast to slow test stages do not show the same behaviour. Instead, after an initial drop in friction, the measured μ tends to increase to a constant residual value.

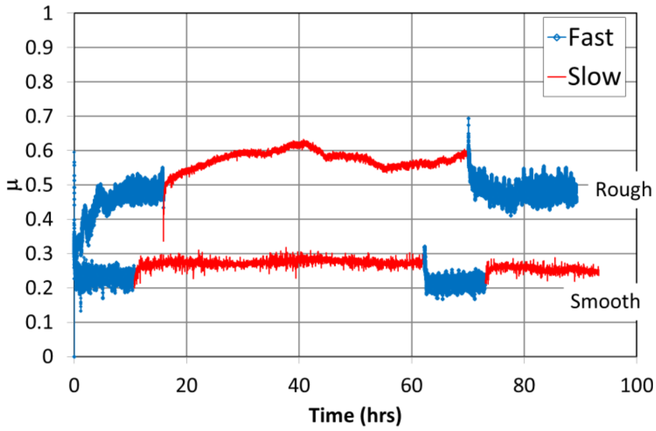

Figure 6. Example rough and smooth interface tests for GOG sample.

A summary of the peak and residual values for rough and smooth tests; and fast and slow stages from all eight tests is shown in Figures 7 and 8 for the SNS and GOG samples.

The interface friction value is plotted against the corresponding test stage number. Where drawn, lines are shown connecting two points show the initial peak and subsequent residual value. If not shown, the residual value was also the highest measured value for that particular test stage.

From Figure 7, the following points are noted:

- For fast test stages, the initial peak value (μ_{peak}) was generally found to be the 'global' peak friction value.
- When sheared against the rough interface at the fast speed, an increase in shearing displacement (and test time) tends to result in smaller differences in peak to residual values.
- Slow tests on the rough interface generally result in a peak residual value. Apart from test stage 3, all slow tests resulted in μ higher than the corresponding fast tests.
- There appears to be a general trend of increasing μ value to about 0.6 for the rough interface by the end of test stage 4 (>10m shear displacement at the characteristic radius).
- Shearing against the smooth interface results in a lower large-displacement μ value of between 0.2 and 0.25. This value is attained after test stage 2, corresponding to between 7m and 17m of shear displacement.

The following observations are made for the behaviour of the GOG sample summaried in Figure 8:

- Fast rough tests consistently exhibit $\mu_{peak}>>\mu_{res.}$

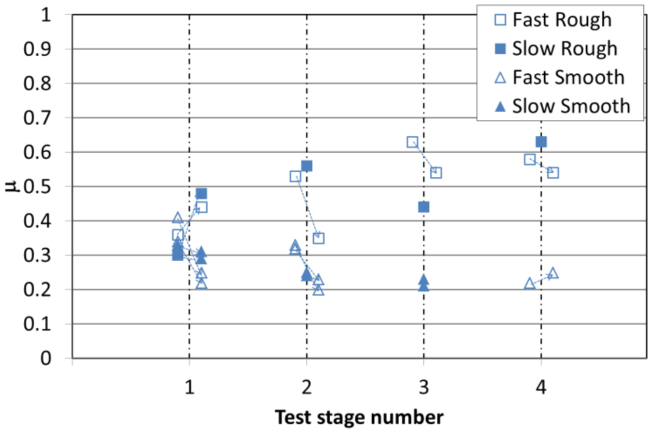

Figure 7. SNS summary results showing peak and residual interface friction values.

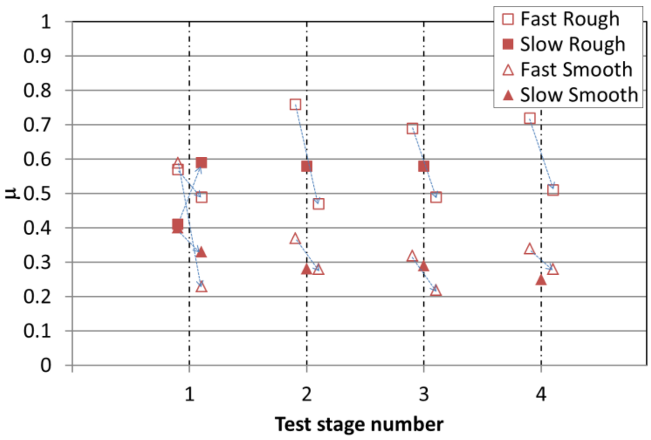

Figure 8. SNS summary results showing initial peak and residual interface friction values.

- Rough $\mu_{fast,res}$=0.5 from 2m to over 8m of shear displacement.
- Slow tests undertaken on the rough interface are also very consistent with residual values at about μ=0.6, where $\mu_{fast,peak}>\mu_{slow}>\mu_{fast,res}$.
- Though initial peak to residual differences were smaller for the smooth interface than for the rough interface, tests completed using the smooth interface exhibit greater variability in residual values; ranging from μ=0.2 to 0.35.

In general, it is observed that:

- $\mu_{peak,GOG}>\mu_{peak,SNS}$; and
- For both soils, μ_{smooth} is approximately $0.5\mu_{rough}$.

3.3 *Imaging results*

Over 100 minutes of video was recorded during the imaging of interface shearing for the sieved GOG sample. Two 20s sections of video were analysed for this investigation: the first at the start of the shearing process (T=0min), and the second after several metres of shear displacement at the characteristic radius (T~90min). The results of PIV analysis undertaken on the two video sections are shown in Figure 9 (start) and 10 (end).

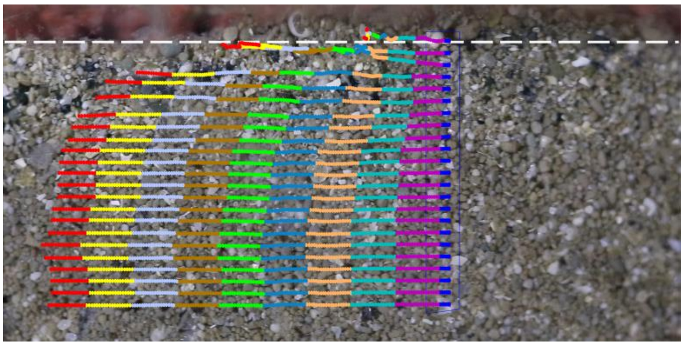

Figure 9. PIV analysis of sieved GOG sample at the start of shearing; showing shear zone of approximately 2mm thickness.

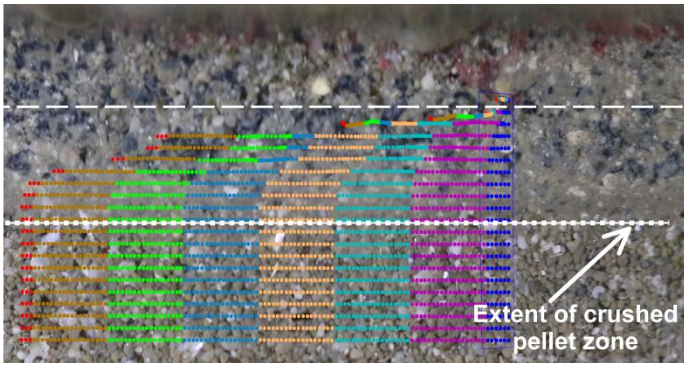

Figure 10. PIV analysis (sieved GOG sample) of the end of shearing showing shear zone of approximately 1mm thickness and extent of CPZ.

The approximate location of the interface is shown in the dashed white line in both images. The approximate width and height of the photographs are 7.4mm and 4.5mm. Individual colour bands shown in the PIV analysis represent 18s of shearing, apart from the start and end bands, where the colours represent less than 18s.

From Figure 9, it can be seen that the shear zone extends to approximately 2mm below the soil-interface boundary. Even below this zone, there appears to be some variation in grain displacement after 30 seconds of shearing. Grains located adjacent to the stationary interface tend to interlock with the interface, and are retarded in horizontal movement.

The PIV analysis undertaken on the sample at the end of the tests indicates that a well-defined shear zone of about 1mm thickness has been developed. The key features of this zone are:

- Crushable grains (unglauconised faecal pellets) are found to be destroyed, forming a crushed pellet zone (CPZ) that is thicker than the shear zone (see Figure 10).
- Within the CPZ, a concentration of glauconised pellets is observed in Figure 10, represented by black grains and fragments.
- Grain movement is concentrated within the upper two-thirds of the CPZ based on the PIV analysis.

4 DISCUSSION

4.1 *Cam-Tor tests*

The summary of all completed test results show that both shear rate and interface roughness influence the measured interface friction value. The initial peak observed in fast tests is likely to be generated by rate effects as discussed by Ganesan et al. (2014). After the initial peak, the interface friction rapidly drops to 50% of the peak value, as discussed previously. Though pore pressures were not measured during the tests, it is highly likely that positive excess pore pressures are generated during the initial shearing against the rough interface during fast, undrained tests. These positive excess pore pressures may cause the reduction in interface friction before sufficient time has passed such that initial excess pressures have dissipated. Figure 11 shows a direct comparison between the initial and tertiary GOG fast tests undertaken with the rough interface, as originally presented in Figure 6.

This figure clearly shows the difference in shear behaviour between the initial test and the tertiary test. Both tests reach the same residual interface friction value of about 0.5, however, the initial test falls to μ=0.3 before 'recovering'. The tertiary test exhibits a higher initial peak friction value of 0.7 (compared to 0.58) but then only falls to the residual value. This figure suggests that approximately 3.5 hours of shearing at the fast rate was required for the positive excess pore pressures generated at the commencement of shearing to dissipate. Following the suggested drainage condition analysis of Ganesan et al. (2014), an estimate for the minimum time required to attain drained conditions can be determined.

Based on this analysis and using c_v=0.04mm^2/s (based on Kuo, 2011 and Ganesan et al., 2014) and a sample drainage height of 18mm, it is found that as expected, the peak initial friction value represents undrained conditions. It is then found following Terzaghi's standard consolidation theory that drained conditions would be expected to prevail after more than 2.3 hours of shearing.

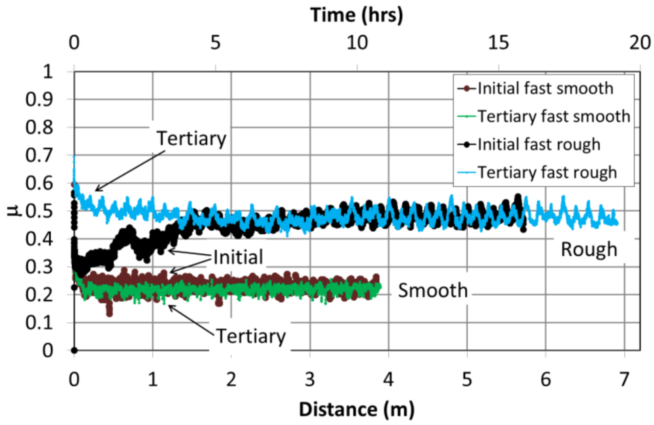

Figure 11. Comparison of initial and tertiary GOG test stages for rough and smooth interfaces.

Though not discussed in detail here, it is evident from Figure 5 that a similar behaviour is present for the SNS samples tested against the rough interface. Briefly, the initial peak of about 0.5 rapidly falls to 0.2 (a reduction of 60%) before 'recovering' back to 0.45. The tertiary stage has a peak of 0.62 before exhibiting a residual of 0.55, between which, the friction only falls to 0.48 (a reduction of 22% from the peak).

A similar comparison can be made of the GOG fast tests completed on the smooth interface, also presented in Figure 11. It is clear from this figure that the smooth interface does not generate positive excess pore pressures during shearing. The only difference between the initial and tertiary tests relate to the initial peak interface friction. This variation (μ=0.6 for the initial and 0.32 for the tertiary test) is likely due to the difference in soil structure immediately after consolidation and after several metres of shearing. Though unlikely to significantly alter the soil structure (compared to shearing against the rough interface), there may be some rearrangement and alignment of particles/clay platelets that causes a lower peak to be registered.

4.2 *Imaging*

The completed PIV analysis on wet sieved GOG samples shows that the developed shear zone initially involves a greater number of soil grains (2mm thick) before concentrating to a 1mm thick band. This observation may indicate that the shear mechanism and hence thickness of the shear band is related to grain size. Initially, the tested sample has D_{50} of approximately 150μm, however, by the end of the test, the material representing the shear zone exhibits a particle size about one order of magnitude smaller than the initial shear zone. This reduction in grain size is likely to result in a change in the shear behaviour. Whereas interlocking of grains will initially dominate (resulting in a greater number of grains being involved), as the crushable pellets are destroyed by the shearing mechanism, the behaviour will tend to sliding, involving a smaller number of particles. The observations made by Kuo (2014b) and Kuo and Bolton (2014b) demonstrate that interface shearing of clay on a rough surface results in a minimal-thickness shear band. On the other hand, when crushable grains are sheared against a rough interface, a similar behaviour to that observed in this study was noted; with a reduction in shear zone thickness over the duration of the test.

The wet-sieved sample prepared for the imaging experiment will initially not be representative of the shearing behaviour exhibited by the reconstituted sample containing material finer than 38μm, as tested in the Cam-Tor. However, once the CPZ has developed the behaviour is expected to similar to the Cam-Tor sample with sand-sized particles 'floating' within a silty clay matrix.

5 CONCLUSIONS

This paper has presented soil-interface test results obtained from a new interface shear testing apparatus called the Cam-Tor. This device addresses several of the limitations of previous interface testing machines and provides data relevant to the design of hot-oil pipelines. The key results are as follows:

- The Cam-tor is found to be a suitable device for interface testing of soft marine sediments.
- Roughness influences the interface friction of both SNS and GOG samples, with the smooth interface generating about $0.5\mu_{rough}$.
- Influence of shear rate is complicated; behaviour of GOG samples is summarized by $\mu_{fast,peak} > \mu_{slow}=0.6 > \mu_{fast,res}$ for the rough interface.
- PIV analysis of the start and end videos show the development of a crushed pellet zone when sheared against the rough interface.
- Shear zone reduces from ~ 2mm to 1mm by the end of the test, and may coincide with a change in shear mechanism driven by particle size.

REFERENCES

Ganesan, S., Kuo, M. & Bolton, M. 2014. Influences on pipeline interface friction measured in direct shear tests. *ASTM Geotechnical Testing Journal*, 37(1): 94-106.

Kuo, M. 2011. Deep ocean clay crusts: behavior and biological origin. *PhD dissertation*: Cambridge University.

Kuo, M. 2014a. ENI Ghana wet sieving, *Cambridge University Technical Services confidential report for Fugro*.

Kuo, M. 2014b. New insights into the micromechanics of soft clay shearing on rough and smooth interfaces, In *Proc. Int. Symp. Geomechanics: Micro to Macro, Cambridge, UK*.

Kuo, M., & Bolton, M. 2013. The nature and origin of deep ocean clay crust from the Gulf of Guinea. *Geotechnique* 63(6): 500–509.

Kuo, M. & Bolton, M. 2014a. Shear tests on deep-ocean clay crust from the Gulf of Guinea. *Geotechnique* 64(4): 249-257.

Kuo, M. & Bolton, M. 2014b. Imaging of crushable grains when shearing against rough interfaces. *Proc. Int. Symp. Geomechanics from Micro to Macro, Cambridge, UK*.

Oliphant, J., & Maconochie, A. 2007. The Axial Resistance of Buried and Unburied Pipelines. *Proc. SUT Offshore Site Investigation & Geotechnics Int. Conf. London, Sept 11–13*.

Thomas, F., Rebours, B., Nauroy, J-F. & Meunier, J. 2005. Mineralogical characteristics of the Gulf of Guinea deep water sediments. In Gourvenec & Cassidy (eds), *ISFOG 2005*.Taylor & Francis Group, London.

White, D. and Take, A. 2002 GeoPIV: Particle Image Velocimetry (PIV) software for use in geotechnical testing. *Cambridge University Engineering Department Tech. Report, D-SOIL-TR322*.