Interface Testing of Natural Soils for Offshore Pipelines and Foundations

by

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Fourth-Year Undergraduate Project

I hereby declare that, except where specifically indicated, the work submitted herein is my own original work.

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1. Technical Abstract

A constant supply of gas and oil is critical to the way we live today. A large proportion of the oil used worldwide is produced offshore. To collect and transport this resource, hundreds of kilometres of pipelines traverse our seabed. Particularly at deep offshore sites, these pipes may be laid directly on the seafloor. Under the action of hot oil flowing through them, they undergo hundreds of thermal expansion and contraction cycles. This in turn leads to axial movement, self-embedment and lateral buckling. Understanding how friction develops between the pipeline and the seabed is crucial to the safe and efficient design of pipelines. When the friction produced can be fully modelled, then the pipeline working conditions can be known, allowing a safe, adequate pipeline design to be developed. Devices such as the Cam-Shear, Tilt Tables and the Low Stress Shearbox have all made steps towards characterising this behaviour, however none have managed this completely. The new Cam-Tor shearing device has the required properties to fully characterise the initial peak and residual friction values.

This project undertook a schedule of tests on the Cam-Tor to investigate the effect of: interface roughness, shearing speed and sample location on the interface friction coefficient in marine clay. In addition to this, wet sieving of the natural and reconstituted clay samples, from the Southern North Sea (SNS) and West Angola, was conducted to appreciate the composition of the materials. An imaging test was also designed to facilitate Particle Image Velocimetry (PIV) analysis of the shearing behaviour at the interface.

It was observed that initial shearing stages always have a peak in friction due to the inertial changes associated with the clay moving from stationary. Fast shears produce higher peaks than slow shears. This may be due to the greater inertial change required to shear fast. Secondary fast shears continue to exhibit peaks, due to the inertial shift required to move from slow to fast. Secondary slow shears have no peak. All peaks occur after approximately

1° of rotational displacement which is equal to 0.44 mm of linear displacement at the characteristic radius.

Slow residual friction values are always higher than the corresponding fast ones. Fast shearing stages generate excess pore pressures, which reduce the clay's shear capacity. Rough residual values are also higher than the corresponding smooth values. Rough interfaces are able to interact with the clay material, generating more resistance through interlocking with the particles. The smooth interface seems to slide over the clay with minimal interaction. Smooth slow tests on the two clay samples yielded very similar results, in contrast with the differing values experienced in all other tests. This shows that in this case the material is interacting so little with the interface that it barely has an effect.

Shearing of the SNS and Angolan clays using the rough interfaces seemed to generate fully drained and undrained behaviour during the slow and fast shears respectively. Shearing of the SNS material with the smooth interface generated no pore pressures, as the fast and slow stages had the same residual values. Smooth shearing in the Angolan clay produced less of a difference between fast and slow shears, indicating maybe drained and partially drained conditions in the slow and fast stages respectively.

Wet sieving of the SNS sample showed that reconstitution had a large effect on the clay. This was also seen in the Cam-Tor tests. Fast rough shears had the capacity to sufficiently alter the material, so that in later stages less resistance was available to shearing. Wet sieving revealed that the Angolan clay sample was much more consistent than the SNS. This may be due to the more resilient nature of the Angolan clay. It was a siltier material, containing the hard, glauconised, faecal pellets of burrowing invertebrates. It changed much less than the SNS sample under the action of reconstitution.

Imaging the test showed that only the top millimetre of sample was sheared by the interface. Below this depth the clay was unaffected.

Further testing on the Cam-Tor could include different speed shearing, pauses between shearing stages and the measurement of pore pressures, to fully verify the mechanisms which are in action. Imaging a smooth interface test would also be helpful to confirm the expected sliding behaviour.

Contents

2. Introduction

The world we live in today depends heavily on oil and gas. A large proportion of this comes from offshore wells. Due to the competitive nature of this industry, detailed data is hard to source, but in the US approximately 30% of total oil production is offshore[i]. To tie deep wellheads to risers, shallow wellheads to shore, and for many other applications, hundreds of kilometres of pipelines are required. Some of these are trenched, that is placed in a trench just below the seabed, while others are laid directly on the seabed. This is particularly the case in deep regions, where the threats of fishing nets and anchors are perceived to be minimal.

Deep offshore oil pipelines are laid cold on the seabed. Temperatures on the sea floor are low. To ensure that piped oil has a low enough viscosity to flow, it is therefore heated. When this hot oil flows through the pipelines, they undergo hundreds of thermal expansion and contraction cycles; which cause axial movement along the length of the pipe. This in turn can lead to self-embedment and lateral buckling. Fig. 1 shows a schematic drawing of this process. This cyclic behaviour may continue throughout the life of a pipeline, depending on its usage. The pipe may experience pauses, different shearing speeds and different shearing directions. Fig. 2 shows an image of a pipeline on the seabed, confirming that the described behaviour is occurring. In Fig. 2 the seabed material has formed a small trench at the buckle and the pipe has burrowed into the material, to the left and right of the buckle.

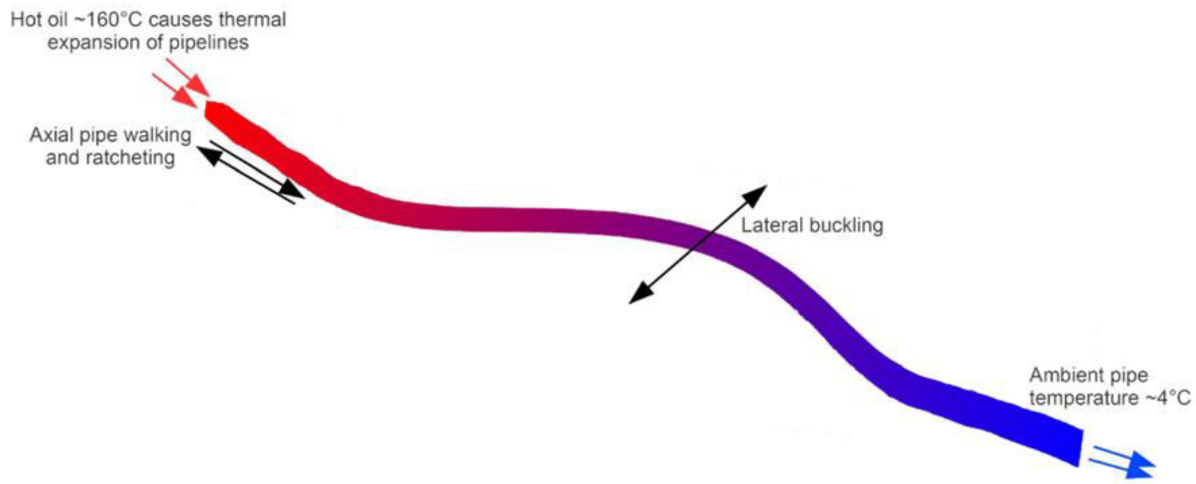


Figure 1 - Schematic Illustration of Pipeline Behaviour[ii]

Understanding these behaviours is crucial in safe pipeline design.[iii] Without a thorough understanding, pipes have to be over-engineered and monitored extensively to ensure they remain within their working limits. When the behaviour is better understood, the pipeline design can be improved to safely control movements and increase resource efficiency. The key parameter to investigate here is the interface friction coefficient between the pipe and the seabed. The friction developed will govern all movements.

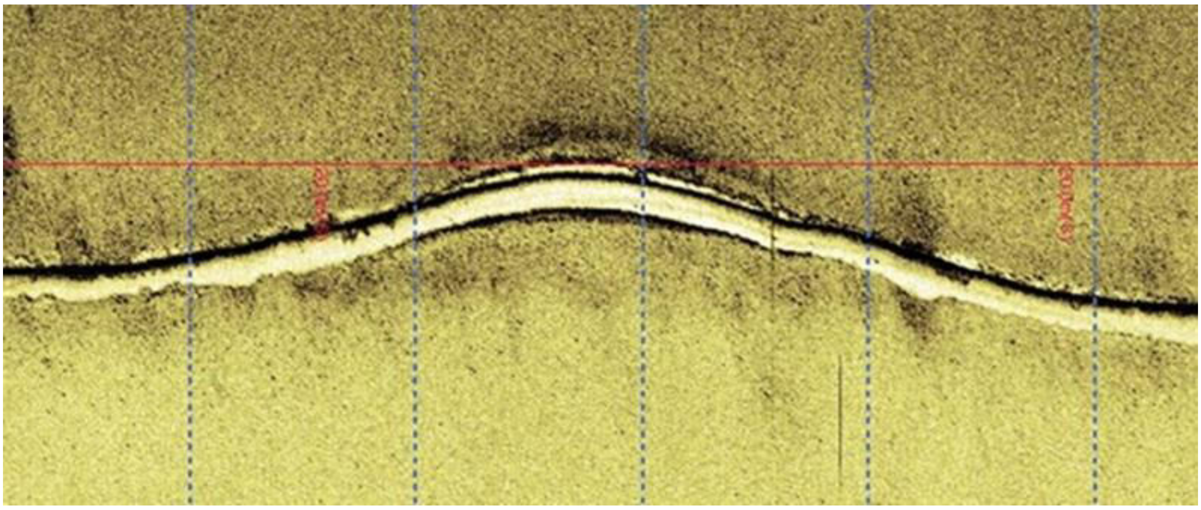


Figure 2 - Image of Subsea Pipeline[iv]

The research to date in this field is quite extensive, but is somewhat hindered by the limitations of current testing equipment. Ring-shear devices can achieve long shearing distances. However they are only able to work under high applied stresses, due to high machine friction in the apparatus. The Low Stress Shearbox, developed by the University of Western Australia (UWA), can test under very low applied stresses, though unfortunately it is limited by its short shearing distances. Tilt tables, used by the University of Texas at Austin (UT Austin), and the Cam-Shear, developed in Cambridge University Engineering Department (CUED), are similarly limited by their shearing distances. Short shearing distances only allow the peak interface friction coefficient, not the residual, to be investigated.

Each of these shearing devices has its benefits, but none are able to fully characterise the behaviour of pipelines. The existing shear devices with their test conditions and limitations are summarised in Table 1, which is augmented from Ganesan, Kuo and Bolton (2014)[iii].

Shearing Device	Sample condition	Interface	Stress level (kPa)	Comments / Limitations	Reference
Ring Shear	Remoulded	Rough & smooth	20 to 60	- Only remoulded samples can be tested due to the nature of sample preparation - Apparatus internal friction limits the minimum achievable stress	Colliat et al. (2011)[v]
	Remoulded	Rough & smooth	50 to 400		Lemos & Vaughan (2000)[vi]
	Remoulded	Rough & smooth	10 to 50		Fugro (2010)[vii]
Tilt Table	Remoulded	Smeared	5 to 30	- Only remoulded samples can be tested due to the nature of sample preparation - The stress distribution on the interface varies depending on the angle of the table - Shearing displacement is limited to the size of the table	Pederson et al. (2003)[viii]
Low Stress Shearbox (UWA)	Remoulded	Rough & smooth	>2.5	- Only remoulded samples have been tested - Shearing displacement is limited to size of interface material	White et al. (2012)[ix], Hill et al. (2012)[x]
Cam-Shear	Remoulded	Rough & smooth	1 to 4.5	- 190 mm shearing distance in one direction	Ganesan et al. (2014)[iii]

Table 1 - Summary of existing interface shearing devices[iii]

The requirements for an appropriate shearing device are:

- Low applied stress – to simulate the weight of a pipeline,
- Long shearing distances – as are seen in the field,
- Multiple speeds – as the speed of pipeline movement will vary,
- The possibility of testing undisturbed samples – as are seen by pipelines in the field.

All of these have been met in the new Cam-Tor, developed by CUED with GDS Instruments, shown in Fig. 3 (L). The Cam-Tor device shears a cylindrical soil sample against a stationary interface. The interface is attached to a load cell which allows a constant normal stress to be applied. The load cell can also measure the torque generated, allowing the interface friction coefficient, μ, to be evaluated. Fig. 3 (R) schematically shows the test.

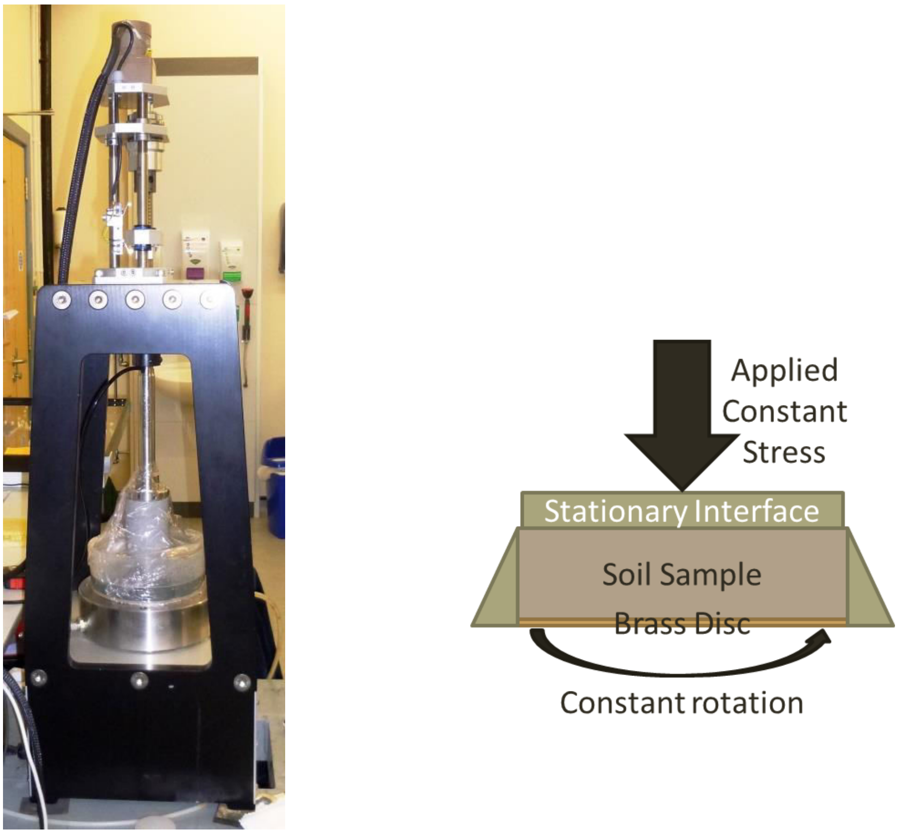


Figure 3 – (L) Cam-Tor Device, (R) Schematic of Cam-Tor test

3. Methods

3.1. Cam-Tor Testing

A schedule of tests for the Cam-Tor was initially developed. Then in a meeting at the beginning of Michaelmas 2013 this was adjusted and agreed upon with BP and Fugro, see Table 2. This consisted of eight tests to investigate the influence of: interface roughness, shearing speed and sample location, on the interface friction coefficient in marine clay.

Test	Stage	Sample	Depth (m)	σ'_{v0} (kPa)	Interface	Shearing rate (deg/s)	Shearing rate* (mm/s)	Time (min)	Distance (deg)	Distance* (m)	Cumulative distance* (m)	Time (hrs)	
1	1	High PI	-	4	Rough	-		1440				24	consolidation
1	2			4	Rough	0.2273	0.1000	60	818.28	0.36	0.36	1	fast shearing
1	3			4	Rough	0.0023	0.0010	1440	198.72	0.09	0.45	24	slow shearing
1	4			4	Rough	0.2273	0.1000	60	818.28	0.36	0.81	1	fast shearing
											1.61	50.00	
2	1	High PI	-	4	Rough	-		1440				24	consolidation
2	2			4	Rough	0.0023	0.0010	1440	198.72	0.09	0.09	24	slow shearing
2	3			4	Rough	0.2273	0.1000	60	818.28	0.36	0.45	1	fast shearing
2	4			4	Rough	0.0023	0.0010	1440	198.72	0.09	0.53	24	slow shearing
											1.07	73.00	
3	1	Low PI	-	4	Rough	-		1440				24	consolidation
3	2			4	Rough	0.2273	0.1000	60	818.28	0.36	0.36	1	fast shearing
3	3			4	Rough	0.0023	0.0010	1440	198.72	0.09	0.45	24	slow shearing
3	4			4	Rough	0.2273	0.1000	60	818.28	0.36	0.81	1	fast shearing
											1.61	50.00	
4	1	Low PI	-	4	Rough	-		1440				24	consolidation
4	2			4	Rough	0.0023	0.0010	1440	198.72	0.09	0.09	24	slow shearing
4	3			4	Rough	0.2273	0.1000	60	818.28	0.36	0.45	1	fast shearing
4	4			4	Rough	0.0023	0.0010	1440	198.72	0.09	0.53	24	slow shearing
											1.07		
5	1	High PI	-	4	Smooth	-		1440				24	consolidation
5	2			4	Smooth	0.2273	0.1000	60	818.28	0.36	0.36	1	fast shearing
5	3			4	Smooth	0.0023	0.0010	1440	198.72	0.09	0.45	24	slow shearing
5	4			4	Smooth	0.2273	0.1000	60	818.28	0.36	0.81	1	fast shearing
											1.61		
6	1	High PI	-	4	Smooth	-		1440				24	consolidation
6	2			4	Smooth	0.0023	0.0010	1440	198.72	0.09	0.09	24	slow shearing
6	3			4	Smooth	0.2273	0.1000	60	818.28	0.36	0.45	1	fast shearing
6	4			4	Smooth	0.0023	0.0010	1440	198.72	0.09	0.53	24	slow shearing
											1.07		
7	1	Low PI	-	4	Smooth	-		1440				24	consolidation
7	2			4	Smooth	0.2273	0.1000	60	818.28	0.36	0.36	1	fast shearing
7	3			4	Smooth	0.0023	0.0010	1440	198.72	0.09	0.45	24	slow shearing
7	4			4	Smooth	0.2273	0.1000	60	818.28	0.36	0.81	1	fast shearing
											1.61		
8	1	Low PI	-	4	Smooth	-		1440				24	consolidation
8	2			4	Smooth	0.0023	0.0010	1440	198.72	0.09	0.09	24	slow shearing
8	3			4	Smooth	0.2273	0.1000	60	818.28	0.36	0.45	1	fast shearing
8	4			4	Smooth	0.0023	0.0010	1440	198.72	0.09	0.53	24	slow shearing
											1.07		

Table 2 - Proposed Test Schedule for Cam-Tor

The interfaces were provided by Fugro. The material used was stainless steel. The surface roughness of the coatings was characterised by the profilometer, Taylor Hobson Precision: Form Talysurf. The smooth interface had a polished finish and initially had an average roughness (R_a) of 0.30 µm. The rough interface has been treated and initially had an average roughness of 6.08 µm. The initial profiles of the surfaces are shown in Fig. 4. The average roughness of the smooth interface remained within tolerance throughout testing, not exhibiting any visible discolouration. However the roughness of the rough interface varied considerably throughout the testing period. The interface also changed visibly, displaying rust coloured patches, as shown in Fig. 5.

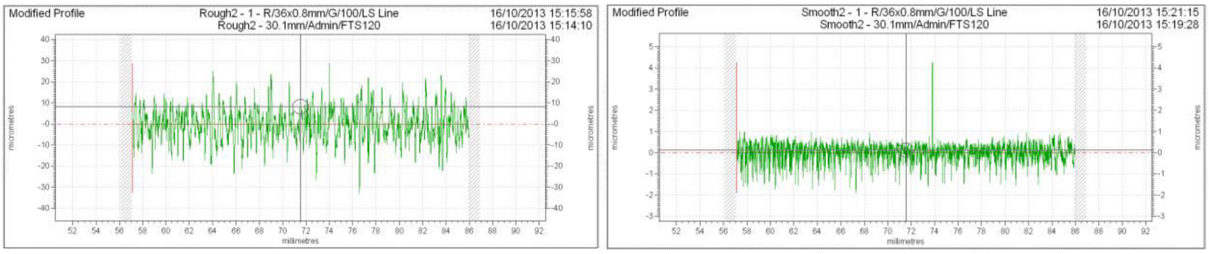


Figure 4 - Rough (L) and Smooth (R) Interface Profiles prior to testing

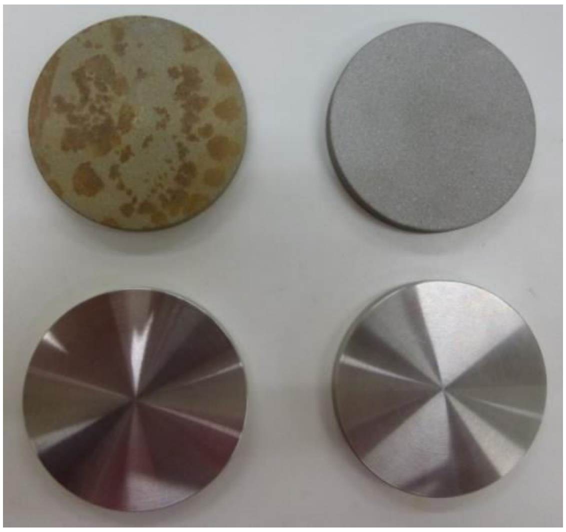


Figure 5 - Rough (Top) and Smooth (Bottom) Interfaces, (L) after two uses and (R) initially

Two speeds were proposed for testing, “fast” and “slow”. These were 0.1 mm/s and 0.001 mm/s based on Hill et al.’s (2012)[x] back-bone curve. This curve shows a change in mechanism when plotting residual stress ratio against velocity. These speeds should represent fast and slow shearing behaviour. It is expected that the fast shear will be sufficiently fast to prevent drainage. Therefore undrained conditions, with the generation of excess pore pressures, will prevail in the fast shearing stages. The slow is expected to be sufficiently slow to allow drainage, or at least partial drainage. The linear speeds correspond to the shearing rate at the characteristic radius of the sample. This was calculated by evaluating the torque over the sample, assuming an increase in strain with each cycle. The characteristic radius was found to be 0.72R.

To investigate the effect of sample location, two clay samples were provided by Fugro. One was to be of low plasticity index and the other of high. Both were piston cores. The first sample was from a depth of 22.90 m below the seabed, in the Southern North Sea (SNS). It was described as a silty CLAY, with an approximate Particle Size Distribution (PSD): clay 60%, silt 38%, sand 2%. This was a low plasticity index clay. The second set of tests was undertaken on a high plasticity sample, from the seabed (0 m depth), in offshore West Angola. The SNS sample was reconstituted at approximately one and half times the liquid limit, as per Burland 1990[xi], to increase the repeatability of the tests. The sample data was not available at the time of reconstituting the Angolan sample, so this was unfortunately not possible.

The Cam-Tor device tests a soil sample of diameter 70 mm and height 22 mm. The sample is held securely in place, on top of a de-aired brass disc. This allows free drainage during consolidation and shearing. Pore pressure cannot currently be measured here to verify drainage. Testing occurred in a water bath and cling film was used to prevent water loss through evaporation. See Fig. 6.

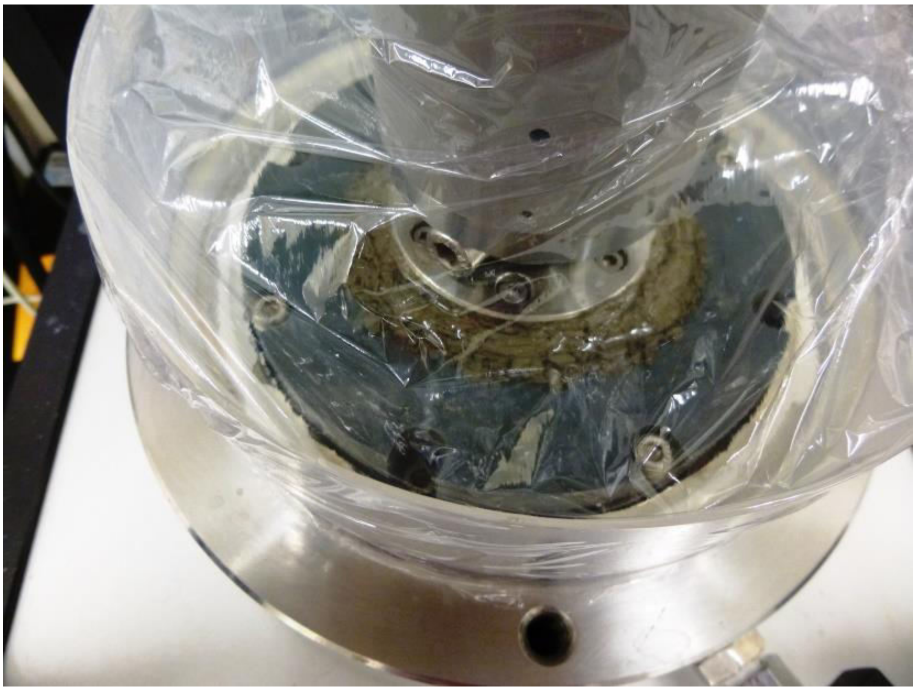


Figure 6 - Photograph during 01-11Rough1

Each test has two stages, firstly consolidation and secondly shearing. This suite of tests were all consolidated to 4 kPa and tested at an over-consolidation ratio (OCR) of 1. This stress level is thought be characteristic of the conditions around offshore pipelines on the seabed.

To consolidate, an axial stress is applied to the sample through the load cell, which was attached to the interface. In the initial planning stages, the completion of primary consolidation was expected to take 24 hours and to be carried out in one stage. This was optimistic. The interface has a diameter of 68.75 mm. During the first tests a lot of material was exuded out through the gap between the interface and the sample holder, see Fig. 6. In light of this, an extra consolidation stage was added, initially taking the sample to 2 kPa and then up to 4 kPa. During consolidation, GDS lab software was used to monitor axial displacement against log time in real time. When the data curve appeared to have turned to the corner, i.e. completed primary consolidation, the next stage of testing could progress.

Post-consolidation, testing proceeded to the shearing stages. The sample here rotated beneath the stationary interface, which continued to apply a constant axial stress of 4 kPa. Each stage was terminated when it appeared that a stable residual value had been reached.

3.2.Wet Sieving

To better understand the composition of the soil samples, wet sieving was undertaken. This is different from "conventional" sieving where the material is broken down into the smallest components possible. Wet sieving aims to better preserve the natural structure of the soil, using water pressure to push the particles through the sieves and gently separate stuck particles.

In this case a nozzle attached to the hot tap was used to direct and fan the water; this has a similar effect to partially covering the end of a pipe with a thumb. The nozzle allows the fan of water to be directed accurately, preventing splashing and the loss of material. Prior to sieving the sample was weighed and its water content measured. This allows the dry weight of material present to be calculated. Water can then be added to the sample and left for maybe twenty-four hours, to allow it to soften. This was particularly necessary in the case of the natural samples which have low natural water contents. The material could then be sieved, adding the sample bit by bit. Small portions are added as this helps to prevent the clogging of the finer sieves with excesses of fines. Once the entire sample is through, the material retained on the sieves can be emptied into weighing dishes of known weight. The samples were then photographed, using a Digital SLR camera, and dried in the oven for twenty four hours. After this they were weighed and the Particle Size Distributions could be drawn, based on the initial total dry weight.

In each soil type a natural sample and a reconstituted sample were sieved. The wet sieving was carried out according to Kuo and Bolton (2013)[xii]. Fig. 7 shows the basic apparatus used. In total eleven sieves were used in this process, ranging from 38 – 300 µm.

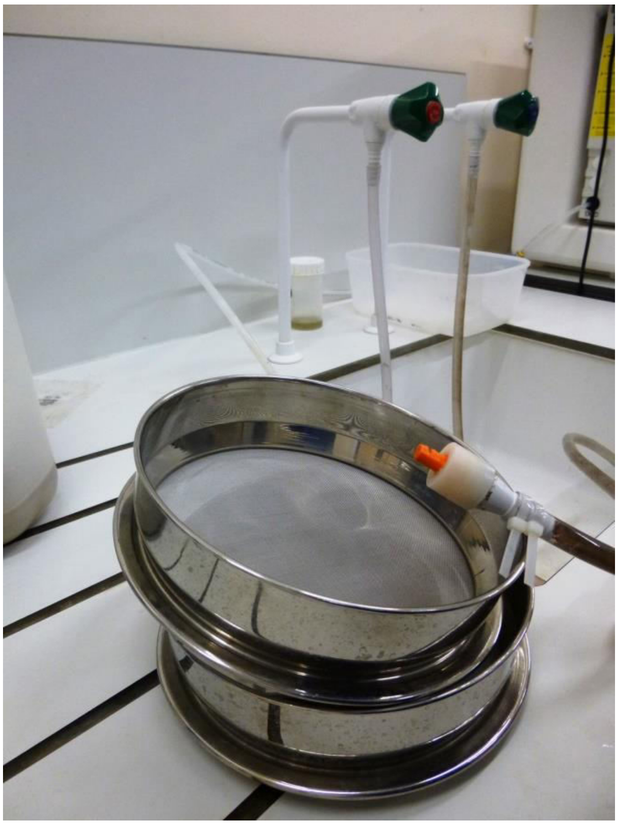


Figure 7 - Wet Sieving Apparatus

3.3.Imaging

As part of this project, a test rig was designed by the author to image the Cam-Tor test. The aim of this was to gain understanding of the behaviour occurring within the Cam-Tor. An initial design sketch of the set-up is shown in Fig. 8 and the finished item in Fig. 9. A few changes were made to the design from the initial sketch. The main alteration was to reduce the height of the supporting block, to allow the load cell of the Cam-Tor to be positioned more easily.

The set-up consisted of: an acrylic tube, through which the sample could be viewed; a drilled brass disc covered with a piece of filter paper, to support the sample and allow free draining; a top cap, made of porous material, with an average roughness of 23 µm. A larger diameter tube was used than that of the Cam-Tor, as this presents less curvature to the field of view of the Digital SLR camera, thus improving the quality of the images. A different interface material therefore had to used, as the interfaces provided by Fugro came in only one size. As the camera was only able to see the edge of the sample, the interface was made to be tight fitting with the tube; thus minimising the material being exuded through the gap.

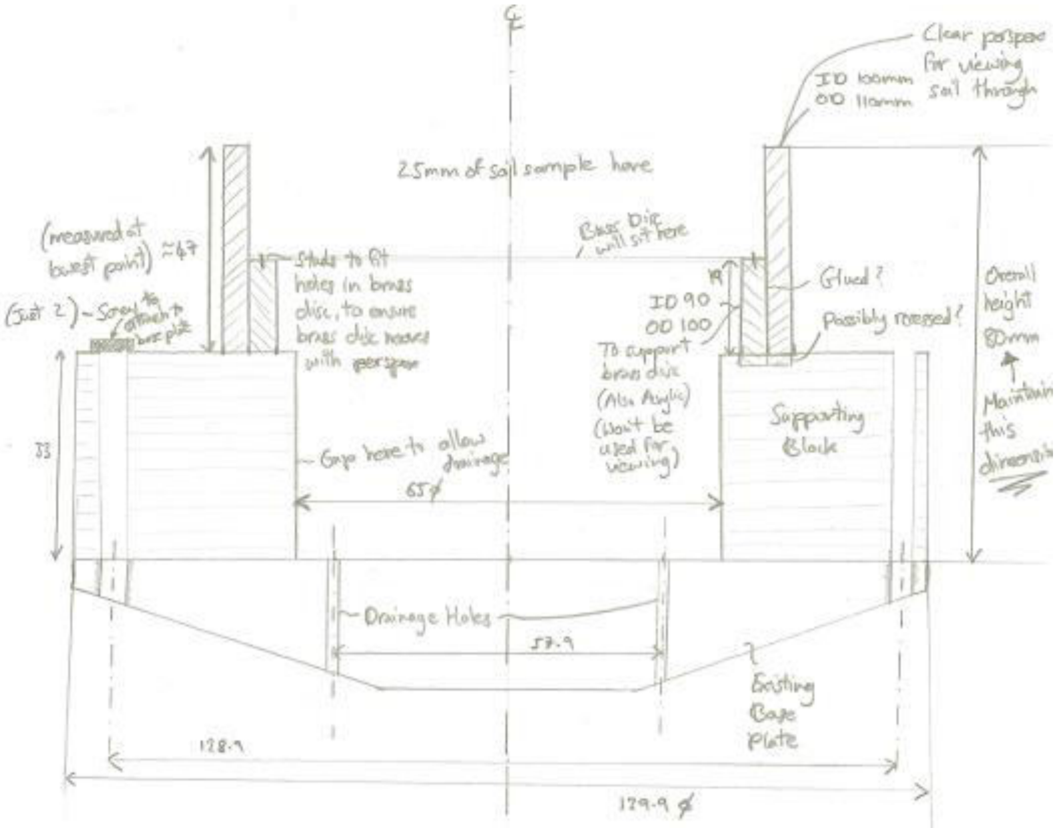


Figure 8 - Design sketch of set-up for imaging the Cam-Tor test

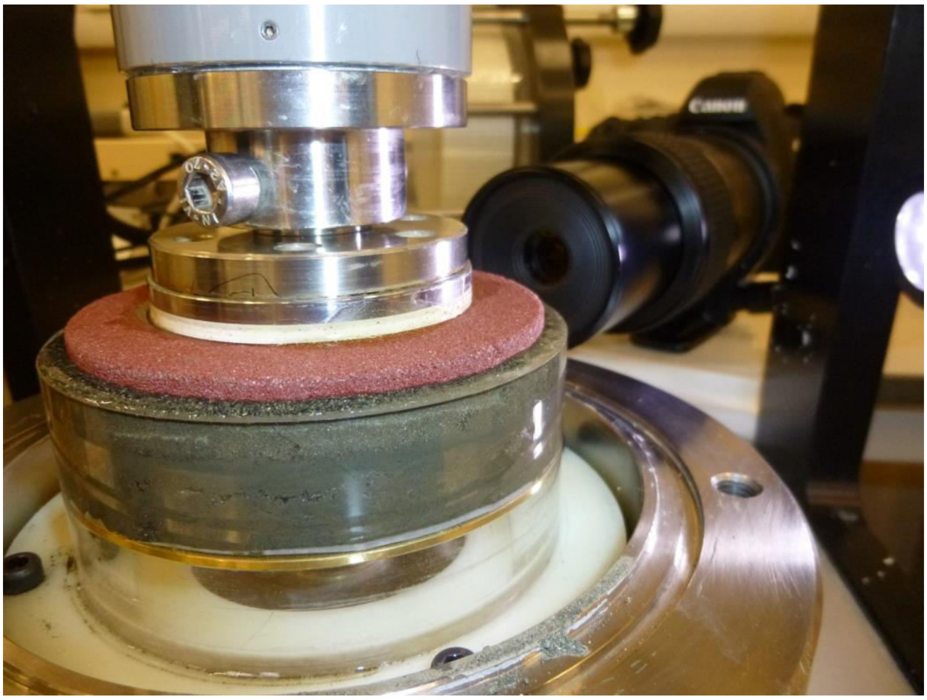


Figure 9 - Set-up for imaging the Cam-Tor test

The initial intention was to use a GoPro video camera to record the test. This was to be used as it was small enough to be attached to the side of the test-rig. Therefore it would facilitate the analysis of long shearing distances. Unfortunately poor clarity, resolution and excessive distortion precluded its use. Instead a dedicated macro lens for a DSLR was used. This arrangement resolved the three issues of the GoPro.

The material in the imaging test consisted of approximately 2 cms of reconstituted Angolan clay, supporting approximately 1 cm of wet sieved material. The top 5 mm layer of material was the section which was viewed by the camera. This top section was analysed as the material - interface interactions are the most interesting behaviours. The wet sieved material was used for its distinct particles. These are easier for the software to isolate and for the naked eye to track in the footage, than finer clay particles.

The Digital SLR camera was used to video the test in 20 minute chunks. Sections of video to be analysed were cut from the original footage. Stills were then extracted from these clips at a frequency of 6 frames per second. Using Particle Image Velocimetry (PIV) software in MATLAB, the frames were then analysed to identify the paths of the particles during shearing. The PIV was carried out in line with White and Take (2002)[xiii]. Firstly a mesh is created; this is the area within which the analysis will take place. A fixed number of points will be identified and tracked within this mesh. If a particle moves too far between frames the software will not be able to locate it and a (!) signifying a wild vector will appear in the analysis. The results can be compiled to track the particles through the shearing.

4. Results

Tests were named by the date they started and the interface used, DD-MM Interface#. Usually the same rough or smooth interface is used for subsequent tests, except when the profilometer was not available to measure the average roughness between tests. The graphs which follow show interface friction coefficient, μ, plotted against time. μ is defined in Eqn. 1.

$$\mu = \frac{\tau}{{\sigma_v}'}$$

Equation 1 - Defining mu

Where τ = interface shear stress, evaluated at the characteristic radius

${\sigma_v}'$= vertical effective stress

The raw data from the Cam-Tor tests appears very noisy, so a moving average has been used to smooth it out, see Fig. 10. The following plots use seven point moving averages over all the data, except the sharp, fast initial peaks, as data would be lost there. The noise is due to the high logging frequency, one point every three seconds, and the large volume of data collected, shearing time was between a day and a half and two weeks. The moving average of the fast stage appears a little noisier than the slow when plotted against time, as there is some cyclical behaviour occurring.

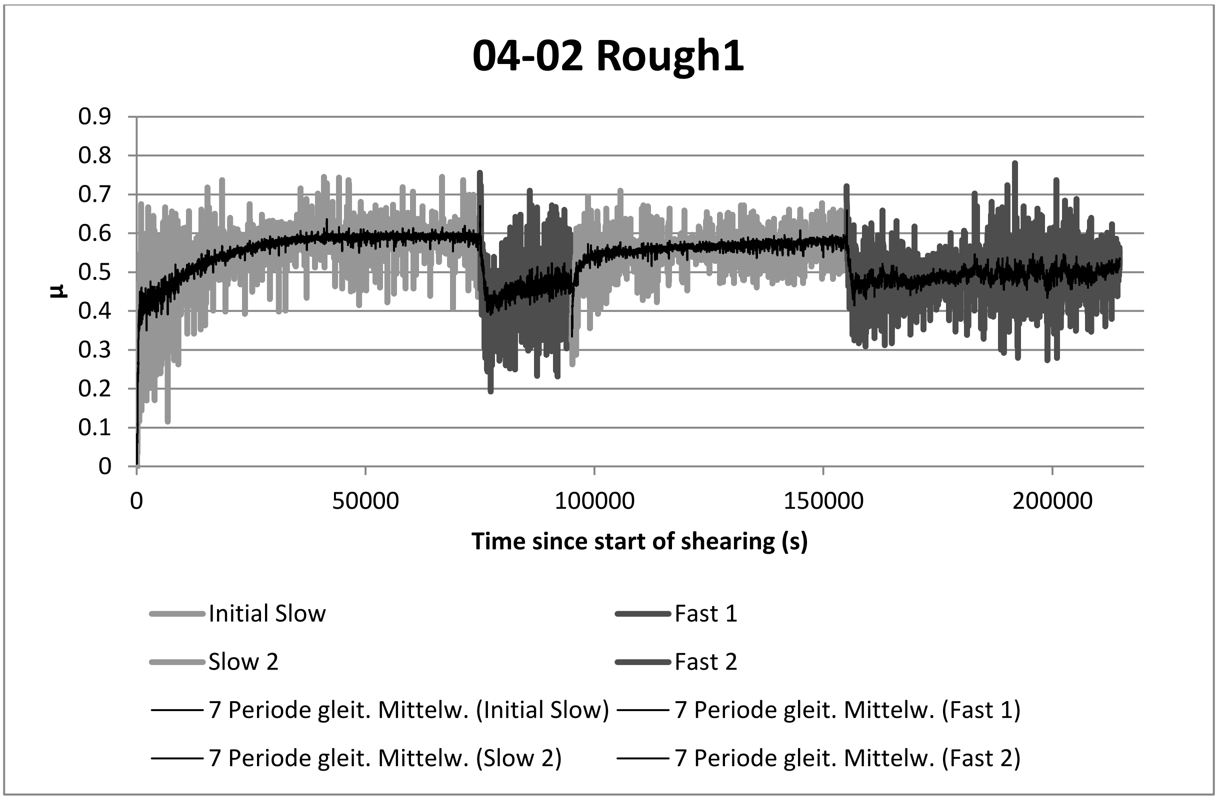


Figure 10 - Shearing curve raw data with moving averages from 04-02 Rough1

4.1. Southern North Sea

The first test, 01-11Rough1, had only one consolidation stage and used a water bath of saline solution with salinity of 103%. All subsequent tests used tap water for the water bath, as there was concern over the suitability of the materials to resist corrosion during long duration tests, particularly in the presence of saline solution. The sequence of shearing stages on this test was: fast, slow, fast, slow. The first stage had an initial peak of 0.36 and then increased gradually to 0.44. The slow stage dropped initially and then increased smoothly to a residual value of 0.56. The next fast stage had a peak value of 0.63, higher than all previous values. It then dropped and regained somewhat to 0.54, slightly lower than the slow residual but higher than the previous fast residual. The final slow then dropped and smoothly increased to 0.63, the highest residual seen in this test.

The second test, 04-11 Rough1, used two stages of consolidation, as did all subsequent tests. Sometime during the final stage of this test a “dam” of clay was formed. The exuded clay material piled up higher than the water level, preventing water from covering the interface. See Fig. 10. This shouldn’t affect the test results, as the sample should have remained saturated below the clay. Future tests used a greater volume of water during testing, to prevent this happening again. This test had stages: slow, fast, slow, fast. The initial slow had a peak of 0.3 and then increased to a residual value of 0.48. The next fast stage peaked to 0.53 and then dropped to 0.35. The next slow shear increased to a residual value of 0.44, lower than the first slow. The final fast stage, where the dam formed, a peak of 0.58 was recorded, followed by a residual value of 0.54, though the curve may still have been rising at completion of the test.

Figure 11 - Dam formed during last stage of 04-11 Rough1

The third and fourth tests, 11-11 Smooth1 and 16-11 Smooth1, follow the same schedule: fast, slow. The third test was repeated as the observed behaviour was so different to the preliminary tests and the two preceding tests with the rough interface. The difference occurred due to the different clay used in preliminary testing and the differing response to smooth and rough interfaces in the SNS sample. However the two tests demonstrated almost identical behaviour, confirming that this was not an anomalous result. 11-11 Smooth1 had a fast peak of 0.41, dropping to a residual of 0.25. The slow also had a residual value of approximately 0.25. 16-11 Smooth2 had a lower fast peak of 0.34, with a residual value equal to 0.22. The slow residual was estimated to be 0.24, though some cyclic behaviour seems to be appearing. Near the beginning of this stage, there is a significant spike visible in the results. This occurred due to the Cam-Tor device being hit by a large box being dragged past in the lab. Apart from the spike, the apparatus and results seem unaffected. To prevent the recurrence of this incident, the base of the device was tucked further under the desk, resulting in less protrusion into the lab.

The fifth test, 22-11 Smooth1, with schedule: slow, fast, slow, fast, was also repeated. The sixth test, 04-12 Smooth, repeated the first three stages, with a much longer initial slow stage. This ran for nearly twelve days covering six full 360° shearing cycles. The aim was to investigate the seemingly cyclic behaviour of the slow stages with the smooth interface. The initial slow stage of 22-11 Smooth1 had a peak of 0.3 and a residual of 0.31. The fast stage then peaked to 0.33, before dropping and regaining to a residual value of 0.2. The subsequent slow stage maintained this residual value. The final fast stage had a relatively low peak of 0.22 before dropping and regaining to 0.25. The repeat test demonstrated similar values. The initial slow shear had a slightly higher peak of 0.33 and a slightly lower residual of 0.29. The fast stage peaked similarly to 0.32, then dropped and regained to 0.23, where the slow residual remained, albeit briefly.

Interface friction coefficients were noticeably lower under the smooth interface, compared with the rough.

Table 3 shows the full Southern North Sea testing schedule and Figs. 12-14 show the curves described by the text above.

	Test	Stage	Sample	Depth (m)	s'v0 (kPa)	Interface	Shearing rate (deg/s)	Shearing rate* (mm/s)	Time (min)	Distance (deg)	Distance* (m)	Cumulative distance* (m)	Time (hrs)	Stage
01-11 Rough1	1	1	SNS Slurry	29	4	Rough	-		1440				24	consolidation
	1	2			4	Rough	0.2273	0.1000	722	9846.636	4.33	4.33	12.03333	fast shearing
	1	3			4	Rough	0.0023	0.0010	491.4	67.8132	0.03	4.36	8.19	slow shearing
	1	4			4	Rough	0.2273	0.1000	898.4	12252.3792	5.39	9.75	14.97333	fast shearing
	1	5			4	Rough	0.0023	0.0010	624	86.112	0.04	9.79	10.4	slow shearing
													69.6	
04-11 Rough1	2	1	SNS Slurry	29	2	Rough	-		1440				24	consolidation
	2	2			4	Rough	-		2880				48	consolidation
	2	3			4	Rough	0.0023	0.0010	1081.8	149.2884	0.07	0.07	18.03	slow shearing
	2	4			4	Rough	0.2273	0.1000	539.7	7360.4286	3.24	3.30	8.995	fast shearing
	2	5			4	Rough	0.0023	0.0010	806.7	111.3246	0.05	3.35	13.445	slow shearing
	2	6			4	Rough	0.2273	0.1000	2769.35	37768.3953	16.61	19.96	46.15583	fast shearing
													158.6	
11-11 Smooth1	3	1	SNS Slurry	29	2	Smooth	-		1440				24	consolidation
	3	2			4	Smooth	-		2880				48	consolidation
	3	3			4	Smooth	0.2273	0.1000	1451.5	19795.557	8.71	8.71	24.19167	fast shearing
	3	4			4	Smooth	0.0023	0.0010	1626.35	224.4363	0.10	8.81	27.10583	slow shearing
													123.3	
16-11 Smooth2	4	1	SNS Slurry	29	2	Smooth	-		1440				24	consolidation
	4	2			4	Smooth	-		2880				48	consolidation
	4	3			4	Smooth	0.2273	0.1000	1153.55	15732.1149	6.92	6.92	19.22583	fast shearing
	4	4			4	Smooth	0.0023	0.0010	2638.75	364.1475	0.16	7.08	43.97917	slow shearing
													135.2	
22-11 Smooth1	5	1	SNS Slurry	29	2	Smooth	-		1440				24	consolidation
	5	2			4	Smooth	-		2880				48	consolidation
	5	3			4	Smooth	0.0023	0.0010	1004.2	138.5796	0.06	0.06	16.73667	slow shearing
	5	4			4	Smooth	0.2273	0.1000	2860.65	39013.5447	17.16	17.22	47.6775	fast shearing
	5	5			4	Smooth	0.0023	0.0010	7283.1	1005.0678	0.44	17.66	121.385	slow shearing
	5	6			4	Smooth	0.2273	0.1000	1401.45	19112.9751	8.41	26.07	23.3575	fast shearing
													281.2	
04-12 Smooth1	6	1	SNS Slurry	29	2	Smooth	-		1440				24	consolidation
	6	2			4	Smooth	-		5760				96	consolidation
	6	3			4	Smooth	0.0023	0.0010	17077.25	2356.6605	1.04	1.04	284.6208	slow shearing
	6	4			4	Smooth	0.2273	0.1000	2381.4	32477.5332	14.28	15.32	39.69	fast shearing
	6	5			4	Smooth	0.0023	0.0010	441.1	60.8718	0.03	15.35	7.351667	slow shearing
													451.7	

Table 3 - Actual Cam-Tor schedule for Southern North Sea samples

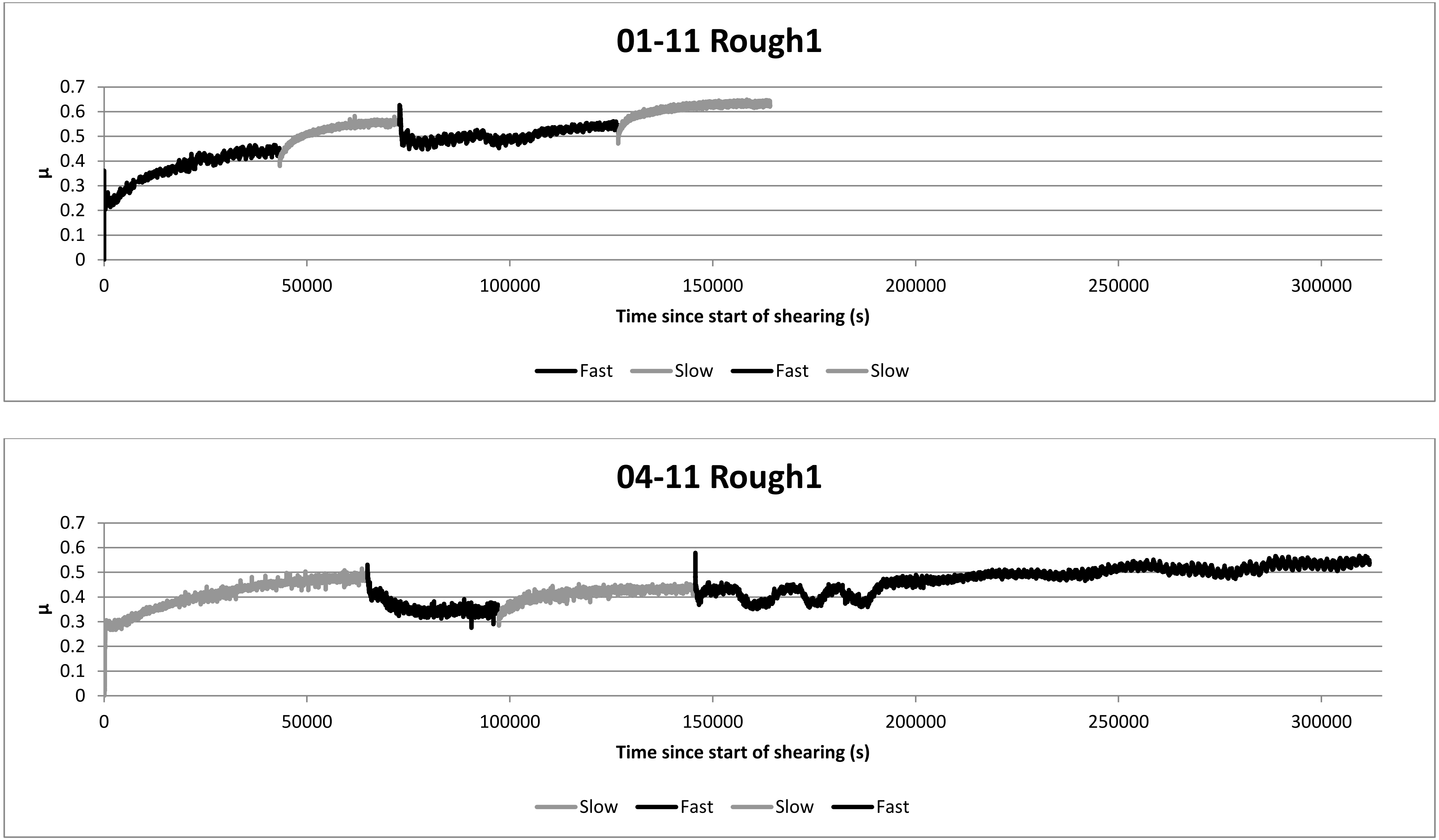
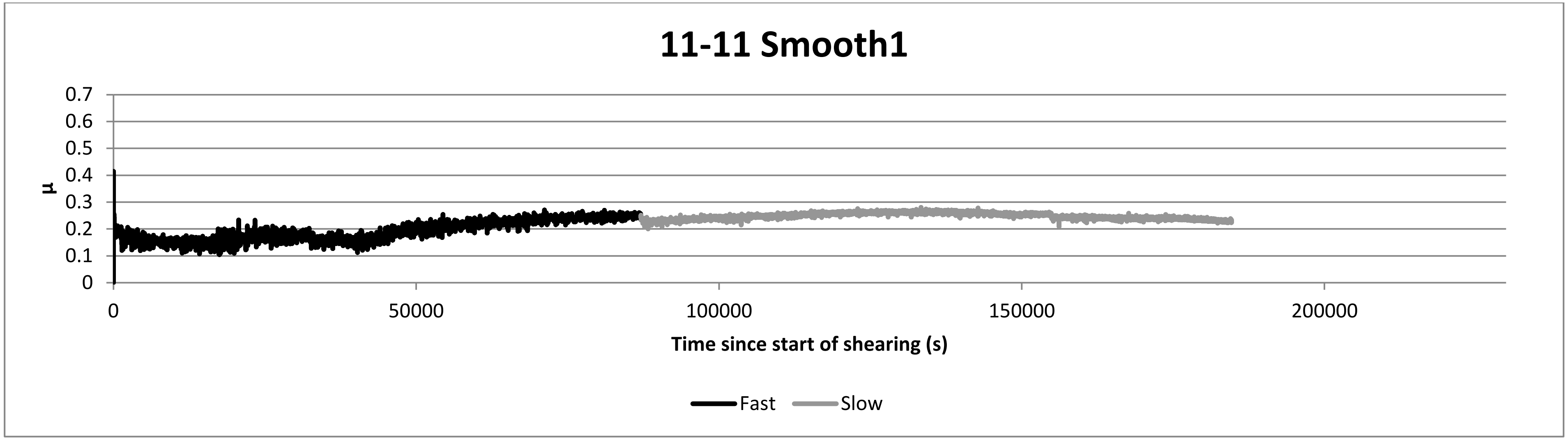


Figure 12 - SNS tests using rough interfaces



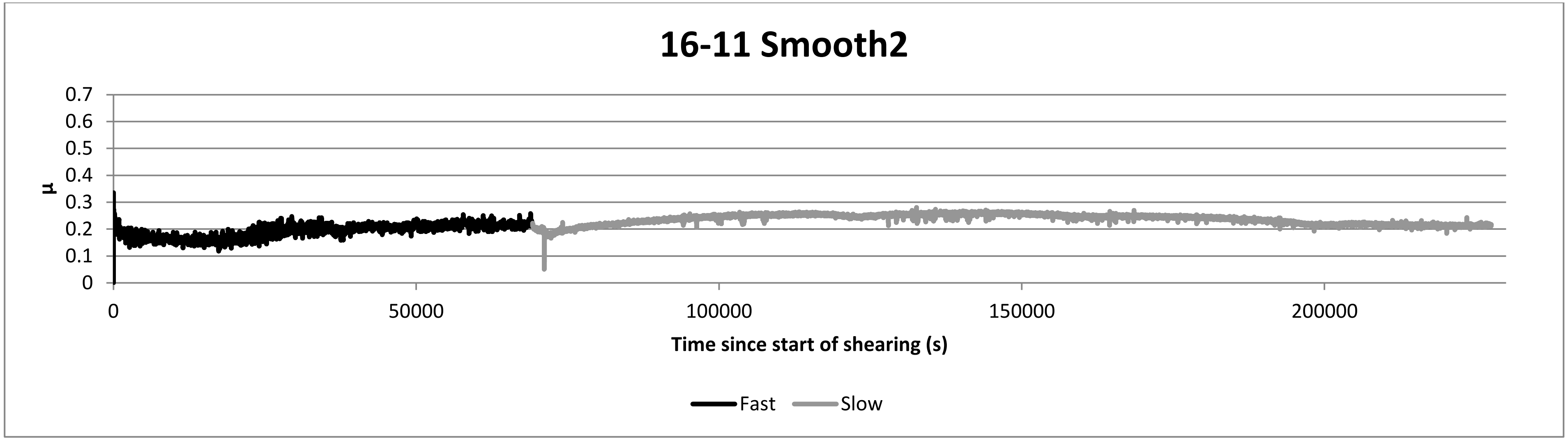
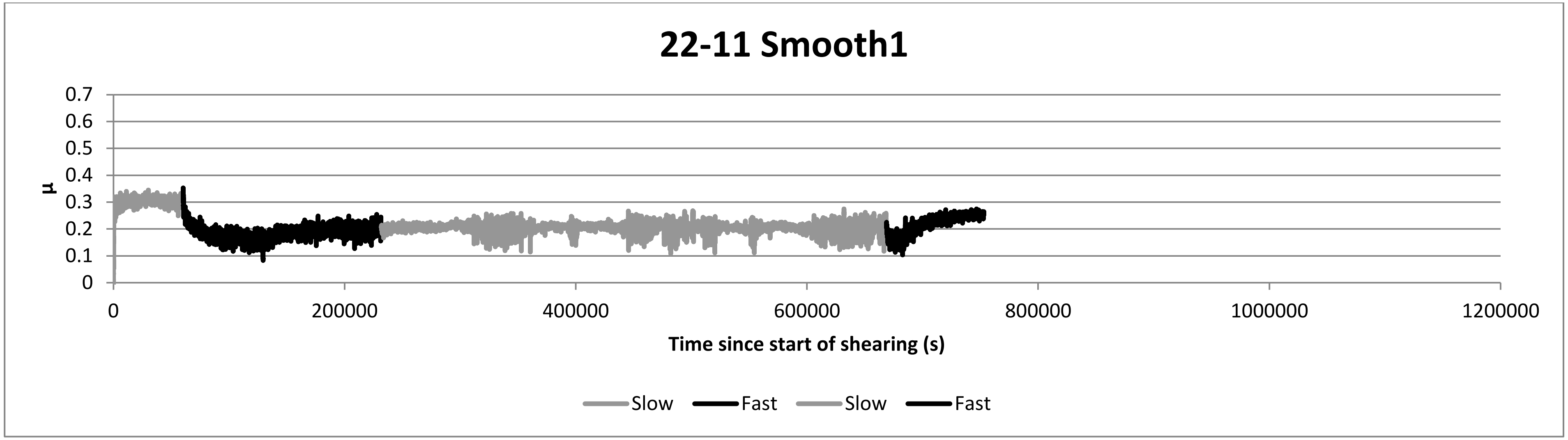


Figure 13 - SNS fast-slow smooth interface tests



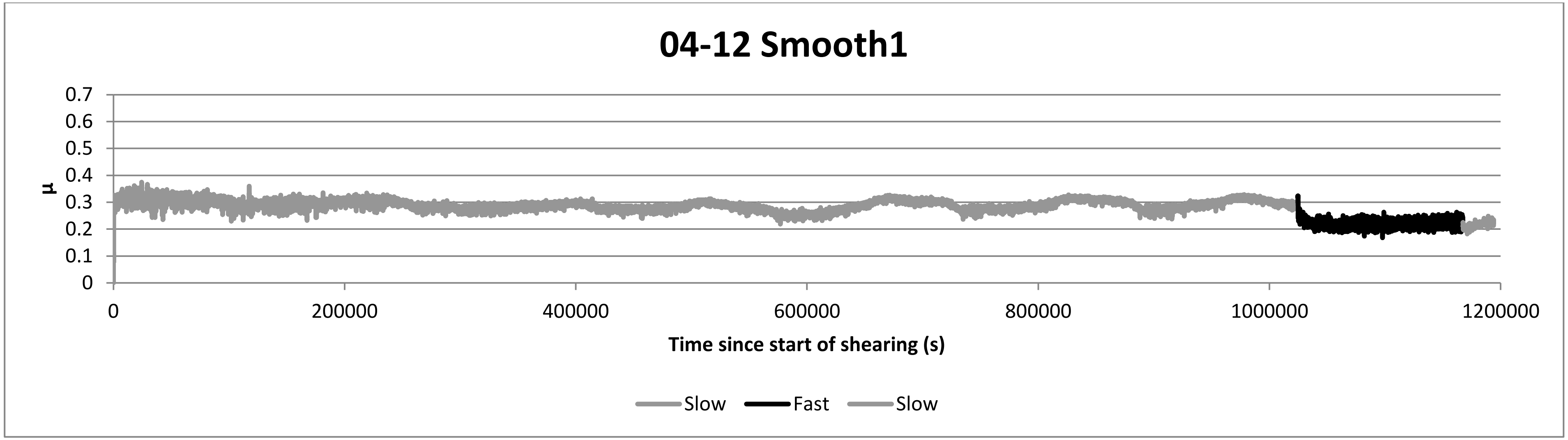


Figure 14 - SNS slow-fast smooth interface tests

4.2. West Angola

The testing schedule for the West Angolan sample was more straightforward than for the SNS sample, see Table 4. However the sample data had not yet arrived when the sample was reconstituted. Therefore the required water content was approximated. This led to an initially too high water content meaning that the sample underwent bearing failure during the 2 kPa consolidation stage. The sample was remixed to reduce its water content and testing continued.

Generally interface friction coefficients are higher with the West Angolan sample than in the Southern North Sea clay.

	Test	Stage	Sample	Depth (m)	s'v0 (kPa)	Interface	Shearing rate (deg/s)	Shearing rate* (mm/s)	Time (min)	Distance (deg)	Distance * (m)	Cumulative distance* (m)	Time (hrs)	Stage
28-01 Rough1	1	1	Angola Slurry	0	2	Rough	-							consolidation
28-01 Rough1-Take2	1	1	Angola Slurry	0	2	Rough	-		1440				24	consolidation
	1	2			4	Rough	-		2880				48	consolidation
	1	3			4	Rough	0.2273	0.1000	952.5	12990.2	5.71	5.71	15.875	fast shearing
	1	4			4	Rough	0.0023	0.0010	3254.55	449.1279	0.20	5.91	54.2425	slow shearing
	1	5			4	Rough	0.2273	0.1000	1151.75	15707.57	6.91	12.82	19.19583	fast shearing
													161.3	
04-02 Rough1	2	1	Angola Slurry	0	2	Rough	-		750.25				12.50417	consolidation
	2	2			4	Rough	-		2880				48	consolidation
	2	3			4	Rough	0.0023	0.0010	1249.7	172.4586	0.08	0.08	20.82833	slow shearing
	2	4			4	Rough	0.2273	0.1000	334.3	4559.183	2.01	2.08	5.571667	fast shearing
	2	5			4	Rough	0.0023	0.0010	1000.9	138.1242	0.06	2.14	16.68167	slow shearing
	2	6			4	Rough	0.2273	0.1000	993	13542.53	5.96	8.10	16.55	fast shearing
													120.1	
10-02 Smooth1	3	1	Angola Slurry	0	2	Smooth	-		1440				24	consolidation
	3	2			4	Smooth	-		2880				48	consolidation
	3	3			4	Smooth	0.2273	0.1000	641.75	8752.187	3.85	3.85	10.69583	fast shearing
	3	4			4	Smooth	0.0023	0.0010	3095	427.11	0.19	4.04	51.58333	slow shearing
	3	5			4	Smooth	0.2273	0.1000	650.15	8866.746	3.90	7.94	10.83583	fast shearing
	3	6			4	Smooth	0.0023	0.0010	1206.6	166.5108	0.07	8.01	20.11	slow shearing
													165.2	
17-02 Smooth1	4	1	Angola Slurry	0	2	Smooth	-		1440				24	consolidation
	4	2			4	Smooth	-		2880				48	consolidation
	4	3			4	Smooth	0.0023	0.0010	5584.55	770.6679	0.34	0.34	93.07583	slow shearing
	4	4			4	Smooth	0.2273	0.1000	1435.65	19579.39	8.61	8.95	23.9275	fast shearing
	4	5			4	Smooth	0.0023	0.0010	2277.55	314.3019	0.14	9.09	37.95917	slow shearing
	4	6			4	Smooth	0.2273	0.1000	2265.183	30892.57	13.59	22.68	37.75306	fast shearing
													264.7	

Table 4 - Actual Cam-Tor schedule for Angolan samples

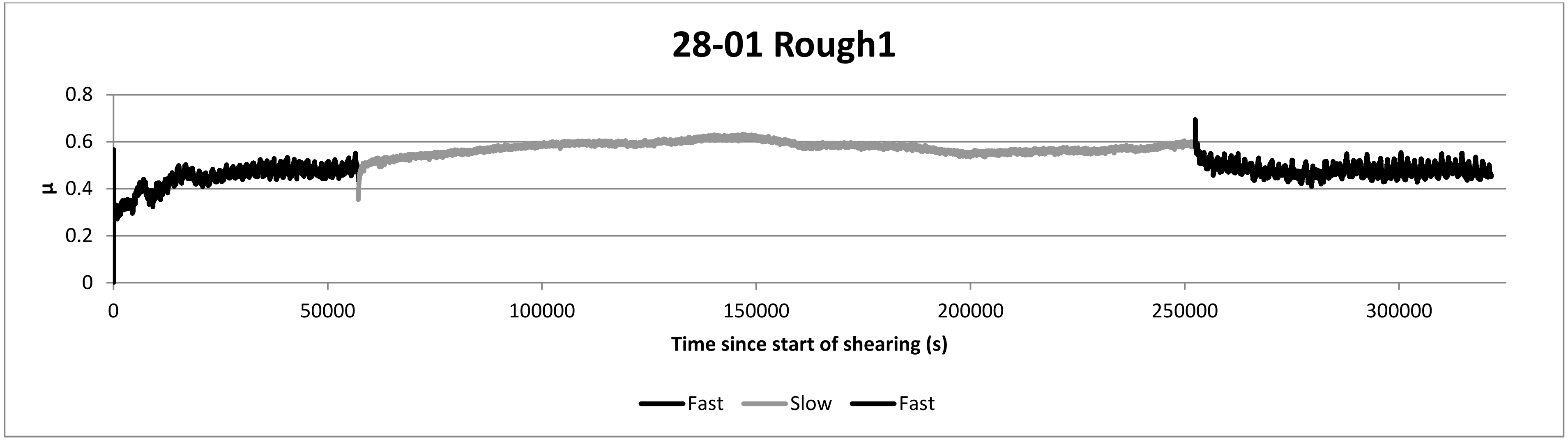
The first test, 28-01 Rough1, had shearing stages: fast, slow, fast. The initial fast peak value was 0.57, there was then a drop and regain to 0.49. The following slow stage had an approximate residual value of 0.58. The final fast stage had a higher peak of 0.69, dropping to a residual of 0.49. This is equal to the residual of the first fast stage.

The second test, 04-02 Rough1, followed the test schedule: slow, fast, slow, fast. The slow stage had an initial peak value 0.41, gradually increasing to 0.59. This is slightly higher than the slow stage from 28-01 Rough1. The first fast stage had a relatively high peak of 0.76, dropping and regaining to a residual of 0.47. The subsequent slow stage reached 0.58, but may have continued to increase beyond this, if this stage had been allowed to continue. The final fast stage also had a high peak, 0.72, reaching an eventual residual value of 0.51.

The third Angolan test, 10-02 Smooth1, had the sequence: fast, slow, fast, slow. The initial fast peak was 0.59, similar to the rough fast peak, 28-01 Rough1. This dropped to a residual value of 0.23. The slow stage then increased to 0.28, which is lower than rough residual values. The following fast stage had a peak of 0.32, dropping and regaining slightly to 0.22. The final slow stage was slightly lower than the first, with a value of approximately 0.25.

The final test, 17-02 Smooth2, followed the sequence: slow, fast, slow, fast. The initial slow stage was longer than usual, running for nearly four days and covering two full 360° cycles. This stage had a peak of 0.4, similar to the rough initial slow peak, this gradually dropped to approximately 0.33. However the cyclic behaviour may have continued, if given the opportunity. The first fast stage had an initial peak of 0.37, which dropped to a residual value of 0.28. The following slow stage exhibited a slightly higher residual value of approximately 0.29. The final fast stage then peaked at 0.34 before dropping to 0.28, the same as the previous fast residual. This final stage has a break in the results. This occurred due to a glitch in the GDS software, which sometimes occurs when monitoring tests remotely, using Team Viewer. Team Viewer is software which allows remote access to a PC. It was highly useful in this project as it meant that test progress could be monitored twenty four hours a day, without having to in CUED by the Cam-Tor device. The glitch allows the test to continue running, but unfortunately the data is lost.

All the curves described above can be seen below in Figs. 15 and 16.



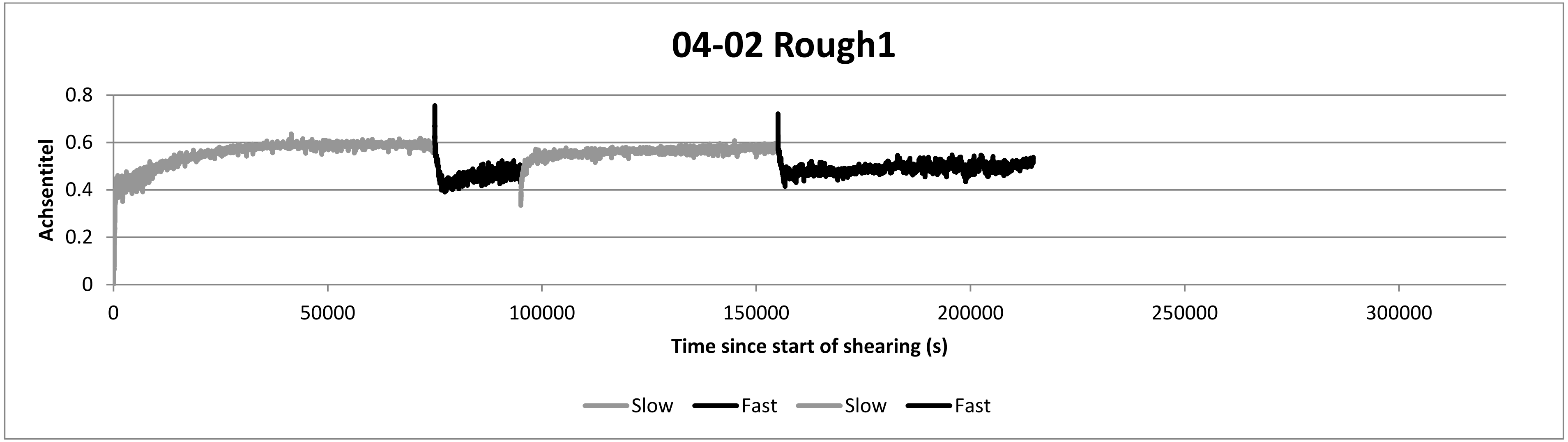


Figure 15 - Angolan rough interface tests

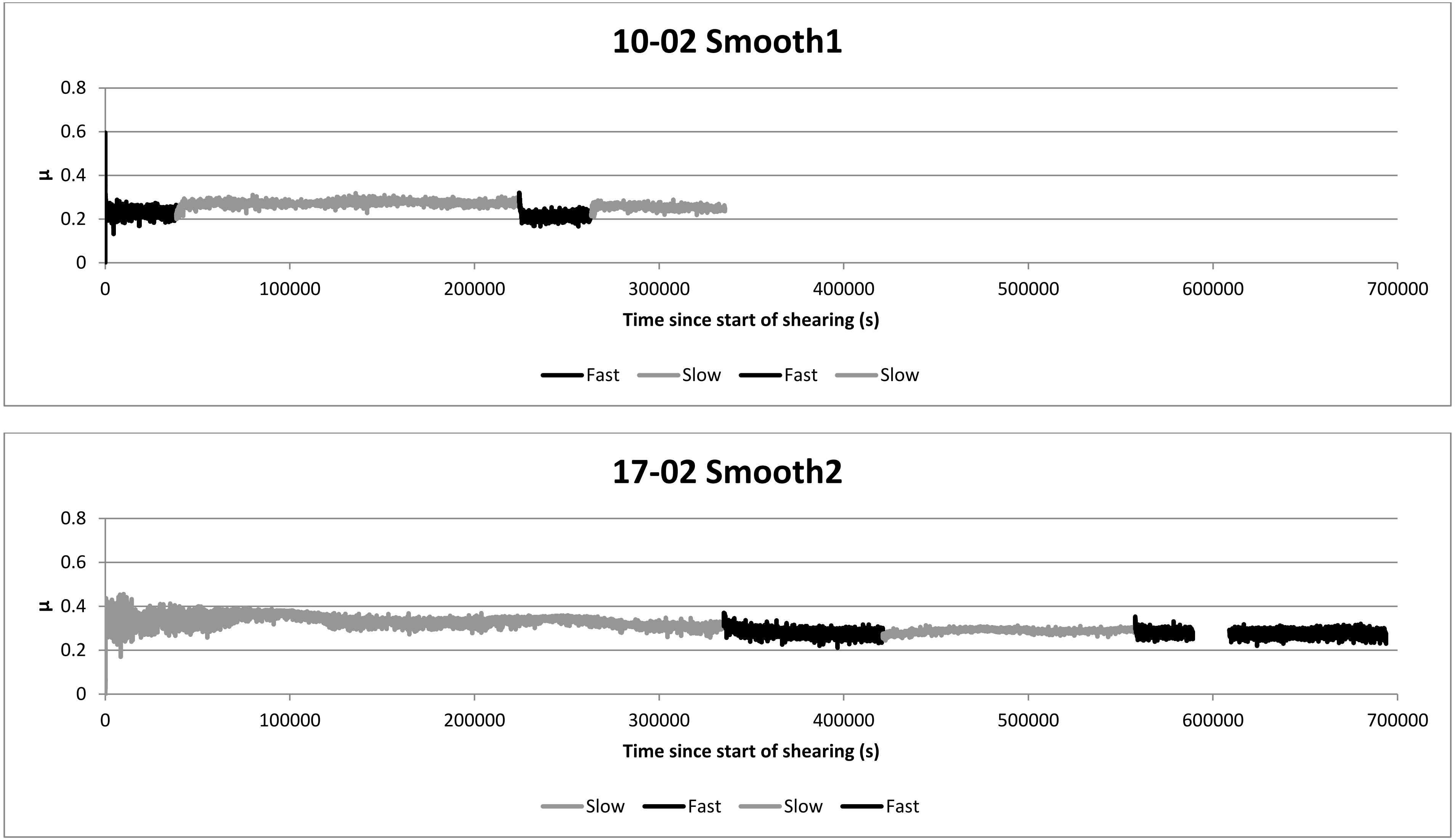


Figure 16 - Angolan smooth interface tests

4.3. Wet Sieving

Four soil samples were wet sieved. Two of these were natural samples taken straight from the piston cores, and two were reconstituted. The reconstituted Southern North Sea sample had also been sheared in the Cam-Tor prior to sieving. Fig. 17 shows the resulting PSDs.

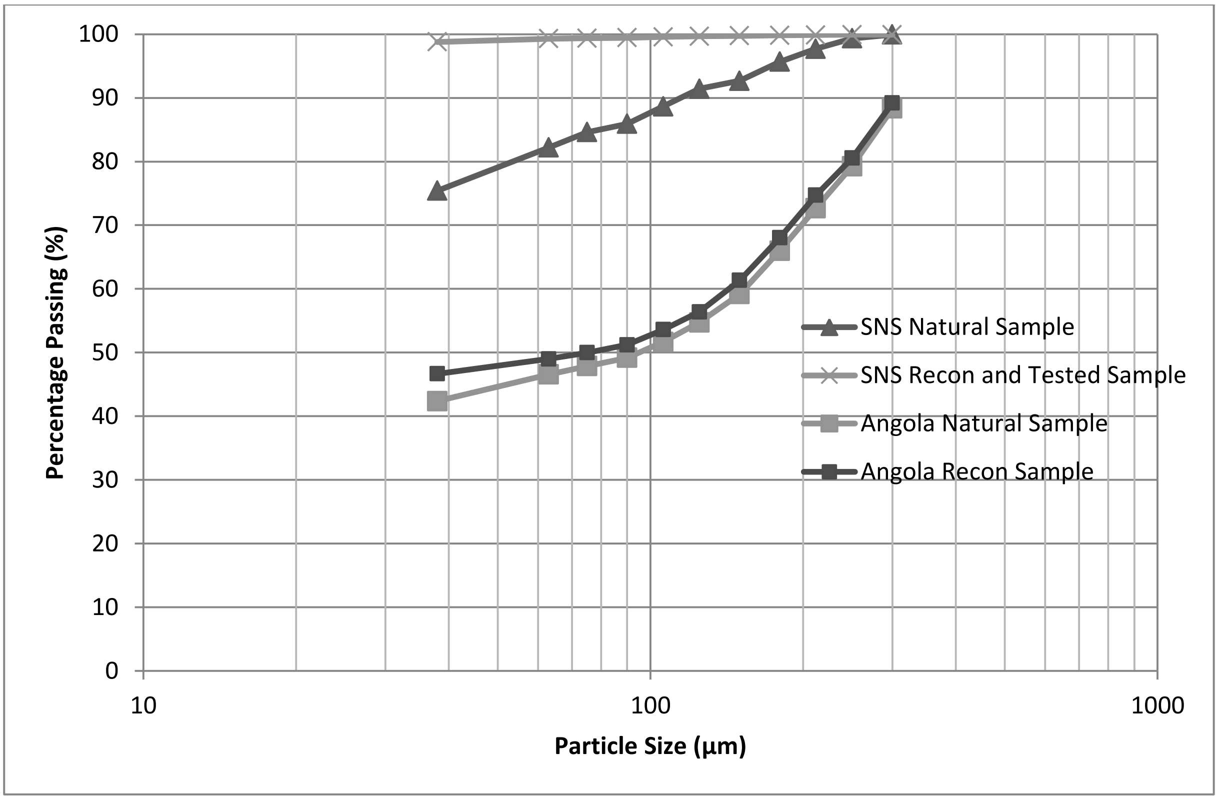


Figure 17 - PSDs from all wet sieving

Fig. 18 (Top) shows the SNS natural sample material caught in the 125 µm sieve. This mainly consists of clay particles, though some quartz like sand particles are visible in the left of the picture. Fig. 18 (Bottom) shows the reconstituted and tested sample material caught in the 125 µm sieve. A much smaller sample was tested in this analysis. The background material seen in the picture is the weighing dish, not clay. The only material remaining in the dish is the quartz-like material. The clay particles have been broken down by the reconstituting process. The SNS sample exhibits a much greater change in structure due to reconstitution.

The Angolan clay was much more interesting and varied. It contained the expected clay particles, but also the glauconised faecal pellets of burrowing invertebrates and a selection of marine debris, including sponge spicules and shell fragments. See Fig. 19, these are pictures of the material caught in the 212 µm sieve. This sample showed much less change due to the process of reconstituting; this is demonstrated by the minimal change in the PSD's shown in Fig. 17 and the similarities of the samples in Fig. 19.

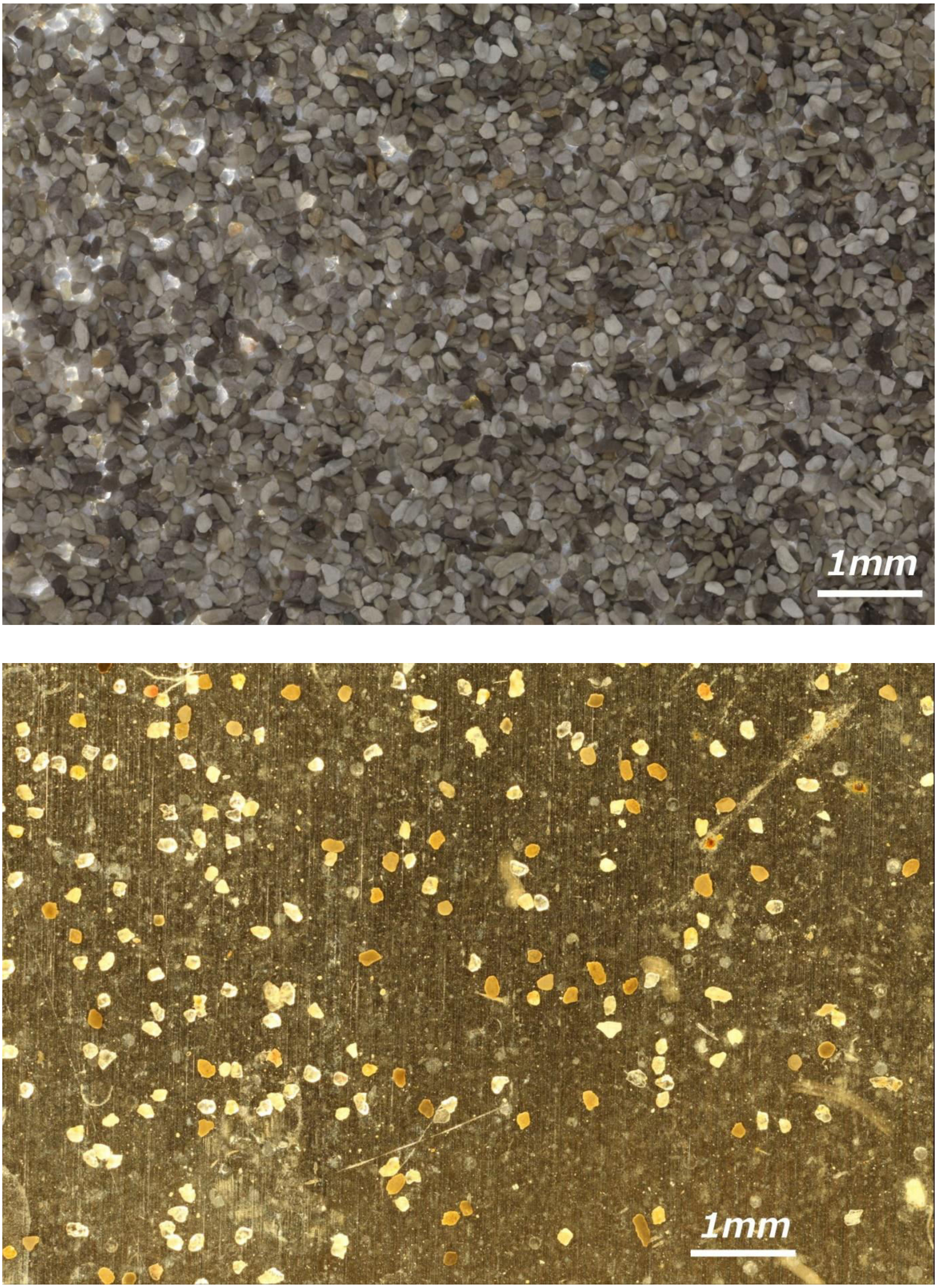


Figure 18 - SNS 125 µm material, (Top) Natural, (Bottom) Reconstituted and Tested

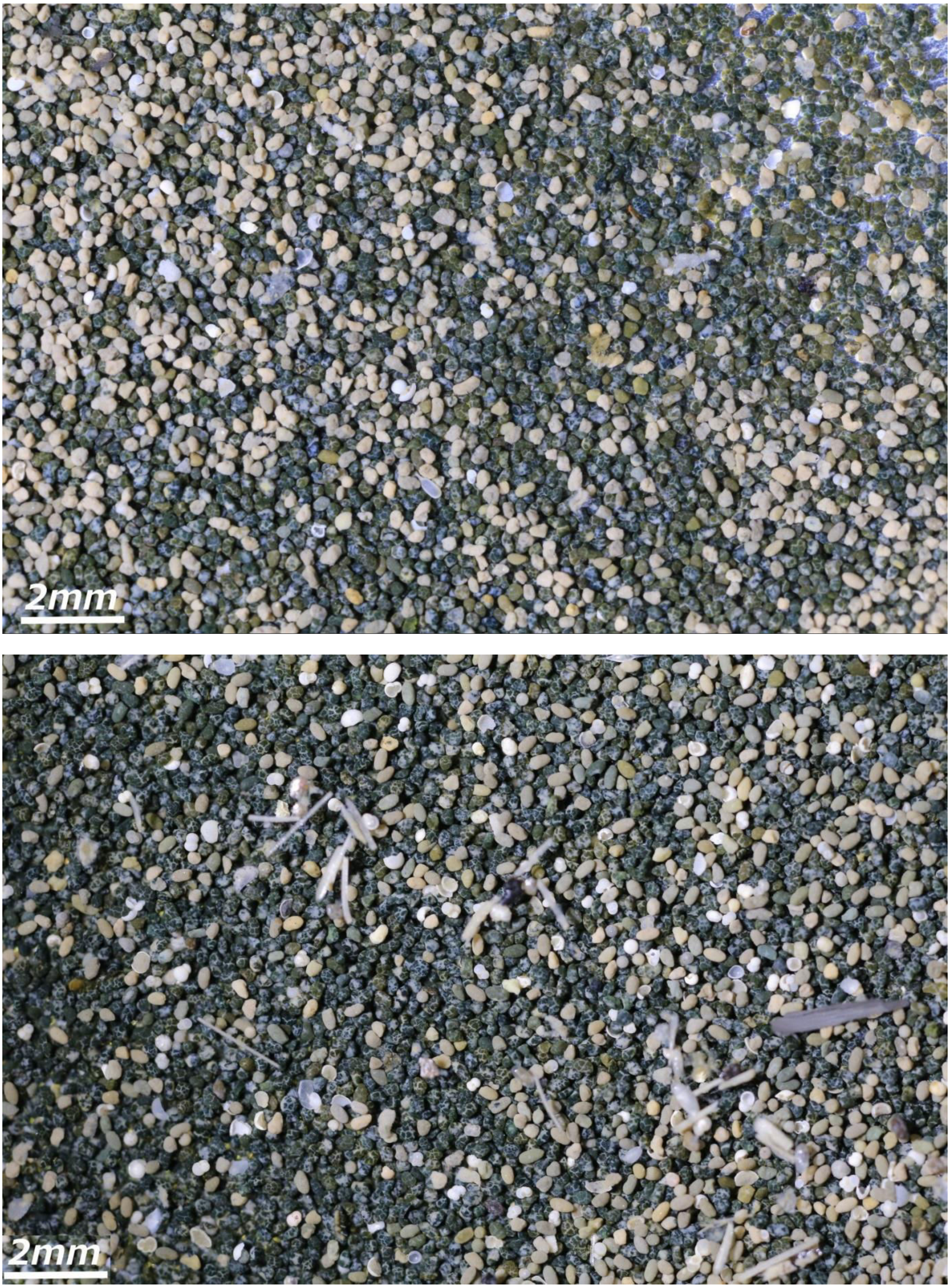


Figure 19 - Angola 212 µm material, (Top) Natural, (Bottom) Reconstituted

4.4.Imaging

In the imaging test, one hundred minutes of video were recorded during shearing. Two twenty second clips were analysed: the start of the shearing and a clip towards the end of the test. Only twenty second long clips could be analysed, as after this point the particles within the mesh had moved out of the frame visible by the camera. A long thin mesh of similar size was used in both analyses. The mesh is long to allow the zone of influence to be evaluated. It only needs to be thin, as this allows for a clearer analysis, as the particle traces don't overlap too much. The first mesh is circled in Fig. 20; the blue line marks the extents of the area and the tiny red crosses mark the monitored points.

Figure 20 – Mesh used in first PIV analysis (indicated by blue lines)

PIV is used to plot the movement of the marked points through a number of frames. In these analyses around 120 frames are used. Figs. 21 and 22 show stills extracted from the shearing video clips. The results of the PIV analysis of the preceding and subsequent images are overlain on the stills. The sample is moving from right to left, below the stationary interface. The colours are used so that visually the movement of particles with time can be seen. The overlay allows visible patterns within the particles to be compared with the results of the PIV. Fig. 21 shows the PIV from the analysis of the initial shearing and Fig.22

shows the PIV from towards the end of the shearing.

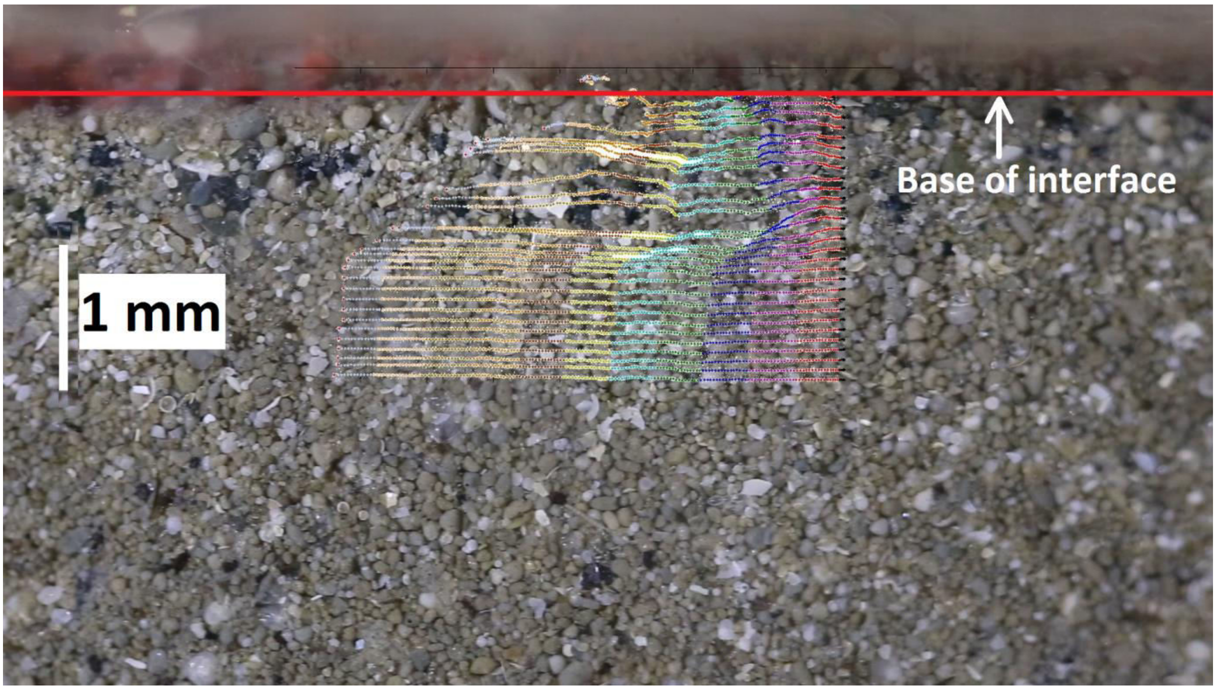


Figure 21 - PIV analysis from initial shearing

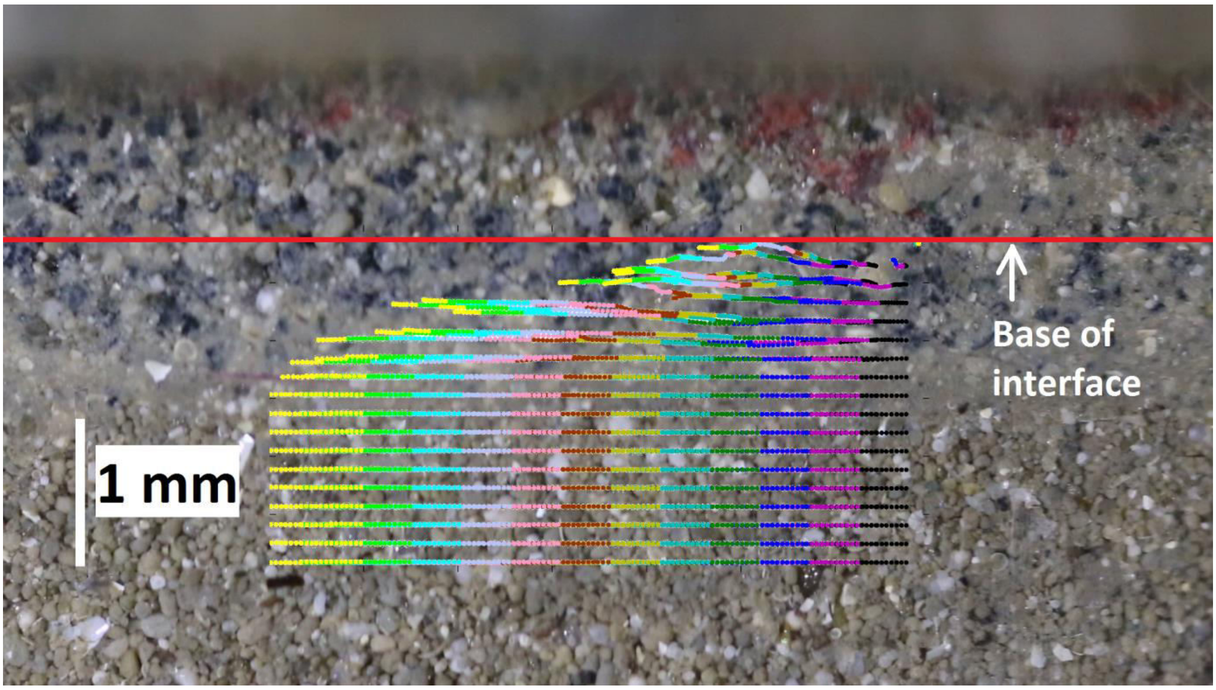


Figure 22 - PIV analysis from near the end of the shearing

Between Figs. 21 and 22 the interface moved down through the frame, as the material consolidated. The top of the PIV dots in the figures mark the lower edge of the interface. At both stages of analysis, a depth of approximately 1 mm below the interface is affected by the shearing. Below this depth the material rotates round at a constant speed. In Fig. 22 a shear band of smeared particles is visible.

5. Discussion

In this section the imaging and wet sieving results will be discussed first, as they aid the understanding of the Cam-Tor results. General trends which permeate all the Cam-Tor testing will then be explored, before finally delving into the less standard results in some detail.

5.1.Imaging

From the PIV analysis of the shearing, it is clear that only the top 1 mm of material is affected by the shearing process. This is similar to Kuo and Bolton (2014)[xiv], where a zone of turbulence of 1.5mm is seen. It is expected that this depth is related to the average roughness of the interface and possibly also the nature of the roughness. Therefore this result cannot be directly applied to the rest of the testing, where a different interface was used. However, the Kuo and Bolton (2014)[xiv] testing which used rough polypropylene as an interface material, agrees well with the testing carried out in the Cam-Tor. Therefore it is expected that rough interfaces generally will have a depth of influence in the order of 1mm.

At the interface, pulses of water movement are seen periodically in the video footage. These are easily identifiable as small particles are carried with the water. The stress seems to build up over ten to twenty seconds, as the particles move over each other; in this period there seems to be a general downward movement of water and particles away from the interface. Then when the particles' motion has become sufficiently jittery due to jamming, the pressure is released in the sudden upward movement of the water. This may be an indication of pore pressure generation. This behaviour is also seen in the PIV analysis as the particle traces seem to move gradually downwards before jumping up again. This was also observed by Kuo and Bolton (2014)[xiv] in a similar PIV analysis of the Cam-Shear device.

The analysis of the initial behaviour and the end section are very similar. This implies that the mechanism set up within the first twenty seconds of shearing is representative of the mechanism generally. When the video footage was played back, this indeed seems to be the case. A clear difference between the two stages is visible in the background images. By Fig.

22 a shear band of smeared clay has developed which is not seen in Fig. 21. The band may be made up of soft, fine clay particles which have been destroyed by the interface. Some of the harder, glaucanised pellets are still visible above.

5.2. Wet Sieving

The reconstituted SNS sample was additionally tested in the Cam-Tor prior to sieving. The Angolan sample had only undergone the process of reconstitution. As discussed above, the zone of influence of the rough interface is only around 1 mm. The height of the full sample was initially 22mm; therefore the effect of this shear band should not have a significant impact on the wet sieving results.

The SNS sample showed a much greater change in PSD due to the process of reconstitution. This is due to the presence of soft material which is easily broken down. The Angolan clay contains harder, glauconised, faecal pellets. These are more resistant to destruction by shearing. The Angolan clay is also much silitier clay than the SNS sample, with an increased percentage of larger particles.

The PSD for the natural SNS sample was substantially different to the accompanying approximate PSD provided by Fugro. The reason for this discrepancy is the difference in the methods used. “Conventional” sieving aims to breakdown the particles into the smallest components possible. Wet sieving aims to better preserve the natural structure of the soil. As pipelines only exert a low axial stress on the seabed, wet sieving will give a more realistic soil grain size, as seen by the pipeline. The level of “reconstitution” seen by the pipeline in the field will depend on the damage caused by the pipe laying. This can vary significantly depending on the method employed, the sea state, the pipe coating and the ground conditions.

5.3. General Trends

The general form of the Cam-Tor results, particularly with the rough interface, is shown in Fig. 23. Initial fast stages have a higher peak than slow stages, but the residual slows are higher than the fast. Secondary slow stages don’t have a peak value, whereas fast stages always do. Fast stages also generally have two stages to their curves, a drop and then a regain. These effects are all investigated below.

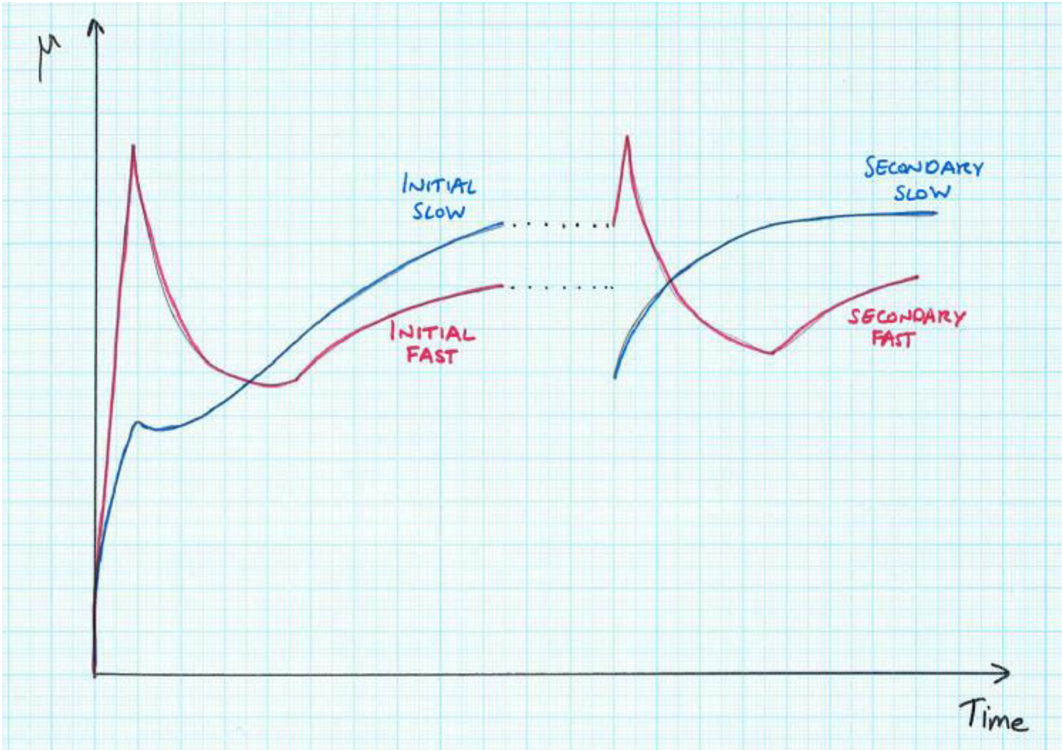


Figure 23 - General form of Cam-Tor results, particularly rough interface

On the initial shearing stage of every test, whether fast or slow, a peak is seen in the interface friction coefficient. This can be thought of as a breakthrough stress, which must be overcome to allow shearing to begin. On all tests: fast and slow, rough and smooth, the peak occurs after a rotational displacement of approximately 1°. See Fig. 24 for examples from the initial stages of SNS testing. The displacement of 1° to reach the peak is also seen in the Angolan sample and in secondary fast shearing stages. 1° of rotational displacement corresponds to a linear displacement of 0.44 mm at the characteristic radius. Kuo (2014)[xv] found a linear displacement of approximately 0.2 mm to reach the peak interface shear stress in the Cam-Shear, using a rough interface material and an axial stress of 1 kPa. The difference in these may be due to the applied axial stress condition.

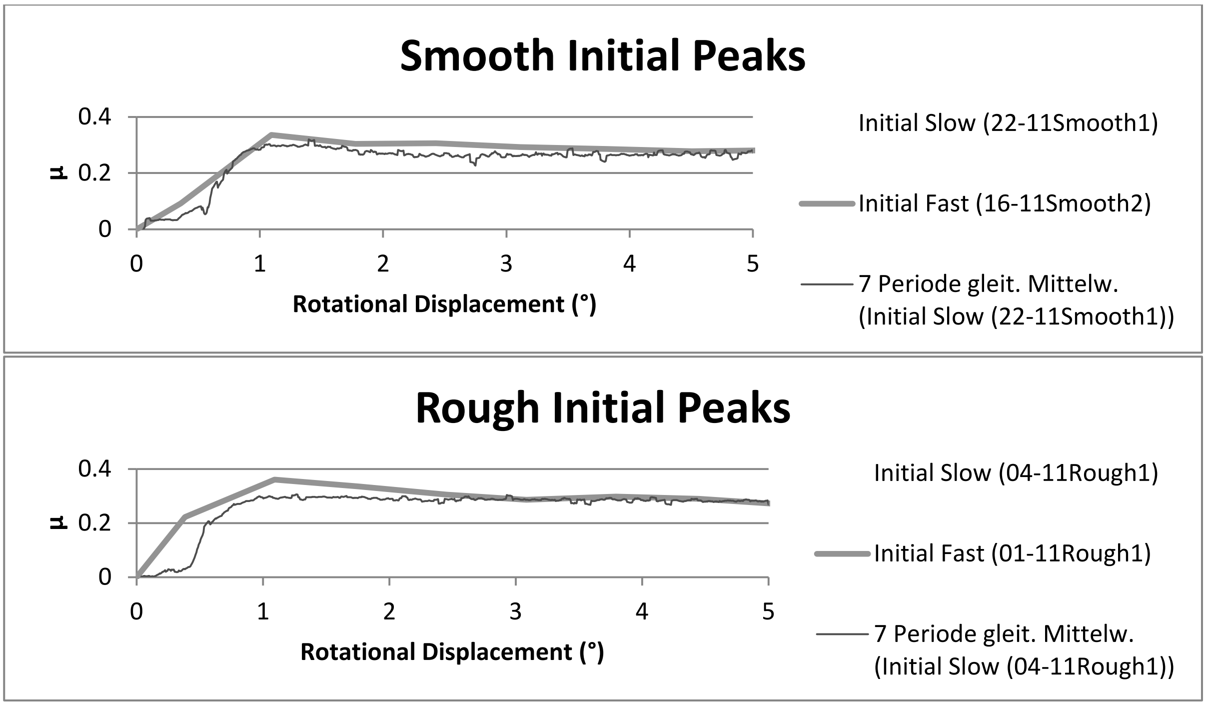


Figure 24 - Initial peaks using (Top) smooth interface and (Bottom) rough interface on SNS samples

Fast shearing stages always have a peak, whether they're the initial stage or a secondary one. After the peak, μ then drops, before regaining somewhat. It is expected that the peak occurs due to the inertial effects produced as the sample starts to move or speeds up. The peak occurs quickly and pore pressure generation may be suppressed by the speed. It is expected that the fast shearing stage is sufficiently fast to be undrained. Therefore pore pressures must be generated. The regain seen in most fast stages may mark the beginning or the stabilisation of the generation of excess pore pressures. At this point, there is sometimes a change in the axial displacement rate. This is discussed in Sections 5.4 and 5.5. Without measuring the pore pressures, it is challenging to verify exactly what is happening.

Slow shearing stages only have an initial peak when they are the first shearing stage. On secondary slow stages, where the slow stage comes after a fast shear, there is no "breakthrough" required. This is due to the fact that the speed is decreasing, so the inertial shift has no effect. The general form for a slow stage is a smooth increase to a residual value. It is expected that the slow shear is sufficiently slow to be drained, or at least partially drained.

There are some trends which are visible from the initial stages of the tests. Fig. 25 shows the interface friction coefficients associated with the initial stages of all the Cam-Tor tests. Fast peak values are always higher than slow ones. This may be as there is less of an inertial shift to a slow stage, than to a fast. Therefore less resistance is built up in the clay. By the time the residual value is reached, the slow stages are higher than the fast ones. The difference in these is due to the generation of excess pore pressures in the fast tests, but not in the slow shears which are at least partially drained. The generation of pore pressure under a fixed total stress reduces the effective stress in the clay, as Terzaghi's Principle of Effective Stress[xvi] states in Eqn. 2. This leaves less available resistance to shearing.

$$\sigma = \sigma' + u$$

Equation 2 - Terzaghi's principle of effective stress

Where σ = Total stress

σ' = Effective stress

u = Pore pressure

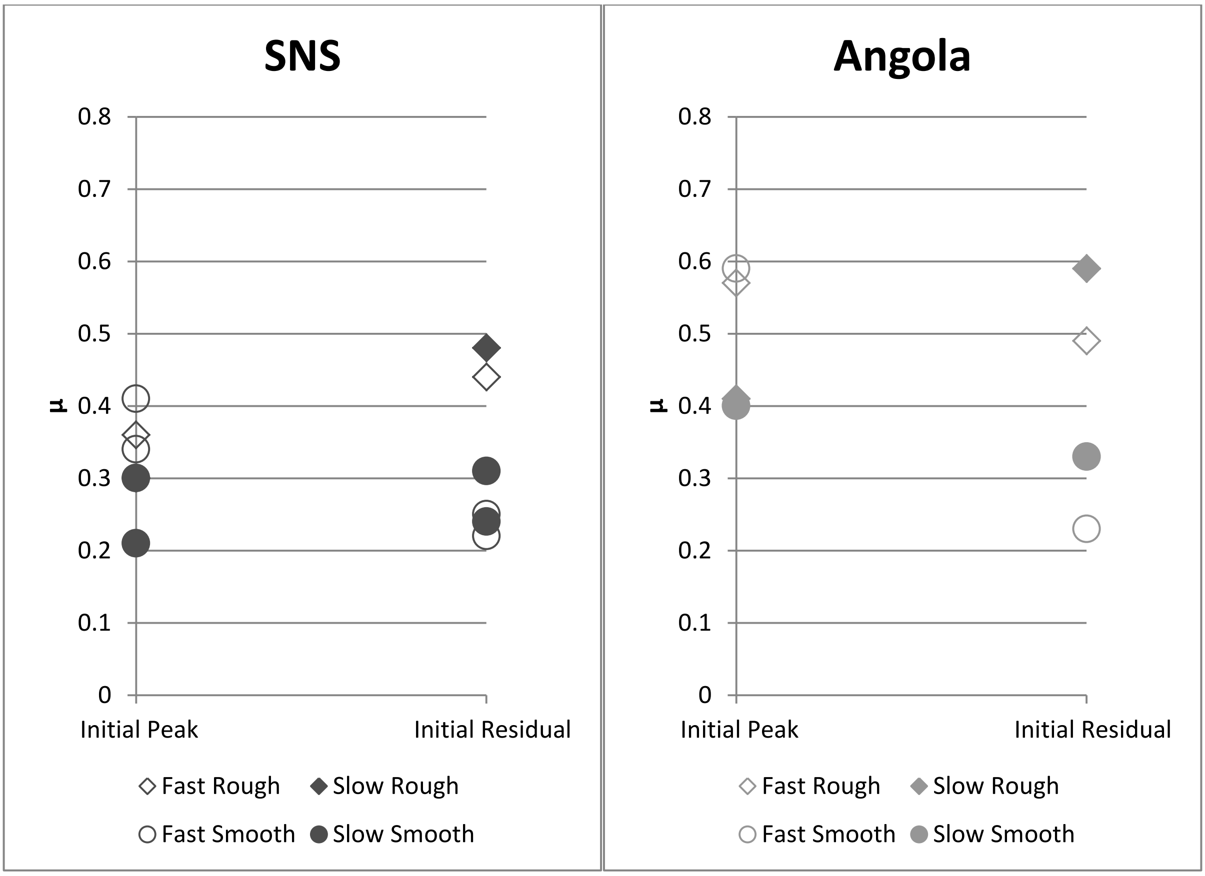


Figure 25 - Peak and residual μ for (L) SNS and (R) Angola

The maximum initial peak μ value seen in the SNS is around 0.4 with the fast shear and 0.3 with the slow. In the Angola sample, the maximum value is closer to 0.6 with the fast and

0.4 with the slow. Kuo and Bolton (2014)[xiv] tested a similar material from the Gulf of Guinea in the Cam-Shear. The Cam-Shear is included in Table 1 in Section 2. This testing device has a capacity for 190 mm of shearing in one direction, so it can only really characterise the peak behaviour. The peak μ values achieved in the Cam-Shear were approximately 0.6, using a rough interface, an axial stress of 4 kPa and a faster shearing speed than the Cam-Tor fast speed, and approximately 0.5, using a rough interface, an axial stress of 4 kPa and a faster shearing speed than the Cam-Tor's slow speed. These agree well, particularly the fast test.

Rough residual stages are higher than smooth ones. This is probably as the smooth interface has less ability to interact with the material. The rough interface can interlock with particles, generating more resistance by this interaction. The smooth interface is much more likely to slide over the material, engaging with it less, therefore developing less resistance. All the sets of Angola points are higher than their respective SNS sets, except the smooth residuals. The slow smooth residual μ values are around 0.33 and the fast smooth residual values are around 0.23. This agrees with the above reasoning, as the smooth residual μ values depend less on the material, as they have limited interaction with it. Fig. 26 shows the difference in how the interfaces might interact. The smooth interface can slide over the particles, leaving them relatively undisturbed. The rough interface either forces particles to dilate due to riding over the interface asperities or they may shear and breakdown. Either mechanism may allow the generation of excess pore pressures.

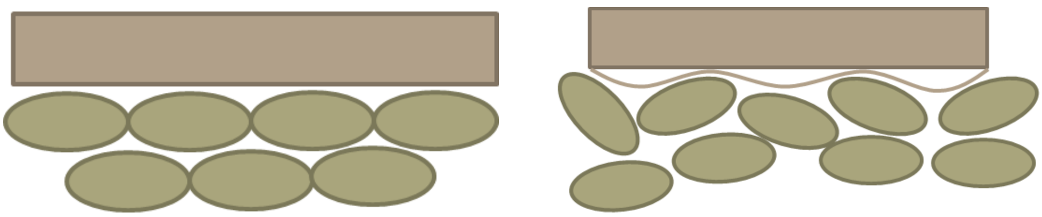


Figure 26 - Schematic diagram of smooth (L) and rough (R) interfaces

5.4.Southern North Sea

The first test, 01-11 Rough1 shown in the top of Fig. 12, had an initial fast shear. There was an increase in μ from fast to slow of 0.12. This increase marked the dissipation of the pore pressure generated from the interactions of the rough interface at speed. The subsequent fast stage had a 0.1 higher residual value than the initial and the following slow shear was 0.7 higher than the previous slow. This was not the expected behaviour. However the water bath in this test, and only this test, was a saline solution. Salt is known to have a significant effect on soft marine clays. Bjerrum (1954)[xvii] in his study on Norwegian Marine Clays found that nearly a factor of two decrease in shearing strength can occur due to the complete leaching of a normally consolidated marine clay. It would be expected that some leaching would occur during the long consolidation stages that were seen after this test. Therefore the higher interface friction coefficients seen in this test may be as a result of less leaching of the strengthening salts taking place. Another difference with this test was the single consolidation stage used. This may not have been as effective as the subsequent dual stage consolidation. If the final two stages are viewed in isolation, they seem sensible. A drop in μ of 0.9, due to pore pressure dissipation, was seen. This is similar to the value seen in the first two stages. Consolidation may have continued during the initial stages of testing, resulting in this self-contained second test.

The second test, 04-11 Rough1 shown in the bottom of Fig. 12, had an initial slow shear. There was a drop in μ of 0.13 as pore pressures were generated by the fast shear. The second slow was 0.04 lower than the initial slow stage. This occurs due to the effect of the fast shear on the clay structure. As was shown by the wet sieving and the photographs of the SNS sample, the sample structure is significantly altered by the process of reconstitution. It follows that shearing the clay will have a similar effect on the small portion within the area of influence of the interface. As the clay structure is partially destroyed, this will reduce its capacity to resist shearing, resulting in a lower μ value. The final fast stage of this test had a normal peak and drop, but then proceeded to regain to 0.54, higher than all previous residuals in this test. This seems like strange behaviour when the capacity was expected to be reduced by the effect of the previous fast shear. However, during this stage the “dam” formed, isolating the interface from the water bath. This may have prevented the further leaching of salts out of the clay, thereby allowing the clay to strengthen. The μ of 0.54 is equal to the residual value seen in the previous test on a secondary fast shear, which would support the leaching theory. Though it does appear that this stage may have continued to increase beyond this μ value, if it had been given the time; so there may have been some drying effect of the clay contributing. Fig. 27 shows the axial displacement and μ curves against square root time for the first and second fast shearing stages. There is a clear change in axial displacement gradient rate in the second fast graph. However, it is impossible to tell whether axial displacement is as a result of consolidation or material being exuded out the sides of the sample holder.

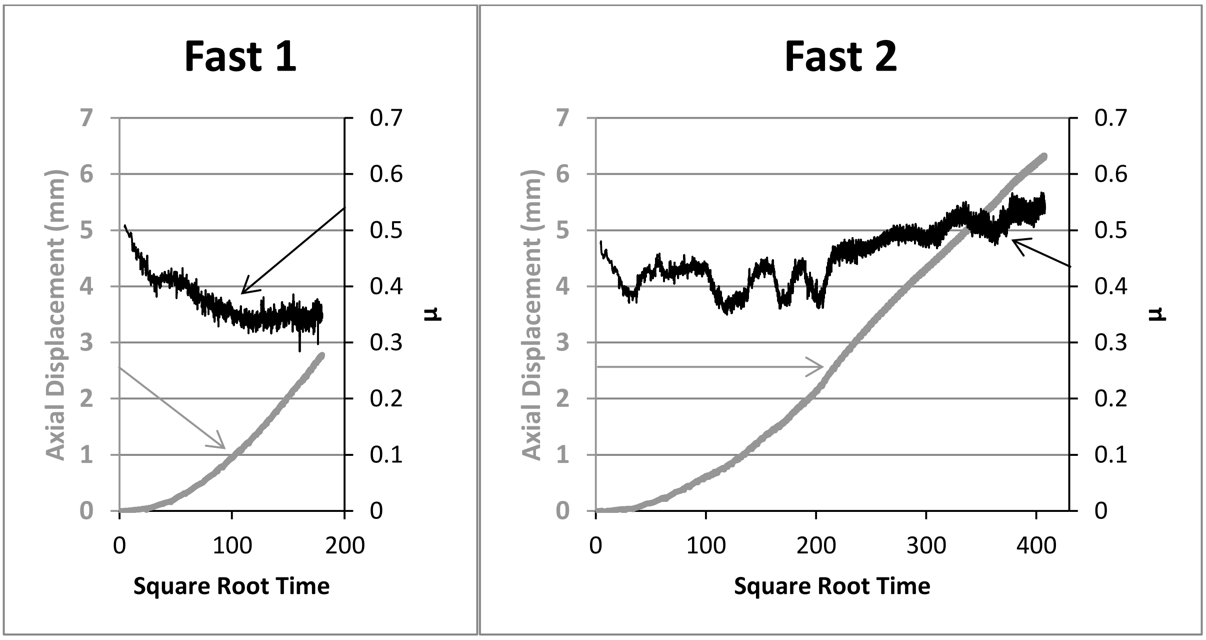


Figure 27 - Axial displacement and μ against square root time for fast shears 1 and 2 [04-11 Rough1]

The third and fourth tests, 11-11 Smooth1 and 16-11 Smooth2 shown in Fig.13, have an initial fast stage. The peak μ values for the initial fast shear were 0.41 and 0.34. This is a difference of 0.07. This may occur due to variability in the clay material at the interface for the different tests. The fast residual values of 0.25 and 0.22 agreed well with each other. The slow residuals were approximately equal to the fast residuals, though cyclic behaviour makes it challenging to identify the true value. This means that no pore pressure was generated by the fast shear, or that the pore pressure generated was equal in the fast and slow shears. This indicates that the smooth interface is causing less disturbance of the sample, therefore generating less pore pressure. This supports the theory that the smooth interface slides over the clay, not fully engaging with it as the rough interface does.

The fifth and sixth tests, 22-11 Smooth1 and 04-12 Smooth1 shown in Fig.14, have an initial slow shearing stage. The μ values for all the stages match fairly well between the two tests. There is a difference of 0.03 between the two initial slow peaks. This is less than half the difference observed in the fast smooth repeat tests. The clay variability may have less of an effect with the lower inertial shift, or there may have been less variability between these particular test samples. There was a drop of 0.11 and 0.06 from the slow stages to the subsequent fast residual values. The residuals then remain constant across the fast and the next slow stage, at 0.21 and 0.23 on the two tests. These values are similar to the residuals seen on both stages, of 11-11 Smooth1 and 16-11 Smooth2. This would be expected, as the smooth interface slides over the clay. The higher residual of the initial slow is unexpected. The cause may be that during consolidation material adheres to the interface. The slow shear is not sufficiently fast to remove this material, so soil on soil shearing, deeper in the sample, proceeds. Soil on soil shearing provides greater resistance to shearing, due to the high level of interaction between interlocking clay particles. Thereby a higher μ value is seen than when shearing occurs at the interface. The following fast shear allows the stuck material to be freed, and the shear region returns to the interface. On the fifth test, 22-11 Smooth1, a final fast shear was also conducted. This stage regained to higher than the residual of the previous two stages, by 0.04. Fig. 28 shows the axial displacement and μ curves of the first and second fast stages, of 22-11 Smooth1, against square root time. Much less axial displacement occurs during the second fast shear. Some consolidation may have occurred allowing the sample to sustain this higher stress level.

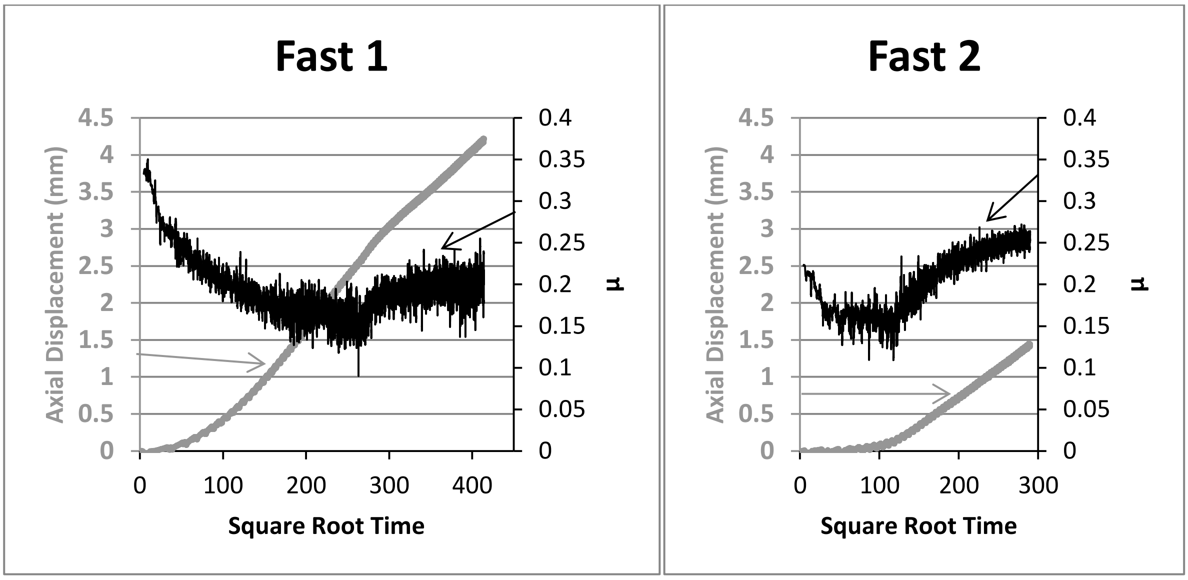


Figure 28 – Axial displacement and μ against square root time for fast shears 1 and 2 [22-11 Smooth1]

5.5.West Angola

The first test on Angolan clay, 28-01 Rough1 shown in the top of Fig. 15, had an initial fast shear. The initial fast residual is equal to the secondary fast residual, 0.49. An increase of 0.09 for the middle slow stage was recorded, where a residual μ of 0.58 was achieved. This change was due to the dissipation and regeneration of excess pore pressures.

The second Angolan test, 04-02 Rough1 shown in the bottom of Fig. 15, had an initial slow shear. This slow had a residual μ of 0.59, this is very similar to the slow residual seen in the previous test. The fast residuals were also broadly similar to the previous test values. The consistency seen within these results is much greater than within the SNS results. This may be due to the nature of the clay and it's response to reconstitution. As the Angolan clay structure is more resistant to change, it should present a less variable material to the interface. From the initial slow to the first fast shear, a drop in μ of 0.12 is seen. This is due to the generation of excess pore pressures. The following slow shear had a slightly lower residual value than the initial stage. However it appears to be still increasing, and may have reached the former value in time. Therefore the fast shear, in between the two slows, has not affected the clays capacity to resist shearing. This was to be expected by the small difference in the Angolan PSDs (Fig. 17) due to reconstitution. To the final fast shearing stage, a drop of 0.07 is seen. This represents a generation of slightly less excess pore pressure.

The third Angolan test, 10-02 Smooth1 shown in the top of Fig. 16, had an initial fast stage. The residual values for each of these stages have μ values approximately equal to half of the values seen in the corresponding tests using the rough interface. From the initial fast residual to the subsequent slow, an increase of 0.05 is seen. This was approximately half of the value associated with pore pressure generation using the rough interface. This is in line with the thought that the smooth interface is less able to generate pore pressures due to its limited interlocking potential. The two fast stages are approximately equal with residual μ values equal to 0.22 and 0.23. The second slow residual was 0.03 lower than the first slow residual. From the shape of the curve, and when compared to the longer slow stage of the next test, it may be that the clay did not reach its true slow residual value in the first slow stage. It seems that if it had been given longer, it would have oscillated to a lower value.

The final test, 17-02 Smooth2 shown in the bottom of Fig. 16, had a long initial slow stage. The residual values seen in this test are a little higher than those seen in the previous test. Similarly to the above test, the second slow stage is lower, by 0.04, than the first slow. It does appear that a general downward curve is being followed by the successive stages. The two fast stages in this test had the same residual value of 0.28.

Table 5 summarises the changes in residual μ values between subsequent stages and the inferred drainage condition based on these. The key points of this table are that the changes in μ between residuals, with the rough interface, are similar in both SNS and Angolan clays. This indicates the same drainage conditions exist during testing. Probably the fast shears are undrained and the slow shears drained. The smooth interface in the SNS sample seems to generate no pore pressure, as there is no change in μ. Therefore both shears are in the same drainage regime, drained. The smooth interface in the Angolan sample demonstrates a change in μ of approximately half that seen with the rough interface. This may indicate partial drainage during the fast test.

Clay	Interface	Estimated change in μ	Inferred Drainage Condition at End of Stage
SNS	Rough	0.09 – 0.13	Fast – Undrained Slow – Drained
	Smooth	0	Fast and Slow – Drained
Angola	Rough	0.07 – 0.12	Fast – Undrained Slow – Drained
	Smooth	0.03 – 0.05	Fast – Partially drained Slow – Drained

Table 5 - Summary of pore pressures and possible drainage conditions

6. Conclusions

In the imaging test, a depth of influence of 1 to 1.5 mm was observed with the 23 µm roughness interface material. This is expected to be in the same order of magnitude as the depth of influence when using the rough interface, which was used in the other Cam-Tor tests. Pulses of water movement seen in the video footage are an indication of pore pressure generation. The movements are similar to those described in Kuo and Bolton (2014)[xiv], where a similar PIV analysis of the Cam-Shear was undertaken. The particle behaviour observed in the PIV analysis seems to be constant from the start to the end of the shearing. However a shear band of smeared particles does develop.

The SNS sample was shown to be broken down much more by the process of reconstitution than the Angolan, see Figs. 17-19. The harder, glaucanised, faecal pellets in the Angolan clay may have provided the increased resistance. The PSDs given by the wet sieving of the natural samples may be closer to the soil state seen by the pipelines on the seabed. Though is depends on the conditions occurring during the laying of the pipeline.

The general form for all Cam-Tor results is outlined in Fig. 23. Initial slow shears have a peak, and then increase smoothly to a residual value. Secondary slow stages don't exhibit a peak value, as the inertial shift required is not available when the sample is slowing down. The secondary slow shears tend to the same residual values as the initial slow stages. Fast stages always have peak values, as they are either moving from stationary or speeding up considerably. These peaks may be occurring due to the inertial shift, resulting in pore pressure suppression. The regain seen in most fast tests, after the drop from the peak value, may mark the start of the generation of excess pore pressures after this initial suppression. All peaks, fast and slow, occur after approximately 1° of rotational displacement. This is equal to a linear displacement of 0.44 mm.

In the initial stages of the Cam-Tor tests, some clear trends were visible. Fast peaks were always higher than slow ones. This may be due to the greater inertial shift when moving from stationary to fast, rather than to slow. However slow residuals are higher than fast residuals. This is due to the generation of excess pore pressures in the fast stages, which lower the soils effective stress capacity and thus its resistance to shearing, as described by Terzaghi's Principle of Effective Stress in Eqn. 2. Rough residual stages are higher than smooth ones; this seems to be due to the smooth interfaces' lower capacity to interact with the material. The similarity in the smooth residual values for the two samples also supports the theory that the material is less important, as the interface may be sliding over the material.

The use of saline solution in the water bath for 01-11 Rough1 seems to have had a strengthening effect on the clay. The formation of the "dam" in 04-11 Rough1 has had a similar effect by preventing the leaching of the salts out of the clay. In both these tests there is a clear difference between the fast and slow shears, this implies that the fast is at least partially undrained, possibly fully undrained. The smooth tests on the SNS clays showed little or no difference between fast and slow generally. This implies that both stages were equally drained, or partially drained.

The Cam-Tor tests on the Angolan samples exhibited less variability than the SNS tests. The Angolan tests always showed differences between fast and slow shears, even with the smooth interface. The particles of the Angolan clay may have been better able to interact with the interfaces, allowing some pore pressure to be generated even with the smooth interface. The smooth interface was only able to generate about half the resistance and pore pressure seen by the rough interface.

From the changes in μ between subsequent fast and slow shears it can be inferred that during SNS and Angolan rough shears the fast stages are undrained and the slow stages are drained. During SNS smooth shears all stages are drained. During Angolan smooth shears the fast stages are partially drained and the slow stages are drained.

All these results are helpful in developing a fuller understanding of the behaviour of the SNS and Angolan clay samples. Pipeline designs in these materials will be able to benefit from these results; building up a better picture of the material responses in various situations.

7. Further Testing

The addition of pore pressure transducers to the Cam-Tor test would be helpful. Without these it is impossible to verify exactly what is happening within the test. These will be challenging to install, as pore pressure is easiest to measure under back pressure conditions. However currently in the Cam-Tor set-up, the back-pressure cell makes it harder to ensure the interface and load cell are properly aligned with the sample holder. Also the cell cannot be filled with water as the load cell is not designed for this. The back pressure would therefore have to be applied through some water and then air.

Testing in the Cam-Tor at a variety of other speeds would allow the back-bone curve from Hill et al. (2012)[x] to be replotted with this device. This would help to verify that the Cam-Tor data set is in line with other known data sets, for example the CUED Cam-Shear, the UT Austin Tilt Tables and the UWA Low Stress Shearbox.

Allowing varying length pauses between shearing cycles would be useful. In the field, pipelines may rest on the seabed for variable amounts of time between contraction and expansion cycles, depending on the pipe usage. Investigating the length of pause required for a slow stage to generate a peak through the inertial shift, may be worth considering. The general effect of pauses is also relevant.

Imaging a test using a smooth interface would be useful. This would confirm the mechanism of shearing which is taking place. It is expected that the interface is in fact sliding over the material and having minimal interactions with the particles. It would be expected that the pulses of water viewed with the rough interface may not be present with the smooth. The pulses indicate pore pressure generation; much less pore pressure is expected to be generated with the smooth interface.

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