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Effect of clay activity and interface surface material on residual undrained interface strength: implications on pipeline-seabed interaction analysis

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ABSTRACT

Characterization of the geomechanical behavior of the seabed along a high-pressure high-temperature (HPHT) pipeline route is important for understanding risks from geohazards and thermally induced displacements such as axial walking. Axial resistance to pipeline displacement, from the friction between seabed and the contact surface of the pipe, can be estimated through laboratory tests using interface shear box (ISB) and tilt table. Tests performed by NGI in several developements in Gulf of Mexico, South America, and West Africa revealed significant variation in shear resistance, potentially associated with the type of interface material and surface roughness characteristics. This paper illustrates the effect of clay activity and interface surface material on the residual undrained interface strength estimated from interface shear box tests. Two cohesive soil batch samples with varying activity were tested using two different interface plates (steel and silicon carbide sandpaper) of comparable surface roughness. Each soil batch-interface combination was tested under three different initial effective normal stresses and two different over consolidation ratios (OCRs). Undrained residual interface strength envelopes were developed for each soil batch-interface combination. The results from tests performed on steel interface showed an increase in residual undrained interface strength with plasticy and clay activity whereas a reverse trend was observed in the results of the tests performed using the sandpaper interface. This reinforces the importance of the choice of interface plate material (in addition to surface roughness) for PSI testing program to accurately capture the resistances offered by the seabed to pipe displacement.

Keywords: Pipe-soil interaction; Interface Shear Box (ISB); clay activity; interface surface.

1. Introduction

Subsea pipelines, including infield flowlines, risers, water and gas injection lines, and gas export pipelines, are essential components of oil and gas field infrastructure. Excessive axial pipeline expansion poses a significant risk, potentially leading to cumulative pipeline walking and uncontrolled lateral buckling. Such issues can compromise the structural integrity of the entire subsea system (Carr et al., 2006; Bruton et al., 2007). Axial expansion primarily occurs due to variations in temperature and pressure within the pipeline, while the resistance to this expansion relies on the shear resistance between the coated pipeline surface and the seabed soil.

Estimating this 'friction' between the pipeline and the seabed is crucial, typically achieved through a pipe-soil interaction (PSI) analysis following SAFEBUCK guidelines (Atkins, 2015) and DNV Recommended Practice-F114 (2017). These analyses utilize parameters derived from laboratory testing to characterize the interface shear resistance under drained and undrained conditions. The most common laboratory tests comprise interface shear box (ISB) and tilt table (TT) tests where a soil specimen is sheared over an interface plate at normal stresses, typically ranging between 2 and 20 kPa, representative of the bearing pressure applied by the pipeline to the seabed, influenced by its curvature and the 'wedging' factor (White and Randolph, 2007). The tests measure the cohesive and frictional resistances between the soil specimen, representing the surficial seabed soils and an interface plate representing the surface coating of the pipe. The tests yield undrained and drained residual interface strength envelopes, which are then scaled to the operating pipeline weight and coating roughness to estimate frictional resistance against axial and lateral movement.

The effect of normal stresses, drainage condition, stress history of the soil specimen (relevant for undrained conditions) on shear resistance derived from the laboratory tests on fine-grained soil is well-documented (Pedersen et al. 2003, Najjar et al. 2007, Hill et al. 2012, Ganesan et al. 2013, Kuo et al. 2015, Meyer et al. 2015, Boukpeti and White 2017, Westgate et al. 2018, Westgate 2022). This study was motivated by NGI's extensive laboratory testing across hydrocarbon development areas in the Gulf of Mexico, South America, and West Africa. Significant variations in shear resistance were observed, associated with interface plate types and roughness characteristics. This paper studies the effects of clay activity, plasticity, and interface surface material on friction resistance. Additionally, the ISB tests conducted in this study address a data gap in the global database of residual undrained interface strength

(Westgate et al. 2018, Westgate 2022) within the 4 to 7 micrometers (microns) average surface roughness range of the interface.

2. Interface shear box testing

Interface shear box tests are typically performed at fast and slow shear rates to notionally simulate undrained and drained conditions respectively. Shear rates of 0.1 mm/sec, estimate using the method of Gibson and Henkel (1954), are common and have been used for much of the published database to measured undrained conditions. Although faster rates can be employed, a rate of 0.1 mm/sec is typically sufficient to attain minimum resistance conditions before the influence of viscous effects are mobilized.

2.1. Interpretation of test results

ISB tests examine the behavior of soil interacting with interfaces by shearing it across plates designed to replicate pipe coatings. The objective is to ascertain the residual shear resistance of the soil under defined normal stress conditions on the interface surface. In this study, the test specimens were sheared until they reached a cumulative horizontal displacement of about 22 mm, at which point the shear stress had stabilized at a residual value. The cumulative average shear stress between displacements of 15 mm and 20 mm was considered as the residual undrained shear stress. Fig 1 shows typical strain softening behaviour of the test specimen with horizontal displacement, where the shear stress converges to a residual shear stress value.

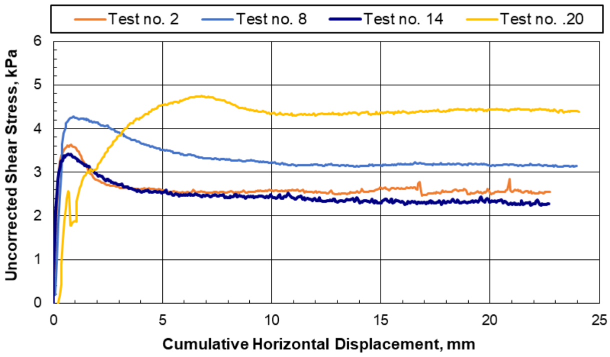

Figure 1. Uncorrected shear stress vs cumulative horizontal displacement

During shearing, the ring containing the soil specimen directly interacts with the interface plate and the sheared soil. All interface plates used are corrected for the friction between the ring and interface plate. Figure 2 shows typical ring friction values for each soil and surface combination. The residual undrained interface shear strength is derived by subtracting the cumulative average of ring friction between 15 mm and 20 mm horizontal displacement from the uncorrected residual interface shear stress.

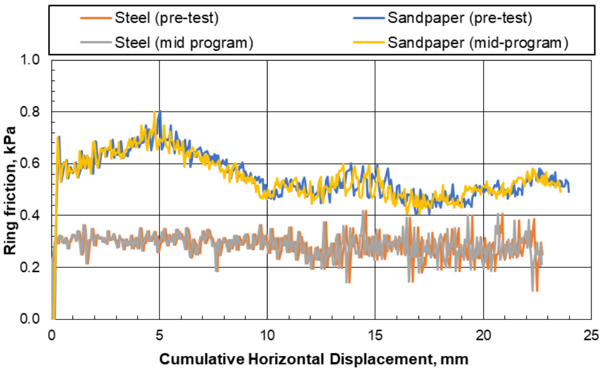

Figure 2. Ring friction vs cumulative horizontal displacement

2.2. Residual undrained interface strength

The model for undrained residual interface strength utilizes the SHANSEP stress history framework, as proposed by Ladd and Foott (1974). It employs this framework to estimate the undrained axial residual resistance caused by variations in pipe weight during the pre-commissioning phase. Additionally, it simulates the pre-loading of normal stress by incorporating an overconsolidation ratio (OCR). The undrained residual interface strength ratio is expressed as a power law:

$$(\tau_{res,int}/\sigma'_{no})_{oc} = (\tau_{res,int}/\sigma'_{no})_{nc}(OCR)^{m} \quad (1)$$

where:

$\tau_{res,int}$= undrained residual interface shear stress;
σ'_{no}= initial effective vertical stress;
subscripts nc and oc refer to normally-consolidated and overconsolidated conditions respectively;
OCR = overconsolidation ratio; and
m = plastic volumetric strain ratio.

The m parameter can be significantly lower than the typical values (0.7 to 0.9), due to the inefficiency of the interface failing to mobilize soil-soil failure. Generally, smooth surfaces exhibit lower m values than rough surfaces, as low as 0.2 to 0.4 for smooth polypropylene and smooth steel surfaces (Westgate et al. 2018).

3. Experimental design

In this study, twenty-four (24) ISB tests were performed on two different batch samples to study the effect of normal stresses, stress history, plasticity, clay activity, and interface material on the frictional resistance under undrained conditions. Table 1 presents the overview of the experimental design.

Fig. 3 shows the ISB testing device at Norwegian geotechnical Institute (NGI), Houston laboratory.

Table 1. Experimental design

	Initial normal effective stress (kPa)	OCR	Surface roughness
Batch 1 (high activity clay)	2, 5, 10	1, 2, 4	Steel, Sandpaper
Batch 2 (silty clay)	2, 5, 10	1, 2, 4	Steel, Sandpaper

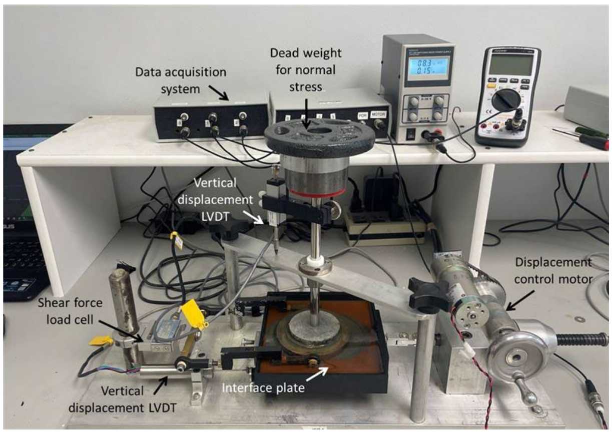

Figure 3. Interface shear box testing device, including the control box and data acquisition systems (courtesy NGI Houston)

3.1. Interface surface

A steel interface plate of average surface roughness equal to 4.4 microns and a sandpaper plate of average surface roughness equal to 6.6 microns were selected for this study as shown in Fig 4.

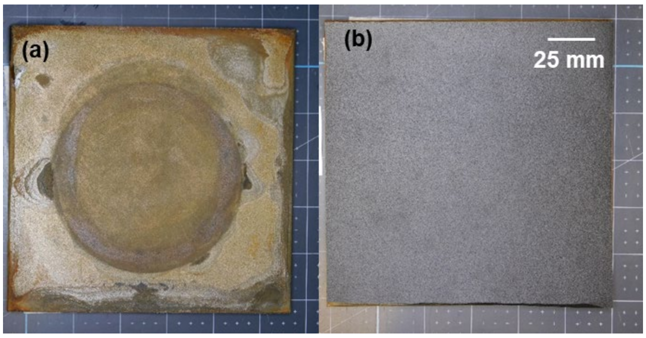

Figure 4. Interface plates used in this study: (a) Steel; and (b) silicone carbide sandpaper.

The surface roughness was measured using a Mitutoyo profilometer (Surftest SJ-310 Series). Ten readings were taken across the interface surface in the direction of shearing to estimate the average surface roughness.

3.2. Stress history

The ISB tests were run at lab induced OCRs of 1, 2, and 4 study the effect of stress history on the residual undrained interface strength ratio.

4. Batch samples

4.1. Sample preparation

In order to identify the effects associated with clay activity on the interface shear behavior, two batch samples were studied: Batch 1 comprising the as-received soil, and Batch 2 prepared by adding silt-size particles to Batch 1 to lower the plasticity. The fine-grained soil of Batch 1 consists of 53% silt and 47% high plasticity, montmorillonite clay. Montmorillonite is known for its high potential for absorbing water and swelling. The liquid limit (LL) and plasticity index (PI) of Batch 1 were evaluated to be 146% and 114%, respectively, classifying the soil as clay with high plasticity (CH) according to the Unified Soil Classification System (USCS). Batch 2 had a silt content of 82%, with LL = 54% and PI = 37%.

5. Results

Twenty-four (24) ISB tests were performed as part of this study, with all test conditions and results presented in Table 2. Each soil and surface pair included one test for repeatability at the intermediate stress level under normally consolidated conditions.

Table 2. Summary of ISB test results

Test no.	Batch	Initial normal effective stress, σ'_{n0} (kPa)	OCR	Interface surface	Undrained stress ratio, $\tau_{res,int}/\sigma'_{n0}$
1	Clay	2	1	Steel	0.44
2	Clay	5	1	Steel	0.46
3	Clay	5	1	Steel	0.55
4	Clay	10	2	Steel	0.67
5	Clay	5	2	Steel	0.63
6	Clay	5	4	Steel	1.00
7	Clay	2	1	Sandpaper	0.56
8	Clay	5	1	Sandpaper	0.54
9	Clay	5	1	Sandpaper	0.53
10	Clay	10	2	Sandpaper	0.85
11	Clay	5	2	Sandpaper	0.82
12	Clay	5	4	Sandpaper	0.99
13	Silty clay	2	1	Steel	0.63
14	Silty clay	5	1	Steel	0.41
15	Silty clay	5	1	Steel	0.51
16	Silty clay	10	2	Steel	0.64
17	Silty clay	5	2	Steel	0.60
18	Silty clay	5	4	Steel	0.72
19	Silty clay	2	1	Sandpaper	1.05

Test no.	**Batch**	**Initial normal effective stress, σ'_{n0} (kPa)**	**OCR**	**Interface surface**	**Undrained stress ratio, $\tau_{res,int}/\sigma'_{n0}$**
20	Silty clay	5	1	Sandpaper	0.79
21	Silty clay	5	1	Sandpaper	0.82
22	Silty clay	10	2	Sandpaper	0.98
23	Silty clay	5	2	Sandpaper	1.28
24	Silty clay	5	4	Sandpaper	1.61

5.1. Effect of prestressing on residual undrained interface strength

Fig 5 shows the undrained residual shear strength envelopes for various soil-interface combinations based on the ISB test results. The residual undrained shear strength ratios increase with OCR following the power law.

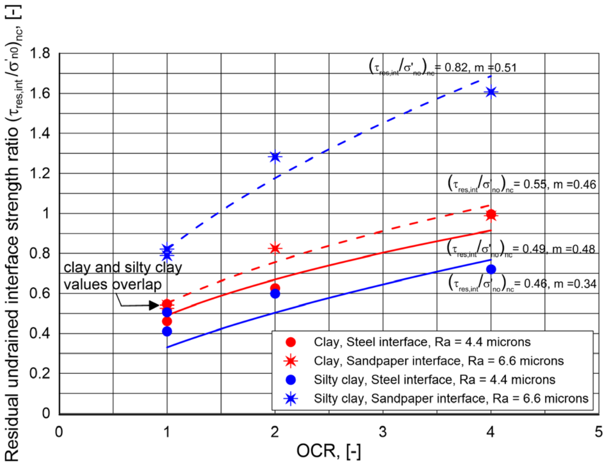

Figure 5. Residual undrained interface strength ratio vs OCR

The silty clay specimen on the sandpaper interface has the highest residual undrained interface strength envelope followed by clay with the sandpaper interface and clay with the steel interface. The silty clay with the steel interface has the lowest residual undrained interface strength envelope.

5.2. Effect of plasticity and clay activity on residual undrained interface strength

Fig 6 and Fig 7 show the effect of plasticity and clay activity on residual undrained interface strength ratio, respectively. An increase in residual undrained shear strength ratio was observed with increasing PI and clay activity in the case of the steel interface. The opposite trend was observed for the sandpaper interface.

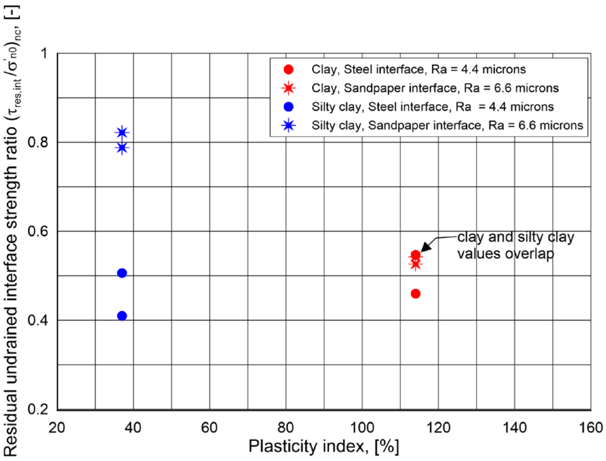

Figure 6. Normalized undrained interface shear strength vs plasticity index.

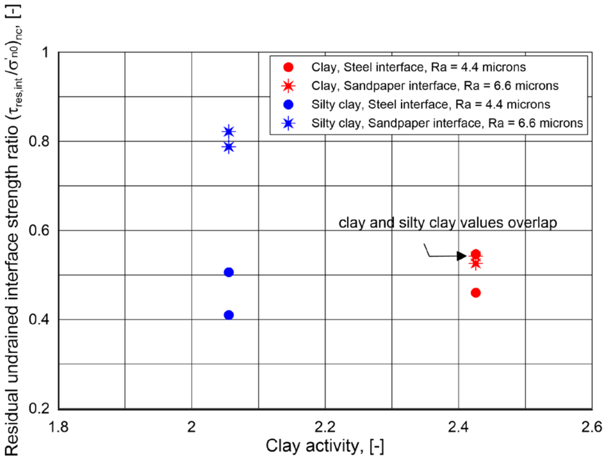

Figure 7. Normalized undrained interface shear strength vs clay activity.

The increased interface strength ratio with higher plasticity for the steel interface could be attributed to increased adhesion of the soil specimen to the interface plate as shown in Fig 9.

Figure 8. Adhesion on the clay specimen to the steel interface plate during shearing

The higher silt content for both surfaces could have created the large differences in interface strength ratio at lower PI. For the rougher sandpaper interface, increasing interparticle and surface engagement would lead to higher shear resistance, while for the smoother steel interface, increased interlocking of the silt-size particles would lead to an increase in translational particle movements along the smoother surface, resulting in lower shear resistance. These trends are consistent with sand interface behavior which is more influenced by interparticle engagement and relative roughness of the interface surface as compared to clay interface behavior.

5.3. Effect of interface roughness on residual undrained interface strength

Fig 9 shows the effect of interface plate roughness on residual undrained interface strength ratio, limited to normally consolidated specimens. The data are compared to the clay test database published in Westgate et al. 2018 and reprised in Westgate (2022) showing a best fit to the data using the model proposed by Meyer et al. (2015). The residual undrained strength ratios obtained from this study, which plot in the gap between surface roughness values of 2 and 10 microns, are mostly higher than the best estimate trendline, in particular the silty clay tests on the sandpaper, clearly showing that higher silt content leads to higher residual undrained shear resistance. The tests on the clay specimens suggest that the transition between smooth and rough conditions lies closer to the lower end of the 2 to 10 microns range.

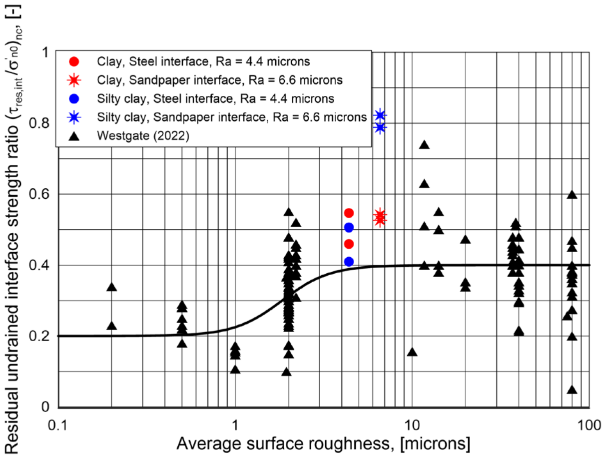

Figure 9. Residual undrained interface strength ratio vs average surface roughness

6. Conclusion

Twenty-four ISB tests were performed on clay and silty clay soil specimens using steel and sandpaper interface plates with different intermediate surface roughness. The clay soil specimen has higher plasticity and clay activity than the silty clay specimen. The objective of this study was to investigate the effect of plasticity, clay activity, and surface interface on residual undrained interface shear strength. The ISB tests also serve to address the average roughness data gap between 2 and 10 microns from the Westgate et al. (2018) clay database, confirming that for clay soils the transition between smooth and rough surfaces is closer to 2 microns than 10 microns. The study also corroborates the OCR *m* parameter, ranging from values of 0.45 to 0.61, which bound the mean value of 0.50 for all surface roughness values tested in the Westgate et al. (2018) clay database.

The tests performed on the steel interface showed an increase in residual undrained shear strength with increasing plasticity and clay activity. However, the reverse trend was observed in the tests performed using the sandpaper interface. This is likely due to interparticle and interface engagement with the silty clay, leading to higher resistance against the slightly rougher sandpaper and lower resistance against the slightly smoother steel.

However, the results from tests performed using the steel interface showed a higher variability compared to results from tests performed using sandpaper interface. This observation is consistent with NGI's experience with performing ISB tests on steel interfaces on several site investigation programs in Gulf of Mexico, South America, and West Africa. During the test process the steel plate tends to oxidize when in contact with water for a prolonged period, which may affect the residual undrained shear strength. This suggests that pipeline-specific coatings should be used as far as practical for ISB testing. Roughness alone should not be used as the criterion for selecting surface materials.

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