



# Effect of Soil Composition, Interface Roughness, and Drainage Response on Shear Strength During Low Normal Stress Interface Shear Box Testing

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**ABSTRACT:** Subsea pipelines are a crucial component of offshore infrastructure for the development of oil and gas fields. These pipelines experience thermally induced axial and lateral displacements due to temperature changes during operation. The frictional resistance to these displacements can be drained or undrained, depending on the rate of pipe displacement and soil drainage characteristics, and is also affected by normal stress levels and pipe surface coating characteristics. This paper examines the effect of soil composition, shearing rate, and interface roughness on the transition from undrained to drained residual interface shear stress during cyclic interface shear box (ISB) tests. The cyclic ISB testing comprised continuous cyclic shearing at a fast shearing rate of 0.1 mm/s to achieve undrained residual conditions. Cyclic shearing was continued through the drainage transition until steady state conditions were achieved, followed by a pair of confirmatory cycles at a slow shearing rate of 0.001 mm/s. Tests were conducted on smooth, intermediate, and rough interface plates using three different normally-consolidated soil specimens with varying fines and sand content. The study provides insights into the drainage behavior of transitional or mixed soil types often encountered in intermediate and shallow water depths gas export pipelines, and its effect on residual interface strength as it relates to the governing load transfer mechanisms. The paper builds upon a large body of work amassed over the past two decades on low normal stress interface shear testing and provides further guidance on the conduct and interpretation of these tests for development of pipe-soil interaction parameters used in pipeline design.

**Keywords:** Pipe-soil interaction; Interface shear box test; subsea pipelines

## 1 INTRODUCTION

Subsea pipelines, which include infield flowlines, risers, water and gas injection lines, and gas export pipelines, play an essential role in oil and gas field infrastructure. The structural integrity of these systems must accommodate axial expansion and potential cumulative pipeline walking which can influence lateral pipeline buckling. Such phenomena pose a significant risk to the entire subsea network (Carr et al., 2006; Bruton et al., 2007). Axial expansion is driven by temperature and pressure variations within the pipeline as well as seabed slope, while the resistance to this movement depends on the shear resistance at the interface between the coated pipeline surface and the seabed soil.

Accurate estimation of the shear resistance or 'friction' between the pipeline and the seabed is important and is commonly performed through a

combination of site-specific interface shear testing and pipe-soil interaction (PSI) analyses, following guidelines such as those published within the SAFEBUCK Joint Industry Project (Atkins, 2015) and the DNV Recommended Practice-F114 (DNVGL, 2017). The site-specific interface shear testing most often comprises laboratory element tests such as the interface shear box (ISB) and tilt table (TT) tests, which assess the shear resistance of soil specimens interacting with a simulated pipeline coating.

In ISB and TT tests, a soil sample is sheared against an interface plate under normal stresses that approximate the bearing pressure applied by the pipeline, accounting for the pipe embedment and the curvature of the pipeline, i.e. the so-called 'wedging' effect (White and Randolph, 2007). These tests are designed to represent the seabed's surface soil and the roughness of the pipeline's coating, providing data on

both cohesive and frictional resistances. The resulting undrained and drained residual interface strength envelopes are used to scale the shear resistance to the pipeline's operational weight, any pre-loading effects during commissioning due to changes in pipe weight, and the project-specific coating properties to estimate the shear resistance affecting axial movement.

The influence of normal stresses, drainage conditions, and the stress history of the soil specimens on shear resistance derived from these tests has been well-studied, both for fine-grained soils (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) and coarse-grained soils (O'Rourke et al., 1990; Subba Rao et al., 1998; Dove and Frost, 1999; Dietz and Lings 2006; Milewski et al., 2019; De Leeuw et al., 2020; Westgate et al., 2021). These studies contribute to understanding the behavior of the pipe-soil interface and the factors that influence the reliability and safety of subsea pipeline systems, allowing for development of reliable PSI models and ensuring the effective prediction of frictional resistance and aiding in the mitigation of pipeline walking and lateral buckling, critical to the integrity of subsea infrastructure.

While laboratory tests like ISB and TT are becoming more routinely performed for measuring residual interface strength, there is still a lack of a consensus for testing procedures across the offshore industry. For example, recent project-specific testing programs have ranged from exclusively using the ISB device for both fast (notionally undrained) and slow (notionally drained) shearing to combining the ISB and TT devices to capture undrained and drained shearing, respectively. While the TT device is generally considered to only capture drained shearing, ISB test procedures vary from monotonic to cyclic shearing, often involving a small number (e.g., 2) or a larger number (e.g., 18) cycles of fast shearing, followed by 1 or 2 cycles of slow shearing. Most cyclic ISB tests performed to date include intervening consolidation periods (typically 30 minutes in duration) between pairs of undrained cycles (Boukpeti and White, 2017), adding complexity to the interpretation of shear resistance, but allowing the undrained to drained transition to be assessed.

This paper presents a preliminary subset of a larger dataset aimed at studying some of the procedural aspects of interface shear testing for a range of sand and clay mixtures. The objective of the testing program is to study the effects of soil composition, interface roughness and drainage condition on the residual interface shear strength. The results show that residual interface strength decreases with increasing fines content, with the rough surface exhibiting the

highest strength, but surprisingly followed by smooth surface, with the intermediate surface generating the lowest resistance across all soil types. Slow shearing rates consistently resulted in higher interface strength than fast rates for intermediate and rough surfaces, with the rate effect amplifying as fines content increased. For smooth surfaces, this trend was observed only for the clay specimen. The interpreted results would change depending on how many cycles are performed, and at which cycle the undrained resistance was defined. These findings highlight the complex influence of soil composition, interface roughness, and shearing rate on the shear behaviour and offer some insights into planning ISB test programs for PSI analysis.

## 2 LABORATORY TESTING PROGRAM

Nine cyclic interface shear box (ISB) tests were conducted on three batches of soil samples with varying fines content (with fines here defined at 63 microns): 0% (pure silica sand), ~90% fines (a natural marine clay sample from the Gulf of Mexico), and a 50/50 mixture by dry weight of the pure silica sand and marine clay (~50% fines). The cohesive soil (~90% fines) batch was prepared at a water content of 10% above the liquid limit to ensure remolded soil to be normally consolidated at the low normal stresses applied during the test. The 50/50 mixture soil sample was prepared based on the dry weight of the clay and sand content to provide the desired ratio (50-50). The test specimens, from respective soil batches, were prepared directly into a circular confining ring and gently rodding the soil into the ring into place to fill any voids. The nominal dimensions of the test specimen are 76.2 mm in diameter and 13.8 mm in height. The tests were performed using the custom ISB device at the Norwegian Geotechnical Institute (NGI) in Houston, Texas (**Error! Reference source not found.**).

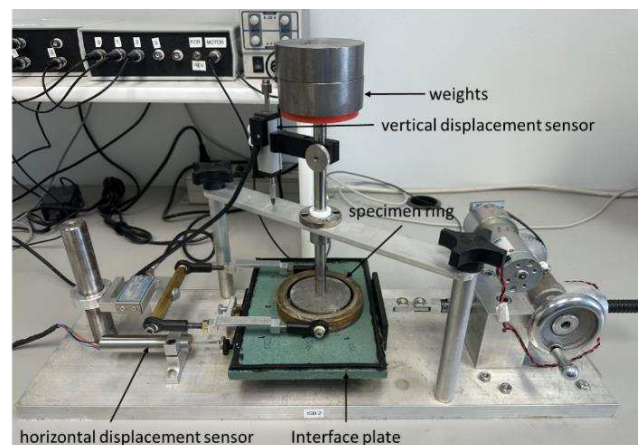


Figure 1. Interface shear box device (credit: NGI, Inc.).

The dead weight vertical loading system applies normal stress to the specimen through a stainless steel loading rod that passes through a guide bushing. The load cell that measures horizontal shear stress utilizes two independent, vertically-free moving load transfer arms to avoid any vertical or horizontal torque being applied to the specimen. The soil specimen is confined in a bronze confining ring that rests on the interface plate.

Interface surfaces comprised smooth, intermediate, and rough plates to simulate a range of pipeline surface roughness. The smooth and intermediate surfaces were made of polypropylene with average surface roughness ( $R_a$ ) of 0.1  $\mu\text{m}$  and 2.5  $\mu\text{m}$ , respectively. The rough interface plate was made from sandpaper with a surface roughness of 12  $\mu\text{m}$ . Each test consisted of 18 cycles of fast shearing at a rate of 0.1 mm/s followed by 2 cycles of slow shearing at a rate of 0.001 mm/s, where rates are based on the direct shear box drainage estimation approach of Gibson and Henkel (1954). All tests were performed at an initial normal effective stress of 5 kPa and at normally consolidated conditions. Machine friction between the ring confining the specimen and the interface plate was measured by shearing without soil specimen. A correction was then applied to the test results by subtracting the force due to machine friction from the residual interface shear strength. Tests were performed in order of decreasing fines content to limit the effects of any sand particle abrasion on the surface roughness for subsequent testing.

### 3 RESULTS

The laboratory test program and results are summarized in **Error! Reference source not found..** The residual interface strength ratio is defined as the ratio of the residual interface strength,  $\tau_{res}$ , to the initial normal effective stress,  $\sigma'_{n0}$ . For fast cases, the residual interface strength ratio is taken as the minimum residual interface shear stress ratio across all 18 cycles, after correcting for machine friction. For slow cases, it is taken as the calculated average residual interface shear stress ratio for the final two cycles.

Figure 2 presents results of shear stress (uncorrected for machine friction) versus displacement for the clay-sand mixture on the intermediate surface, showing typical cyclic ISB test behaviour comprising an initial peak resistance followed by reducing shear stress with each fast cycle (gray lines), then increasing shear stress for the two slow cycles (black lines). Vertical deformation during

fast shearing (not shown) was generally limited to soil loss but during slow shearing included consolidation.

Table 1. Laboratory testing program.

% fines	Surface material	$D_{50}$ ( $\mu\text{m}$ )	$R_a$ ( $\mu\text{m}$ )	Residual stress ratio, $\tau_{res}/\sigma'_{n0}$	
				Fast	Slow
90	PPL	<1	0.1	0.26	0.33
90	PPL	<1	2.5	0.10	0.23
90	SP	<1	12	0.21	0.44
50	PPL	30	1	0.36	0.30
50	PPL	30	2.5	0.14	0.21
50	SP	30	12	0.40	0.56
0	PPL	205	0.1	0.32	0.39
0	PPL	205	2.5	0.24	0.32
0	SP	205	12	0.54	0.57

Note: PPL = polypropylene, SP = sandpaper, estimated degree of saturation >95% but was not confirmed

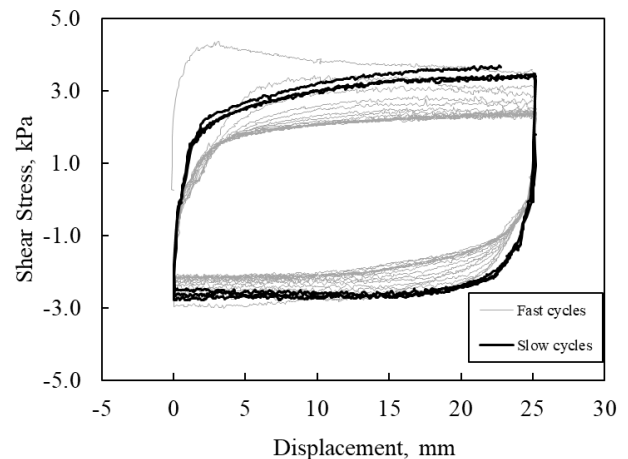


Figure 2. Uncorrected interface shear stress versus cycle number for the clay-sand mix specimen on intermediate interface surface.

Figure 3 presents the corrected residual interface strength ratio (i.e., after subtracting machine friction) through the full twenty cycles for the three soil samples tested on the smooth polypropylene interface.

During fast shearing, the sand specimen generally exhibits the highest residual strength, followed by the clay-sand mix and then the clay specimen. The shear mechanism for sand particles across a smooth surface is sliding. Here, the shear stress increases for the sand specimen during the initial cycles which is likely due to a small increase in roughness from abrasion, given the very low initial roughness of 0.1  $\mu\text{m}$ , with the shearing mechanism transitioning from sliding to include some portion of particle rolling once the surface roughness exceeds the roughness of the particle itself. Given the low stress conditions, plowing is minimized but some element of plowing is

necessary to create the increase in roughness (Shooter and Tabor 1952). For the clay-sand mix and the clay specimens, there is a reduction in undrained stress ratio through cycle 4 and 3, respectively. The increase in shear resistance through the remaining fast shearing cycles for the clay specimen suggests some continuous hardening occurred.

During slow shearing, the sand specimen maintains the highest residual interface strength. While there is scatter in the sand specimen data suggesting there is a reduction in shear strength during slow shearing theoretically there should be no change. The clay specimen demonstrates a higher residual interface strength during slow shearing, as expected. However, the behavior of the clay-sand mix is reversed; the reduction in resistance during slow shearing may be due to a change in the shear mechanism, where only friction (governed by the coarse fraction) influences the resistance rather than friction plus cohesion occurring during fast shearing.

Figure 4 presents the corrected residual interface strength ratio through all twenty cycles for the three soil samples tested on the intermediate polypropylene interface. During fast shearing, the sand specimen exhibits the highest residual strength followed by the clay-sand mix and clay specimens. Again, the sand specimen requires several cycles to achieve a steady residual value, possibly due to some increasing roughness from abrasion. The clay-sand mix and clay specimens again require approximately three to four cycles to achieve their minimum undrained values. Similar to the previous case, the increasing resistance suggests continuous hardening through later fast cycles for the clay specimen.

During slow shearing, the sand specimen shows no effect of drainage, while the clay-sand mix and clay specimens each show higher drained values compared to the undrained minimum values, as expected.

Figure 5 presents the corrected residual interface strength ratio through all twenty cycles for the three soil samples tested on the rough sandpaper interface. During fast shearing, the sand specimen exhibits the highest residual strength, followed by the clay-sand mix and clay specimens, consistent with the polypropylene surfaces. The clay-sand mix and clay specimens now require approximately ten cycles to achieve their minimum undrained values. In this case, there is strong evidence of continuous hardening through later fast cycles for the clay specimen.

During slow shearing, the sand specimen showed no change in resistance, while the clay-sand mix and clay specimens each show higher drained values compared to the undrained minimum values, consistent with the intermediate surface.

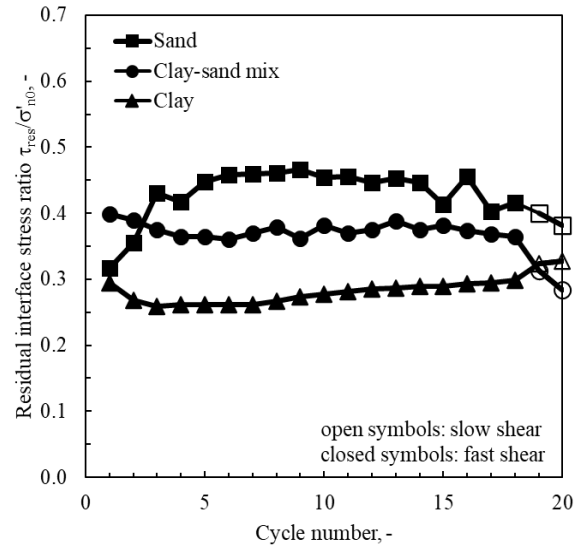


Figure 3. Corrected residual interface strength ratio versus cycle number for the smooth interface surface.

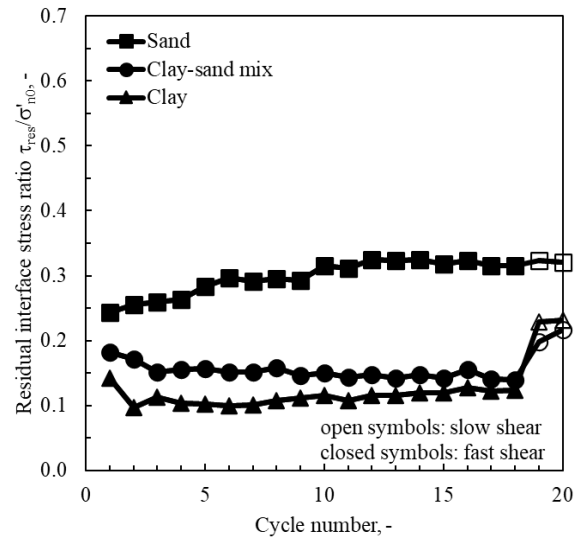


Figure 4. Corrected residual interface strength ratio versus cycle number for the intermediate interface surface.

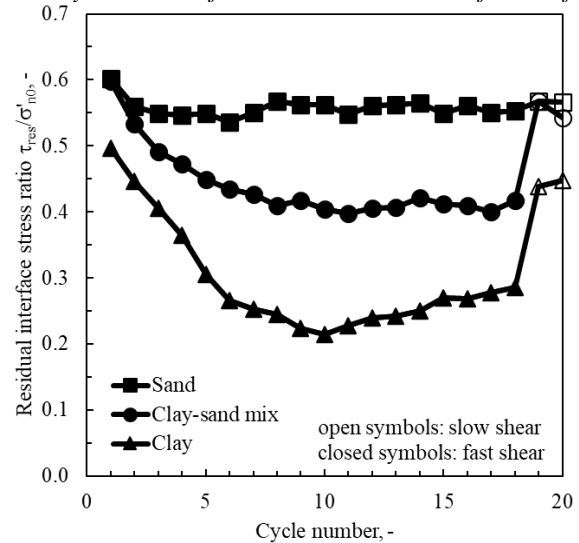


Figure 5. Corrected residual interface strength ratio versus cycle number for the rough interface surface.

Figure 6 illustrates the residual interface strength ratio versus fines content. As expected, the test results indicate a general trend of decreasing residual interface strength ratio with increasing fines content for all interface surfaces for the fast shearing stages. In general, the rough interface resulted in the highest residual interface strength for the soil specimens. The rough interface produces greater mechanical interlocking between the soil particles and the interface surface, increasing the shear resistance through internal shearing within the soil.

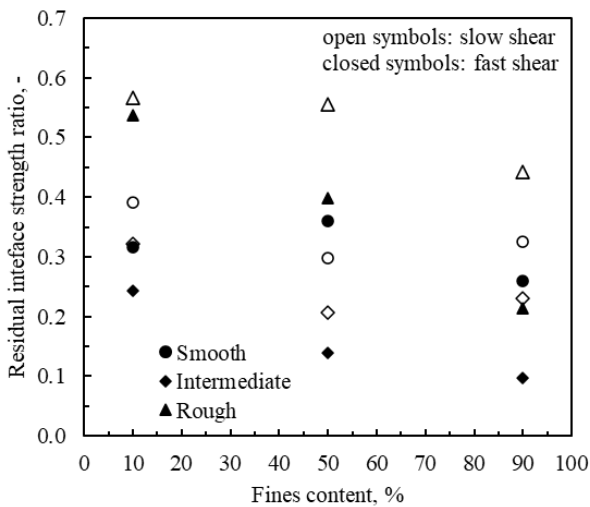


Figure 6. Residual interface strength ratio vs fines content.

The tests performed on the smooth surface showed a higher interface strength than the intermediate surface for both undrained and drained conditions. For the smooth polypropylene interface, the absence of surficial asperities can lead to more uniform normal stress distribution and higher bonding between the soil and the surface, creating a soil-soil failure during fast shearing due to cohesion between the clay particles and the surface, which is absent during slow shearing due to loss of cohesion. The intermediate interface surficial asperities are insufficient to fully interlock with the soil particles, preventing uniform distribution of normal stresses and reducing the bond between the particles and surface. This reduces the shear resistance by developing localized stress and voids along the interface.

#### 4 CONCLUSIONS

This study investigated the residual interface strength of three soil specimens (pure silica sand, clay-sand mix, and natural marine clay) across varying interface surface roughness conditions and shearing rates. Results indicate that for fast shearing, residual

interface strength decreases with increasing fines content, with sand exhibiting the highest strength, followed by the clay-sand mix and natural clay. Surface roughness significantly influenced strength, with the rough interface ( $R_a = 12 \mu\text{m}$ ) producing the highest residual strengths due to mechanical interlocking, while the smooth interface ( $R_a = 0.1 \mu\text{m}$ ) showed higher strength than the intermediate surface ( $R_a = 2.5 \mu\text{m}$ ) potentially due to more uniform stress distribution and stronger bonding between clay particles and the surface.

Cyclic shearing resulted in continuous hardening of clay specimens in later fast cycles, particularly on rougher interface surfaces. The sand specimen on the smooth polypropylene interface required multiple cycles to stabilize, likely due to surface abrasion and a transition from sliding to rolling and plowing mechanisms. Drained shearing consistently produced higher residual strengths compared to undrained conditions, especially for fines-rich soils.

The trends in published datasets mask the limitations of relying solely on generalized interpretations of shear mechanisms, particularly at low to intermediate surface roughness, where the influence of normal stress distribution and bonding is not fully captured. Across all tests, the intermediate roughness consistently exhibited lower undrained and drained strength ratios compared to both smooth and rough surfaces, underscoring the importance of surface characteristics on interface shear behaviour.

While shear mechanisms for sands and clays are often treated distinctly, the findings emphasize the need to account for clays' higher shear resistance at very low roughness and sands' tendency to increase roughness through abrasion during shearing. The choice of undrained strength ratio from the individual ISB tests significantly impacts data interpretation; monotonic tests alone can lead to overestimation of strength ratios for clay and clay-sand mixes and underestimation for sands. Additional shearing cycles, as performed in this study, provide a more accurate representation of undrained strength ratios.

In summary, it is important to fully consider various shearing mechanisms based on soil composition, interface roughness, and soil drainage to plan ISB tests in order to accurately estimate the axial friction factors for PSI analysis.

#### AUTHOR CONTRIBUTION STATEMENT

**Roneet Das:** Conceptualization, Formal Analysis, Writing- Original draft, Visualization. **Zachary Westgate:** Conceptualization, Validation, Writing – Review and Editing, Visualization. **Steve Garmon:**

Data Curation, Investigation, Writing – Review and Editing

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