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Interface friction angles of a marine clay from interface ring shear and interface shear box tests

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ABSTRACT: Most driven pile designs for offshore renewable energy projects in clay rely on the ICP design methods, which are based on interface friction angles. Similarly, pipe-soil interaction studies for offshore oil and gas pipeline projects are based on interface friction angles between seabed and pipeline. These interface friction angles are commonly measured by interface ring shear and interface shear box tests. In this study, a series of comparison test results from Bromhead ring shear and interface shear box tests on a Gulf of Mexico clay are presented. Three surface roughness values, i.e., 0.02, 10, 20 micrometer and two normal stresses, i.e., 5 kPa and 50 kPa are selected to represent driven piles and offshore pipeline materials and design conditions. Overall, the drained residual shear strengths and interface friction angles from the different test methods agreed well, especially when the normal stress was 50 kPa. The measured interface friction angles increased with surface roughness values when the normal stress was 50 kPa. The interface friction angles were high when the normal stress was 5 kPa, compared to the normal stress of 50 kPa case.

Keywords: Interface shear strength; residual strength; interface shear box; pile; pipe-soil interaction

1 INTRODUCTION

For pile design and offshore pipeline engineering, steel-soil or pipe-soil interaction, i.e., interface friction is an important design parameter. Drained residual friction angle (δ_{res}) is usually obtained using the interface ring shear or the interface shear box test (Quinteros et al., 2023). The interface friction angle governs the shear stress that can be mobilized on the shaft of a driven pile (Jardine et al., 2005).

The interface ring shear (or ring shear interface) tests are widely used for driven pile designs and offshore renewable energy projects. In offshore oil and gas pipeline projects, DNV (2021) recommends interface shear box and tilt table tests (Najjar et al., 2007) for pipe-soil interaction studies. It is rare to perform interface shear box tests in the offshore renewable energy industry. Likewise, the interface ring shear tests are rarely implemented in the pipe-soil interaction studies for offshore oil and gas project. The two tests, interface ring shear and interface shear box tests measure principally the same soil property, i.e., drained peak and residual shear strength (or friction angle) with different test conditions. The fast-shear stages in the interface ring shear are to create a fabric on the shearing plane similar to that adjacent to a driven pile, followed by a slow shear to measure drained peak and ultimate friction angles (Jardine et al., 2005). The interface shear box test has a similar fast and slow shear stages to represent thermal cycles of expansion and contraction of pipeline, and axial frictional resistance from the seabed (Westgate et al., 2018). The interface ring shear tests are performed with no less than 50 kPa normal stresses, whereas the interface shear box tests are performed under low normal stresses (lower than 10 kPa) that are relevant to the offshore pipeline-seabed interaction.

It appears that the studies comparing interface ring shear and interface shear box tests on clay materials are very limited. Liu et al. (2021) presented a set of paired interface shear test results from Bishop ring shear device and direct shear device with an inferior interface set-up (interface shear box) on fine sand and chalk. They used a single normal stress level of 200 kPa and three surface roughness ranges, i.e., 1-2 μm, 7-9 μm, and 10-15 μm. They presented different interface friction angles from two test methods on the same material and test conditions.

The test set presented in this paper is a part of ongoing research program that involves performing paired interface ring shear and interface shear box tests on multiple soils from different continents with comparable test conditions, such as interface material roughness and normal stresses. In this paper, a set of paired interface ring shear and interface shear box test results on an offshore marine clay is presented and discussed. Three surface roughness values, nominal roughness of 0.02, 10, and 20 μm, were chosen to cover pile design and offshore pipeline engineering practices. Two normal stresses, i.e., 5 kPa and 50 kPa conditions were selected for comparison.

2 TEST MATERIALS AND METHODS

2.1 Test soil

The test soil was collected from the shallow depth (0.0-1.0 m) of the seabed in an offshore project site in Keathley Canyon, Gulf of Mexico. Water depth of the sampling location was approximately 2027 m. A set of shallow seabed materials along the planned pipeline was collected, manually mixed without changing their initial moisture contents, then cured to constitute a batch sample. After the batch preparation, the soil was stored in an air-tight container until it was used for testing. Basic index properties of the test soil are summarized in Table 1.

Table 1. Index properties of the test soil for interface shear box (ISB) and interface ring shear (IRS) tests.

Property	Value
Natural water content	129.7 %
Fine content (<0.074 mm)	93.9 %
Clay fraction (<0.002 mm)	57.0 %
Silt content	36.9 %
Sand content	6.1 %
D_{50}	1.7 μm
Liquid limit (LL)	110
Plasticity index (PI)	78
Calcium carbonate content	30 %
Unified Soil Classification System	CH

Table 2. Dimensions of the tested specimens for interface shear box (ISB) and interface ring shear (IRS) tests.

Nominal		Specimen height (mm)	
Surface roughness (μm)	Normal stress (kPa)	Interface shear box	Interface ring shear
0.02	5	18.4	5.1
	50	13.7	5.1
10	5	13.7	5.1
	50	16.8	5.1
20	5	11.3	5.1
	50	16.8	5.2

The test specimen sizes for each test are summarized in Table 2. The width of the specimens for interface ring shear apparatus was 15 mm (100.0 mm outer and 70.0 mm inner diameters). The interface shear box device has a top (circular) shear box of 63.4 mm (2.5-inch) inner diameter.

2.2 Interface materials

Three interface materials, shown in Figure 1, were fabricated and used to replicate the potential pile materials and offshore coated pipeline surfaces. These surface roughness values from Polypropylene, Fusion Bonded Epoxy (FBE), and multi-layer coating (3LPE) materials have been used for different offshore pipeline projects. The rough interface material for the interface ring shear is the porous disk that is often used for the conventional torsional ring shear tests. In some offshore pipeline projects, a roughened pipe coating material (R_a=20 μm) is used to improve the pipe-soil interaction and to reduce the pipe-walking load(s) at the end of the pipeline. The surface roughness of the interface materials could be presented in various ways, e.g., R_{max}, however, for simplicity only average surface roughness, R_a values are presented.

- Smooth: nominal R_a = 0.02 μm,
  - Interface ring shear: Polypropylene
  - Interface shear box: Polypropylene
- Medium rough: nominal R_a = 10 μm,
  - Interface ring shear: roughened steel
  - Interface shear box: coating material (FBE)
- Rough: nominal R_a = 20 μm
  - Interface ring shear: bronze, porous
  - Interface shear box: coating material (3LPE)

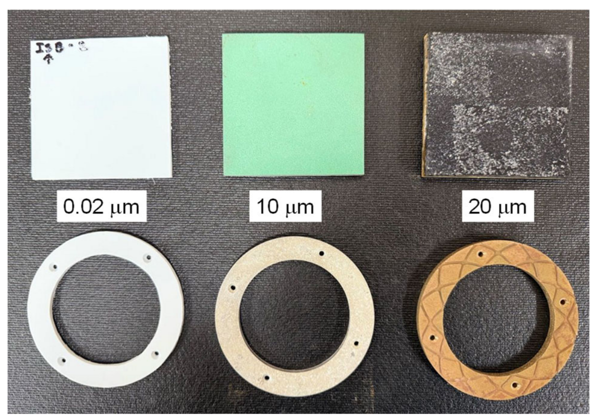

Figure 1. Interface materials for testing program.

Uesugi and Kishida (1986) proposed a critical roughness value, above which the interface fails by soil-soil shearing, rather than soil-interface (Liu et al., 2021). The critical roughness value concept by Uesugi and Kishida (1986) may not be applicable for clay materials or the critical roughness value for clay could be much higher than the original value (0.9) for sand materials, as Liu et al. (2021) implied. Stark (2016) presented a very rough porous disk (R_a=700 μm) for torsional ring shear tests to ensure the failur occurs within the test specimen, not at the interfce. This suggests that the surface roughness values used in this study are low enough that the failure occurs between the soil and the interface materials.

When the interface materials are not porous (Polypropylene and steel), a bottom porous disk (R_a=20 μm) provided drainage during consolidation for the interface ring shear setup. For interface shear box tests, the interface materials are not porous, thus the water was drained through the top porous stone.

Surface roughness of the interface materials were measured by a commercially available surface profilometer, generally following ASTM D4417. The measured average surface roughness (R_a) values of the interface materials before and after the tests are presented in Table 3.

Table 3. Measured average surface roughness (R_a) of interface materials for interface shear box (ISB) and interface ring shear (IRS) tests.

Nominal		**Avg. surface roughness, R_a (μm)**			
Surface roughness R_a (μm)	**Normal stress (kPa)**	**ISB**		**IRS**	
		Before	**After**	**Before**	**After**
0.02	5	0.018	0.020	0.017	0.043
	50	0.018	0.036	0.017	0.111
10	5	9.711	9.418	9.929	9.086
	50	10.43	8.588	10.07	9.929
20	5	-	17.44	-	21.93
	50	17.44	-	22.37	-

2.3 Test methods

The interface shear box tests followed the procedure presented by Westgate et al. (2018) that is commonly used in offshore pipe-soil interaction studies. To mimic the pipelay and pipeline operations, a set of fast shearing to a certain horizonal displacement is followed by a slow shear to measure the drained shear strength.

In the interface shear box tests, a gap between the top half of the shear box and the interface material, approximately 0.5 mm, was created by the gap screws before shear. The gap screws were left in touch with the interface material during the repeated forward and backward shearing so that the gap opening remained the same. Frictions from the testing device itself and the gap screws touching the interface materials were separately measured and corrected, as discussed by Won and Minozzo (2025). In the interface ring shear tests, however, no friction correction was made.

The interface ring shear tests were performed using a Bromhead type device, generally following the ICP method described by Jardine et al. (2005).

In this testing program, two normal stress conditions, i.e., 5 and 50 kPa were applied. The normal stress of 5 kPa is to mimic a typical normal stress for offshore pipeline projects. The normal stress of 50 kPa is the recommended minimum value in the ICP method (Jardine et al., 2005) to reduce the errors associated with friction in the Bromhead and Bishop test devices.

To consolidate the test specimens to 50 kPa, 4 incremental loads were applied in stages. For 5 kPa consolidation stress, a single stage of loading was applied. For comparison with the interface shear box tests, in the interface ring shear tests, the reconsolidation stresses prior to the slow shear were set to 50 kPa.

Table 4. Shear rates for interface shear box (ISB) and interface ring shear (IRS) tests.

Shear rate (mm/min)			
Interface shear box		**Interface ring shear**	
Fast	Slow	Fast	Slow
5.9	0.06	500.0	0.02

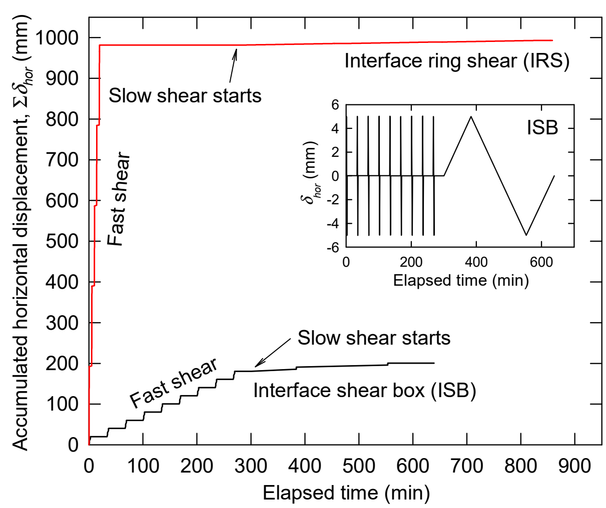

Figure 2. Shear rate comparison between interface shear box and interface ring shear tests (0.02 μm surface roughness and 50 kPa normal stress).

The interface ring shear tests have a substantially faster shear rate (about 85 times faster) than the interface shear box tests for the fast shear, as shown in Figure 2 and Table 4. For the slow shear stage, the interface shear box tests have a shear rate three times faster than the interface ring shear, as tabulated in Table 4. In addition to the difference in shear rates, the total horizontal displacements for the interface ring shear (approximately 1010 mm) were 5 times the horizontal displacements of the interface shear box tests (approximately 200 mm), as shown in Figure 2. As shown in the inset of Figure 2, the horizontal displacements in the interface shear box involved the repeated forward and backward movements. To compare the two test methods, especially for the interface ring shear tests, certain procedures, such as consolidation stages deviated from the ICP method. The test specimens with a high initial moisture content (129.7 %) could have been air dried to limit the vertical displacement less than 15 % during the consolidation stages. However, to compare the test results from two different test methods with the same initial moisture content condition, no air drying was made.

3 RESULTS AND DISCUSSION

In Figure 3 and Figure 4, as an example, accumulated vertical displacements during consolidation and shearing processes are presented for the nominal interface surface roughness of 0.02 μm and normal stress of 50 kPa case.

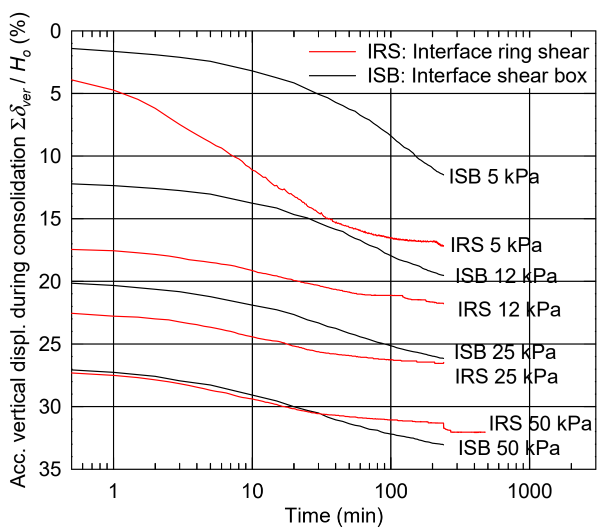

Figure 3. Vertical displacements during consolidation (0.02 μm surface roughness and 50 kPa normal stress).

To be consistent with the interface shear box tests, in the interface ring shear tests, the multi-stage consolidations to 50 kPa proceeded even though the settlement exceeded 15 %. As shown in Figure 3, the vertical displacements of the tested specimen exceeded 15 % at the first stage of consolidation (5 kPa). To achieve the normal stress of 50 kPa, the vertical displacements were allowed to exceed 15 %. During consolidation stages, extruded soils from the test devices were negligible. In the given example, the final vertical settlements during the staged consolidation stages were in general agreement, i.e., 33.1 % and 32.1 % for interface shear box and interface ring shear tests, respectively.

As shown in Figure 4, during the slow shear stage the accumulated vertical displacements during shear from the interface ring shear test (53.0 %) were higher than the ones from the corresponding interface shear box test (46.4 %).

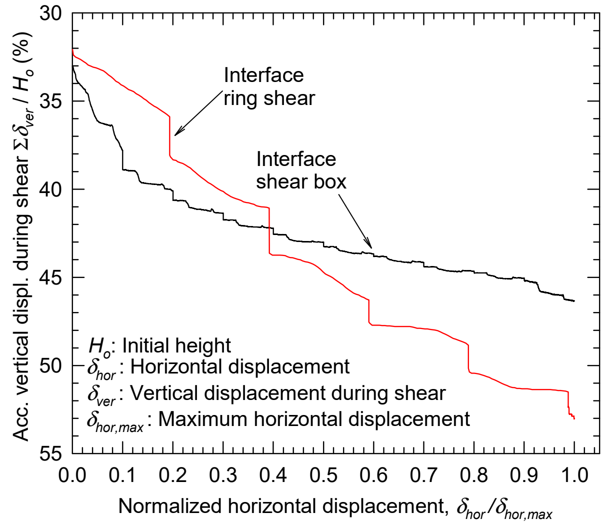

Figure 4. Accumulative vertical displacements during shear (0.02 μm surface roughness and 50 kPa normal stress).

Figure 5. Soil loss from (a) interface shear box and (b) interface ring shear tests (0.02 μm surface roughness and 50 kPa normal stress).

As shown in Figure 5, substantial amounts of soil were lost during the shear stages. In the interface shear box tests, if the gap between the interface material and the top shear box was too big, the shear could occur within the soil, not between the interface material and the soil. On the other hand, without the gap screws' support during the repeated shear, the top shear box would move downwards making a contact with the interface material due to the loss of soil, thus the results would be erroneous (Won and Minozzo, 2025). A few repeated tests with different gap sizes confirmed the gap size (approximately 0.5 mm) used in the interface shear box tests was appropriate.

In the interface ring shear tests, according to Stark and Eid (1993), the magnitude of wall friction increases with the depth of the specimen, thus the plane of least wall friction occurs at or near the soil-interface material. Excessive settlements (more than 15 %) would result in a failure plane occurring at or near the soil-interface material. Contrary to the conventional torsional ring shear, a failure plane at the soil-interface material due to the excessive settlement is desirable for the interface ring shear tests. The gap between the interface materials and the ring were 0.3, 0.03, and 0.06 mm for the interface materials with surface roughness value of 0.02, 10, and 20 µm, respectively. The shear between the interface and soil was confirmed by visual observations after the take-down. The soil specimens within the ring shear apparatus showed no indication of shear within the test specimens, whereas the interface shear materials and the contact area of the soil exhibited shear tracks or striations, as shown in Figure 6, as an example.

Figure 6. Example of shear tracks and striations from interface ring shear test (10 µm surface roughness and 5 kPa normal stress).

The measured shear strength values from the fast shear stages are presented in Figure 7. In order to compare the shear strengths over the entire shearing process, the horizontal displacements (δ_{hor}) from the interface shear box and interface ring shear tests were normalized by their maximum horizontal displacements ($\delta_{hor,max}$). In Figure 7, the maximum horizontal displacements were 200.6 mm and 993.5 mm for the interface shear box and the interface ring shear tests, respectively. Sharp peaks and zero values are from either changes in shear directions in interface shear box or initiations of shear after consolidation and wait time between the fast shears in interface ring shear tests. A little attention has been paid to the shear characteristics and peak values from the fast shear stages even though these fast stages were to mimic the pile driving or thermal cycles of offshore pipelines. After the peak, at fast shear stages, the decayed shear strengths from the interface ring shear test showed lower shear strengths than ones from the interface shear box tests.

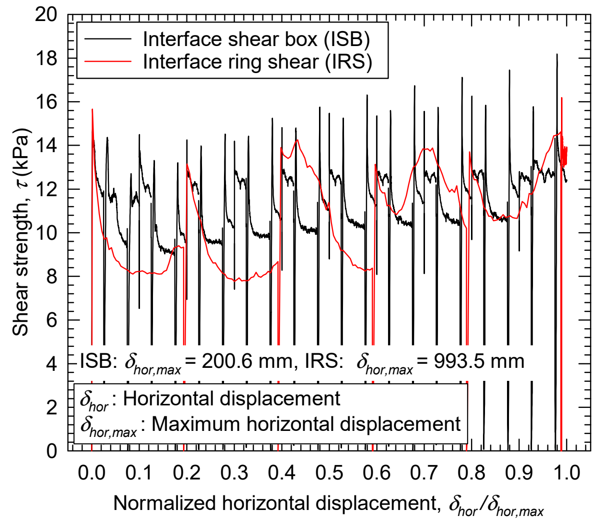

Figure 7. Shear strength profiles at fast shear from interface shear box and interface ring shear tests (0.02 µm surface roughness and 50 kPa normal stress).

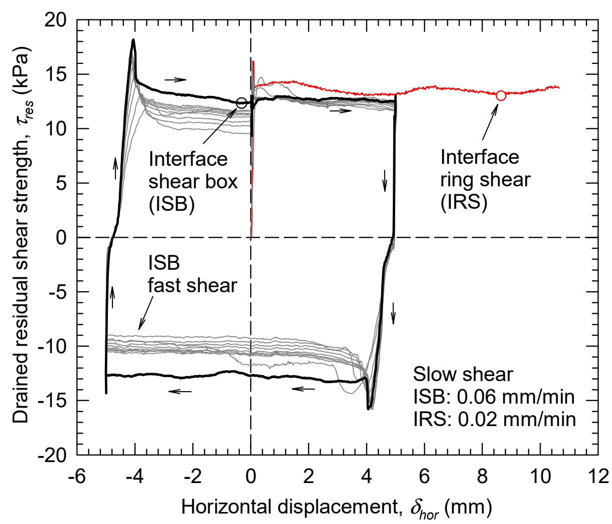

Figure 8. Drained residual shear strengths from interface shear box and interface ring shear tests (0.02 µm surface roughness and 50 kPa normal stress).

An example of failure point selections from the slow shear stages are presented in Figure 8. In this study, we chose the lowest shear strength at a large deformation during the slow shear as the drained residual shear strengh (τ_{res}). These values are not neccessarily at the end of the test data or exceeding 10 mm horizontal displacement for the interface ring shear tests. The large deformation for the drained residual shear strength selection in this paper is at the last shear stage for interface shear box test and more than 8 mm horizontal displacement for interface ring shear. Only ultimate friction angle (δ_{res}) or drained residual shear strengths (τ_{res}) are discussed in this paper. The drained residual shear strengths (τ_{res}) and interface friction angles (δ_{res}) from the interface shear box and interface ring shear tests are summarized in Table 5.

Table 5. Drained residual shear strengths and interface friction angles from interface shear box (ISB) and interface ring shear (IRS) tests.

Nominal		Interface shear strength (kPa)		Interface friction angle (deg.)	
Surface roughness (μm)	Normal stress (kPa)	ISB	IRS	ISB	IRS
0.02	5	5.0	3.6	46.0	40.3
	50	12.3	13.0	14.0	14.7
10	5	4.5	4.4	41.3	45.6
	50	26.3	21.7	27.7	23.6
20	5	4.5	5.4	42.6	51.5
	50	24.0	24.7	25.6	26.7

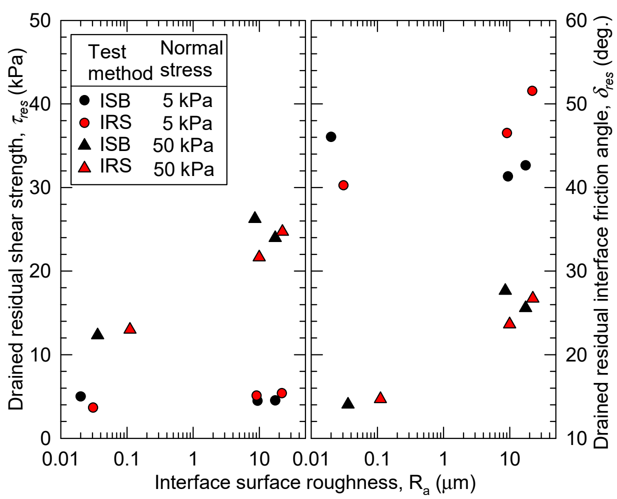

Figure 9. Drained residual shear strengths and friction angles from interface shear box (ISB) and interface ring shear (IRS) tests.

As shown in Figure 9 and Table 5, the drained residual shear strengths (τ_{res}) from the interface shear box and interface ring shear tests are quite comparable for both normal stresses. However, when the test results are presented in interface friction angles (δ_{res}), the difference between the two methods become noticeable, especially when the normal stress is 5 kPa. At 5 kPa normal stress, a small variation either in the normal stress (σ_n) or shear strength would result in a substantial difference in the strength ratio (τ_{res}/σ_n), in turn the friction angle value, i.e., 4.3-8.9 degrees difference between the two methods. As mentioned earlier, the system friction from the interface shear box tests was measured and corrected. The system friction from the interface ring shear tests, however, was not measured and corrected. This uncorrected system friction may have contributed to the difference.

Some interface materials had scratches after the test(s), indicating the actual surface roughness during the shear may not be the same as the initial value, thus the surface roughness values in Figure 9 represent after testing (see Table 3).

Ramey et al. (1998) presented ultimate interface friction angles with plasticity values for clay materials. Compared to the group of ultimate interface friction angle (δ_{ult}) reported by Ramsey et al. (1998), the test material (PI=78) is out of the plasticity index range. The interface friction angles with 10 μm surface roughness and 50 kPa normal stress from this study (23.6-27.7 degrees) are close to the upper bound by Ramsey et al. (1998), and higher than the best fit curve presented by Jardine et al. (2005).

While comparing Bishop and Bromhead type ring shear test apparatus, Ramsey et al. (1998) listed factors that affect the interface friction angles measured in laboratory tests. The factors included the soil grading, mineral composition, interface material, interface roughness, and previous shearing history. Quinteros et al. (2017) pointed out that the interface residual friction angle (δ_{res}) of marine sand could be stress dependent when the vertical effective stresses are less than 50 kPa and δ_{res} is affected by the roughness of the chosen steel interface.

From Figure 9, even though the test points are limited, it is apparent that the interface friction angles depend on the surface roughness and normal stress. For sand materials, Han et al. (2018) and Uesugi and Kishida (1986) reported that the interface friction angles increased with increasing surface roughness of the interface material. From this study on an offshore clay material, the interface friction angles increase with the surface roughness for 50 kPa normal stress. When the surface roughness value was 0.02 μm, the interface friction angles at 50 kPa normal stress were as low as 14 degrees.

Pedersen et al. (2003) reported very high, approaching 60 degrees, interface (secant) friction angles at very low effective stresses, i.e., 10 kPa or 0.01 kPa due to the curved failure envelopes that pass through the origin, based on the thin-specimen direct shear (interface shear box) on kaolinite. At 5 kPa which is very low in the conventional interface ring shear test range, both test methods yielded very high interface friction angles (δ_{res} = 40.3-51.5 degrees) than 50 kPa cases. At 5 kPa normal stress condition, based on the limited number of test points, the surface roughness of the interface material seems to have little effects on the interface friction angle (δ_{res}).

4 CONCLUSIONS

Interface friction angles from a Gulf of Mexico clay with three interface materials were measured using Bromhead ring shear and interface shear box test devices. Three surface roughness conditions, i.e., 0.02, 10, and 20 µm were created. A typical normal stress for offshore pipeline project (5 kPa) and the recommended minimum normal stress from the ICP method (50 kPa) were applied. The measured interface friction angles were 40.3-51.5 and 14.0-27.7 degrees under 5 kPa and 50 kPa normal stresses, respectively. With the limited test data points, it is apparent that the interface friction angles under 5 kPa normal stress were significantly higher than the ones under 50 kPa. Under 50 kPa normal stress, the interface friction angle increased with the surface roughness of the interface material. For 5 kPa normal stress, the effects of the surface roughness of the interface materials appears to be insignificant. The interface friction angles from both test methods agree well when the normal stress was 50 kPa. However, when the normal stress was 5 kPa, partly due to variations in normal stress, the difference between the test methods becomes noticeable.

AUTHOR CONTRIBUTION STATEMENT

J.Y. Won: Project Administration, Conceptualization, Supervision, Methodology, Formal Analysis, Visualization, Data Curation, Writing – Original Draft. **M. Minozzo**: Supervision, Visualization, Data Curation, Writing – Review & Editing.

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