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Interface Testing of North Sea Bedrock for Offshore Wind Applications

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ABSTRACT: Several North Sea sites exhibit potential for offshore wind development, but geological conditions at some locations pose challenges for the design and installation of pile foundations (monopiles or jackets). These foundations are influenced by complex load conditions, with shear behaviour at the soil-structure interface being particularly important, considering that shaft friction contributes significantly to foundation stiffness and load capacity. This paper presents an experimental study on the shear resistance of rock-steel interfaces, aimed at informing offshore pile design. Tests were conducted on weak sedimentary rocks (primarily mudstones) from the UK sector of the North Sea, whereas the steel interfaces were prepared with roughness typical of offshore piles. Direct shear tests were performed under varying normal stress levels, utilising a purposely modified computer controlled apparatus. A parametric study examined the effects of the normal boundary conditions, consolidation period and shearing rate on interface behaviour.

Keywords: Interface testing, rock-steel, direct shear, CNL, CNS

1 INTRODUCTION

Numerous sites around the North Sea have potential for development as offshore wind projects; however, geological conditions at some sites can pose significant challenges to the design and deployment of wind turbine support structures, commonly pile foundations (monopile or piled jacket concepts). Such foundations are subject to complex load conditions and the shearing behaviour of the soil-structure interface is important, particularly where the shaft friction is a significant component of the overall foundation stiffness or load capacity. Across various development areas in the UK Sector of the North Sea (and at numerous other offshore areas in northern Europe and beyond) sedimentary (very weak) bedrock may be encountered within the typical penetration depth of pile configurations relevant to offshore wind applications, impacting the estimated capacity, performance and installation feasibility of pile foundations.

The shearing behaviour of the pile-soil or pile-rock interface is commonly described in practice by the interface friction angle δ and the adoption of representative values obtained through location specific laboratory interface testing is recommended during the design stage of offshore piles (Jardine et al., 2005).

Numerous studies have been performed through the years to investigate the shearing behaviour of soil-steel interfaces. In most cases, configurations of the direct shear, the simple shear and the ring shear apparatus have been utilised (Potyondy 1961, Kishida and Uesugi, 1987, Jardine et al., 1993, Abuel-Naga et al., 2018) and have resulted in the determination of relevant δ values for various soil-steel interfaces, as well as the identification of a number of controlling parameters, such as the roughness and hardness of the steel interface, sand particle size (D_{50}) and clay plasticity, among others.

On the other hand, there is relatively limited information available on the behaviour of rock-steel interfaces for concepts relevant to offshore renewable applications (Ziogos et al., 2021). A significant part of the available literature also focuses specifically on application to chalk (Ziogos et al., 2017, Chan et al., 2019).

This paper presents an experimental program carried out to establish a better understanding of the shear resistance of rock-steel interfaces from very weak North Sea sedimentary bedrock. A parametric study was carried out for a number of test conditions to allow an evaluation of test parameters influencing the interface behaviour. Insights on the test selection and specification as well as the specimen preparation activities aiming to inform the design process of offshore piles are also provided.

2 LABORATORY TESTING

2.1 Test program

Both monotonic and cyclic (reversal) direct shear rock-steel interface tests were performed on very weak rock samples from the Smith Bank formation as sampled from an offshore wind farm development area in the North Sea. The samples were primarily mudstone or mudstone with interlaminations of siltstone, with only small variations in stiffness and strength anticipated between the two rock types based on associated laboratory measurements. The unconfined compressive strength (UCS) of the samples tested typically varied within the range 0.5 to 2.0 MPa.

A modified direct shear apparatus was utilised for the testing, where the rock specimen was displaced horizontally against a specially prepared steel interface under a specified normal load. A lengthways oversized interface was used, to ensure that the effective area remained unchanged throughout the test.

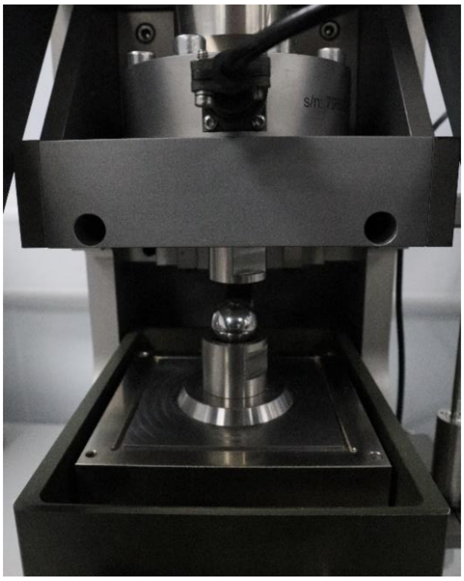


Figure 2-1. Modified direct shear apparatus

2.2 Specimen preparation

Intact rock specimens were used for the tests. Although using power tools (e.g. corer, electric saw etc) is quite common in rock specimen preparation, in this case hand trimming was typically preferred for most of the tested samples, due to the very weak classification of the rock and the friable nature of the samples. The target density of the natural test specimens could not be controlled in any practical way but was representative of the sample rock mass.

Rock specimens were trimmed to an average diameter which was marginally smaller than the diameter of the sample carriage in the modified direct shear apparatus (63.5 mm). This was done to promote minimal shear stress development on the specimen carriage walls and thereby ensure full transfer of normal stress to the rock-steel interface. The specimen carriage was designed to incorporate a small recess in the lower specimen carriage, creating a rock-interface “window” that prevents interference of the carriage material on the test surface. The rock specimen was mounted on top of the steel interface and the normal stress was applied to the upper surface of the specimen.

A S355 mild steel interface plate with a centreline average roughness of 10 ± 2 μm was used for each test, as this roughness value is considered representative for offshore pile applications (Jardine et al., 2005). The roughness of the plate was measured at several positions before and after the test. Generally, minimal degradation of interface roughness was observed during the tests, which is not unexpected, considering the strength and the hardness of the rock specimens, which in most cases could be scratched with a fingernail, indicating a Mohs hardness value < 2.5.

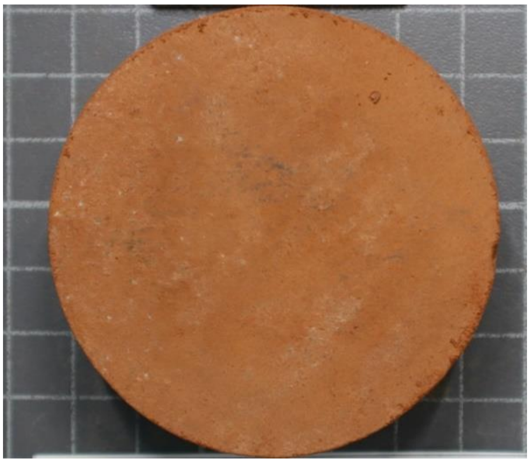


Figure 2-2. Image of a typical test specimen

2.3 Test procedure

The test procedure followed represents a general execution of the Imperial College Pile (ICP) ring shear test methodology (Jardine et al., 2005), modified for adoption with the direct shear apparatus.

Each direct shear interface test included two test sequences of consolidation and shearing. The first sequence involved consolidation under a normal stress equal to the estimated in situ horizontal effective stress. At this stress condition the specimen was subject to “fast” shearing reversals designed to establish a residual state condition of approximately constant shear stress on subsequent reversals, which intended to represent the effect of the pile driving process at the rock-steel interface. This representation is a simplification of the mechanisms developing at the pile-rock interface for a pile driven into a constrained rock mass, where more extensive remoulding may occur, however was considered to be sufficient for a laboratory-scale evaluation of the interface shear characteristics.

The testing program determined that around five fast reversals were sufficient for the purpose of establishing a residual state condition. The fast shear reversals were performed between +10 mm and -3 mm at a target displacement rate of 10 mm/min (maximum achievable by the apparatus) under a constant normal load (CNL) condition. The reversal displacement was limited to -3 mm since trial testing indicated that higher reversal displacements (up to -10 mm) could lead to larger settlement of the specimen which was expected to have a negative influence the quality of the results. The increase in settlement at large reversal displacement was attributed to loss of specimen integrity during large amplitude reversal from a 'pre-contacted' to 'fresh' interface condition.

Once the fast shearing reversals were completed, the specimen was consolidated under a normal stress equal to an estimated radial effective stress adjacent to the pile shaft post pile driving installation which varied with sample depth.

Following consolidation, a "slow" shearing stage under CNL conditions was performed for the monotonic tests; at a rate of 0.5 mm/min up to a target displacement of 10 mm.

For the cyclic tests, a cyclic stage was performed instead of the slow shear stage, comprising one-way load reversals at a constant displacement amplitude at a rate of 0.5 mm/min. Results from monotonic test performed on the same (or if unavailable, on neighbouring samples) were used as reference for the selection of the displacement amplitude to give a desired interface strength mobilisation (typically ranging between 50 and 80 %). Between 100 and 300 cycles of constant amplitude loading were applied depending on the target mobilistation. After the cyclic stage was finished, a short rest period was applied, followed by slow shearing in the same manner as for the monotonic test.

A number of parametric tests varying the normal constraint conditions and shearing rate of the slow shear stage, and duration of the 2nd consolidation stage were performed at the outset of the test program to evaluate their influence, and inform the scheduling and execution of the following tests.

3 TEST RESULTS

3.1 Overview

The majority of the tests exhibited ultimate interface friction angles between 20^o and 25^o, however, values up to 32^o were observed. This could be attributed to the high degree of variation of the sample characteristics within and across the cores used for testing, particularly variation of the particle grading; specimens with a finer particle grading typically exhibiting lower steel interface friction angles

A degree of degradation of many of the specimens was indicated from post-test photographs. This was anticipated (considering the rock characteristics and the testing procedures employed) and is in line with previous research findings (Ziogos et al., 2017).

Figure 3-1. Specimen condition at the end of the test

Degradation was more noticeable at the edges of the specimen that are in line with the direction of shearing. This is consistent with an expected high degree of nonuniformity in the stress state at the specimen-interface during shearing associated with the non-infinite stiffness in the normal axis of the apparatus. Nevertheless, the global shear stress values (and hence the associated interface friction angles) interpreted from the test measurements were expected to be representative for cautious design application.

3.2 Monotonic tests

An example result from a series of fast shearing reversals is shown in Figure 3-2. During the initial reversal runs, a peak shear stress was usually observed which drops with increasing shear displacement within each run. The peak and the high displacement shear stresses tend to reduce between each reversal, until a stable condition is reached where little change is noticed between successive reversals.

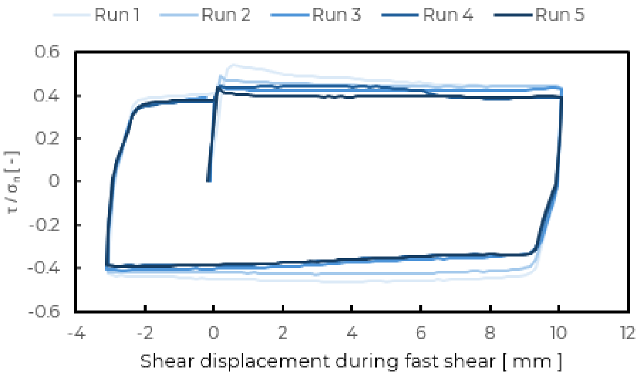


Figure 3-2. Example result of fast shearing reversals

Depending on the applied normal stress, and the specimen characteristics (e.g. strength, presence of laminations), significant settlement was sometimes observed to occur during the fast shearing reversals, leading to material being trapped between the specimen carriage and the interface which adversely affected the measured shear stress. Therefore, some fast shearing stages were stopped if significant settlement was noticed. Drainage conditions could not be confidently assessed during fast shearing stages to the rates of loading applied. However, the measurement could provide an indication about the undrained (or constant normal stiffness) interface resistance during pile driving and the uniformity of the interface condition (Jardine et al., 2005).

As shown in Figure 3-3, a typical response from a slow shearing stage exhibits little or no peak shear stress and only minor change occurs with increasing shear displacement, until the ultimate value is reached. This is consistent with development of an ultimate condition during the preceding fast shear stage.

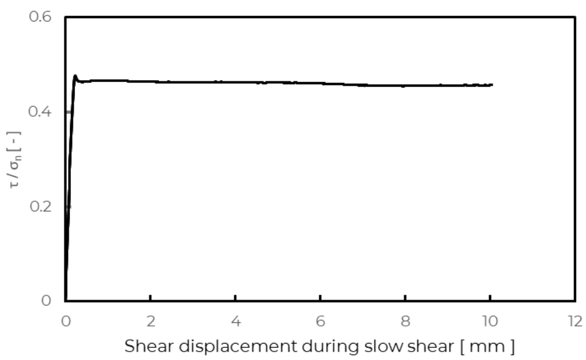
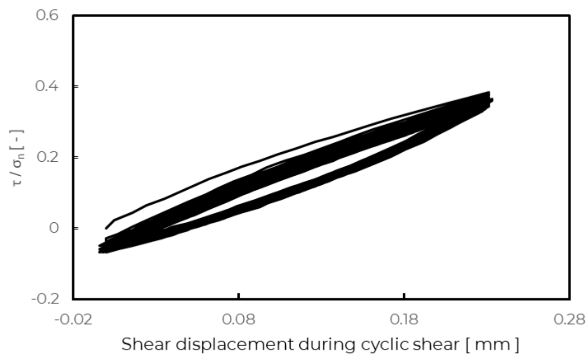


Figure 3-3. Example result of slow shearing stage

Tests where high variation in measured shear stress is observed during slow shearing were considered to have been strongly affected by unrepresentative lodgement or accumulation of material at the specimen carriage edge during fast shearing.

3.3 Cyclic (reversal) tests

Cyclic (reversal) interface direct shear tests were performed to investigate the degradation response of the interface, within the limitations of the direct shear apparatus. Comparison of each cyclic (reversal) test result with the companion reference monotonic test performed on portion of the same (or neighbouring with similar characteristics) sample allowed some general observations to be made on the likely impact of cyclic loading on the interface adjacent to the pile, for the purpose of pile design assessments.



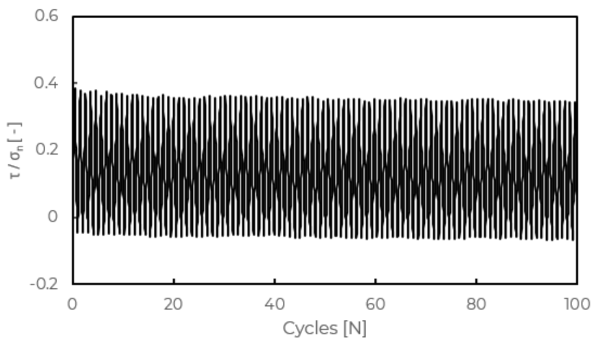


Figure 3-4. Example cyclic degradation response result at 60 % interface strength mobilisation

Limited degradation was typically observed across various cyclic tests, as illustrated in the example result in Figure 3-4. This may be related to the likelihood that residual condition has been reached during the fast shear stages and that no further deterioration of this condition occurs during cyclic loading i.e. that any influencing factors such as changes in stress state or further remoulding or damage of the weak rock are not manifesting further under high-cycle loading, once the residual interface condition is established.

3.4 Parametric testing

3.4.1 Variant testing

The applied test procedures carry a degree of novelty, in the sense that they are not yet considered standard practice across the industry for application to bedrock specimens. Therefore, a number of variant monotonic tests were performed where test stages were varied to investigate the potential impact on the test outcomes. Similar test specimens sourced from the same core sample were used for these tests, to reduce the effect of potential natural variation of the rock mass. Variations on normal boundary conditions of the slow shear stage, duration of 2nd consolidation stage and, slow shearing rate were applied.

3.4.2 Boundary condition

Interface tests are mostly performed under CNL conditions, where the soil/rock-steel interface is free to dilate or contract, i.e. zero normal stiffness (Du et al., 2021, Kishida and Uesugi, 1987). However, there has been considerable development of testing systems in which tests can be performed under Constant Normal Stiffness (CNS) conditions (Zhang et al. 2020, Stavropoulou et al. 2019). In this condition the volume change at the interface is controlled by a given stiffness value (kPa/mm), simulating the confinement provided at the pile- rock interface in the field, thus potentially imposing a more representative loading condition (if a reliable stiffness can be defined).

Three slow shearing stages were performed across tests with varying normal boundary conditions to investigate the effect on the measured shear response. Upon completion of the 2nd consolidation stage CNL, CNS and constant volume (CV) shear stages were performed. The additional shearing stages were performed at the same shear rate of 0.5 mm/min to the same target displacement of 10 mm. A stiffness of 1500 kPa/mm was adopted during the CNS stage based on the anticipated UCS of the sample tested.

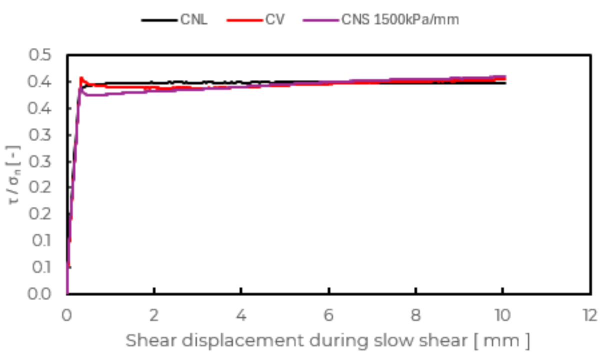


Figure 3-5. Response under varying boundary conditions

Very little variation in the interpreted peak and residual friction angles was observed between boundary conditions, with each test giving remarkably similar residual states. This can be explained by the limited tendency of dilation (or contraction) of the interface, given the planar characteristics of the rock specimen and the steel interface. It is expected that that the impact of boundary conditions would be more significant with increasing roughness of the interface, as has been previously observed for cement-rock interface testing (Stavropoulou et al. 2019).

3.4.3 Consolidation duration

The 2nd consolidation stage of the tests (i.e. prior to slow shear) was typically held until significant volume change had ceased to occur, generally ~1-2 hours. However, to investigate the potential effect of a prolonged consolidation stage (which could potentially lead to the development of bond/adhesion on the interface) a variation test was conducted where a ~16 hour consolidation period was applied prior to slow shear. As shown in Figure 3-6, no significant difference was noticed on the measured response between the two test cases.

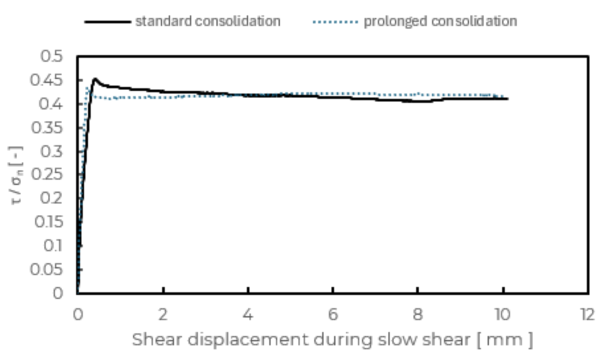


Figure 3-6. Response after varying duration of consolidation

3.4.4 Rate of shearing

A shear rate of 0.5 mm/min was typically adopted for the slow shearing stages as it was considered appropriate for the rock types tested. In two cases, additional variation tests at a slow shearing rate of 0.05 mm/min were performed to investigate potential on the overall shear response. As indicated in Figure 3-7, indiscernible to relative limited difference was noticed on the measured shear stress between the two cases.

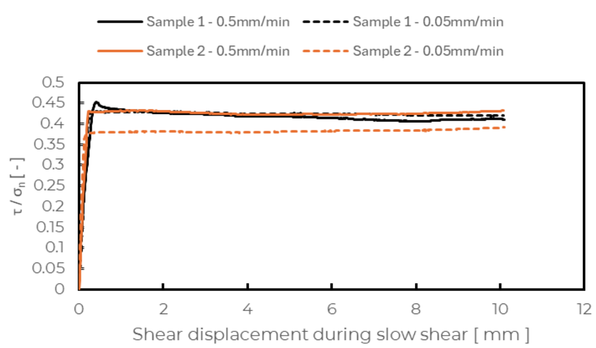


Figure 3-7. Response at varying shearing rate

4 CONCLUSIONS

A range of steel interface shear tests on weak rock samples were performed to provide measurements of interface resistance. An overview of the testing performed and selected results are presented here for discussion. The interface testing performed allowed an insight into the interface shear characteristics of the weak rock specimens which provided direct input to offshore pile design evaluations, reducing the uncertainty which would otherwise have surrounded the selection of appropriate values for design.

The approaches adopted for the interface shear tests can be considered as a development in laboratory testing of weak rock samples collected offshore. The tests indicated that:

- For the mudstone samples tested, the interface friction angle was typically in the range 20° to 25°, varying primarily with particle grading of the rock specimens;
- The applied shearing boundary condition (CNL, CNS, CV) had no significant impact on measured residual stresses and interpreted interface friction angle for the steel interface tested;
- Variation of consolidation duration in the range 1 – 16 hours (i.e. secondary consolidation effects) did not have a discernible influence on subsequent interface shearing characteristics.
- Variation of slow shear rate 0.5 – 0.05 mm/min indicated unnoticeable to limited influence on the measured shear response.

Further testing is recommended to ratify the above conclusions and expand the overall dataset and allow a more detailed interpretation of trends with rock-type and rock characteristics.

AUTHOR CONTRIBUTION STATEMENT

First Author: Data curation, analysis, writing-draft. **Other Authors**.: Supervision, analysis. reviewing and editing.

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