Etude expérimentale du comportement en cisaillement d'interfaces roche-coulis pour les fondations offshore

Characterizing the shear behaviour of rock-grout interfaces for offshore foundations - a laboratory experimental study

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RESUME : La compréhension du comportement des interfaces roche-coulis vis-à-vis du cisaillement représente un enjeu majeur dans la conception des pieux ancrés dans le rocher, particulièrement pour estimer le transfert des charges axiales. Pour un projet d'éoliennes offshore en Irlande, une campagne expérimentale d'essais de cisaillement à rigidité normale contrôlée (CNS) a été réalisée pour caractériser le comportement d'interfaces roche-coulis. Un coulis à très haute résistance, typique des réalisations offshore, a été coulé sur trois types de roches : une marne, un grès et un schiste.

Les conditions in-situ ont été reproduites de manière aussi fidèle que possible, notamment en conférant aux échantillons de roche une rugosité de surface répliquant les profils typiques observés après forage. Le programme d'essais comprend à la fois des essais de cisaillement monotones et cycliques, pour caractériser la résistance aux cisaillement et la dégradation de l'interface au cours des cycles, pilotés en déplacement. Les valeurs de la rigidité normale d'interface ont été estimées à partir des données géotechniques de terrain et de corrélations éprouvées. Dans cette communication sont présentés la méthodologie de préparation des échantillons, notamment la géométrie de la rugosité, l'équipement utilisé, ainsi que les résultats des essais qui apportent des informations utiles à l'ingénieur pour un dimensionnement préliminaire plus pertinent des monopieux d'éoliennes offshore ancrés dans le rocher.

ABSTRACT: Understanding the shear behaviour of rock-grout interfaces is a critical aspect in the design of piles socketed into rock, particularly for axial load transfer assessments. For a planned wind farm development offshore of Ireland, an experimental campaign of Constant Normal Stiffness (CNS) tests was conducted to characterize the shear behaviour of the rock-grout interface. This study utilised an ultra-high-strength grout, typical for offshore rock socket applications, considering three rock types: mudstone, sandstone and siltstone described from site investigation.

The CNS tests were performed to accurately as possible replicate in-situ conditions, the rock samples were prepared with a surface roughness mimicking that of typical post-drilling traces. The testing program included both monotonic and cyclic loading conditions to assess the shear resistance and degradation of the interface under different displacement conditions. The constant normal stiffness values were derived from site-specific geotechnical data and applying relevant correlations. The CNS test results provide valuable insights into the rock-grout interface behaviour directly relevant to the design of monopiles socketed into rock. A detailed methodology for sample preparation is outlined, including the geometry of the surface roughness, offering a practical framework for preparing and executing future CNS testing campaigns. The testing performed aims to contribute to more robust and informed preliminary design considerations for design of offshore monopile foundations in rock.

Keywords: Rock - grout interface; Shear resistance; Constant Normal Stiffness; Monopile; Offshore foundations.

1 INTRODUCTION

Monopiles are increasingly being installed at locations where hard ground such as rock will be encountered. At these locations, monopiles will be installed through the drill and grouted methodology. Hence, it is important to characterise the interface behaviour between the rock, grout and pile. This paper will focus on the interface behaviour between the rock and grout as the interface between the pile and grout is assumed to be higher and enhanced through shear keys. Constant Normal Stiffness (CNS) tests were conducted to characterize the shear behaviour of the rock-grout interface from a recent geotechnical site investigation campaign performed offshore, Ireland.

As indicated by (Johnston et al. 1987; Ooi & Carter 1987 ; Muralha et al. 2014; and Stavropoulou et al. 2021) CNS conditions more appropriately represents engineering applications in which the materials interface is constrained by the surrounding environment, such as the case of rock-groutF interface of drilled and grouted piles. In this scenario, any dilation or contraction occurring during shearing causes the normal stress to vary.

While the aforementioned references, provide guidelines and recommendations for executing CNS testing, the intention of this paper is to apply and expand upon these concepts by providing practical guidance into the planning, execution and example results of a CNS testing campaign within the context of an offshore wind project.

This study specifically assesses three rock types encountered at the offshore site investigation (mudstone, sandstone and siltstone). Furthermore, rock samples were prepared with a surface roughness designed to mimic post-drilling rock roughness. A representative high strength grout material typically used for offshore applications was considered.

The results of the testing campaign aim to contribute to more robust and informed preliminary design considerations for offshore monopile foundations in rock, specifically regarding the shear resistance of the rock-grout interface. This paper also details the practical challenges and lessons learned encountered when using a standard rock shear box for this testing methodology.

2 ROCK CHARACTERIZATION AND PARAMETERS

In the offshore site investigation campaign, rock cores were extracted from five borehole locations within the wind farm area. Water depth in the area ranges between 40 to 50 m. The rock cores were retrieved using the Geobor-S rock coring system, which yields good quality intact rock core samples with a 100 mm diameter. Three distinct rock types were characterized; mudstone, sandstone, and siltstone. The predominant rock type in the area was Mudstone, representing 65% of the recovered material, followed by Sandstone and Siltstone, accounting for 22% and 13%, respectively.

The boreholes were also accompanied by Borehole geophysical logging (BGL) performed using a suite of wireline operated tools: calliper, natural gamma radiation, P and S suspension logger (PSSL), and acoustic borehole imaging tools.

Rock core classification and testing was performed both offshore and in onshore laboratories by means of standard rock classification and strength testing procedures. The following chapters present the relevant parameters required to characterize the rock for CNS testing purposes.

2.1 Rock Characterization

Rock was encountered at depths ranging from 28.0 m to 51.0 m BSF. Figure 1 shows examples of recovered rock cores. The results of rock mass classification parameters determined from offshore and laboratory include Rock Quality Designation (RQD), Rock Mass Rating (RMR), and Geological Strength Index (GSI) the mean values are presented in Table 1.

Table 1. RQD, RMR, GSI

Rock Type	No. of Measurements	Mean RQD [-]	Mean RMR [-]	Mean GSI [-]
Mudstone	20	95	73	76
Sandstone	17	80	62	65
Siltstone	11	75	58	62

2.2 Strength Parameters

The rock strength is derived principally from 15 uniaxial compressive strength (UCS) and correlated from 211 Point Load tests (PLT). Table 2 summarises the UCS tests for each rock type.

Table 2. Uniaxial compressive strength (UCS) test results

Rock Type	No. of Tests	Min. UCS [MPa]	Max. UCS [MPa]	Mean UCS [MPa]
Mudstone	12	5.2	46.8	21.3
Sandstone	3	0.8	34.6	15.7

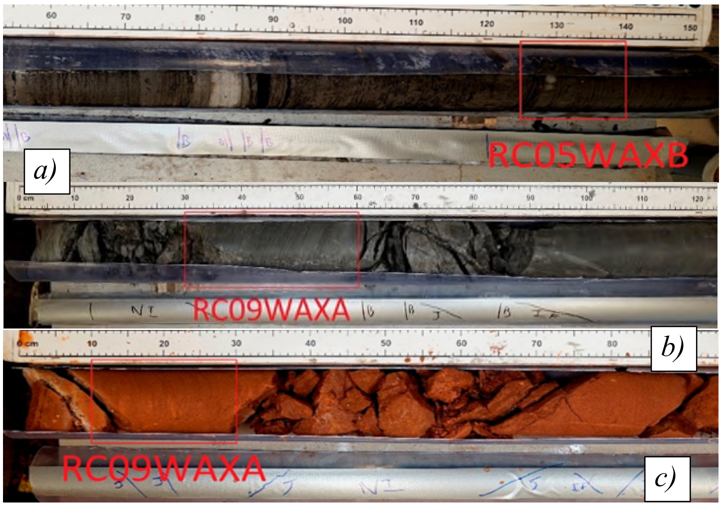

Figure 1. Typical rock cores a) Mudstone, b) Siltstone, c) Sandstone.

Considering the range of the strength values, the mudstone and sandstone could be classified as weak to medium strong and extremely weak to medium strong rocks respectively according to (ISO 14689, 2017). UCS were not performed on Siltstone as it disaggregated during sample preparation activities and there were limited number of samples. Instead, Siltstone UCS was inferred from PLT results. PLT (I_{s50}) results lie in the same range as Mudstone and Sandstone (I_{s50}) and hence a similar factor (k=12) is applied, resulting in values of 1.6 MPa to 46 MPa with a mean of 8.3 MPa indicating a very weak to moderately weak strength.

The strength results are primarily used to inform the range of rock strengths and to estimate the rock shear modulus (G_m) according to the correlation by (Hoek & Brown, 1997). Furthermore, it is highlighted that that the variability on the data has a low impact on the estimation of G_m because these values are also derived using additional correlations and supported by direct shear modulus measures obtained from S-wave velocities (V_s) as discussed in Section 2.3. The UCS tests are accompanied by measurement of the elastic modulus (E_{intact}) and Poisson's ratio (ν), which are also used for derivation of G_m.

2.3 Sound Velocity Tests

The P-wave (V_p) and S-wave (V_s) velocities were determined on rock specimens using two data sources, in laboratory by the ultrasonic pulse transmission (P&S) technique and in-situ measurements acquired from the PSSL (PS suspension logging) where V_p and G (with $G = \rho V_s^2$) were determined. Table 3 summarises the V_p and V_s wave velocities used for the G_m assessment by rock type.

Table 3. V_p and V_s velocities from ultrasonic pulse and PSSL

Rock Type	**No. of tests***	**Ultrasonic Pulse (P&S)**		**PSSL - BGL**	
		V_p **[m/s]**	V_s **[m/s]**	V_p **[m/s]**	V_s **[m/s]**
Mudstone	3 ǀ 20	3459	2144	3550	1725
Sandstone	3 ǀ 11	2529	1217	2744	1110
Siltstone	2 ǀ 4	1513	825	3017	1093

* Number of measurements Ultrasonic Pulse ǀ PSSL

Given that ultrasonic pulse P&S values are obtained in the laboratory on small rock samples, values derived in situ from PSSL are considered more representative to determine G_m. Table 3 indicates higher V_s values for the P&S tests compared to in situ PSSL which is coherent with the testing of competent small scale rock samples in the laboratory which omits larger rock mass discontinuities.

2.4 Derivation of Rock Mass Modulus (G_m)

The rock mass shear modulus (G_m), is used as an input, to inform the level of stiffness required for the CNS testing conditions. Various correlations, summarized by (Puech & Quiterio-Mendoza, 2019), have been used to infer G_m from the available rock strength and geophysical data.

The results from the applied correlations and the direct PSSL measures, were utilized to assess an appropriate best estimate (BE) profile for each rock type, resulting in BE values of 7.56 GPa in Mudstone; 2.5 GPa in Sandstone and 1.4 GPa in Siltstone . BE value assessment placed a higher significance on the PSSL geophysical data due to the larger available data set.

2.5 CNS Stiffness (k) Definition

In a CNS test, the normal stiffness (k) applied to the rock-grout interface is imposed as a boundary condition. The normal stress (σ_n) is controlled to maintain a constant stiffness value during shearing accounting for the variation of the normal displacement (Δh).

The normal stress is adjusted continuously to satisfy equation (1):

$$k = \frac{\Delta\sigma_n}{\Delta h} \tag{1}$$

For a pile socketed in rock (Williams, 1980; Johnston et al., 1987), the $\Delta\sigma$ normal stress variation for concrete/rock interface can be represented as the plane strain expansion of a cylindrical cavity in an infinite elastic continuum. In terms of normal stiffness and considering that the socket radius r is much larger than the increase in radius Δ_r Eq. (2) is obtained.

$$k = \frac{\Delta\sigma_n}{\Delta h} = \frac{E_m}{(1+\nu_m)} * \frac{1}{r} = \frac{2G_m}{r} = \frac{4G_m}{D} \tag{2}$$

E_m and ν_m denote the elastic modulus and the Poisson's ratio of the material, respectively, while D represents the rock socket diameter considered as 12.0 m. The idealised displacement of a pile socketed in rock is presented in Figure 2 as adapted from (Johnston & Lam, 1989).

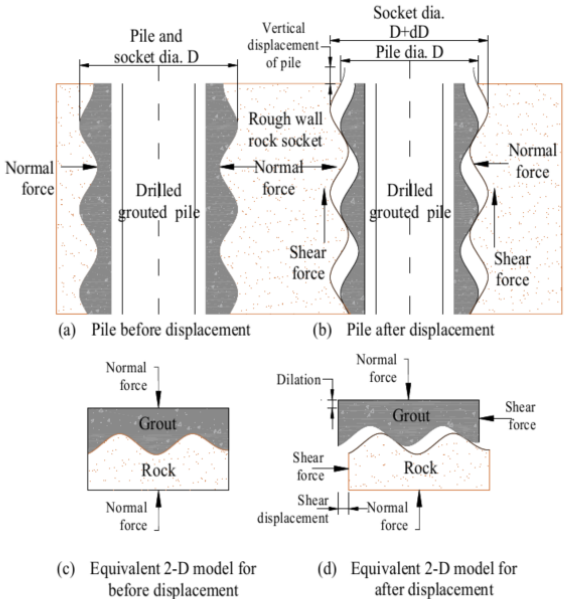

Figure 2. Idealized displacement behaviour of a pile socketed in rock - replicated from (Puech & Quiterio-Mendoza, 2019) adapted from (Johnston & Lam, 1989).

The normal stiffness applied to each interface during CNS tests are summarized in Table 4 per rock type.

Table 4. Stiffness for CNS testing

Rock Type	G_m [MPa]	k [MPa/mm]
Mudstone	7560	2.52
Sandstone	2500	0.83
Siltstone	1400	0.47

A rock socket diameter of 12.0 m is considered.

3 DEFINITION OF CNS TESTING CONDITIONS

This section defines the CNS specific testing conditions, and the recommended activities to prepare and perform CNS testing considering a rock-grout interface.

3.1 Grout Properties

The SikaGrout® - MF9650, a high-strength grout with accelerated early strength development, designed for rock socket grout connections and approved by DNV-GL, was used in this study. Uniaxial Compressive Strength tests (UCS) were performed on the MF9650 grout to confirm the required curing time before conducting the CNS testing program. Figure 3 presents the UCS results in function of the curing time. The results indicate that a curing period of at least one day is sufficient for the grout to exceed the UCS values of the rock. However, a conservative curing time of at least one week was adopted prior to CNS testing to minimize any potential influence of grout properties on the CNS results. Moreover, since the grout strength exceeds the UCS of the rock, failure at the rock–grout interface is expected to occur within the rock.

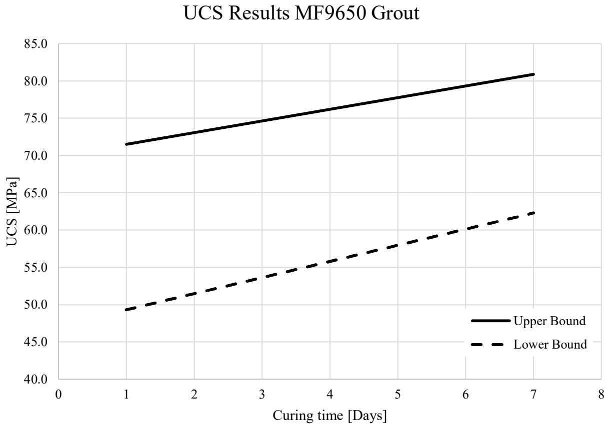

Figure 3. Cured grout UCS results

3.2 Interface Roughness

The surface roughness of the socket wall is often considered a critical parameter for the determination of the ultimate shaft resistance for drilled and grouted piles (Kodikara, Haberfield & Johnston 1992; Seidel & Haberfield, 1995; Nam, 2004).

The surface roughness of drilled shafts can be idealised as a series of straight lines of constant length, forming a series of asperities of varying geometry (Seidel & Collingwood, 2001). This representation has been used in analytical models that consider a statistical distribution of asperities along the shaft wall, in combination with local shear transfer laws as presented in (Nam, 2004) and in the "Monash socket roughness model" of (Seidel & Haberfield, 2002).

Furthermore, a simplification proposed by (Seol et al., 2007) indicates that the natural irregular profile of a borehole could be represented into a regular saw-tooth pattern (Figure 4) with the equivalent regular roughness height (Δr) depending on the chord length (l_a), both linked to the asperity or rugosity angle (θ).

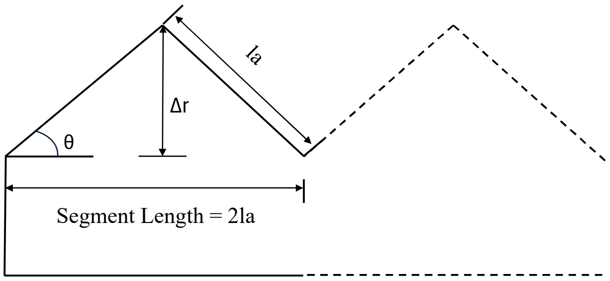

Figure 4. Regular roughness profile for CNS tests (adapted from Seol et al. (2007)

The proposed simplification was used to determine three type of surface roughness created by varying the asperities geometries. Only regular roughness profiles have been considered. Table 5 summarizes the asperities geometries with variations on (Δr) and in (l_a), for all rock types. It is noted that these asperities are in the range of roughness for rock socket caused by drilling tools, as summarized in Seol et al., (2007). A Computer numerical control (CNC) milling machine was used to create the roughness. Figure 5 shows an example of a rock core milled to a specific roughness in preparation of CNS testing.

Table 5. Asperity geometries by rock type

Rock Type	Particle Size [mm]	Geometry Type*	Δr [mm]	θ [°]	l_a [mm]
Mudstone	0.002	1	0.5	5.7	5.0
		2	1.5	15	5.6
Sandstone	0.63	2	1.5	15	5.6
		3	3.35	15	12.5
Siltstone	0.02	2	1.5	15	5.6

*Geometry sorted from the smallest to the highest Δr

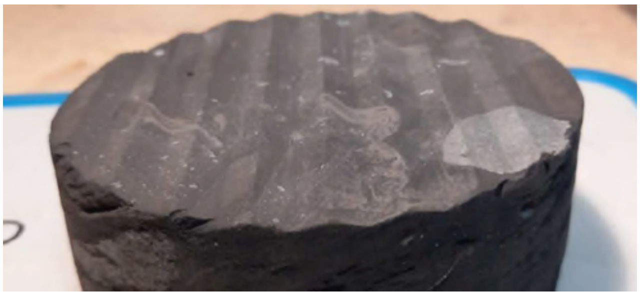

Figure 5. Example of Mudstone Roughness Type 2 after CNC milling.

3.3 Initial Stress

The initial normal stress is typically estimated based on the conservative assessment of the grout hydrostatic pressure at the end of grouting operations. To ensure representative initial stress conditions for CNS tests, it is essential to specify the expected height of the grout column during grouting operations. Grout hydrostatic pressure equivalent to a grout column of 10 m was considered for the calculation of the initial stress. Therefore, an initial normal stress (σ_{ini}) of 100 kPa was applied for the CNS tests.

3.4 Displacement Definitions

Monotonic and Cyclic CNS tests were performed to determine the rock-grout behaviour under different conditions.

- Type A (Static or Monotonic): Horizontal displacement to +2la followed by a reverse displacement to -2 l_a and a return to initial position (i.e. zero displacement);
- Type B (Dynamic or Cyclic): a series of N cycles (25) considered to obtain a stable residual rock-grout interface strength. with amplitudes from 0 to +l_a to - l_a (two-way). The cyclic phase is followed by a "static" test.

The selected displacement types and number of cycles are consistent with those used by (Ooi & Carter, 1987) and (Muralha et al., 2014). The selected displacement aims to represent two magnitude of displacements relevant and applicable to monopile design in rock-socketed holes. A total of 22 tests were carried out, as presented in Table 6.

Table 6. Interface Roughness Geometries

Rock Type	Geometry Type	Number of Tests	
		Static	Cyclic
Mudstone	1	4	4
	2	5	3
Sandstone	2	-*	2
	3	2	-*
Siltstone	2	-*	2

*No tests performed

4 LABORATORY TESTING

4.1 Sample Preparation

A steel square shear box (110*110 mm^2), composed of two half shear boxes, is used as a mould for the preparation of the rock-grout interface. The cylindrical rock specimen, around 100 mm in diameter, is placed in the bottom half shear box, with the roughness main line orthogonal to the shear direction. The top surface of the rock specimen is maintained horizontal. The prominent surface, including the roughness profile, protrudes in the interface shear zone, 10 mm thick. The top half shear box is then fixed by two screws to the bottom one, whereas a gap of 10 mm is ensured by a temporary spacer. The whole system is reversed and the grout is then poured in the second half box (Figure 6).

The grout used for the sealing of the rock specimen as well as the grout part is a MasterFlow9650 cement powder, mixed with tap water, with a water-to-cement ratio of 0.14. The unconfined compressive strength of the grout was greater than 90 MPa, after two weeks.

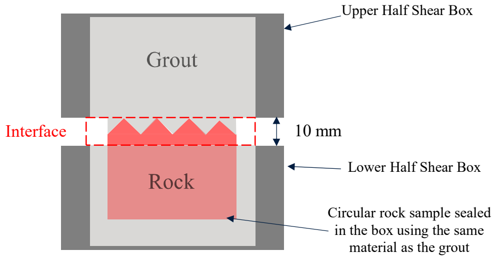

Figure 6. Sample Preparation

4.2 CNS Laboratory Equipment

The CNS testing campaign was first conducted using the GDS Large automated Direct Shear System for rock, built to ASTM standards. The top cap of the GDS system allows for movement in the pitch axis which is measured by 4 independent LVDT's positioned at each corner of the top cap.

The second set of CNS tests were performed at the 3SR Laboratory in Grenoble using the BCR3D (for "Boite de Cisaillement pour Roche selon 3 Directions") machine originally developed for the hydro-mechanical characterization of rock joints (Boulon, 1995) (Figure 7). The second set of CNS tests were performed following GDS apparatus testing difficulties, Section 5.2. The BCR3D equipment is capable of loading on 3 independent axes (x, y and z) with a rigid top cap assembly with no pitch or rotation.

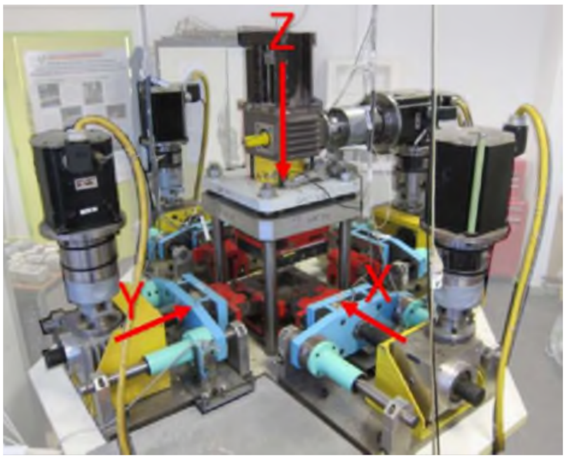

Figure 7. BCR3D equipment, 3SR Laboratory

5 RESULTS AND DISCUSSION

5.1 Validity of Results

To ensure the reliability of the results, various validation criteria were established:

- Visual Inspection: Samples were examined before and after testing to identify any physical anomalies or damage that could affect test integrity. Recorded normal displacements were compared with post-test measurements of asperity geometries to confirm accuracy.
- Apparatus Alignment Control: Pitch and roll of the sample were monitored throughout the test to minimize misalignment and ensure proper load application. The relationship between shear and normal displacements was assessed to verify horizontal alignment of the failure plane and confirm expected CNS response.
- Data Review: Recorded displacements and stress development were analyzed for consistency with expected CNS behaviour based on previous project experience and reference literature (Seol, 2007 and Stavropoulu et al., 2021). This included verifying constant stiffness and monitoring any rotation or tilting of the samples during testing.

5.2 CNS Testing Difficulties

Despite these quality assurance measures, several challenges were encountered when executing CNS tests using the GDS apparatus:

- Low Recorded Normal Displacements and Stresses: In multiple tests, the recorded normal displacements and stresses were very marginal or significantly lower than the asperity height measurements post-test, resulting from the normal displacement of the frame omitting the larger displacements being measured at the 4 displacement sensors positioned at the outer points of the top cap;
- Tilt and Rotation of top cap: A comparison of the normal displacement measurements from the frame sensor and the 4 LVDTs revealed higher normal displacements compared to the frame readings, indicating rotation or tilting of the machine's top cap during shearing of the asperities.

5.3 Conclusion on GDS Equipment Suitability

Based on the aforementioned observations and the imposed asperities resulting in rotation of the top cap the applied normal stiffness was not constant and tended to be lower than the design stiffness. The GDS apparatus was therefore unsuitable for CNS testing on samples with milled asperities, despite complying with the relevant ASTM standard. The apparatus is unable to apply the specified CNS conditions due to the ability of the top cap to rotate up and over the milled asperities leading to different normal displacements over the shearing plane. A decision was taken to consider another apparatus (BCR3D) with a fixed top cap which prevents tilting or rotation.

5.4 Results of Second Campaign – 3SR Laboratory - Grenoble

The validation criteria were also applied to the BCR3D CNS tests. The results were found to be consistent with expected CNS behaviour, furthermore, no rotation or tilt was observed, CNS results showed repeatability and consistency between rock types and asperity geometry. The results are presented per rock and asperity geometry type in Figure 8 to Figure 11 for Mudstone, Figure 12 to Figure 13 for Sandstone and Figure 14 for Siltstone.

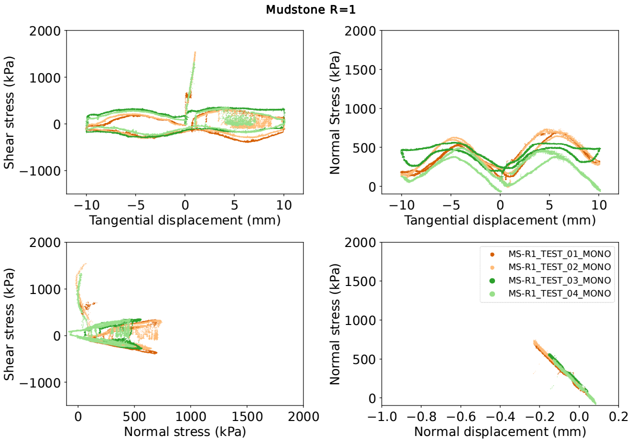

Figure 8. Static-Mudstone, Asperity Geometry Type 1.

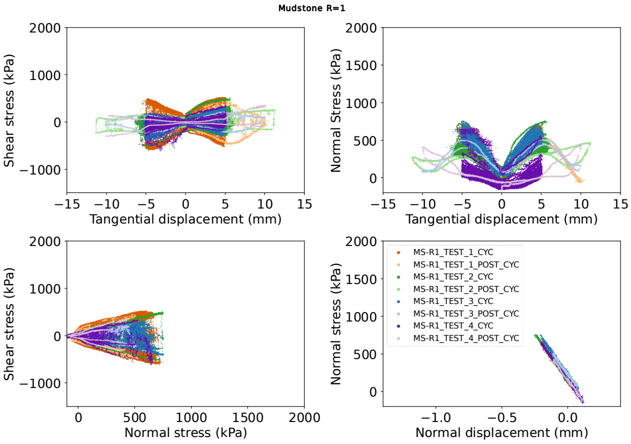

Figure 9. Cyclic-Mudstone, Asperity Geometry Type 1.

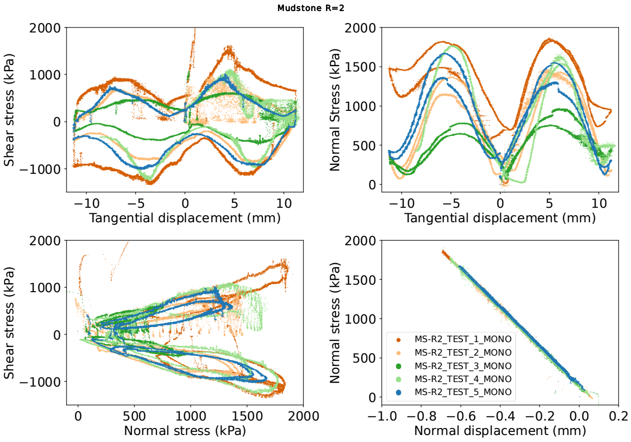

Figure 10. Static-Mudstone, Asperity Geometry Type 2.

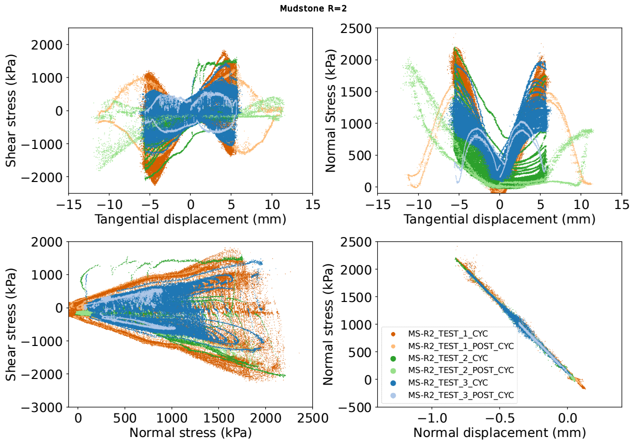

Figure 11. Cyclic-Mudstone, Asperity Geometry Type 2.

6 CONCLUSIONS

A CNS testing program to evaluate the shear behaviour of rock-grout interfaces has been executed considering three rock types, Mudstone, Sandstone and Siltstone, with variations in asperity geometries mimicking surface roughness of typical post-drilling traces in addition to including monotonic and cyclic loading conditions. The main outcomes of the study are noted as follows:

- A characterisation of rock properties and rock mass shear modulus (G_m), considering three rock types has been provided with aim to derive CNS testing parameters, considering in situ data and corelations;
- Stiffness for CNS testing has been derived considering a rock socket diameter of 12.0 m, equivalent to a monopile installed through the drill and grouted methodology;
- The relevant and required parameters such as grout properties, asperity geometry are selected based on industry available materials and data for offshore drilled & grouted applications;
- Two types of tests, static and cyclic, have been defined;

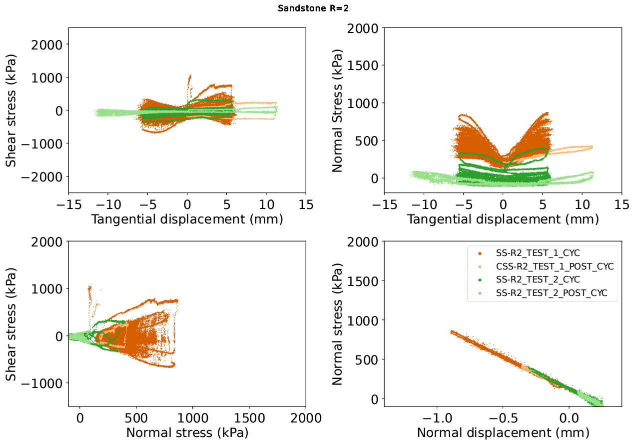

Figure 12. Cyclic-Sandstone, Asperity Geometry Type 2.

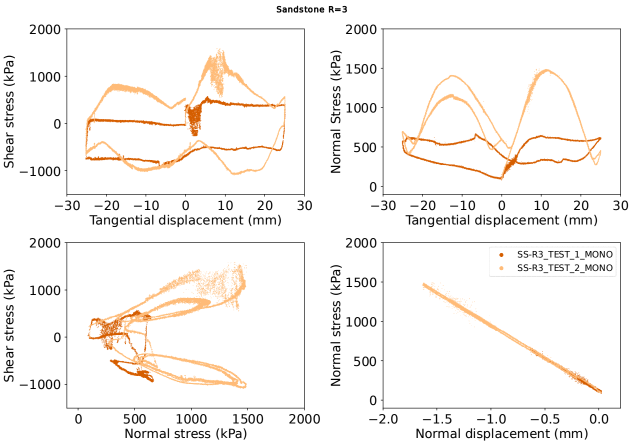

Figure 13. Static-Sandstone, Asperity Geometry Type 3.

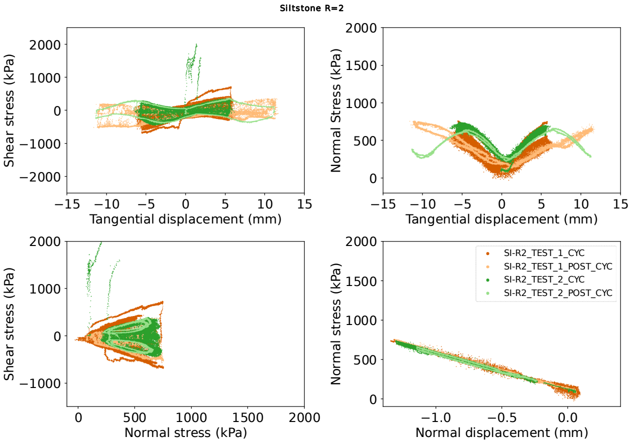

Figure 14. Cyclic-Siltstone, Asperity Geometry Type 2.

- A campaign using the GDS equipment indicated that due to the ability of the top cap to tilt up and over asperities perpendicular to the direction of shear results in it being unsuitable for CNS testing application with milled asperities to determine the interface roughness;
- The results presented contribute to more robust data set and can be used to inform preliminary design considerations for the design of offshore monopiles foundation in similar rock types and provide a preliminary representation of the range of stress expected at the rock-grout interface.
- CNS testing is recommended when considering a monopile installed through the drill & grouted methodology. This paper presents the main insights into the rock-grout interface behaviour relevant to the design of monopiles socketed into rock;
- This paper presents a practical framework and guidance for preparing and executing future CNS testing campaigns.

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