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Characterization of rock/grout interfaces for foundations of offshore wind turbines

Caractérisation des interfaces roche/coulis pour l'éolien offshore

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ABSTRACT: Since a few years, France has been considering the development and construction of offshore wind farms in different sites in the northern and western coasts of the country. The pile foundations of the wind turbines will be installed and grouted in rock formations, the mechanical properties of which can vary significantly according to the location of the site. Given the contrast on the mechanical properties of the grout and the hosting rock, the study of their interface in shear is essential for the improvement of the design methods of offshore piles. The mechanical behaviour of various interfaces is studied with shear tests, under constant normal stiffness, these assumed to be the most representative to *in-situ* conditions. The importance of these boundary conditions is demonstrated comparing the results to tests under constant normal stress and constant volume.

RÉSUMÉ: Depuis quelques années en France, la conception et le développement des parcs éoliens offshore est envisagé dans différents sites le long des côtes françaises. Les fondations profondes des éoliennes seront installées et scellées avec du coulis dans des roches, dont les propriétés mécaniques peuvent varier considérablement d'un site à l'autre. Compte tenu des contrastes entre les propriétés de la roche et du coulis, la réponse mécanique de leur interface en cisaillement doit être étudiée pour améliorer les méthodes de conception des pieux offshore. Le comportement mécanique des interfaces est analysé avec des essais de cisaillement sous la condition de rigidité normale imposée, considérée comme représentative des conditions *in-situ*. L'importance de cette condition aux limites est démontrée en comparaison avec des résultats d'essais sous contrainte normale constante ou volume constant.

Keywords: pile, interface, windturbine, shear tests, offshore

1 INTRODUCTION

Over the past few years, in France, the design of pile foundations for wind turbines has been continuously investigated. However, the existing design codes do not cover all possible *in-situ* cases, and in particular, the ones within the offshore domain. As proposed by (Puech and Quiterio-Mendoza 2019), in a companion paper, a solution for the future foundations of french offshore wind turbines consists of piles drilled and grouted in moderately weak to strong rock formations. For this, it is necessary to correctly estimate the friction that can be mobilised at the rock/grout interface.

In conventional studies, the shear behaviour of a joint is usually investigated with laboratory tests under constant normal load or stress (CNL). However, in engineering practice, the normal stress acting on the joint interface may vary during shearing, and dilation of the joint may be constrained by the confined environment formed across the interface, which often represents a constant normal stiffness (CNS) condition. The CNS direct shear testing technique has been proved to be of some considerable value in the assessment of the development of the shaft resistance in rock grouted pile foundations and it has been, thus, mainly preferred for this study.

The shear response of a grouted interface depends on the characteristics of the rock mass and the grout itself, the initial stress conditions, but also on its roughness. The importance of the socket roughness to shaft resistance has been well recognised by a number of researchers (e.g., Johnston 1977, Horvath and Kenney, 1979, Pells et al. 1980, Johnston and Lam 1989). (Nam and Vipulanandan 2008) suggested that roughness can be represented by a regular sawtooth with a chord length $2l_a$ and an asperity height Δh_a corresponding to a roughness angle θ°, according to the *in-situ* used drilling tool.

Rock/grout interfaces of different mechanical and geometrical properties have been tested in shear, under different boundary conditions. Their shear response and mode of failure are discussed in the following paragraphs.

2 EXPERIMENTAL CAMPAIGN

The rock/grout interface samples are tested in shear using the BCR-3D shear device (Boite de Cisaillement des Roches en 3 Directions, Boulon 1995). This shear box is composed by three orthogonal axes, each one independent of the others: a normal (Z) and two parallel (X and Y) to the interface plane (Figure 1), controlled either in force or displacement. The shearing is applied in a way so that any relative rotation between the two walls of the interface is prevented, while the normal load remains always centred, as a result of a symmetrical and opposite displacement on the interface's active part.

2.1 Boundary conditions

The BCR3D shear box allows the performance of shear tests under various boundary conditions on the normal axis: Constant Normal Load or Stress (CNL), Constant Normal Stiffness (CNS) or Constant Volume (CV). The different boundary conditions allow the manifestation of potentially different failure modes. If one considers an interface system as illustrated in Figure 2 where the upper part of the joint is allowed to move along both normal and tangential directions, the effect of the surrounding rock mass can be modelled using a spring in order to characterize the different normal boundaries.

The normal stiffness k_n of the spring can be expressed as a function of the variation of the normal stress with the variation of the normal displacement:

$$k_n = \frac{\Delta\sigma_n}{\Delta u_n} \quad (1)$$

where $\Delta\sigma_n = \sigma_n - \sigma_{n0}$, with σ_n the current value of normal stress and σ_{n0} the initial value of normal stress, $\Delta u_n = u_n - u_{n0}$, with u_n the current value of normal displacement and u_{n0} the initial value of normal displacement.

A Constant Normal Load or Stress test ($\Delta\sigma_n = 0$) corresponds to a stiffness $k_n = 0$, where the joint is free to dilate or contract with shear. On the other hand, a stiffness $k_n \rightarrow +\infty$ corresponds to a shearing under Constant Volume ($\Delta u_n = 0$), where no variation of normal displacement is allowed and thus, the existence of any roughness is eliminated by a total shearing-off of the asperities. All intermediate values of the stiffness k_n correspond to a shear test under Constant Normal Stiffness, where the failure mechanisms follow a path in between the two above-mentioned limit ones.

In the case of pile foundations, the stiffness normal to the interface is described as a function of the shear modulus G_{rock}, of the hosting rock mass and the radius r of the pile (Boulon et al. 1986):

$$k_n = \frac{2G_{rock}}{r_{pile}} \quad (2)$$

Assuming a value of $G_{rock} \approx 6$ GPa, as illustrated in (Puech and Quiterio-Mendoza 2019), and pile diameters ranging from 2 to 10 meters, typical values of the normal stiffness k_n are of some thousands of kPa/mm (1200 to 6000 kPa/mm with the assumed values).

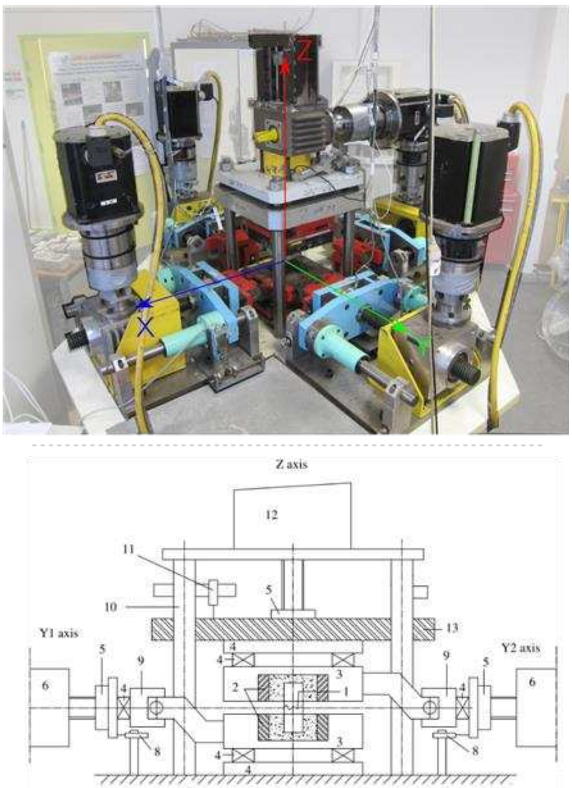

Figure 1. top: the BCR-3D shear device with the three principal loading axis, bottom: Front view section along one shear axis of the BCR-3D (Armand, 2000), 1: interface, specimen to be tested, 2: internal removable shear boxes (sample), 3: external fixed boxes, 4: rail allowing translation of the boxes, 5: load cells, 6: horizontal actuators, 7: rigid base, 8: displacement transducers (LVDT measuring dY1 and dY2), 9: kneecaps, 10: rigid fixed columns, 11: displacement transducer (LVDT measuring dZ), 12: vertical actuator, 13: rigid vertical plate free to move along Z axis

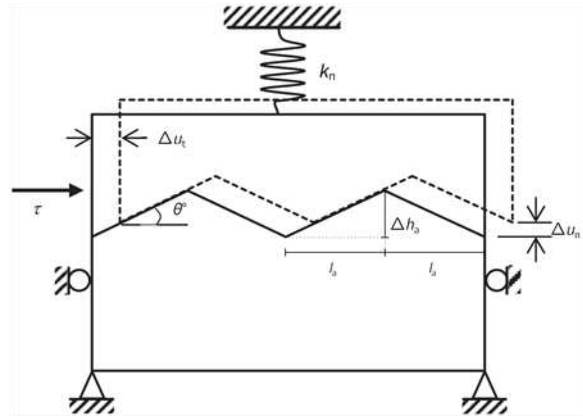

Figure 2. Conceptual model of dilatant joints (Heuze, 1979)

2.2 Shear tests

The interface samples are moulded in two half shear boxes, as illustrated in Figure 3. The rock sample is sealed in the lower half shear box, on top of which the grout is cast. The two half shear boxes are separated from each other by a 10 mm distance, leaving a free interface of this same height.

A typical experimental program starts with the identification of the mechanical properties of planar interfaces under CNL conditions, in order to determine the failure envelope. Then, all interface samples present a roughness in the form of regular sawtooth asperities of different angles and segment lengths. Based on the asperities geometry, the interfaces have been tested following one of the two shear paths described in Figure 4. The principle behind either path involves a first application of shear displacement up to 75% of the segment length $2l_a$, *i.e.* past the asperities peak, followed by shearing towards the opposite direction (-75% $2l_a$). Tests of one two-way shearing cycle (±75% $2l_a$) have been performed (Figure 4a), but also of a combination of a first one-way cycle (+75% $2l_a$ → +25% $2l_a$), followed by a longer two-way cycle (±75% $2l_a$) (Figure 4b).

The impact of the boundary conditions on the response of an interface is discussed through shear tests under constant normal stress and constant volume in the following paragraphs, while the response in shear under applied normal stiffness is investigated on different rock/grout interface samples.

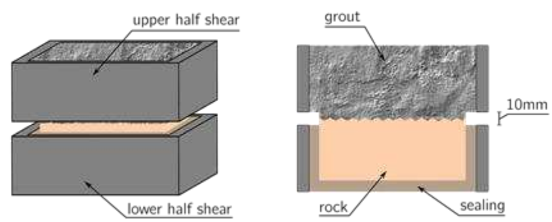

Figure 3. Schematic illustration of an interface sample

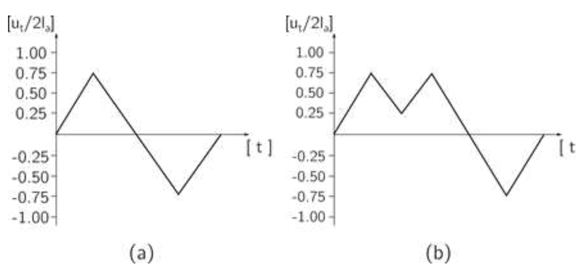

Figure 4. Stress paths as a function of the asperities length of the tested interface

3 EXPERIMENTAL RESULTS

The following experimental results have been obtained through shear tests on different grouted carbonate rock samples, which come from different site locations in France where wind farms are planned to be installed. For confidentiality purposes, some parameters are presented in a dimensionless way and the values of shear stresses are not quantified.

3.1 *Shear tests under Constant Normal Load and Constant Volume*

Two calcarenite/grout interface samples have been tested in shear under CNL and CV conditions. The unconfined compressive strength (UCS) of the grout is about twice the UCS of the tested rock. Both interfaces are tested under the same initial normal stress σ_{n0} = 300 kPa, and are of the same roughness with a regular asperity length $2l_a$ = 10 mm and a height Δh_a = 0.5 mm. Figure 5 shows their response in shear resistance with shear displacement. In the case of the CNL test, a maximum shear stress is achieved shortly after the application of shear displacement. On the other hand, the response under CV is characterized by a clear peak of shear resistance which decreases dramatically after failure due to asperities breakage. Indeed, the maximum measured shear stress corresponds to a shear displacement close to the peak length of the asperities, and equal to $u_t = 0.7l_a$.

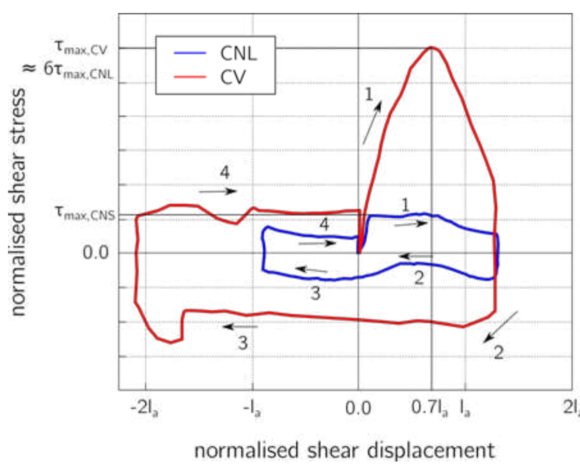

Figure 5. Shear resistance of a calcarenite/grout interface under CNL and CV

As previously mentioned, during a shear test under constant normal stress (k_n = 0), the interface can freely dilate or contract according to its roughness. The dilatant-contractant response of the calcarenite/grout interface is clearly demonstrated in Figure 6, where the interface dilates continuously until the shear displacement matches the asperities peak length l_a. When shearing towards the opposite direction, the dilation is measured lower, as different parts of the interface are mobilized and a possible damage of the asperities has already occurred.

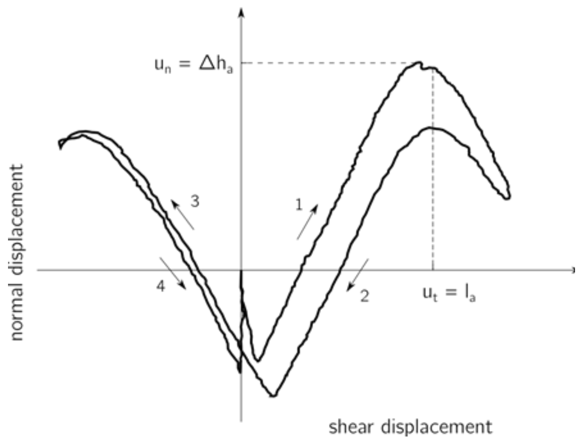

Figure 6. Dilation – contraction of a calcarenite/grout interface tested under CNL

On the other hand, when shearing under CV condition ($k_n \rightarrow +\infty$) , the normal displacement is maintained to zero and thus, a total breakage of the asperities occurs with shearing. This results in a continuous increase of the normal stress, until failure as shown in Figure 7. When shearing towards the opposite direction, the measured normal stress remains practically constant, after the total breakage of the asperities.

These boundary conditions, corresponding to two extreme values of normal stiffness, can give some important insight about the response of an interface in shear. However, in reality, a rock mass is representative of a continuous medium of some given elastic properties, and thus, shearing under an imposed stiffness is considered as the most representative boundaries of the *in-situ* conditions.

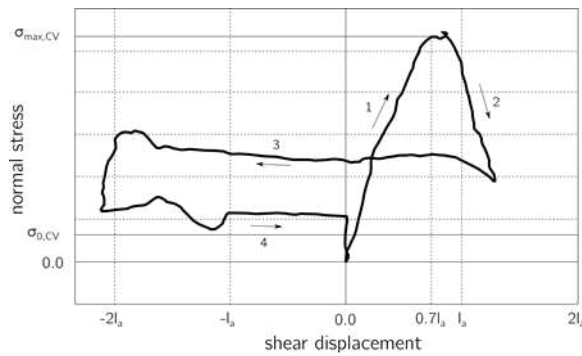

Figure 7. Evolution of the normal stress with shear displacement under CV

3.2 Constant Normal Stiffness tests

In this section, results from shear tests under constant normal stiffness with σ_{n0} = 100 kPa are presented, performed on rock/grout interfaces of different rock type and different roughness.

Two similar calcarenite/grout samples are tested under different normal stiffness, k_1 and k_2, with $k_1 \approx 2k_2$, following the shear path presented in Figure 4b. In that case, the rock properties are greater than the ones of the grout, and thus, failure occurs in the grout. As shown in Figure 8, the shear resistance is measured higher for a higher applied stiffness. This makes sense, given that for a higher normal stiffness, the increase of normal stress is more important and thus, friction is mobilized in a more important way.

This is, however, not the case for a soft limestone/grout interface of a similar roughness, where the UCS of the limestone is significantly lower than the UCS of the grout. As shown in Figure 9, the maximum shear stress achieved during the first cycle of shear under different applied normal stiffness, $k_1 = k_2/3 = k_3/5$, is similar, while the failure mode is in this case not characterized by a clear peak at failure, but by a shear stress plateau.

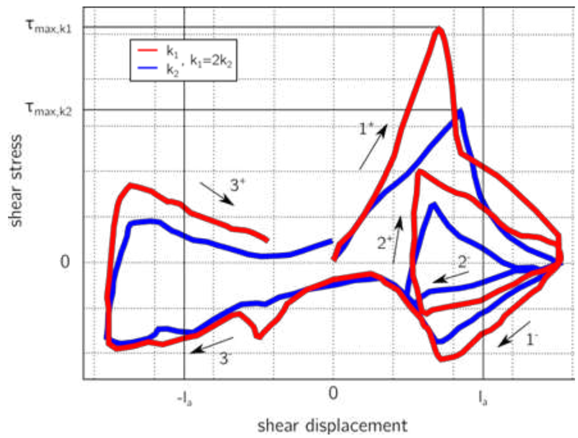

Figure 8. Shear resistance of two similar calcarenite/grout interfaces tested under different applied normal stiffness

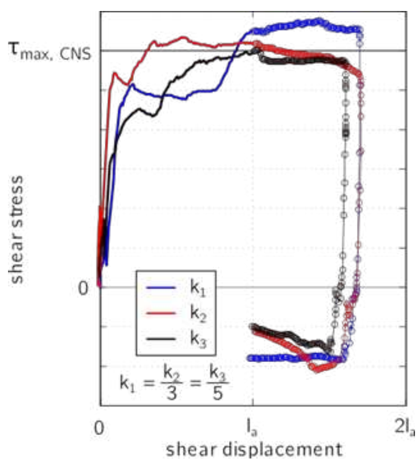

Figure 9. Shear resistance of a soft limestone/grout interface tested under CNS

This behaviour is unexpected in the presence of asperities, since it corresponds to a response of a rather non-rough interface. Thus, a total breakage of the rock asperities since the beginning of shearing is suspected for all three applied normal values of stiffness.

This is indeed the case if the post-shear state of the interface sample (Figure 10) is observed, where a layer of the soft limestone is attached on the grout, and the failure surface occurs within the rock part. This is not a surprise given the contrasting mechanical properties of the two involved materials, unlike the previously tested calcarenite/grout interfaces. At the end, when failure occurs, the roughness of the failure surface does not correspond any more to the initial regular sawtooth of the rock/grout interface.

It is clear that the applied boundary conditions, as well as the mechanical properties of the involved materials, play an important role on the shear response of interfaces. Moreover, the shear behaviour of an interface depends on its initial roughness and its evolution during shearing. Two calcarenite/grout interface samples with different asperities height, but similar chord lengths, have been tested in shear under the same constant normal stiffness.

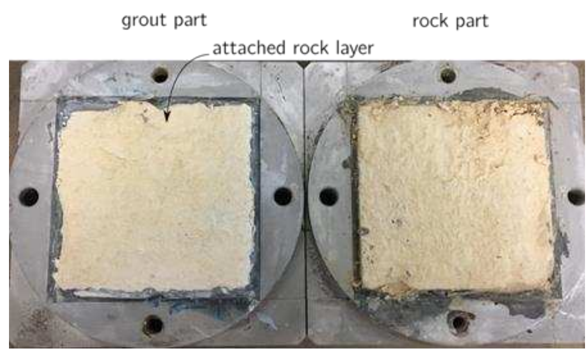

Figure 10. Shear surface of a soft limestone/grout interface tested under CNS

First of all, the shear resistance is measured 6 times higher for an interface with higher asperities, up to a clear peak at failure (Figure 11). Higher asperities mean more important dilation under a given normal stiffness and thus, increase of the normal stress with shearing. Shearing towards the opposite direction, the measured shear resistance remains significantly lower, confirming a brittle breakage of the initial asperities. On the other hand, a lower asperities interface exhibits a different mode of failure, where failure occurs in a less brittle way, with a plateau of shear strength achieved shortly after the shear application. The shear resistance, however, when shearing towards the opposite direction is regained, indicating a modification of the asperities form, a steeper part of which has been activated.

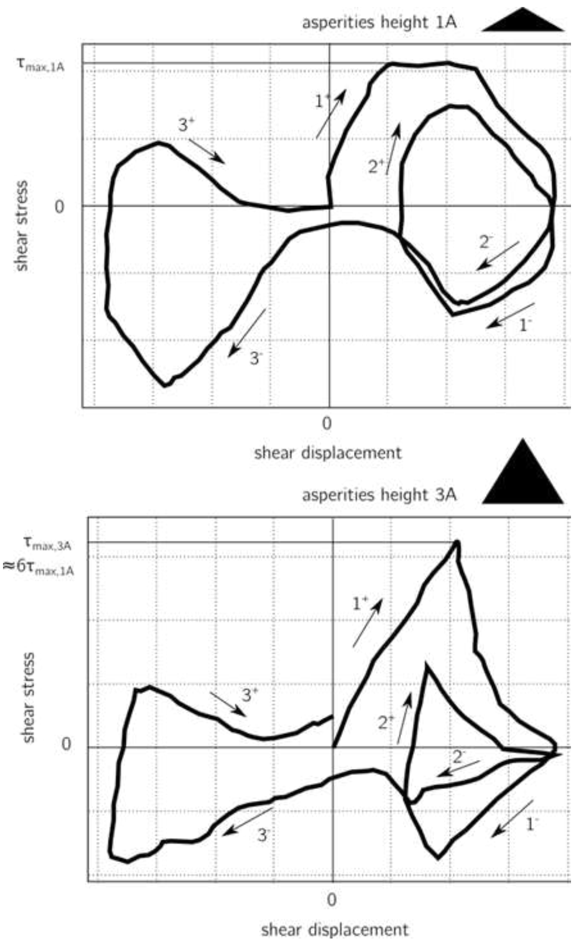

Figure 11. Shear surface of two calcarenite/grout interfaces of different roughness tested under CNS

4 CONCLUSIONS

This paper mainly presents the results of the shear response of rock/grout interface samples, tested under different boundary conditions. The grouted rock samples came from different site locations in France where wind farms are going to be installed. The dependence of the shear response on the applied stiffness has been highlighted through the different results, making a correct estimation of the *in-situ* conditions necessary. Finally, the importance of the mechanical properties of the involved materials, as well as, the roughness of the interface have been pointed out.

5 ACKNOWLEDGEMENTS

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