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An integrated assessment of the ground conditions for foundations design at St-Brieuc Offshore Windfarm

Une étude intégrée des conditions de sol pour le dimensionnement des fondations du parc éolien offshore de St-Brieuc

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ABSTRACT: The proposed St. Brieuc offshore wind farm site is located within the Massif Armoricain comprising shallow Precambrian very weak to strong rock. The adopted foundation solution consists of jacket substructures supported by drilled and grouted steel tubular piles. This paper describes the methodology implemented during the geotechnical field investigation and laboratory testing dedicated to effectively acquire data to allow the completion of the final integration phase of the ground model. Additionally, it discusses the methodology used to develop the ground model with a focus on determining ground confidence levels for consideration at pile design phase. Finally, a multivariate probabilistic assessment is then implemented with a view to support the definition of the confidence level of the geotechnical parameters that will be used at design phase. The methodologies described in this paper are considered of interest to similar industry projects working towards reducing the Levelised Cost of Energy of offshore wind farms.

RÉSUMÉ: Le site proposé du parc éolien offshore de Saint-Brieuc se situe au sein du Massif Armoricain qui se caractérise dans cette zone par un substratum rocheux peu profond d'âge pré-Cambrien très faiblement à fortement résistant. Le type de fondation retenu consiste en une infrastructure de type jacket supportée par des pieux tubulaires en acier forés et cimentés. Cet article décrit dans une première partie la méthode mise en œuvre durant la campagne de reconnaissance géotechnique et du programme d'essais de laboratoire associé afin de permettre la finalisation de la phase d'intégration du modèle de sol. Aditionellement, il discute ensuite de la méthodologie utilisée pour le développement du modèle de sol en se concentrant sur la détermination de niveaux de confiance du sol à prendre en considération lors de la phase de dimensionnement des pieux. Enfin, une évaluation probabiliste multivariée est ensuite mise en œuvre pour confirmer le niveau de confiance des unité de terrain à utiliser lors de la conception de détaillée des fondations. Les méthodologies décrites dans cet article sont considérées comme étant d'intérêt pour des projets industriels similaires visant à réduire le coût actualisé de l'énérgie des parcs éoliens offshore.

Keywords: Geotechnical investigation; ground model; multivariate analysis; jacket substrutures; offshore piles.

1 INTRODUCTION

The proposed St. Brieuc Offshore Wind Farm (the site) is located about 16km off the northern coast of Brittany, France. The project consortium comprises Iberdrola, RES and Caisse des Dépôts. The site is located within the Massif Armoricain comprising shallow Precambrian very weak to strong rock. The main governing factors that influence the rock strength are the regional methamorphism, weathering, laminae and bedding. The adopted foundation consists of jacket substructures supported by rock socketed piles.

The following sections describe the key elements that comprised the geotechnical investigation and integration studies to compile the available datasets into a ground model with focus to obtain a high quality data package to allow a safe and cost effective foundation design. The datasets are then evaluated via a multivariate analysis with the objective to substantiate the interpretations made from the ground model.

1.1 Geological Setting

The site geology is dominated by Precambrian and Lower Palaeozoic rocks of the Cadomian orogenic cycle. The Precambrian has been identified as weakly metamorphosed psammitic rock, namely Brioverian turbidite, submarine fan deposits. They contain pelitic horizons as well as a discrete pelitic zone. These rocks exhibit low grade metamorphism in places, with increased foliation, crenulations of cleavage and the presence of phyllosilicate minerals (muscovite and chlorite) along foliations. Figure 1 shows the St. Brieuc offshore wind farm (the site) boundary, overlain on the geological map of the Bureau de Recherches Géologiques et Minières (BRGM).

1.2 Site surveys and associated integration studies

Following an initial phase of site surveys at concept design by G-tec & Geosea in 2012, this paper concentrates on describing the site detailed investigation carried out by Fugro (2017 & 2018) together with a ground model integration study, currently ongoing by Atkins (2018) dedicated to facilitate the detailed foundation design phase.
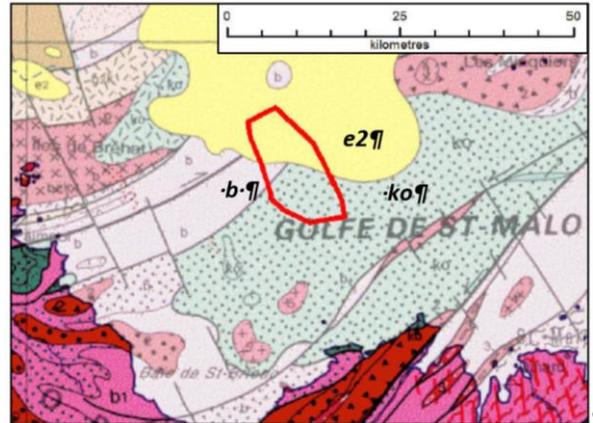

Figure 1: The site boundary overlain on the BRGM Geological Map (Ailes Marines, 2013). Geological units at the site include ko: Palaeozoic, b: Proterozoic and e2: Middle and Upper Eocene.

2 2017/18 GEOTECHNICAL SURVEY

2.1 Scope definition

The scope of the geotechnical campaign was defined by Ailes Marines and independently verified by Lloyd's Register (2017), with the primary objective to facilitate the safe and cost effective design, installation and certification of the Wind Turbine Generators (WTGs). The survey was concentrated to:

- Acquiring sufficient understanding of the geological units to comprehensively determine the design parameters to characterise the three-dimensional conditions across the site, typically one borehole per WTG locations

- Ensuring that the data collected provides adequate inputs for geological unit types, piling design and installation methodologies.

2.2 Borehole geological loggings

A dedicated training in line with project requirements was provided to all geologists involved in the offshore core logging operations. It aimed to focus on geological core description, detailed fracture logging, an assessment of rock quality designation (RQD) and instructions for offshore laboratory testing and sub-sampling. Particular attention was paid on the following parameters as they have a significant impact on pile design:

1. Assessment of rock weathering, particularly focused to identify a transition from weathered to fresh rock conditions;
2. Identification and detailed description of any discontinuity such as bedding and fracture; and,
3. Rock strength assessment based on Point Load strength index.

The purpose of this training was to ensure a standardised, consistent and high quality logging during the whole duration of the fieldwork. It included the definition of a bespoke rock mass rating (RMR) system adapted to account for the likely piling conditions at the site. The content of the training was also updated as the fieldwork progressed to integrate new findings or geological features.

Finally, the quality control of field data was performed by a functional team onshore to facilitate continuous feedback in real-time to the the vessels teams.

2.3 Drilling operations and field testing

Coring was carried out with a wireline Geobor S triple core barrel which allows to recover cores of 102mm diameter and up to 1.5m long. The wireline coring tool was mounted on a platform on top of the American Petroleum Institute (API) outer drill string operated with a heave-compensation system to allow for a constant control of the coring tool depth. In this arrangement, the API drill string acts as a casing that reduces the disturbance of the core during drilling and facilitates the process of retrieving the core.

The core recovery was very satisfactory with an average of 97%. In heavily fractured cores (RQD lower than 25%), the recovery remained acceptable with an average rate of 88% as illustrated by core photograph examples in Figure 2 which allowed alsmost continuous core logging over the whole of each borehole length.

Core logging was directly performed offshore based on ISO 14689-1:2004 and ISO 22475-1:2006 for RQD. Each vessel was mobilised with a laboratory container fully equipped for geological core logging and field geotechnical testing. It included high resolution camera provided with suitable lighting conditions to allow for high quality photographs to be taken, a scale and oven for bulk and dry density (DDEN) testing, and a point load tester.

Figure 2: Example.of core recovered with low and high RQD.

Point load tests were performed at regular depth interval of 1m to assess the rock strength index and were combined with RQD to verify the adecuacy of the borehole completion depth.

Sub-sampling for onshore laboratories was directly performed at completion of core logging. In order to prevent the potential risk of sample failure, during laboratory test preparation mainly due to weakness plans in rock (bedding, laminae and incipient fractures), the amount of intact rock pieces was increased to 3 per core run with a minimum length of 10cm (with full diameter) and

any discontinuities that could affect testing were reported.

The field testing comprised downhole P&S wave logging, high pressure dilatometer tests and a televiewing tool at 20% of the boreholes. They proved altogether benefitial to correlate in situ ground stiffness and morphology together with the core logging and laboratory test data. Additionally, seabed PCPTs and downhole PCPTs across the site were performed to support the characterisation of the sediment profiles.

2.4 Laboratory testing

An extensive programme of laboratory testing was scheduled to determine physical and mechanical properties at each WTG location. This included developing a strategy to optimise both the laboratory workflow and the overall quantity of laboratory testing required.

Uniaxial compressive strength (UCS) tests were performed every two to four meters about 50% of tests including Young's modulus (E) determination and measurement of compression waves (P-WAVE) and shear waves (S-WAVE) prior to testing to infer shear and Young's moduli at low strain. Point load tests were performed on UCS remains for derivation of correlation factors between rock strength index and UCS results.

Brazilian tensile strength tests were performed as close as possible to UCS tests in order to obtain both compressive and tensile strengths in the same lithology.

In heavily fractured zones, UCS tests were performed on samples re-cored into smaller diameter in order to keep an acceptable diameter over length ratio as per ISRM recommendations. When samples were unsuitable for strength tests, DDEN and porosity tests were measured to derive strength based on available correlations between UCS versus DDEN and porosity.

Failure mode of strength tests was carefully assessed as rock failure can be a major issue in rock engineering. A classification based on that presented in Basu et al. (2013) was applied to differentiate failure types such as axial splitting, shearing along single or multiple planes and failure along natural discontinuity.

Complementary tests were performed such as Cerchar abrasivity tests to assess the wear of drilling equipment, to inform on the selection of drill tools for the rock sockets, and slake durability tests to evaluate the weathering resistance of mudstone and weak sandstone.

Geological information such as mineralogical composition or degree of metamorphism were checked with X-ray diffraction and petrographic thin sections.

Constant normal stiffness (CNS) tests were conducted to simulate the behaviour at the pile shaft interface between the rock and the grouted annulus and record the equivalent rock-grout interface shear strength. CNS tests require the determination of two main parameters: the rock-grout interface geometry and the rock mass stiffness which can be determined based on laboratory tests, such as UCS and shear wave measurement; and geological indices such as RMR (Bieniawski 1984) and Geological strength index (GSI) (Hoek 1994). The methodology adopted for assessing those parameters is presented in the companion paper by Puech and Quitero-Mendoza (2019).

3 GROUND MODELLING

3.1 Methodology

An observational ground model (as defined by Parry et al., 2014) for the site has been developed based on the interpretation and integration of four vintages of geophysical survey data, along with geotechnical data from two offshore ground investigation campaigns. The geophysical data was collected during a pre-tender geophysical survey in 2011, a development area survey in 2012, a detailed array area survey in 2016 and an unexploded ordinance (UXO) and export cable survey in 2017.

Geophysical data from the 2012 development area survey and the 2016 detailed array area

survey was integrated with preliminary geotechnical data collected by G-tec & Geosea in 2012 using IHS Kingdom software to form an initial predictive model of the ground conditions at the site. This predictive model was used to plan and inform the detailed intrusive ground investigation undertaken at the site by Fugro in 2017 and 2018. The detailed ground investigation data has subsequently been integrated into the ground model for the site.

The development of this integrated ground model for the site has incorporated (i) an interpretation of the seabed datasets comprising high resolution bathymetry, sidescan sonar and magnetometer and (ii) and interpretation of the sub-seabed datasets including seismic reflaction and refraction data, namely sparker sub-bottom profiler (SBP) and ultra-high resolution seismic (UHRS) data.

3.1.1   Seabed Ground Modelling

The high-resolution bathymetry and sidescan sonar datasets, were used to identify seabed depressions, rock outcrops, boulders and changes in seabed sediment type across the site. Seabed sediments across the site typically comprise sands and gravels with shell fragments, with patches of outcropping rock present across the northern half of the site. Seabed sediments in the north of the site are typically less than 5m in thickness, and weathered Brioverian bedrock is present at shallow depth.

Igneous dykes of the Jersey and St Malo Dyke swarms have been identified at the site from BRGM geological mapping and were correlated with magnetic anomalies on site wide residual field magnetometry data collected in 2012. The site wide magnetometer dataset was acquired with a line spacing of approximately 50m. To constrain the locations of dykes relative to WTG locations, detailed residual field magnetometer data (20m line spacing) was used to identify the thickness and lateral extent of the dykes with a view to confirm the adequacy of ground for pile design and installation.

3.1.2   Sub-Seabed Ground Modelling

The sparker SBP and UHRS datasets acquired at the site were correlated with the available geotechnical data to produce interpretations of the base of superficial deposits, the thickness of residual soils, the top of engineering bedrock and bedrock lithology.

Ultra-high resolution seismic refraction survey data was acquired on three 25m spaced primary lines and two 25m spaced cross lines along each turbine row and was correlated to the available geotechnical data to provide a reference for the top of unweathered bedrock of high intact strength across the site. The seismic refraction survey data indicated that at WTG locations across most of the site underlain by the Neoproterozoic Binic Formation; unweathered Neoproterozoic bedrock of dominantly psammitic lithology with a high intact strength was encountered less than 20m below seabed (BSB). This predictive model was generally confirmed by the 2017 – 2018 geotechnical campaign.

3.2   Engineering Terrain Unit (ETU) Maps

The primary outputs from the integrated ground model of the site comprised ETU maps, location specific detailed geological maps, and engineering cross sections. A ETU mapping approach was used to sub-divide the site area into zones (terrain units) with relatively similar geological and geotechnical properties based on the spatial distribution of the mapped ground conditions and geohazards. This included considering the depth to high strength unweathered bedrock, bedrock lithology and the thickness of superficial deposits and residual soil. For example, the terrain units in the Binic Formation indicate a typical thickness of less than 2m of superficial marine sediments and less than 5m of residual soil.

The terrain unit maps developed for the project were used to inform the 2017 and 2018 intrusive ground investigation by summarising the

expected ground conditions present at each wind turbine and offshore sub-station location.

3.3 *Considerations in confidence levels.*

An assessment of the confidence level in the geophysical interpretation and ground modelling work has been undertaken around the planned WTGs and Offshore Sub-station locations at the site to enable assessments of potential data gaps, and the representativeness of the intrusive ground investigation data to be made. Confidence levels for areas of the site with shallow Neoproterozoic bedrock at shallow depth have been determined qualitatively based on the following criteria:

- Interpretation of the top of high strength rock from seismic refraction data. Locations have been assigned a lower confidence level where there is a poor correlation between the refraction data and the top of unweathered rock of high intact strength in the 2017 and 2018 phase exploratory holes.

- Seismic reflection and refraction data due to artefacts and mis-ties. A lower level of confidence has been assigned to locations where artefacts or mis-ties exist in the seismic geophysical data.

- Interpretation of the base of superficial deposits, and the top of engineering bedrock. Where the geophysical interpretation of these strata boundaries has been confirmed by the 2017 and 2018 phase ground investigation, a higher confidence level has been assigned to the relevant location.

- Interpreted faults and dykes. A higher confidence level has been assigned to faults and dykes that can be correlated across multiple geophysical datasets and on multiple survey lines. A higher confidence level has been assigned to dykes interpreted from the 2017 detailed magnetometer data than those features interpreted from the 2012 site wide magnetometer data.

4 MULTIVARIATE ANALYSIS

4.1 *Methodogy*

The geotechnical campaign described in Section 2 was designed to obtain a high quality dataset to allow the development of an integrated ground model in which the project could have a high level of confidence, as described in Section 3, and subsequently, to facilitate a safe and cost effective foundation design. With the objective to substantiate the interpretations during ground modelling, this section presents an assessment of the shallow rock of the Binic formation in the context of piling conditions.

The analysis results presented in this section have been defined using an in-house EXCEL spreadsheet suited to run a probabilistic multivariate analysis (MVA) following the guidelines by (Phoon and Ching 2014). The MVA determines the conditional mean and standard deviation (SD) values of the UCS and E at a specific WTG location taking into account the full dataset obtained from the other locations with the same terrain unit. The analysis concentrates on the rockhead largely affected by weathering, predominantly affecting the upper 10m strata BSB. It uses the multivariate correlations with the parameters obtained from laboratory testing data.

Table 1. Binic Formation – summary of parameters. BRAS: tensile strength; XRD-Q: quartz content

Parameter	Units	Average	SD
UCS	[Mpa]	56.4	31.9
E	[Mpa]	12,908	4,859
P-WAVE	[m/s]	4,429	560
BRAS	[Mpa]	4.2	2.0
Porosity	[%]	4.2	1.5
DDEN	[g/cm3]	25.2	0.5
RQD	[%]	49.9	17.4
XRD-Q	[%]	54	15

Based on the evidence of data correlation presented by Zhang (2012), Table 1 presents the mean and SD of the selected geotechnical

parameters used in the analysis. The conditional values of UCS and E have been determined using a matrix correlation C, defined as:

$$\delta_{ij} = COV(X_i, X_j)/(SD_i\,SD_j) \qquad (1)$$

Where δ_{ij}, quantifies the degree of linear correlation between the parameters X_i and X_j.

4.2 Variability of mechanical properties

Figure 3 illustrates two cases used to assess the conditional probability of the WTG location specific UCS with respect to the terrain unit parameters presented in Table 1. It shows, in a triple compound line, the adopted lognormal probability density function (PDF) correponding to the UCS of the Binic Formation.
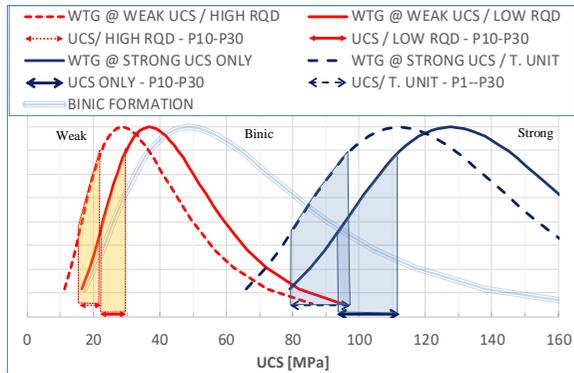

Figure 3. UCS Lognormal functions

The blue solid and dotted lines shown in Figure 3, represent the PDF of a WTG location with strong rock for the unconditional and conditional cases, i.e., the unconditional data represents the PDF of the UCS values obtained at the WTG location only, and the conditional case represents the adjusted PDF taking into account the MVA using the parametres defined in Table 1. The shaded zones represent the percentile range P10 to P30, to illustrate a typical range for defining design parameters. The UCS at a P30 of the unconditional PDF is about 120MPa as oppose to the conditionnal P30 of 95Mpa - i.e.,

the conditional P30 of UCS is 79% of the unconditional P30.

The solid and dotted red lines shown in Figure 3 represent the PDF for a location with weak rock conditioned by the correlation of upper and lower bounds of RQD respectively based on the terrain unit dataset. The shaded areas show the range of P10 to P30 for each of the PDFs. This case highlights that at a specific location, that borehole data recorded high RQD. In the event that the RQD is notably lower in a wider area unidentified by the boreholes at the WTG location, the MVA indicates that there may be a reduction of the UCS P30 of 30MPa to 21Mpa, i.e., the MVA indicates that the potential variability of the RQD and FI may affect the UCS by a reduction of up to 30% of the actual measurement of UCS from the borehole data at such location.

4.3 Depth to high strength rock

A MVA was carried out to assess the potential variability of the depth to high strength rock (HSR) with the objective to verify the sufficient pile length within competent rock. The analysis used the locations identified at a similar terrain unit with a depth to HSR lower than 10m BSB and a SD equal to 3m. The depth range was arbitarily defined based on the possible spatial strength variability that might be unidentifiable from the geophysical data, e.g., the existence of a sub-vertical thin layer of weak rock that may not be visualised from geophysical data.

The results obtained from this MVA indicate that the borehole data that recorded a relatively shallow depth to HSR equal to 0.5m BSB, it may likely be equal to 2.8m BSB considering the correlations of the terrain unit parameters in MVA, i.e., the WTG location should then consider an allowance of HRS in the order of extra 2.3m to allow for local ground variability.

Likewise, an analysis to assess the possible variability of the depth to HSR was carried out studying the effect of influence of adopting lower bounds of RMR and GSI. In this effect, a WTG location that recorded a depth to HSR of 0.7m

BSB with a high percentile of RMR and GSI, was then compared with the hypotetical case that RMR and GSI were in the lowest percentile of the PDF obtained at the same terrain unit. The conditional depth to HSR derived from the MVA was equal to 3.0m BSB with a SD of 2.4m.

5 CONCLUSIONS

Following an iterative process of geophysical and geotechnical site investigations and data interpretatation, a comprenhensive ground model for the site has been developed to inform the detailed design phase. The scope of the detailed geotechnical campaign was defined on advanced engineering understanding of the pile design and installation constraints. The progression of the campaign was continuously monitored and the scope regularly reassessed during the execution phase. The confidence in the interpretations of the different elements contained within the ground model have been evaluated to allow the derivation of ground profiles. It is recognised that the available data contained within the ground model may be insufficient to determine the exact depth to HSR at a given WTG location, due to the natural variability of the ground strata. Nevertheless, a MVA is carried out using the available geotechnical data with the aim to evaluate the sensitivity of the key parameters used for pile design. The UCS and E at WTG specific locations were evaluated using a MVA method correlating the terrain unit parameters associated with the rock mechanical properties. The MVA proves to be a useful tool to inform quantitatively on the potential variability of the ground at each WTG location in the context of the wider terrain unit. Furthermore, it is a practical tool to verify the correctness of the design scenarios considering hypotetical cases that may be unidentiable from the available data.

The continuing development of site investigation technologies that expedite a high quality processing of data together with bespoke methods to effectively facilitate the data integration studies substantiated on a robust engineering basis, are fundamental to allow the development of safe and cost effective design and installation of offshore substructures.

6 ACKNOWLEDGEMENTS

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