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Mitigating pile driving refusal risk for a North Sea offshore wind farm through design and installation planning

Mitigation du risque de refus de pieux battus pour un parc eolien en Mer du Nord durant la conception et la planification de linstallation

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ABSTRACT: The Beatrice offshore wind farm comprises 84 wind turbine generators, each supported by a four-legged jacket structure in water depth down to 55m LAT. The jacket structures were placed into pre-installed 2.2m diameter steel tubular pin piles. The variable ground conditions across the site comprised hard strata and potential obstructions such as boulders and bedrock horizons. Consequently, pile driving refusal was identified throughout the project development as a major risk with severe financial and programme implications.

A drive-drill-drive solution was developed as risk mitigation measure whereby, in the event of refusal, drilling would be undertaken through the obstruction and driving then resumed to target penetration. This paper presents the preparatory geotechnical engineering undertaken to establish a certifiable pile foundation design while accounting for the effects – due to executing the drive-drill-drive mitigation measure - on pile capacity and pile response for the jacket design. At locations where the integrated ground model highlighted higher probability of refusal, the piles were designed allowing for the potential occurrence of drive-drill-drive. For other locations, where refusal would have been an exceptional and unforeseen occurrence, some limited allowance for the beneficial effects of ageing was considered to offset some of the detrimental effects from the drive-drill-drive. The feasibility of the drive-drill-drive mitigation was assessed for scenarios considering obstructions occurring at any depth for any pile. The results were implemented in robust and straightforward procedures to inform offshore decision-making in case of unexpected driving refusal without the need for additional detailed engineering at that moment.

RÉSUMÉ: Le parc éolien de Beatrice comprend 84 turbines, chacune supportée par une structure métallique à quatre jambes à des profondeurs atteignant 55m LAT. Les structures métalliques ont été placées dans des pieux tubulaires préinstallés de 2.2m de diamètre. Les conditions de sol sur le site sont variables et comprennent des couches raides et des obstructions potentielles telles que des blocs de roche erratiques et des horizons rocheux. En conséquence, le risque de refus lors du battage des pieux a été considéré durant le développement du projet comme étant un risque majeur avec de sévères conséquences pour le budget et le programme.

Une solution de battage-forage-battage a été développée pour mitiger ce risque. En cas de refus durant le battage, un outil de forage serait utilisé pour passer l‘obstruction et le battage serait ensuite repris jusqu‘à la

profondeur finale. Cet article présente le travail géotechnique préparatoire entrepris pour établir une conception des pieux certifiable – dans le cas où la solution battage-forage-battage serait employée - tout en considérant les effets sur la capacité des pieux et sur leur comportement pour la conception de la structure métallique. Pour les emplacements où le modèle de sol intégré indiquait une probabilité de refus accrue, les pieux ont été conçus en incluant le potentiel déploiement de la technique battage-forage-battage. Pour les autres emplacements où un refus aurait été un événement exceptionnel et imprévu, une contribution limitée des effets d'évolution temporelle a été considérée pour compenser, au moins partiellement, les effets détrimentaux induits par la solution battage-forage-battage. La faisabilité du battage-forage-battage comme mitigation a été évaluée pour des scénarios considérant une obstruction se produisant à n'importe quelle profondeur pour chaque pieu. Les résultats ont été traduits en des procédures robustes et simples d'utilisation pour informer le processus de décision durant l'installation en mer - sans avoir à recourir à des analyses supplémentaires - au cas où un refus se produirait.

Keywords: Drive-drill-drive; driven piles; pile refusal mitigation; foundation design; installation planning

1 INTRODUCTION

The Beatrice offshore wind farm is located in the Moray Firth, Scotland. The site is approximately 13km off the Caithness coast in water depths ranging from circa 35 to 55m LAT. Once fully operational it will have a capacity of 588MW from 84 wind turbine generators (WTG) providing clean electricity for 450,000 homes.

Offshore installation started in Spring 2017, first power was generated in July 2018 and the wind farm is planned to be fully operational in Spring 2019.

2 BASE CASE DESIGN

The WTGs are supported on steel jacket substructures founded on pre-driven piles. The 2.2m diameter steel tubular piles are driven through a pile installation frame (PIF) lowered on the seabed. The jacket is then stabbed into the pre-driven piles and a grouted (see Figure 1).

The piles are driven proud of the seabed. WTG locations across the site are grouped in clusters based on water depth. In each cluster the pile stick-up height above seabed is varied to provide an even bearing level for the jackets which enables standardisation of the jacket design.

It is essential that the piles are driven to their target penetration within strict tolerances to ensure that the shear keys provided inside the top of the pile are at their target elevation for the grouted connection between piles and jacket stab-ins to work as designed.

Early refusal of a pile, if not mitigated, would prevent the successfull installation of the jacket. Consequently, pile driving refusal was identified throughout the project development as a major risk with severe financial and programme implications.

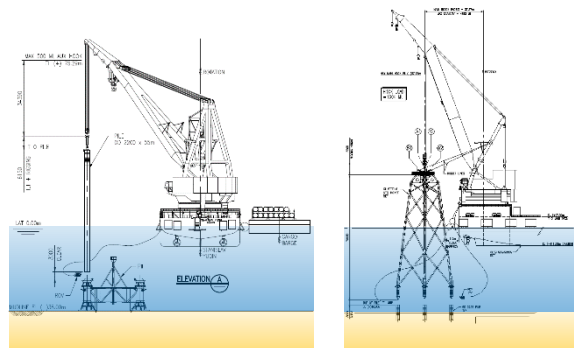


Figure 1. Pile and jacket installation sequence

The pile design is governed by consideration of axial capacity with due allowance for the effects of cyclic loading from wind and wave loading during storm events. The axial pile capacity was assessed using the Imperial College Pile (ICP) design method (Jardine et al, 2005).

Further detail on the general geotechnical design approach and issues for pre-piled jacket substructures is provided in (Manceau and Benson, 2017).

3 IDENTIFIED REFUSAL RISKS

The Site is underlain by Lower Cretaceous bedrock which has been folded and faulted and has an eroded upper surface. During the Quaternary, the British Ice Sheet repeatedly expanded and contracted, and the Moray Firth was the location of fast flowing ice streams that have eroded and disturbed the bedrock, and deposited a late Quaternary succession of glacial till, glacio-fluvial, glacio-lacustrine, and glacio-marine sediments on top of it.

The 3-D ground model developed combining the findings from geophysical surveys and intrusive ground investigations identified and mapped a number of horizons within the Lower Cretaceous, some of which include sandstone beds of limited thickness (see Figure 2). Furthermore, the presence of boulders that may occur randomly across the Quaternary strata could not be ruled out.

Both the sandstone beds in the Lower Cretaceous and the boulders in the Quaternary were identified as being obstructions of limited thickness that may lead to pile refusal.

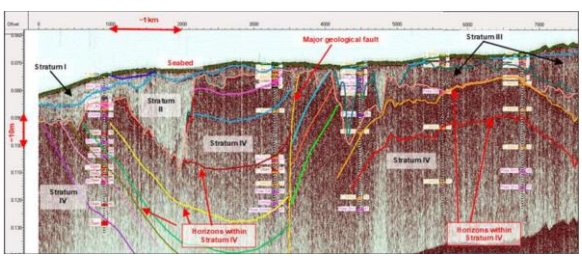


Figure 2. Interpreted horizons

4 DRIVE-DRILL-DRIVE

In the event of premature pile refusal on an obstruction, a drive-drill-drive technique was selected as the preferred mitigation to enable the pile to progress through the obstruction and reach target penetration.

Figure 3 illustrates the drive-drill-drive technique for the case of an obstruction relatively high up relative to the pile target penetration. The various stages are as follows:

1. Drive pile to refusal on obstruction and disengage hammer;
2. Lower drilling equipment and drill to remove the soil inside the pile;
3. Extend drilling through the obstruction to a maximum of 1.5m below the pile tip;
4. Remove drilling equipment;
5. Place backfill to fill open hole below pile tip and inside of the pile; and
6. Re-engage the hammer and drive to target penetration.

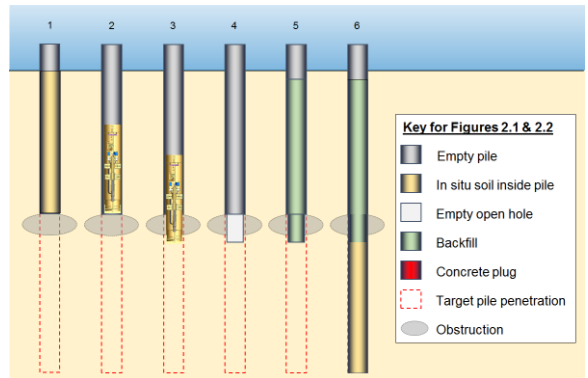


Figure 3. Drive-drill-drive – Without concrete plug

For the case of an obstruction close to the target pile tip elevation, consideration was also given to the installation of a concrete plug to provide sufficient capacity (see section 7).

5 DRIVE-DRILL-DRIVE IMPACT ON PILE CAPACITY

Compared to the baseline design for a fully driven pile, the drive-drill-drive technique will lead to some reduction of shaft capacity and, if drilling is required close to the pile target penetration, some reduction of available end bearing capacity.

A literature review of available published data found that there was only limited data pertinent to the assessment of pile capacity reduction.

5.1 Shaft capacity reduction from drill-drive

Drilling will lead to reduction of shaft capacity:

- Over the drilled length due to stress relaxation;
- Immediately below the drilled section due to stress relaxation and potential changes to the flow path of soil on restart of driving; and
- Immediately above the drilled section due to stress relaxation and potential for material to 'collapse' into the drilled section.

This is illustrated on Figure 4.

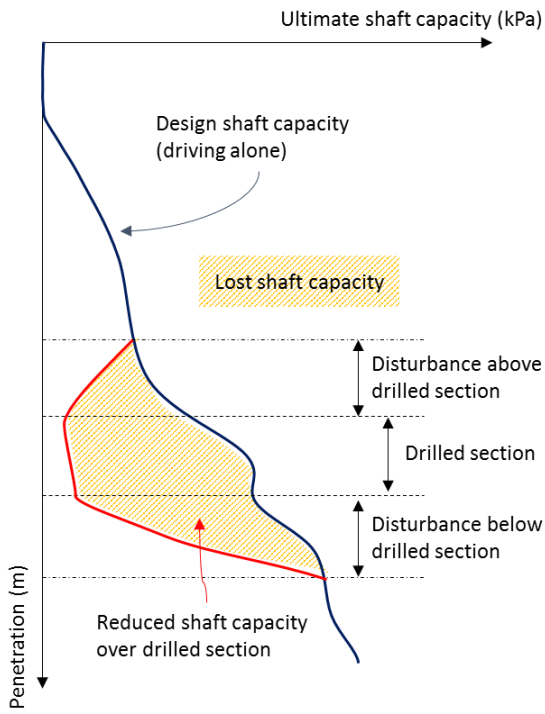
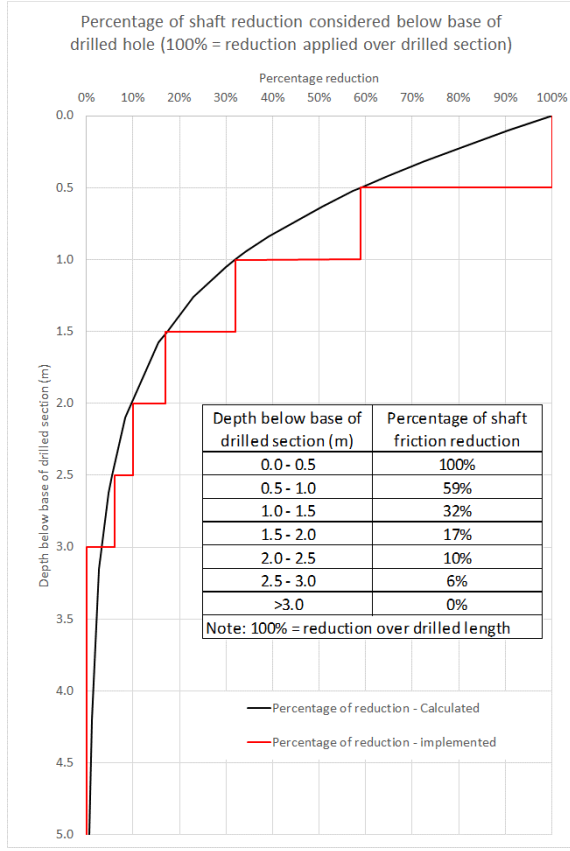


Figure 4. Reduction of shaft friction from drive-drill-drive

Over the drilled section, the reduction of shaft capacity was assessed using a methodology derived based on the work on conductors presented by Overy and Sayer (2007) in sands and on the 1-g small-scale laboratory study conducted on close-ended model piles presented by Carneiro and Jardine (2012) in clays with some modifications to account for large diameters open-ended piles.

For the section immediately below the drilled section, the reduction in shaft capacity was estimated by analogy with the reduction in radial stress from elastic solutions at the edge of a circular area unloaded at the surface of a semi-infinite elastic mass tabulated by Ahlvin and Ulery (1962). Figure 5 illustrates the reduction of shaft capacity (for a pile in sand) below the drilled section.



Depth below base of drilled section (m)	Percentage of shaft friction reduction
0.0 - 0.5	100%
0.5 - 1.0	59%
1.0 - 1.5	32%
1.5 - 2.0	17%
2.0 - 2.5	10%
2.5 - 3.0	6%
>3.0	0%
Note: 100% = reduction over drilled length	

Figure 5. Reduction of shaft friction below drilled section (sand)

For the section immediately above the drilled section, the reduction in shaft capacity was considered by mirroring the reduction in shaft capacity modelled for the section immediately below the drilled section.

5.2 End bearing capacity reduction from drill-drive

In sands, the ICP unplugged end bearing resistance is made up from a component of bearing below the annular area (approximately 70% of the total) and a component of internal shaft friction generated over a relatively short distance above pile tip (approximately 30% of the total). The effect of drilling on both of these mechanisms was considered.

The reduction of the annular component was estimated by analogy with the reduction in vertical stress from elastic solutions at the edge of a circular area unloaded at the surface of a semi-infinite elastic mass tabulated by Ahlvin and Ulery (1962). The backfill was ignored, since any stress relaxation would occur prior to backfill placement and would not be expected to be fully repaired by backfilling. The reduction of the internal shaft friction component of end bearing was estimated by comparing calculated ICP end bearing capacity with drained plug end bearing capacity estimated using the one dimensional method proposed by Randolph et al (1991) considering the influence of the backfill. Figure 6 illustrates the proportion of the ICP end bearing capacity of a fully driven pile considered (for a pile in sand) as a function of the distance from the base of the drilled section to the pile final penetration.

In clays, Jardine et al (2005) suggest that the majority of the ICP end bearing component for unplugged piles originates from end bearing below the pile annulus, with little conttibution from internal shaft friction. The end bearing reduction was therefore assumed in a similar manner to the reduction of the annular component in sands.

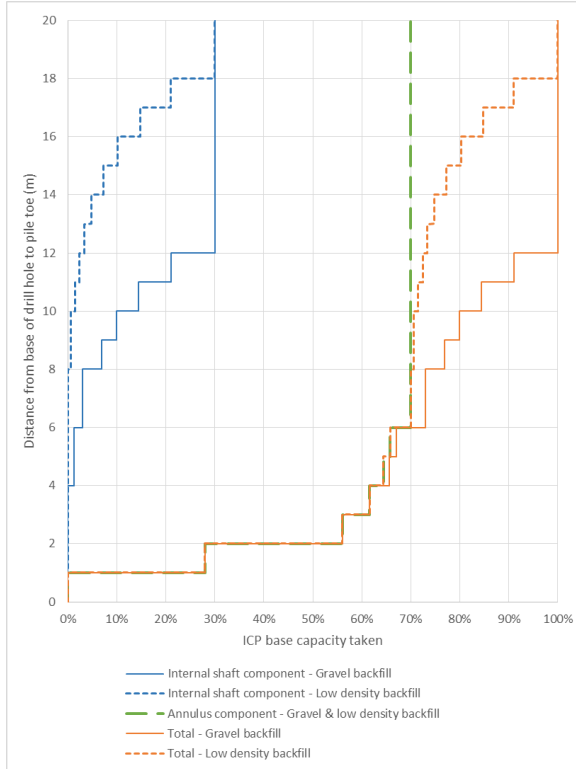


Figure 6. Proportion of ICP end bearing of a fully driven pile considered vs distance between base of drilled section and final pile tip penetration

6 LIMITED ALLOWANCE FOR PILE AGEING

6.1 Ageing

The shaft capacity of driven piles increases over time, a phenomenon commonly referred to as ageing. The effects are particularly significant in sands where evidence from pile load tests indicates that the shaft capacity 100 day after pile driving can be more than double the shaft capacity 10 days after pile driving as calculated using the ICP method (see Figure 7). However the capacity gains can be brittle and prevented by high amplitude cyclic loading. In clays there is also evidence of ageing but the capacity gains are more modest.

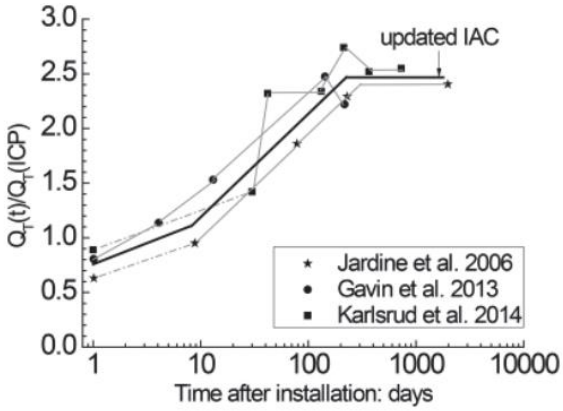


Figure 7: Updated Intact Ageing Characteristic (Rimoy and Jardine, 2015)

The quantification of ageing remains an area of active research and the pile penetration in the baseline design did not allow for any beneficial effect from ageing.

However, the installation programme included significant time lapses between pile installation, jacket installation, WTG installation and WTG commissioning. Prior to the WTG installation the piles would be subjected to limited cyclic loading only over a period in excess of 200 days and this was assessed to not have any detrimental effect on pile capacity or prevent the development of ageing. In fact some of the very low level cyclic loading would probably accelerate the pile ageing process.

Some limited allowance for the benefits of ageing in sands was therefore considered to justify acceptable pile capacity in the case that drive-drill-drive installation was used. The increases in shaft capacity from ageing partially, and in some instances completely, offset the reductions of shaft capacity and end bearing capacity from the drive-drill-drive installation technique.

7 CONCRETE PLUG

For cases where drilling is required close to the pile tip leadign to a severe reduction of pile capacity from the drive-drill-drive and only modest increases of shaft capacity can be justified from ageing, consideration was given to installing a concrete plug at the base of the pile to increase the available geotechnical end bearing and achieve the required level of safety in compresison.

8 IMPLEMENTATION

A tool was developed to calculate pile axial capacity in the event that the drive-drill-drive mitigation was implemented. It considered:

- Reductions in shaft capacity and end bearing capacity resulting from the drive-drill-drive installation technique (as discussed in Section 5);
- Increases in shaft capacity resulting from the limited ageing allowance in sand layers; and
- End bearing capacity from concrete plug

8.1 The known unknowns

For locations where the ground model identified the presence of horizons associated with sandstone beds that may result in refusal, the pile design considered the potential reduction of capacity (compared to the baseline fully driven pile capacity) resulting from the potential use of the drive-drill-drive mitigation to progress the pile through the identified sandstone beds. No allowance was made for ageing in these cases; the reduction in capacity from potential drive-drill-drive were offset by increasing the pile penetration (compared to the baseline fully driven case). In addition, the design included the provision of high steel grade cans at pile tip.

8.2 The unknown unknowns

For locations where the ground model did not identify any sandstone beds, the risk of refusal was deemed low but could not be completely ruled-out.

If such an unexpected refusal occured and the drive-drill-drive mitigation were implemented,

the pile capacity would be reduced compared to a fully driven pile. A more refined engineering approach was adopted to assess conditions where such piles could be safely used. The approach included a limited allowance for ageing (i.e. pile capacity gains over time).

During the installation planning phase, the tool was used to assess the impact of the drive-drill-drive mitigation measure being deployed to progress through a 1.5 thick obstruction at any elevation. For every location, the assessment defined the range of depths where, if a refusal occured:

- The pile could be accepted with the drive-drill-drive mitigation without the requirement for a concrete plug;
- The pile could be accepted with the drive-drill-drive mitigation with the provision of a concrete plug; and
- The pile could not be accepted and had to be abandoned and the WTG location micro-sited.

The results were presented graphically and in tabular format (see Figure 8).

WTG Location	Design Penetration	Pile Tip Penetration at Start of Drill-out					
		Single Drill-out FEASIBLE		Concrete Plug Required		Single Drill-out NOT FEASIBLE	
		from (m)	to (m)	from (m)	to (m)	from (m)	to (m)
BE-A5	40.0	0.0	40.0	20.0	40.0		
BE-E10	48.0	0.0	48.0	44.0	48.0		
BE-E11	44.9	0.0	39.5	38.0	39.5	39.5	41.5
		41.5	44.9	41.5	44.9		
BE-F9	39.7	0.0	35.5	22.0	27.0	35.5	37.5
				32.5	35.5		
		37.5	39.7	37.5	39.7		
BE-F10	43.8	0.0	43.8	40.0	43.8		
BE-F11	31.2	0.0	31.2	28.5	31.2		
BE-F12	28.5 [x]					0.0	28.5
BE-G9	37.6	0.0	37.6	28.0	37.6		
BE-G10	37.1	0.0	37.1	33.0	37.1		
BE-H9	43.0	0.0	43.0	16.0	43.0		
BE-H10	41.4 [x]					0.0	41.4
BE-J9	36.2	0.0	32.0			32.0	34.5
		34.5	36.2	34.5	36.2		

Figure 8: Typical tabular output for offshore decision-making

These easy to use outputs were created to inform decision-making offshore in the event of an unexpected driving refusal without the need for further analysis at that time and delay.

9 CONCLUSIONS

For the Beatrice offshore winfarm the WTGs are supported on steel jacket substructures founded on pre-driven piles. It is essential that the piles are installed to target penetrations within strict tolerances. The base case design assumed driven piles designed using the ICP method.

Pile driving refusal was identified throughout the project development as a major risk with severe financial and programme implications.

The 3-D integrated ground model identified and mapped some horizons within the Lower Cretaceous including sandstone beds of limited thickness. Furthermore, boulders could be randomly distributed in the Quaternary. The risk of refusal on obstructions of limited thickness such as sandstone beds or boulders could not be ruled out and a mitigation measure had to be developed.

The mitigation measure consisted of the use of a drive-drill-drive instllation technique in case of refusal. A methodology was developed to estimate the reduction of pile capacity (compared to a fully driven pile) resulting from stress relaxation occuring during the drilling. At locations where a significant risk of refusal on mapped sandstone beds had been identified, the pile penetration was increased such that the pile capacity would remain adequate in the event of the drive-drill-drive being used.

At locations where the ground model had not identified any sandstone beds the piles were sized assuming a fully driven installation. However, the risk of refusal on an obstruction requiring the use of the drive-drill-drive technique to install to target penetration could not be ruled out. For these locations, some limited increase of shaft capacity in sand layers owing to ageing was allowed for. The possibility of installing a

concrete plug in the event of drilling near the target penetration was also considered. The impact of the drive-drill-drive mitigation measure being deployed to progress through a 1.5 thick obstruction at any elevation was assessed for every location. The outputs were presented in simple easy-to-use graphical and tabular formats to enable decision-making offshore without the need for any analysis at that time.

The pile driving refusal mitigation methodology was developed in collaboration between Atkins and Seaway Heavy Lifting. Early engagement with BOWL and DNV-GL was essential in achieving approval. The engineering work undertaken in the design and installation planning phases was key in de-risking the project.

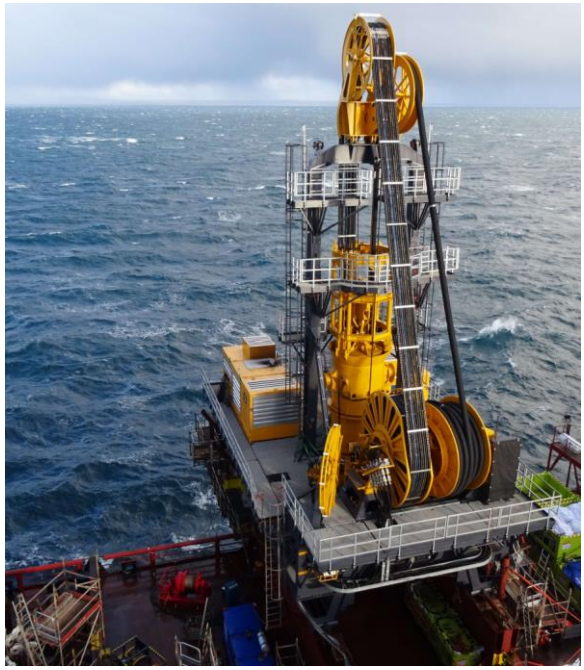


Figure 9: Drilling spread mobilised offshore

Eventually, all 336 piles for the WTG jackets totalling more than 14 km and 44,000 tonnes were successfully driven to target penetration before the end of 2017. All the jackets have also been succesfully installed and turbines installation is currently ongoing. First power was generated in July 2018.

10 ACKNOWLEDGEMENTS

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