Large Scale Offshore Static Pile Tests – Practicality and Benefits

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Abstract
Iberdrola is developing the 350MW Wikinger offshore wind farm in the German Baltic Sea where ground conditions are dominated by Glacial Tills and Chalk. A review of current pile design methods highlighted significant design uncertainties that could lead to unnecessarily conservative pile dimensions for the seventy four-legged jacket wind-turbine support structures and one six-legged offshore substation. To address these concerns, the project commissioned, in advance of final design, offshore dynamic and fully autonomous static pile load tests, that were completed 10 weeks after driving, on 1.37m diameter piles with penetrations of up to 31m, in water depths of around 40m. This paper provides an overview of the testing and its practicalities as well as outlining the project risks and opportunities that justified the field testing programme. Lessons learned are shared and conclusions are drawn regarding pile test feasibility, design and planning. Cost-benefit analysis demonstrates the potential value of offshore static testing in future offshore developments that face comparably difficult ground conditions.

1. Introduction

Iberdrola is developing the Wikinger Offshore Windfarm (OWF) in the German Baltic Sea, halfway between the German island of Rügen and the Danish island of Bornholm. Seventy Wind Turbine Generators (WTG) and one Offshore Substation (OSS) have now been installed in water depths between 35m and 42m, giving a 350MW total installed capacity.

The WTGs are supported by four legged jackets founded on open steel piles with outside diameters of 2.7m (106") while the OSS relies on a six legged jacket with 3.66m (144") diameter piles. The bearing layers consist of Glacial Till over Chalk, which, in terms of the Lord et al. (2002) classification system, varies from Grade D (structure-less low density) to Grade A1/A2 (structured low to medium density). Further details on the range of soil conditions encountered at the site and on the selection of test pile locations are provided by Barbosa et al. (2015).

The pile loading is predominantly axial and shaft resistance governs design. A review of current design methods and related onshore pile tests (Barbosa et al., 2015) highlighted significant uncertainties and led to the decision to conduct advance dynamic and static offshore tension tests in two phases. Phase I involved installing nine piles at three test locations giving a representative spread of the OWF's ground conditions. Pile driving monitoring and Dynamic Load Testing (DLT) was performed on six piles at the End of Driving (EoD). Intermediate DLTs were also incorporated after short driving pauses necessitated by the test arrangements.

A rest period of 10 weeks followed pile installation to allow excess pore pressures to dissipate (particularly in the Tills) and soil set-up to progress, especially in the Chalk. This rest period was the maximum possible within the project deadlines. It also matched the time that could be safely expected to elapse between pile driving and WTG installation.

Phase II of the advance field trials involved Static Load Tests (SLTs) on one pile from each of the trio driven at the three locations, followed by a re-strike DLT on an identical adjacent test pile. The test piles' details were as follows:

- outside diameter 1.37m, downscaled by 50% diameter from the production piles to reduce load test equipment size and costs;

- wall thickness of 40mm, identical to the production piles to ensure similar remoulded chalk interface thicknesses (see Muir Wood et al., 2015); and
- penetrations of 16.8m to 31m, that were representative of the production piles, considering a conservative estimate of set-up and safety factors allowable after pile testing.

2. Risks and Opportunities

2.1 Risks

The project's interest in conducting offshore pile tests was motivated by risks perceived around the design consent process. Difficulties in establishing a comparable onshore test site for another Baltic Sea Chalk OWF had indicated a high risk of delays to design consent, and consequently the start of construction (Knight, 2012). The risk associated with delays to construction and first power were quantified and resulted in a significant loss of project present value and other potential long term losses such as reduced energy tariffs.

Design consent assurance was critical to the project's €1.4bn Final Investment Decision (FID), which had to be made just before the major supply and installation contracts could be signed. However, the 2nd and 3rd releases from the German BSH regulatory body required to start construction are generally granted at a much later stage. Therefore, developers have to proceed at risk in the intervening period between FID and BSH releases. Any design changes or conditions imposed at the release stage are likely to result in variations requiring scope, programme and cost re-negotiations with pile supply, fabrication and installation contractors. Restricted vessel availability and installation windows may also result in longer weather downtimes and further project costs and delays.

The adjusted risk cost, which considered both event probabilities and the possible consequences of problems with BSH releases, was conservatively valued in the low 10s of €M. An offshore test programme, at a cost below this risk cost was therefore economically attractive.

2.3 Opportunities

A tender process was launched in 2013 to evaluate the appetite for, technical feasibility and costs of offshore pile testing. Several submissions were received detailing various feasible technical solutions. The proposals were carefully reviewed and technical details discussed with potential contractors with the aim of ensuring test quality and avoiding and mitigating potential pitfalls at an early stage. This process led to a competitive tender that allowed an extensive offshore pile test campaign at a cost that was significantly lower than the adjusted risk costs discussed above. The offshore testing campaign created opportunities to:

- optimize pile design and save pile steel;
- validate the DLT equipment and procedures to be used later during construction; and
- inform the selection of noise mitigation systems to minimise pile driving impact on marine mammals.

Optimized pile design was expected to generate significant steel savings because of the combination of less stringent design factors being required and the possibility of improved design soil parameters being justified, especially for the Chalk. Site specific pile testing allowed the partial factors used in design to decrease from 1.4 to 1.1 in compression and 1.5 to 1.15 in tension (DIN 1054, 2010-12). However, during the final design it was found that reducing the partial factors alone did not yield practical benefits as the associated benefit was counterbalanced by an increase in expected cyclic degradation during the design storm. Nonetheless, the test results justified considerably improved design soil parameters allowing large reductions in pile steel.

A further requirement by BSH (2011) is that DLTs are performed during construction on at least 10% of the WTG locations to demonstrate sufficient pile capacity. This requirement is particularly onerous for developers as the standard DLT interpretations do not recognize any contribution to pile capacity from set-up after driving. In media such as Chalk that can develop marked set-up, EoD DLTs can give highly conservative indicators of operational pile capacity. However, if DLTs are to be conducted at later dates it is necessary to recover instrument cables to deck for sealing and conditioning before returning them to the seabed employing systems that ensure safe storage, easy retrieval and reliable operation at the re-strike date. It is also necessary to remobilise vessels, equipment and personnel to carry out the re-strikes and DLT measurements. In this respect it is important on Health & Safety grounds to undertake, if possible, the operations without divers.

Additional benefits were taken from the testing campaign by applying experience gained from the Phase I driving monitoring and the Phase II testing to the procedures applied during the DLTs of the production piling operations. Noise mitigation system monitoring during the trials also informed the choice of noise mitigation systems for construction. Noise emissions during test pile installation were considerably higher than expected and very close to the threshold limit imposed by the German authorities. The noise emission prediction models were therefore revised and it was concluded that more effective mitigation systems would be required during construction. The noise emission monitoring trials allowed for the proper planning and design of the final mitigation systems and so avoided costly construction stops.

3. Pile Test Campaign

3.1 Selection and design of pile testing systems

EA-Pfähle (2014) and DIN EN 1997-1 stipulate a number of criteria for SLTs that exclude constant rate of penetration procedures (CRP) and require a maintained load (ML) approach. The selection and design of the pile testing system was dominated by the SLT requirements with the three most appropriate and important objectives being to:

1. provide test data to allow the pile design to meet the BSH and DIN requirements;
2. define ultimate pile resistance and load-displacement behaviour under slow monotonic loading, including the piles' short-term creep characteristics; and
3. investigate the cyclic stiffness under a load cycle imposed around the characteristic pile load and other load levels.

In order to satisfy these objectives and maximise the value of the SLTs, the key technical issues addressed during the procurement process were:

1. rules to guide the specification (during testing) of load increments to ensure load-displacement behaviour was captured without ambiguity and clear criteria set for the definition of the ultimate pile resistance;
2. accuracy and precision of pile displacement and load measurement systems; and
3. stability and control of the applied pile load in the offshore environment.

Designing the SLT system to achieve the technical objectives involved assessing the ultimate pile resistances for each test location. Underestimates would lead to an inability to provide unambiguous definitions of ultimate pile resistances, whereas overestimates would lead to over-dimensioned and potentially unaffordable testing systems. The final design requirement set for the load system was to apply a maximum load of 15MN; several times the required design load estimated by the project team. However, the set-up developed in Chalk proved far greater than expected and the 15MN rig capacity proved insufficient to obtain full failure at the two Chalk dominated locations. Extrapolation of the pile creep trends observed under maintained load stages and correlation with the successful parallel dynamic re-strike tests allowed the tension capacities to be estimated for these cases with reasonable confidence.

Three different pile testing systems were considered during the tendering process: (i) floating vessel/barge solutions, (ii) jack-up rigs and (iii) fully autonomous seabed systems. The successful tenderer (Bilfinger Construction GmbH) proposed the fully autonomous seabed systems indicated in Figure 2, essentially consisting of a central SLT pile, two outer reaction piles (one of which was used for DLTs during Phase II) and a reaction beam. Even in the relatively mild Baltic Sea conditions, the main technical disadvantage of any floating solution was its susceptibility to variations in the verticality and magnitude of the applied loads due to actions of currents, waves and tides. While a jack-up rig would provide a more stable platform for undertaking the SLTs, technical disadvantages included potential disturbance caused by the spudcan footings, possibly affecting the testing campaign and the later jacket installation.

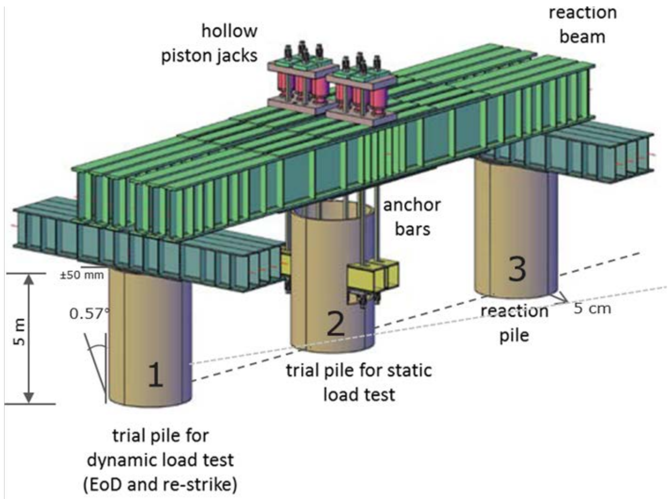

Figure 2: General arrangement for sea bed testing system.

Detailed discussions with the Authors led to a final pile testing system that worked well. One limitation was the load carrying capacity of the connection system deployed to link the test pile to the loading assembly. The potential risk of an insufficient system capacity was raised at various stages, but it was not feasible within the project timescales and resources to raise its rating. While a higher capacity would have proved valuable, the static and one-way cyclic testing offered good load control and high resolution load and displacement measurements.

Recognising that the field testing programme would have to be limited and could not address all of the scientific questions raised concerning driven pile behaviour in Chalk, Iberdrola, Imperial College and GCG made a successful research grant application to Innovate UK and launched a Joint Industry Project (JIP) that involved close analysis of the Wikinger offshore tests and new experiments at the St. Nicholas site at Wade in Kent (Buckley et al., 2017).

3.2 Pile driving and Phase I testing

The pile testing campaign (Phases I and II) was performed between September 2014 and January 2015. The custom built pre-piling template shown in Figure 3 ensured accurate positioning of the three test piles driven at each test location.

Figure 3: Pre-piling template

The piles were driven with a hydraulic Menck MHU800S hammer whose output was limited to 500kJ during driving, as contractually stipulated. A major pile installation challenge was to control the hammer energy output to avoid excessive set per blow. Resistance to driving was low, with an average 8 blows required per 0.25m penetration.

Installation pauses were planned for each pile to allow the pile guides to open and avoid damaging the DLT sensors; driving halted for between 5 and 25 minutes, when the piles were approximately 7m from target depth, The interruptions resulted in a noticeable increase in the resistance to driving at the Chalk dominated locations, with a higher hammer blowcount measured at re-start and over a limited distance of 1 to 5m after as shown in Figure 4.

Buckley et al (2017) give further details of advanced stress wave matching analyses of the DLT data undertaken as part of the associated JIP. The stress wave matches confirmed shaft resistances between 10 and 20kPa during continuous driving in Chalk.

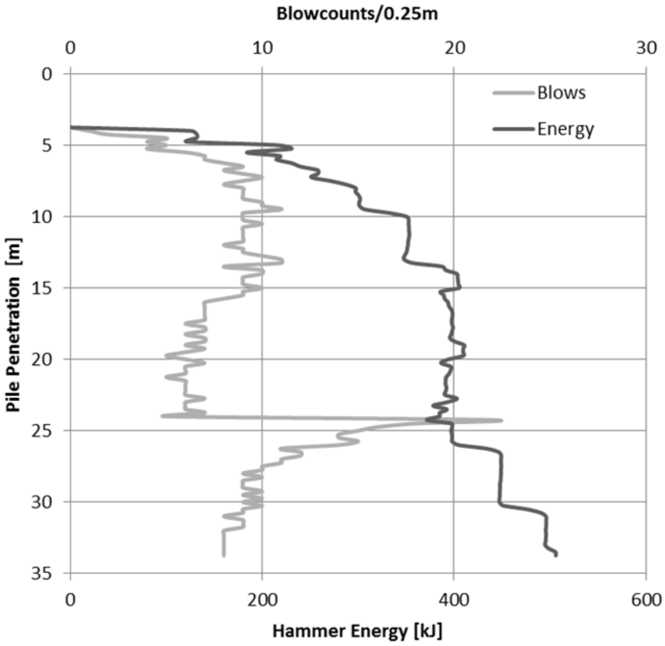

Figure 4: Driving records location 1

The pile capacities interpreted at the re-start of driving at the Chalk dominated test locations were 2.5 times those before each (5 to 25 minute) driving pause, although these gains degraded rapidly after re-starting (see Figure 4). No such short term capacity gains were evident after the driving pause at the Glacial Till dominated test location.

Following pile installation the 100m long dynamic pile monitoring instrument cables were recovered back to deck and conditioned for storage. The recovery was managed by an ROV and personnel on deck. The cables were pulled below the pre-piling template and returned to the vessel, so that the template could be recovered without damaging any cable. On deck, the cable connections were sealed in waterproof terminations and the cables reeled onto a special drum that was then lowered to the seabed. Its position was logged carefully in the survey system to facilitate later recovery.

3.3 Post driving operations and Phase II testing

Once the Phase I work was completed and all the cables safely secured, the pre-piling template was retrieved and modified for later service as a static pile displacement measurement reference system during Phase II of the testing campaign (see Figure 5). The pre-piling template top section was removed and a displacement measurement set-up added into the centre SLT pile position. This consisted of a guide cone, a moveable ring and a subsea extensometer system provided by NGI allowing pile head movement measurements to be made at three points relative to a remote datum.

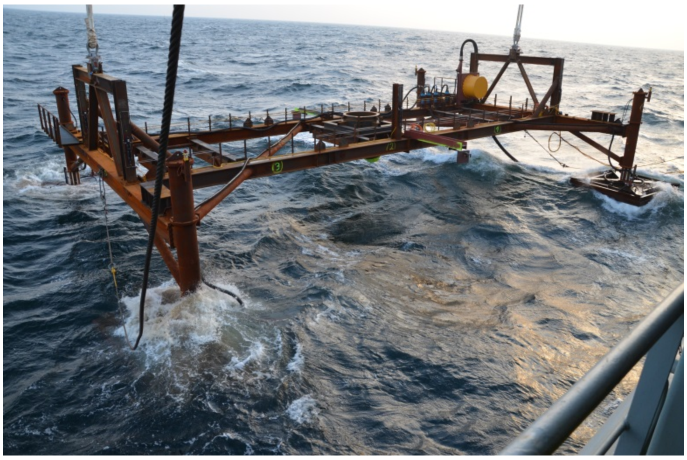

Figure 5: Reference frame

The moveable ring was positioned by lowering the reference frame's extended mudmats in a stepwise procedure. The moveable ring finally rested on pre-installed brackets placed on the outside of the SLT pile. The position of the moveable ring was confirmed by the displacements measured in the subsea extensometers. After placing the reference frame, the test frame shown in Figure 6 was lowered to the seabed. A guide cone facilitated the placement of the connecting and loading system for the centre SLT pile. The test frame was rotated until the catcher plates contacted the reaction piles and then lowered onto the reaction piles. With the frame in position, locking plates were hydraulically activated and latched into a steel ring inside the SLT pile. The latching process was monitored through subsea cameras installed in the test frame.

Figure 6: Load test beam and frame

Static testing was then initiated. The test loads were applied in tension by hydraulic actuators fed from the surface vessel and the loads were measured by subsea load cells. The SLT was conducted as a maintained load or creep test in accordance with EA-Pfähle (2014). Loading was applied through an array of jacks on the seabed frame that were fully programmable by the test operators. Each load step was maintained for at least 30min and the full SLTs took between 13 and 18 hours to complete.

3.4 Phase II: Static Load Test results

The SLT experiments were performed to meet a failure criterion defined by the semi-logarithmic creep rates developed under maintained load steps. The critical 'failure' rate was chosen as 4mm/log cycle of time, which was adjusted up from the 2mm/log cycle of time specified in EA-Pfähle (2014) to take account of the relatively large test pile dimensions.

It was fundamentally important to have a stable load system and a high resolution displacement measurement system in order to accurately determine the creep rates developed under each load step. The displacement measuring system was stable to around 10μm and the hydraulic loading system was also very steady, limiting load variations to within ±40kN in tests that applied up to 15MN. Overall, the system was able to perform the three SLTs without any malfunction. Figure 7 presents the load versus time trends for the Glacial Till dominated location, demonstrating the excellent load control achieved. Post-failure cyclic loading was also applied successfully at this test location.

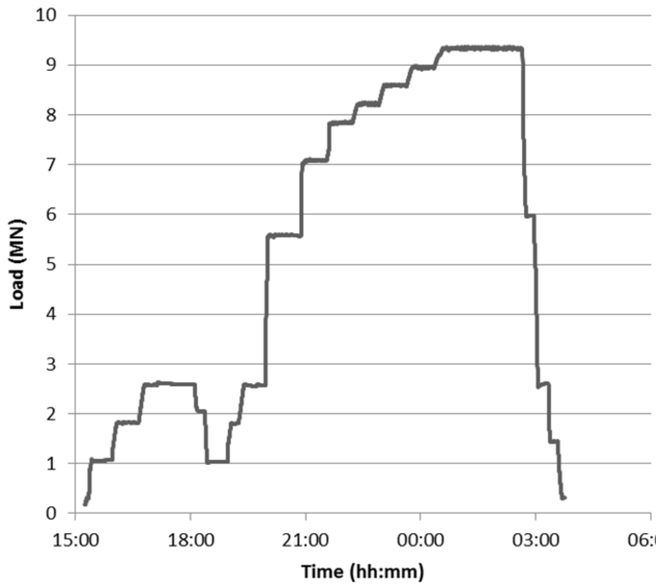

Figure 7: SLT load vs time for Glacial Till dominated location

Three equal load steps were applied at the start of each test, with predefined 30 minute pause periods (see Figure 7). Once a 2.6MN load had been reached (which corresponds to half the WTG characteristic tension load, so accounting for the test pile scale factor) the pile was unloaded to the first load step before being reloading back to 2.6MN. From this point onwards, the magnitudes of the load steps were determined by the creep rates measured in the previous stages following the procedure outlined by Barbosa et al. (2015).

The stable resolution of the displacement measuring system allowed reliable creep rate measurements to be made for each load step. Creep was negligibly small at the Glacial Till dominated location within the envelope of the expected loads and only became noticeable after reaching 5.6MN. Creep rates increased over the following load steps until failure was determined at 9.3MN (see Figure 7). The 4mm/log cycle of time failure criterion is compared with the measured data in Figure 8. The creep rates approached the failure criterion 15 to 30 minutes into the final maintained load period, before increasing markedly as the load period extended.

The final displacement was 29mm and the displacement recorded after final unloading was 22.5mm. Even this 'post-failure' movement is not large compared to the maxima that the jackets can tolerate. A 22.5mm movement of one corner would give a 0.1° inclination over the footprint of the WTG jackets, which is five times less than the allowable operational inclination of 0.5°.

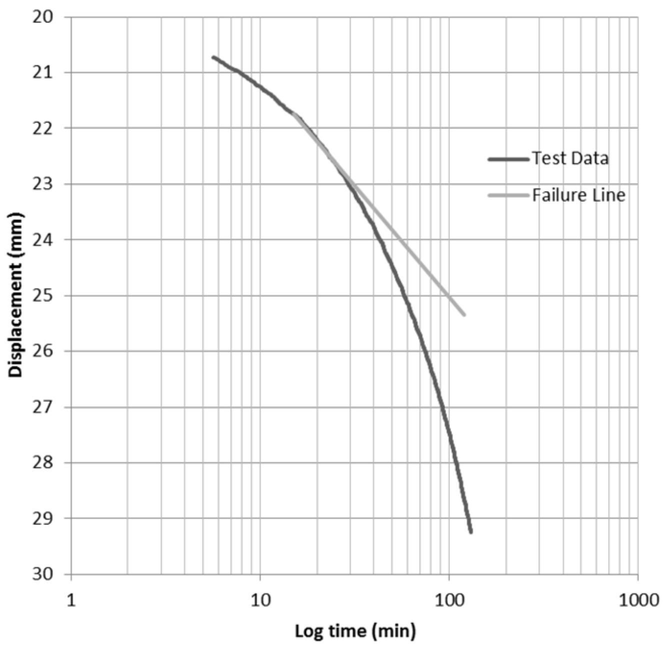

Figure 8: Displacement vs log time at failure load step; Glacial Till dominated test location.

3.5 Phase II: Dynamic Load Tests (DLTs)

DLTs were performed at each of the three test locations following the SLTs by re-striking identical adjacent piles. The first step was to recover the cables stored on the seabed with an ROV and return them to deck (see Figure 9). The long term re-strike DLTs were then performed with a hydraulic Menck MHU800S hammer whose maximum driving energy was increased to 800kJ.

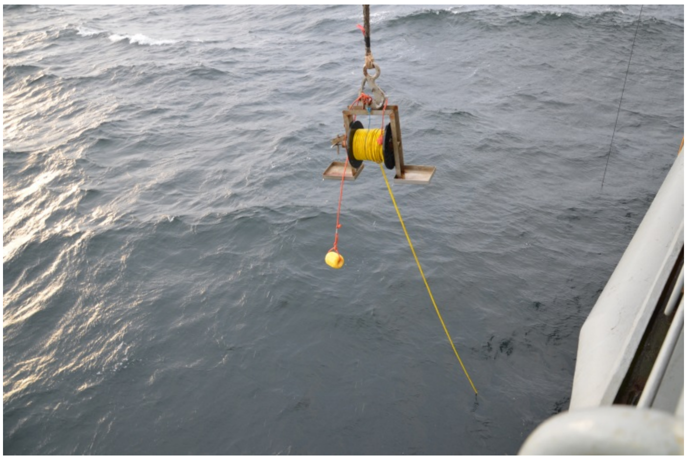

Figure 9: Recovery of DLT cable stored on the seafloor

A permanent set per blow of at least 2mm is recommended by ASTM D4945 (2012) to mobilize full pile capacity during DLTs. After the 10 weeks rest period the permanent set per blow achieved at the Chalk dominated locations were only marginally greater than this (3mm) and the toe response of the recorded stress wave signals were weak. When further blows were applied at maximum energy, shaft resistance decreased and set increased allowing clearer definitions of the toe response. Further signal matching analysis concluded that the full pile capacity was not measured during the initial re-strike DLTs. This experience highlighted the importance of hammer selection and the careful consideration of waiting periods and set-up effects.

Stress wave analysis of the Phase II DLTs by Buckley et al. (2017) indicated that overall pile capacities had increased by up to 6 times over the 10 weeks that followed EoD. The impact on pile design can be gauged by considering, in Figure 10, the pile capacities 'measured' by DLTs at the two Chalk dominated locations normalized by the (scaled down) characteristic compressive load that the WTG jacket piles are expected to carry. As shown, the long term capacity far exceeds the required value even though the EoD capacity falls well below the design requirement. The remarkable gains seen after even short term driving interruptions evidently continued to accumulate at the Chalk dominated locations over the piles' 10 week ageing period. Significant, but notably smaller, gains in capacity were inferred from the single Phase II DLT performed at the Glacial Till dominated location.

The DLT outcomes provided additional information that helped to improve confidence in the extrapolation required to interpret the SLT capacities at the two Chalk dominated sites, assuming that in the SLTs reverse end bearing does not occur in the essentially free draining structured chalk and that the tensile shaft friction from the SLTs equates to the compressive shaft friction from the DLTs.

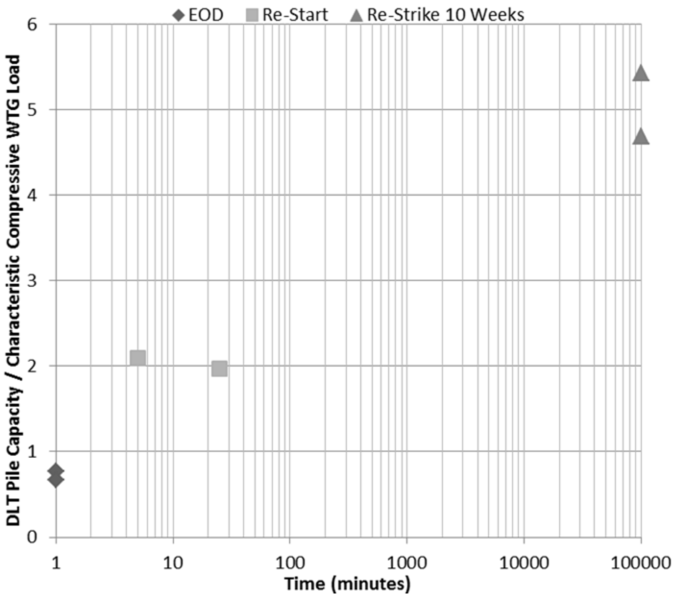

Figure 10: DLT pile capacity for Chalk dominated location normalized by the downscaled characteristic WTG load

4. Cost Benefits

The offshore pile testing campaign was hoped to mitigate the Wikinger OWF's foundation design consent related risk. The benefits that flowed from the testing can be considered under direct and indirect headings. Direct benefits included:

- the optimised final design permitted by the testing reduced the total (2.7m diameter) pile lengths by around 3km, saving 8000t of steel, 16000t of CO_2 emissions and tens of millions of Euros in supply and fabrication costs; and
- several further million Euros of savings in installation costs that were permitted by the reduced pile lengths.

Indirect cost benefits included:

- tens of millions of Euros in lower adjusted risk costs relating to possible consenting and project commissioning delays;
- potential savings of €1M in noise emission system costs resulting from shorter pile lengths and reduced hammer energy; and
- a further saving of €1M was achieved through optimization of DLT testing, equipment and procedures for the 286 production piles, leading to a diver-free DLT campaign during construction.

Overall about 75% of the offshore pile testing campaign expenditure was recuperated immediately from the direct cost benefits. Considering both direct and indirect contributions, the benefits greatly outweighed the pile testing costs. Far greater project design, fabrication and construction cost savings could have been realised had it been possible to carry out the testing at an even earlier stage, allowing the results to be fed back into optimizing the WTG and OSS jacket structures' design. For example, it may have been possible to move to three legged WTG jackets, to a four legged OSS jacket or to have homogenized the OSS and WTG structures' pile diameters.

5. Lessons learned

The primary lesson learned from the experience at Wikinger is that advanced offshore pile driving trials and loading tests can be conducted successfully in water depths of around 40m leading to substantial economic benefits. Specific recommendations from the Phase I and Phase II testing include:

- Allow for set-up and long term ageing assessments when planning DLTs. It is vital to plan for long term instrument functionality as well as secure cable and termination storage and recovery. These features are key to enabling safe and effective long term re-strike tests without diver interventions;
- Expect and allow for significant attrition rates in the DLT instrumentation systems. Cables are fragile and prone to damage during handling and 25% attrition rates can be expected even when great care is taken.
- Apply best practice rigorously in specifying, installing and protecting DLT sensors and connections enables long-term storage and use with very good survivability.
- For remotely operated SLT systems, special attention is required to the connections between (i) the pile and the displacement measuring system and (ii) the pile and the loading system. Both have to be sufficiently robust to operate offshore. Over-sizing and provision of secondary connection systems are both advisable.

SLT systems based on the principles outlined in this paper can offer excellent performance. There are however, great benefits in engineering systems with higher load capacities. Systems that can operate at 20 to 40MN would offer benefits in cases such as Wikinger where static capacities were greater than anticipated.

6. Conclusions

For Iberdrola's 350MW Wikinger OWF in the German Baltic Sea, a review of current pile design methods by Barbosa et al. (2015) highlighted significant design uncertainties that could lead to unnecessarily conservative pile penetrations for seventy four-legged jacket WTG support structures and one six-legged OSS jacket in ground conditions that are dominated by Glacial Tills over low-to-medium density Chalk. Consequently, full scale field tests were conducted on 1.37m diameter piles, driven to penetrations of up to 31m, in up to 40m of water depth..

This paper provides an overview of the project risks and opportunities that justified a substantial offshore pile testing programme. The main points raised are:

1. There were significant risks around the consenting process, particularly in relation to the potential need to establish a comparable onshore test site.
2. The project addressed these concerns by commissioning, in advance of final design, offshore dynamic and fully autonomous static pile load tests on six piles sited at three representative WTG locations across the Wikinger OWF site.
3. Careful consideration was given to alternative testing technologies. Procedures and techniques were developed that led to the tests being conducted successfully in water depths of around 40m up to 10 weeks after driving.
4. Pile capacities increased enormously over the 10 week ageing period. There is great value in allowing for such set-up periods when undertaking static or dynamic load testing.
5. It is vital to consider in long term testing instrument functionality as well as secure cable and termination storage and recovery. Some instrument attrition should be anticipated.
6. Static Load Testing systems based on the principles outlined can offer excellent performance. Still greater benefits could be taken by engineering systems that offer higher load capacities, in the 20 to 40MN range.
7. Special attention is required when undertaking static load testing to ensure good connections between (i) the pile and the displacement measuring system and (ii) the pile and the loading system. Both have to be sufficiently robust to operate offshore
8. Cost-benefit analysis demonstrates that the field testing was justifiable economically and could be applied effectively in future offshore developments that face comparably difficult ground conditions.

Acknowledgements
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