Monitoring of driving and high-strain dynamic load tests of open-ended steel pipe foundation piles for offshore wind turbines

Schallert, M. & Klingmüller, O.
GSP mbH, Germany

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ABSTRACT: At the beginning of 2011 the German Federal Maritime and Hydrographic Agency has published application instructions for the standard 'Design of Offshore-Wind turbines'. Dynamic pile tests and monitoring of the driving process need to be executed for large scale driven foundation piles of offshore wind turbines in the German North and Baltic Sea.

The paper describes the successful application of dynamic pile tests and monitoring of the entire driving process of open ended steel pipe piles at the first commercial offshore wind park in the German North Sea including measurements of transferred energy and stresses in the pile. Special loading conditions, wireless data acquisition, pile preparation, transducer attachment and some results will be shown and discussed. Also it will be shown that important information for reliable fatigue verification can be obtained for offshore foundation piles from high-strain dynamic testing.

1 INTRODUCTION

In Germany the installation of foundation piles with large diameters for offshore wind turbines with a rated power of 5 MW and more and in water depth of 20 to 40 m is a new challenge whereas the monitoring of driven piles for offshore platforms in oil and gas industry is common practice. In relation to the goal to reduce the carbon dioxide emission until 2020 by 40% in Germany the federal administration has decided to subsidize the offshore wind power production. In most of the planned and approved windmill-power plants in the German North Sea and Baltic Sea wind turbines will be built up on open-ended driven steel pipe piles as monopile or tripile foundation. Because of a high portion of lateral and cyclic loading, such piles have to be installed in strong consolidated soil. For these piles it is important to determine static axial bearing capacity during and after installation as accurately as possible. The axial ultimate capacity is the basis to consider effects of cyclic loading conditions and for lateral resistance assessment in the design method. Regarding the bearing capacity in these cases there is no sufficient experience available so far. Static load tests for high proof loads (up to 50 MN) can be assumed to be not feasible for foundation piles at offshore wind parks in water depth of 20 to 40 m.

In addition to the geotechnical aspects of pile axial capacity monitoring renders exact stresses along the pile axis as well as data of hammer performance.

Early 2011 the German Federal Maritime and Hydrographic Agency has therefore published application instructions for the standard 'Design of Offshore-Wind turbines'. Following these instructions dynamic pile tests and monitoring of the driving process need to be executed.

2 OFFSHORE WIND PARKS IN GERMANY

At the end of 2009 the construction of the first offshore wind park in Germany, Alpha Ventus, was completed. This project was a government-funded pilot and research project of 3 different energy trading companies. The initial start-up of the wind park was April 2010. 60 km north of the coast 12 wind turbines (5 MW) were installed in the North Sea at water depth of 30 m at 6 tripod and 6 jacket structures. The tripods and jackets are founded by approximately 40 m long driven steel pipe piles with diameters of approximately 1.8 m to 3.5 m. The wind turbines are designed for a lifetime of 20 years. Until December 2011 an electricity of more than 230 GWh was produced. Development and production of the wind turbine components was done from 20 European companies. The investment was 250

Million Euro [www.alpha-ventus.de].

Only a few km northwest of this wind park another wind park (Borkum West II) 35-45 m long piles are driven as foundation for tripods as substructure of 80 wind turbines (5 MW) at water depth between 28-33m since fall 2011. The tripod structures will be placed on top of pre-driven piles (pre-piling) [www.trianel-borkum.de].

Since March 2010 the first commercial wind park in the German North Sea is under construction. This wind park (BARD Offshore 1) is located approximately 100 km north of the coast. 80 wind turbines with a rated power of 5 MW each will be installed at water depth of up to 40 m. The foundation consists of a tripile-structure [www.bard-offshore.de]. More detailed information about this project is given in chapter 3. Approximately 70 turbines have been installed at the time of this presentation.

Baltic 1 is the first commercial wind park in the German Baltic Sea with 21 wind turbines (2.3 MW) 16 km away from the coast. The foundations, 37 m long Monopiles (L=37m, ∅ 4.3m) have been driven with an average of 3000 blows to a penetration of approximately 20 m at water depth between 16 m and 19 m. The towers were connected via transition piece to the piles. The beginning of installation was in March 2010 [www.enbw.com/baltic1].

32 km north of the island of Rügen the wind park Baltic 2 is planned to be constructed in the German Baltic Sea. 80 wind turbines with 3.6 MW each shall be founded at 39 Monopiles (max. L=72m, ∅ approximately 6m) at water depth 23m to 35m and at 41 jacket structures (piles L approximately, 46m, ∅ approximately. 3m) at water depth between 35 m and 44 m [www.enbw.com/baltic2].

Furthermore at several locations met masts were installed for acquisition of important environmental data such as wind speed or wave height either as Wind Park internal (wind park Amrumbank West and Nordsee Ost) or as research tower such as FINO 1 and FINO 3 in the North Sea or FINO 2 in Baltic Sea.

In December 2011 there were 113 German offshore wind projects in the phase of being approved or being planned registered at the German Federal Maritime and Hydrographic Agency (Dahlke, 2011).

3 FOUNDATION OF WIND TURBINES OF THE FIRST COMMERCIAL WIND PARK IN THE GERMAN NORTH SEA

3.1 *Project data*

The first commercial wind park in the German North Sea, BARD Offshore 1, is still under construction (Fig. 1).

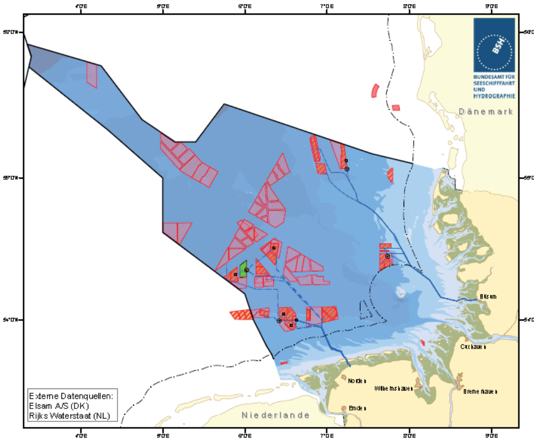

Figure 1. Offshore wind projects in the German North Sea marked red, BARD Offshore 1 is green marked [www.bsh.de].

The subsoil mainly consists of sandy soil with intermediate layers of silt and clay. The sand layers are of middle and high density at the depth of pile bottom section at most of the turbine locations. The penetration length of the foundation piles vary dependent on the soil conditions.

The foundation consists of a tripile structure with 3 vertical open-ended driven steel pipe piles (Fig 2).

Figure 2. Wind turbines (typ BARD 5.0) in the German North Sea, wind park BARD Offshore 1 [www.bard-offshore.de].

The maximum water depth is approx. 40 m and the pile lengths vary from 80 m to 90 m. The diameter of the piles is approximately 3 m with differing wall thickness.

Until July 2012 foundations of 64 windmills (192 piles) have been installed.

3.2 *Monitoring and dynamic pile load tests*

The driving system is a hydraulic hammer MHU 1900S with a 100 t ram. During driving the energy is increased in steps. The Pile Driving Analyzer (Model PAX) from Pile Dynamics, Inc., USA with wireless data transmission was used for monitoring the driving process and also for restrike tests.

Figure 3. Strain and acceleration sensors, wireless data transmitter (left), Pile Driving Analyzer - Model PAX (right).

Figure 4. Measurement equipment attached to the pile after bolting (left) and during driving (right).

Strain and acceleration sensors as well as wireless data transmitter (Fig. 3) will be attached at the installation platform WindLift1 to the pile top section (Fig. 4) at opposite sides using a special bolting and bonding procedure.

The advantage of the use of the wireless equipment for dynamic load testing (DLT) is that there is no main cable required from sensors to the data acquisition unit. The handling during pile installation can be improved significantly and it avoids any cable defect or incorrect measurements due to the influence of moisture at the cables and connections. The data transmission is based on Bluetooth technology and works over a distance up to 100 m. The wireless transmitters have an extended battery pack with a working time of approximately 30 hours. A very long time of operability is important under the special operational conditions as the radios have to be switched "on" before the lifting. Either because of the procedure of setting and driving or because of the the weather condition it can be that there is an onterruption in the driving.

Measurements were carried out by GSP engineers (Schallert et al., 2011) at all three foundation piles of a wind turbine location at approximately 10 % of all locations. This is in accordance to the above cited application instructions. Strain and acceleration are recorded for each blow of the entire driving process.

Fig. 5 shows typical results of the monitoring of driving of these piles. On the left side the transferred energy (EMX) and the blow count (BLC in blows/m) are illustrated. The middle diagram shows the max. compression (CSX) and tension stress (TSX) at the location of transducers at the pile top section. On the right side of the figure the distribution of the capacity calculated by the CASE-method for CASE damping factors J_c=0.8 and J_c=0.4 is given to define a lower and an upper bound.

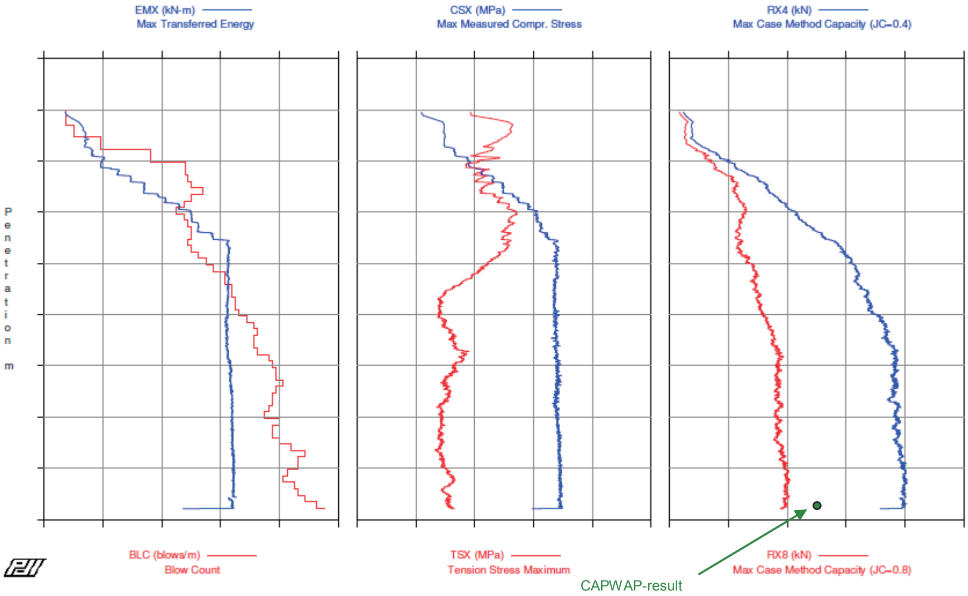

Figure 5. Typical results of monitoring the driving process.

One of the last blows of the driving process of the tested piles was evaluated by full modeling of the pile in the soil with CAPWAP-procedure to determine ultimate bearing capacity, skin friction distribution and toe resistance at the time of end of driving.

A sample of wind turbine locations piles were tested again (restrike tests) with a small number of hammer blows after a certain waiting time. From these measurements setup of the piles in the specific soil could be calculated.

In Fig. 6 the skin resistance calculated by CAPWAP-analysis is shown as average of the results from 3 foundation piles at a typical sand soil profile. For the purpose of comparison the results of soil investigations by cone penetration testing (CPT) are given. Also the predicted skin friction for the sand layer (115 kN/m²) is drawn in the figure. It can be seen, that the prediction of pile axial capacity from soil investigation underestimated the mobilized capacity by high-strain testing for the conditions of the shown sandy soil profile. This could lead to a conservative pile design although it is self-evident that in case of high cyclic and horizontal loads like it is the case of such foundation piles these parts of loading need to be considered in the design.

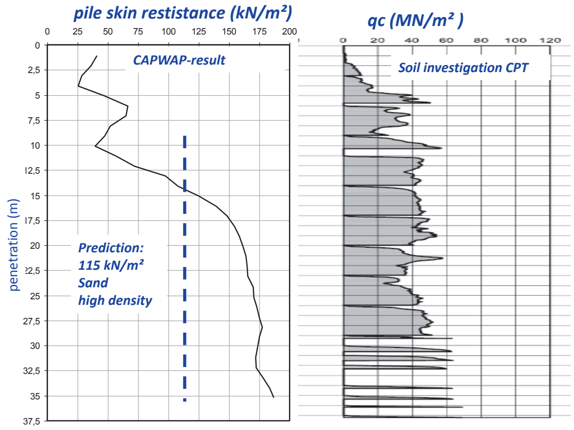

Figure 6. Skin resistance distribution at a sandy soil location (left), results of CPT-tests (right).

Further CAPWAP-analysis of blows at less penetration was carried out for optimization of the pile design at locations of comparable conditions for future installations. Additionally the stresses along pile axis are calculated by CAPWAP (fig. 7) what is important for reliable fatigue verification and durability of the structure. Especially at cross sections of high bending from later loading conditions it is essentially to know the axial stresses (tension and compression) as exactly as possible to verify the influence of the driving process on the lifetime.

More detailed results from this and other projects will be published after termination of the installation.

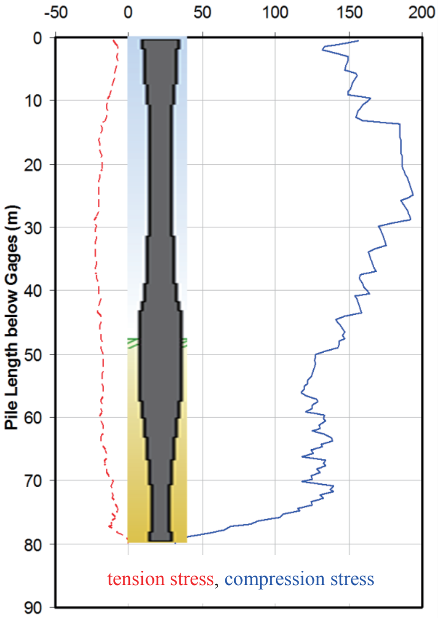

Figure 7. Stresses calculated by CAPWAP along the pile axis: tension (left), compression (right).

4 DISCUSSION

Results so far show that monitoring and dynamic pile load tests are extremely important for the verification of safety and to support the optimization of design and installation.

CAPWAP evaluation procedure provides models of the pile in the soil for high reliability of capacity prediction. For the “best match” especially the multiple variations in pile impedance in this specific design had to be carefully modeled.

Steel pipe piles with large diameter as foundation for offshore wind turbines at locations of high water depth underlie a high portion of lateral and cyclic loading as in the described example for three pile foundations and even more for monopiles. For lateral loading conditions there are mainly heuristic approximate calculation methods available so far to predict the bearing capacity. This is currently still in the state of research.

To achieve the required lateral resistance the piles need to penetrate deep enough in strong consolidated soil. Therefore heavy driving has to be applied to the piles and stress control is important to be done by monitoring of the driving process by the described measurements.

For determination of the influence of cyclic loading on the axial and lateral bearing capacity of the piles there are suggestions for calculation methods published from Richter et al. (2010), Kirsch and Richter (2011), Achmus et al. (2005) and other writers. These methods are based on the knowledge of the axial pile bearing capacity from static tests. As was shown static axial load test are not possible to be executed under the environmental conditions offshore. Dynamic high-strain load testing is the only measuring method to obtain reliable results regarding the axial bearing capacity. The dynamic axial pile load test can provide a basis for the assessment of lateral resistance as the strength of the embedment is defined by the evaluation of the measurements on the pile top. For this reason the application of this method becomes even more important in future, especially for piles of large diameter (Monopiles).

A possible procedure to directly obtain lateral resistance for such piles, depending on depth, soil type and pile diameter, from axial bearing capacity determined by dynamic load tests and full modeling procedure is discussed as alternative or in addition to other methods (Kirsch and Klingmüller, 2011).

A carefully executed analysis of the axial shaft resistance distribution by CAPWAP-procedure enables the geotechnical engineer to revise the interpretation of the soil description as given from standard soil analysis methods and interpretive tools.

The results of a full modeling procedure can further be used to define approximate bilinear p-y-curves (p – lateral soil resistance force, y – corresponding lateral displacement). This procedure requires accurate data quality from monitoring of the pile driving process as well as a reliable approved CAPWAP-analysis especially of the axial static displacement (quake values) for each modeled soil element.

The CAPWAP model yields a unit axial shaft resistance $R_{ult,i}$ and an axial static displacement (quake) q_i for each soil element. The friction must be taken as friction acting on the outer surface of the pile for open ended pipe piles. The shear stiffness k_s of the soil layer i of 1 m thickness is then given as Eq. (1):

$$k_s = \frac{R_{ult,i}}{q_i} \quad . \tag{1}$$

The shear stiffness depends on the shear modulus and the lateral resistance is related to the elastic modulus. Using a relationship of Cooke (1974) it can be shown that from the axial shear stiffness taken from CAPWAP-analysis the lateral resistance stiffness k_h can be defined as Eq. (2):

$$k_h = \frac{k_s}{4 \cdot \pi \cdot r_0} \cdot \ln\left(\frac{r_m}{r_0}\right) \cdot \frac{2 \cdot (1-\nu^2)}{1-\nu-2 \cdot \nu^2} \tag{2}$$

k_h = horizontal stiffness
k_s = vertical stiffness
$r_m = 2.5\,L\left(1-\nu\right)$
L = unit length of pile segment
r_0 = pile radius
ν = Poisson's ratio.

This stiffness values are given for unit length of pile segment. These resistances are important for the determination of the lateral static equilibrium, as well as for the definition of the lateral cyclic load limits.

The proposed approach, based on measurements of strain and acceleration during pile driving and on CAPWAP-analysis, provides an independent assessment of the lateral resistance and can be used to stabilize the interpretation of soil resistance from conventional methods.

Based on results of further project data the method currently will be validated.

5 SAFETY CONCEPTS

Dynamic pile load tests have been accepted for the verification of axial bearing capacity of piles in several codes around the world. The national German recommendations ("EA-Pfähle", EAPfaehle 2012) represent a state of a code of practice and also refer to the determination of ultimate capacities by dynamic load tests. The 'Handbook Eurocode 7 - Geotechnical design – Part 1: General rules' from 2011, published by the German Institute of Standards (DIN), combines DIN EN 1997-1:2009, DIN EN 1997-1/ NA:2010 (national appendix) and DIN 1054:2010 (additional national rules to DIN EN 1997-1,) to one work of German rules in geotechnical design.

According to EC7 results of dynamic load tests need to be calibrated on the results of static load tests (Klingmüller and Schallert, 2012) on similar piles in similar soil conditions. The German national application document of EC7 defines safety factors (correlation factors) that reflect the source of the static test results – same site, similar site or experience. Also the number of executed dynamic tests, the way of data evaluation - direct methods (i.e. CASE) or full modelling (i.e. CAPWAP) - is taken into account for definition of the resistance factor of safety.

According to the application instructions for the standard 'Design of Offshore-Wind turbines' from 2011, published by the German Federal Maritime and Hydrographic Agency, in Germany dynamic pile tests in general need to be executed for large scale driven foundation piles for offshore wind turbines at a minimum of 10% of the wind turbine locations of the wind park. The total number of tests depends on the variation of the soil conditions and has to be defined by the geotechnical project engineer. The dynamic load tests need to be applied at least at two locations of each geotechnical soil profile in the area of the wind park and should be carried out in the beginning phase of the project.

Due to the facts, that

- static load tests are not realizable for the describe piles, loading and ambient conditions offshore,
- in case of driven piles driving logs can provide information about the soil resistance and variations in pile installation method are assumed to be less compared to cast in place piles,
- because of a lot of experience in calibration of dynamic on static load test at driven steel pipe piles in non-cohesive soil in northern Germany

calibration for such piles can be carried out using the correlation factors for the case of the existence of a static test at a similar site. Thus, the equivalency of static and dynamic load tests is assumed for steel pipe piles driven in sand.

However, at the described project in chapter 3 the load and resistance factor design method defined in DIN 1054:2005 was still valid. The static axial bearing capacity can be determined from dynamic load test. The resistance and correlation factors valid for static load test can be used also for dynamic load test in the case the number of dynamic tests is twice the number of static tests.

In this project the variation of results from dynamic load test from 3 piles at one wind turbine location in sandy soil is very small (coefficient of variation <0.05). This fact supports the above mentioned assumption of equivalency of static and dynamic load tests.

German codes currently do not clarify the application of wave equation analysis in combination with dynamic load tests. But it would be necessary to honor the evaluation of driving logs by wave equation analysis (driveability studies) in the safety concept if these calculations are carried out in addition to dynamic load test with full modelling analysis procedure at the same site. A procedure of the application of the wave equation analysis for offshore Monopiles is given from Rausche and Klingmüller (2005).

Especially for foundation piles of offshore structures the results from wave equation analysis by GRLWEAP 2010 Offshore Wave program, including fatigue analysis, would give important information for the optimization of the pile design. The fatigue analysis provides the blow count and maximum compressive and tensile stresses for each pile segment and each depth value analyzed. These results can be verified by or calibrated respectively on results of dynamic load test. Therefore the combination of both methods should lead to reduced factors of safety.

6 CONCLUSIONS

On the basis of the introduced case history and experience and because there are no reliable calculation methods available to predict the bearing capacity of large scale driven steel pipe piles as foundation for offshore wind turbines with a high portion of lateral and cyclic loading it could be shown that dynamic pile testing is an important measurement method for cost-effective constructions. As instrument of quality assurance high-strain testing and monitoring of the driving process lead to a reliable verification of axial pile capacity.

An approach to determine the lateral resistance from axial pile shaft resistance calculated by CAPWAP-procedure was given. It shows how the axial shear stiffness can be utilised to calculate bilinear p-y-curves for lateral loading. Further on-going studies are expected to increase the reliability of this approach.

In case of high working loads especially for conditions of offshore wind turbines where no other measurement method is realizable dynamic testing plays a key role in the safety concept.

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