Uncharted Territory on the Seabed

Monitoring Procedures and Assessment Model for the Foundations of Offshore Wind Turbines

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Project information: Monitoring Procedures and Assessment Model for the Foundations of Offshore Wind Turbines
Project management:
BAM – Federal Institute for Materials Research and Testing
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Project partners:
- BSH – Federal Maritime and Hydrographic Agency
- BARD Building GmbH

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7.1 Getting the Balance Right

Offshore wind turbines enter unknown territory, especially where the foundations are concerned. This is because offshore wind power can only make use of the experience from the common offshore constructions used by the oil and gas industry to a limited extent. The offshore wind industry has tried to reduce foundation dimensions, especially the pile lengths, as much as possible compared with those of the oil and gas industry. This is because with the large number of wind turbines involved it can provide considerable economic advantages. On the other hand, the stability of the foundations is additionally at risk because due to the much larger number of cyclic loads they are subjected to it is very difficult to predict how they will behave. Since offshore wind farms are manufactured in series, every systematic fault in the foundation acts as a series fault for a large number of turbines. This calls for monitoring – and the right dimensions of pile foundation, the most common type of foundations used for wind turbines.

Where the foundations of onshore wind turbines are concerned, the local ground is explored and it is usually also possible to refer to experiences with comparable locations. Where offshore foundations are concerned there has not been any such comparable experience in the German North Sea to date. This has resulted in a degree of uncertainty about what pile diameters and lengths are necessary. The pile designs could be undersized or oversized. If the foundation is undersized the stability of the structure is endangered and – as a result of series production – so is the whole wind power plant. If the foundation is oversized it will drive up the costs unnecessarily. The foundations of offshore wind farms thus represent a great structural challenge. This situation is aggravated for wind turbines out at sea because of the high number of load cycles, the unfavourable relationship between impacting horizontal forces and the comparatively low weight of the wind turbine (= great torque to be expected), the high cost pressure, the consequences of "series faults", the effective lack of offshore wind knowledge at German project locations until Alpha Ventus, and the high cost of inspection and maintenance.

7.2 Observing and Monitoring

The use of structure monitoring systems is an elementary component of project requirements. They can close the gaps in structural experience and guarantee the stability of foundations in operation. In the geotechnical field the "lack of experience" and especially any defects discovered during the verification of the stability can lead to compulsory measuring and monitoring being prescribed, whereby it is possible that not just monitoring will be compulsory, but also the provision of active countermeasures. The so-called observational method then replaces the verification of stability or represents this verification of stability. The observational method includes measurements, the representation of meaningful indicators and intervention thresholds, the representation of the structural model involved and its degradation, and the representation of possible countermeasures.

The RAVE research project "Monitoring Procedures and Assessment Model for the Foundations of Offshore Wind Turbines" was a joint project carried out in association with wind turbine manufacturer BARD, whose five-megawatt machines have been erected in close proximity to Alpha Ventus, at the BARD Offshore 1 wind farm (80 × 5 MW). A new type of foundation was used here, the Tripile.

Peripheral Anecdote (I): Slimness has its price
Like the tripod, the tripile is a three-legged foundation. In this case, three steel piles of about 40 or 50 metres in length are driven into

Fig. 7.1 Offshore wind turbines with tripile foundations. © Ocean Breeze Energy GmbH & Co. KG

the seabed but, unlike the tripod, they extend several metres above the surface of the water, where they are connected with one another by means of a square transition piece (Fig. 7.1). The basic idea behind the tripile patented by BARD, which has in the meantime been declared insolvent, is that the tensile forces on the foundation in the sea act particularly on the grouted section, the point of contact between pile and load-bearing structure. If something goes wrong there it can only be fixed using divers with a great deal of effort, if at all.
This is why the BARD idea was to" do everything of significance above water". The transition piece and the grout sections for the piles are above the waterline, which means that virtually all repair work can be done by ship, without the need to deploy divers. The steel piles can also be designed to be slimmer, the piledriving is quicker and the slim steel piles can reduce costs. The patented piles really are slimmer than those used on the tripods. But whether this actually saves cost depends on the current steel price, because this slimness also has its price. Inside, the walls have to be substantially reinforced and instead of one thick tube there are now three slim tubes sticking up out of the water. Just these three steel elements and the transition piece of the tripile weigh 500 tons.
On top of this you have the steel for the wind turbine and its tower. According to the manufacturers, 120,000 tons of steel was used in the construction of the BARD Offshore 1 wind farm and its 80 turbines plus transformer station.
Björn Johnsen

7.3 All Beginnings: The PC and a System Identification Procedure

The research project investigated the difference between indirect procedures for monitoring structures, where straightforward load monitoring is used as the basis of assessing the load-bearing capacity of the foundation, and direct procedures. In the latter case the load-bearing capacity itself is directly determined by analysing the actual course of load displacement of the piles.

Based on this, a new system identification method was introduced that can be used to determine the load displacement curves for the pile using the operating data of the offshore wind turbine. This basis creates a simple finite element model for the pile with a freely selectable approach for the tangential and axial bedding in the seabed, the so-called "t-z curves" or "t-z springs" – the derivation of non-linear axial spring characteristics. Vertical counterforces work bottom to top on the foundation

Fig. 7.2 Horstwalde test field. **a** Driving a pile, **b** View of the test field with ten piles (length 20 m, diameter 0.7 m). © BAM

or steel pile from the seabed, almost like springs. Or, as Isaac Newton put it, for every action there is an equal and opposite action.

This project also initially focused on developing a computer model where identifiable loads, forces and data were entered and further developed in order to identify the "system offshore foundation/ pile supporting structure" as precisely as possible. Here the forces do not in any way act linearly; if for example a pile is pulled out of the foundation soil, this results in a non-linear displacement curve. The computer model and procedure were theoretically tested and the performance limits for the pile foundations determined. This was followed by a subsequent reference test at the Federal Institute for Material Testing (BAM) test field in Horstwalde near Berlin (Fig. 7.2).

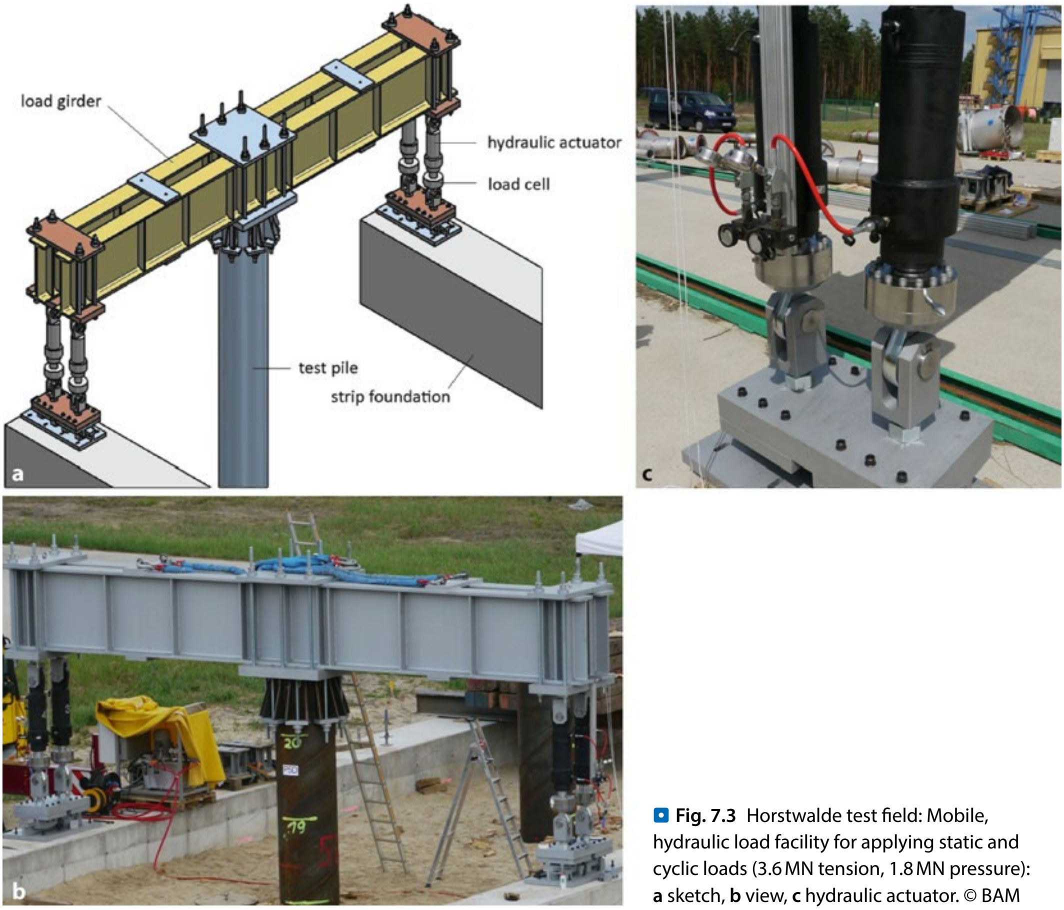
7.4 Field Trials at the Bottom of the Berlin Glacial Valley

The load facility in Horstwalde (Fig. 7.3) allows half-scale offshore piles, around 20 metres in length, to be driven into the ground. The Berlin sand is densely bedded and has a comparable grain size to that in the floor of the North Sea. Like the sea, the high water table – it is located in the former Berlin glacial valley – provides complete saturation of the ground. The load tests on the sandy Berlin-Brandenburg ground confirmed the opportunities offered by the method and model that were developed. The load-bearing capacity can be determined from incomplete force and deformation recordings. The great challenge for an offshore foundation consists of two important questions: what quality does it have and how accurate is the structural model for the piles? And how accurately can the structure be measured and monitored?

7.5 The Early Piles: Still Not Very Resilient

An important finding of the field tests with the driven piles relates to the increase of load-bearing capacity with time. During the piledriving the ground material is disturbed around the pile sleeve. The load-bearing capacity of the pile is therefore rather poor after installation. With time the ground tenses up again around the pile sleeve, and the load-bearing capacity can increase sharply. The load-bearing capacity on the pile sleeve is determined by the dilatancy. Dilatancy is the volume change observed in a compacted granular material when it is sheared (Fig. 7.4).

It is also a fact that when a pile is repeatedly subjected to load its load-bearing capacity is altered.



■ **Fig. 7.3** Horstwalde test field: Mobile, hydraulic load facility for applying static and cyclic loads (3.6 MN tension, 1.8 MN pressure): **a** sketch, **b** view, **c** hydraulic actuator. © BAM

The difficulty is estimating this accurately over its service life, because the load-bearing capacity does not decrease in a linear manner over the 20-year service life of an offshore wind turbine, and the loads caused by wind and waves, and their yearly trends, are too diverse. The impact and the evaluation of extreme events, such as severe storms, are also important.

On balance it is clear that large driven offshore steel piles, and especially so-called young piles, exhibit a significant increase in load-bearing capacity when the turbine first goes into operation.

7.6 No Signal in Normal Operation

As with many system identification methods, and similar to dynamic pile load tests, the procedure developed in the project only delivers good results when it is sufficiently near to the load. Since no continuous extreme loads are to be expected in offshore operation, but rather underlying cyclic loads, the prerequisite for model identification is seldom found. In "normal operation" the measurement signal is simply too small. It only displays signals when there is a major storm, when for example 50 % of the possible bearing load of the offshore foundation has been reached.

This does not however represent a weakness of the method developed, because this method can and should only display results for very large load amplitudes with plastic changes on the pile. This meant

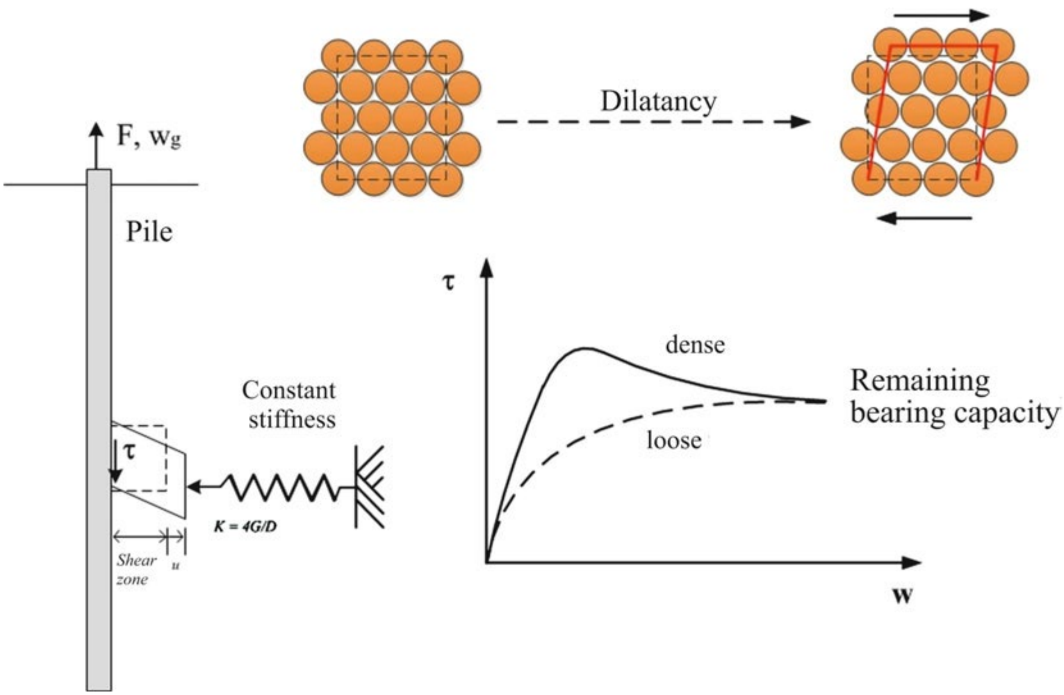


Fig. 7.4 Driven pile dilatancy model: shear load on a compact aggregate grain material causes an increase in volume that results in a pronounced maximum load-bearing capacity. © BAM

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that it was primarily the quality of the measurement installation that was tested.

Peripheral Anecdote (II): We are not measuring for tsunamis, but for the North Sea

This is most certainly a case of pile degradation: a volcano erupts in Iceland, triggering a tsunami that surges across the German Bight and, among other repercussions, snaps a pile in a wind farm. But such a tsunami is not really very likely. It is far more likely that pile degradation will occur as a result of weaker extreme events, such as an extreme event that occurs once a year. Then you would certainly find material fatigue. But you would also find that the pile can recover after a few days' rest – without storm or wind turbine operation. So there is a cure.
Björn Johnsen

7.7 Testing out at Sea Still Not Completed

As well as developing models and carrying out field tests on land, the research project also included trials of the new structure monitoring method on a wind turbine out at sea. In this case it was on a wind turbine belonging to our project partner in the BARD Offshore 1 wind farm in the direct vicinity of Alpha Ventus. The wind turbine manufacturer's structure monitoring system was positioned on one side. The manufacturer had installed this measurement technology at the beginning of 2014, towards the end of the research project. The measurement technology was implemented in the manufacturer's data system.

The centrepiece of the measurement technology concept turned out to be the choice of the right acceleration sensor. The difficulty was in getting a low-noise measuring signal for the relatively small and low-frequency vertical acceleration vibration in the pile. Only then is it possible to calculate the displacement amplitudes of the pile with sufficient accuracy. To achieve this, the acceleration sensors that take the accurate measurements have to point in the three spatial directions (height, width, depth). Several months of experiments and tests in the laboratory of the Federal Institute for Material Testing showed that a special seismic sensor model was most suitable. So many laboratory tests were necessary because the data provided by the manufacturer was often insufficient and its use for offshore applications turned out to be not possible. A false initial selection on land would have had effects offshore that could only be remedied with difficulty. The system has to be simple and robust, but still be able to measure the slightest vibrations very accurately – and last for many years out at sea.

Project partner BARD had also previously attached strain gauges as a rosette around the outside of the pile.

Because the measuring equipment was only installed in 2014, the tests and any subsequent monitoring programme on the BARD test system could not be completed. The measurements are to be continued.

» Monitoring procedures for offshore structures are important. The main problem is when in future it displays damage or just unscheduled degradation on the pile. What measures can and must the wind farm operator take? Here there is still a significant need for research and above all development.
Matthias Baeßler, Department 7.2. Civil Engineering, Federal Institute for Material Testing

7.8 Outlook: Please Continue to Develop Countermeasures

An accurate forecast of the load-bearing capacity of typical offshore piles and also the measuring of the condition of their load-bearing capacity in a monitoring concept is a difficult task. Unless absolutely uneconomically dimensioned, cases will therefore inevitably occur where the sufficient load-bearing capacity cannot be verified upon installation and where a definite identification of the load-bearing capacity cannot be made during operation.

The more uncertain this starting position appears to be, the more important the applicability of countermeasures needed to counteract any progressively failing foundation. With this in mind the project analysed the main possibilities of countermeasures. It is however urgently recommended that practical countermeasures should be developed to maturity for application.

The findings of the research project and the practical experience brought in by the project partner for the trials, planning and implementation of the measurement and evaluation concept, as well as the knowledge gained about procedural possibilities and limits, represent great added and utilisable value. The new VDI Guideline 4551 “Structure Monitoring and Evaluation of Wind Turbines and Platforms” currently being drawn up takes experience from this project into consideration and places the corresponding possibilities for action offshore at the disposal of planners.

7.9 Sources

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