PROGNOSIS OF UNDERWATER PILE DRIVING NOISE FOR SUBMERGED SKIRT PILES OF JACKET STRUCTURES

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Abstract: *Offshore pile driving noise has gathered more and more attention during the last decade. Especially the huge number of monopile foundations for wind turbines contribute to the noise emission into the water column. Besides monopiles, also jacket structures can be found as foundations for e.g. transformer stations or service platforms in wind farms and at deeper locations, e.g. for oil and gas platforms. A general difference between monopiles and skirt piles that are often applied for fastening jacket structures is the identification of the critical scenario for underwater noise prognosis. For monopiles, the highest noise levels are observed at final embedment, when the highest hammer energy is applied. While monopiles have a certain stick-out above the sea surface at the end of piling, the top of skirt piles is submerged at final penetration. Thereby, the increasing hammer energy with penetration depth and the simultaneously decreasing free pile length in the water make it hard to define the critical scenario from an acoustical point of view.*
In this contribution, the measured underwater noise levels of four submerged skirt piles for a transformer station are compared to the levels that have been predicted by a comprehensive FE modelling approach before the offshore installation started. Thereby, the FE model included a careful derivation of the excitation force by the hammer as well as a detailed layered soil profile and noise mitigation measures. Based on the results from measurement and simulation, it is possible to gain a valuable insight to the development of underwater noise with increasing embedment of submerged skirt piles.

Keywords: *Pile driving noise, offshore constructions, simulation, prediction, measurement, finite element method*

1. INTRODUCTION

Offshore pile driving noise gained increasing importance during the last decade, in part due to the growth in offshore wind farm construction activities. Within Europe, developments on regulatory requirements regarding underwater noise are related to the European Union's Marine Strategy Framework Directive (MSFD) [1] that was adopted in 2008. As described in this directive, the emission of noise in the waters under the jurisdiction of Member States of the European Union is to be seen as pollution. Within the OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic and its counterpart for the Baltic, BIAS (Baltic Sea Information on the Acoustic Soundscape), guidelines and legislation are being developed that regulate our dealing with the marine environment. This recognition of underwater noise due to pile driving has led to the definition of sound-related restrictions by a number of national authorities in Europe. Most notably, these restrictions define the maximum allowable sound levels emitted from the vibrating pile into the water column during pile driving, which may not be exceeded. Such limitations are, for example, set by the permitting authorities of Belgium, Germany and the Netherlands. A number of noise mitigating measures have been developed by the industry in order to meet those limitations, see e.g. [2][3].

In wind farm construction, especially the installation of a large number of monopiles as foundations for the wind turbines contributes to the noise emission into the water column. Besides monopiles, also jacket structures can be found, e.g. as foundations for transformer stations or service platforms (see Fig. 1). Jacket structures are also used at deeper locations for oil and gas and other platforms. In the wind industry, jackets are typically founded on so-called skirt piles in a post-piling approach: After placing the jacket itself on the sea bed, piles are inserted into the skirt sleeves, which are tubular sections at the lower end of the legs of the jacket structure, and driven to final penetration depth.

Fig.1: Typical example of a skirt pile jacket before installation, with the skirt sleeves visible at the lower end of the jacket legs.

A general difference between monopiles and skirt piles is the identification of the critical scenario for underwater noise prognosis. For monopiles, the highest noise levels are typically observed at the final embedment depth, when the highest hammer energy is applied. At the end of piling, the monopiles still have a certain stick-out above the sea surface. In contrast, the top of skirt piles is submerged at final penetration depth. Thereby, the increasing hammer energy with penetration depth and the simultaneously decreasing free pile length in the water column make it hard to define the critical scenario from an acoustical point of view: The excitation force on the pile head increases (→ higher noise levels), while the sound directly radiating from the pile into the water reduces with pile submersion (→ lower noise levels). In this contribution, the noise levels that have been predicted by a FE model prior to the actual offshore installation are compared to the levels measured later on during installation of the submerged skirt piles for a transformer station.

2. DESCRIPTION OF THE SITE-SPECIFIC BOUNDARY CONDITION

For the project described in this paper, four skirt piles with an outside diameter of 2.44m (96") and a length of 82m were driven into the sandy sea bed through the jacket structure, which was placed in 40m water depth. Each of the piles was driven to a final penetration of 65m below sea bed. Consequently, the pile top crossed through the water line at about 42m penetration, and was at a depth of 23m below sea level at final penetration. Driving was executed with a submersible MENCK MHU-3500iS hydraulic impact hammer of the latest generation, operated at varying energy levels of up to 2000kJ to match the gradually increasing driving resistance.

In order to comply with the applicable noise level limitations, a combination of noise mitigation measures was applied. Close to the pile, a so-called grout annulus bubble curtain (GABC) was generated by blowing air into the annulus between the skirt sleeve and pile. Within the annulus, the air bubbles were protected from the current resulting in a stable air-water mixture that acted as an impedance barrier to the pressure waves generated by the pile during each hammer strike. At the top of the annulus, about 10m above sea bed, the bubbles drifted out and were subjected to the current, carrying them away from the pile. The main noise mitigation measure consisted of a double big bubble curtain (DBBC) and was located at a greater distance from the pile, enabling it to capture water-borne as well as soil-borne sound waves (see Fig. 2).

Fig.2: Situation during pile driving: hydraulic hammer visible on top of a skirt pile, with the double big bubble curtain (DBBC) active.

Bubble curtains are commonly applied in wind farm construction. The system comprises a weighted air hose with nozzles at regular intervals, laid out around the pile driving location on the sea bed. A continuous air supply from a compressor array on a dedicated vessel generates an air curtain surrounding the piling site, again acting as an impedance barrier. The hose layout is project specific; in this case, an elongated semi-oval shape was chosen with its long axis in line with the prevailing tidal current, with a spacing between the two hoses that slightly exceeded the water depth.

3. NUMERICAL MODELLING OF PILE DRIVING NOISE

The finite element method (FEM) is used to model the sound propagation due to the pile driving both in water column and soil (see [4-6]). To predict the sound emission into the water column, an approach has been chosen that splits the calculation into one main model and two pre-calculations to ensure for a high precision along with tolerable calculation times. In a first step, the pile excitation force due to the hammer impact is determined in a separate pre-calculation FEM model, which takes the pile, the impact hammer, the anvil as well as the contact parameters between the different components into account at a very high level of detail [7][8]. In contrast to common approximation procedures, which are often used to estimate the excitation force (e.g. following *Deeks and Randolph* [9]), a far more detailed description of the excitation force acting on the pile head is possible with the chosen approach. The model explicitly takes into account the mass and geometry of the ram weight, the anvil and further possible components between hammer and pile head. The contact parameters, which significantly influence the characteristics of the excitation force, have been specifically derived for offshore pile driving. Due to this approach, the high-frequent signal contents are also considered, which is an important prerequisite for accurately determining the resulting noise emission.

The excitation force is used as an initial boundary condition for the main propagation FEM model, which is 2D rotational symmetric and consists of the pile, the surrounding water column and the different soil layers. The radial extension of the model is usually 1km. The mesh properties are chosen in a way that signal frequencies up to a maximum of 1kHz are taken into account, as the energy transfer from typical offshore piles into the water column occurs significantly low-frequent at around 100-150Hz. The soil, which – as a secondary transmission path *pile → soil → water* – gains importance especially when considering sound mitigation systems, is represented by linear-elastic elements. Besides the propagation of the occurring pressure waves, this approach also includes the developing seismic shear waves. The coupling between pile and soil is realized by a special contact (see [10]), which allows for a precise modelling of the energy transmission from the pile into the soil. An impedance boundary condition is applied at the free water surface to enforce total reflection, while at the lateral edge of the water column and at the edges of the soil layers non-reflective boundary conditions have been realized to ensure a reflection-free propagation of the pressure waves out of the computational domain. As the linear-elastic modelling does not reproduce the energy losses due to plastic deformations caused by the pile-soil interaction, corresponding Rayleigh damping parameters for these losses are determined in a further separate pre-calculation model based on an extended Wave Equation Analysis of Pile Driving (WEAP) approach. Therefore, an additional implementation of the radial displacements is added to the conventional WEAP scheme and the pile head force derived in the first FE pre-calculation is used [11].

The DBBC is considered by integrating two non-reflecting impedance boundary conditions vertically into the water column, which act like perfectly absorbing, concentric enveloping surfaces surrounding the pile. These boundary conditions represent an optimally working DBBC that ideally absorbs the emitted pressure waves within the water column. Practical realizations are more or less capable of achieving this maximum mitigation potential. For the project at hand, an additional GABC that was not included in the numerical model has been applied on-site to ensure the necessary reduction.

The mentioned approaches and procedures that the calculation model is based on have been validated within the frame of profound offshore measurement campaigns and allow for a reliable prediction of the pile driving noise emissions into the water column. The applied modelling approach corresponds to the latest procedures that have been successfully developed in the BORA project [12]. Within BORA, the described modelling approach has been comprehensively validated by measurements during construction of the wind farms BARD Offshore 1 (tripiles), Global Tech I (tripods) and Borkum Riffgrund 01 (monopiles). Altogether, the numerical models were able to reproduce the measured sound levels with very high accuracy [13-15]. Therefore, the model can be regarded as validated for a variety of boundary conditions regarding pile diameter and water depth. For further details on the modelling as well as on the validation it is referred to [7][8][12-15].

4. INTERPRETATION OF THE MEASUREMENT DATA AND COMPARISON TO THE NUMERICAL PREDICTION RESULTS

In Fig. 3, the development of the sound exposure levels (SEL) over penetration depth is shown, which have been measured on-site for all four skirt piles at 750m distance to the jacket centre. Furthermore, the SEL levels as predicted prior to the offshore installation by the FE model are inserted into the diagram for scenario 1 (pile head flush with the sea surface) and scenario 2 (final penetration depth). Note that all SEL levels have been normalized to a hammer energy of 2000kJ to allow for a better comparison.

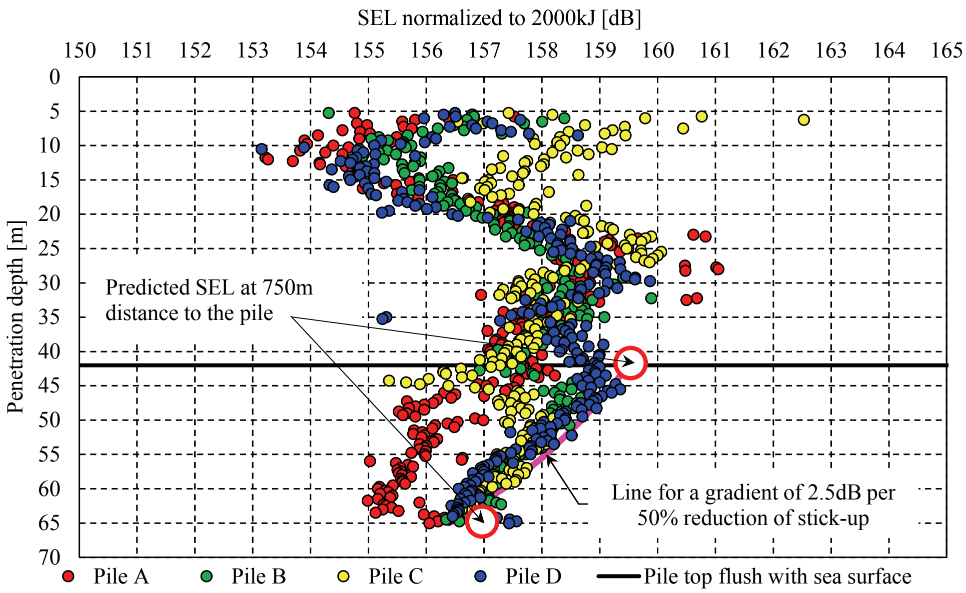

Fig.3: Predicted SEL levels ○ for scenario 1 (pile head flush with sea surface) and scenario 2 (final penetration depth) versus measured SEL levels • • • • over penetration depth at 750m distance. All levels normalized to 2000kJ.

It can be observed that the predicted SEL fits very well with the noise levels that have later on been measured on-site. Due to the additional application of a GABC that was not included in the model, however, the measured levels are slightly lower compared to the predicted ones. This corresponds with experiences from other projects, where the extra mitigation effect of an additional GABC has been reported to be about 1dB to 3dB.

Between the four different piles, a certain variance in the noise levels can be observed. On the one hand, this is due to slightly different distances between the piles and the fixed measurement position. Due to the specific characteristics of the wave guide and corresponding interference effects, the logarithmic decay of the levels with range is only met as a general trend. In practice (both in measurement and simulation), a more or less pronounced oscillation about the decay curve is observed, with dedicated minima and maxima. For the current site, the possible deviation of the SEL ±50m around the 750m position has been determined to +0.0dB/-2.6dB by the numerical model. Furthermore, possible shading or scattering effects by the jacket structure may have occurred for some of the piles. On the other hand, every pile encounters slightly different soil conditions during piling, which also have a direct influence on the resulting underwater noise.

For all four piles, a certain systematic regarding the development of the SEL with penetration can be observed that is divided into four more or less pronounced phases: (i) Phase 1 shows a decreasing trend of the SEL at the beginning of the pile driving for penetration depths between 5m to about 10/15m. This effect is caused by the change in pile-soil interaction, due to which the pile toe reflections of the impact pulse strongly reduce within the first meters of penetration, as a considerable damping of the signal only occurs in the embedded part of the pile. (ii) In phase 2, the SEL is constantly increasing for penetration depths of 15m to about 25m, as the proceeding embedment of the pile leads to a higher radiation of energy into the upper soil layers. (iii) Within phase 3, this effect fades away, as most of the energy radiated from the deeper parts of the pile will be subject to attenuation along their comparably long soil propagation paths. Therefore, the SEL (normalized for energy) remains fairly constant over the entire penetration interval of phase 3. (iv) Phase 4 finally begins, as the pile head is flush with the sea surface at a penetration depth of 42m. From this point on, the free pile length in the water constantly reduces. Per 50% reduction of the remaining stick-up above the sea bed, a reduction of about 2.5dB can be observed in the measurement data. This effect is reproduced by the numerical model: The reduction of the free pile length in the water from 40m (scenario 1) to 17m (scenario 2) results in a decrease of the normalized SEL from 159.5dB to 156.9dB.

As the actual hammer energy is not constant, but increases with pile penetration, phases 1 to 3 are usually not relevant for dimensioning the mitigation measures. With the applied hammer energy profile of this particular case, the most critical noise emission occurs when the pile head is flush with the sea surface (scenario 1). The free pile length then corresponds to the water depth, while already considerable hammer energies are applied (here: 1400-1600kJ). Once the pile head starts to submerge, the resulting decrease of the SEL is more pronounced than the increase due to raising of the hammer energy. The hammer energy at final penetration depth (scenario 2) has been 2000kJ, which results in a ΔSEL of +1.0/1.5dB compared to 1400/1600kJ in scenario 1, while the reduced free pile length from 40m to 17m yields a ΔSEL of -2.6dB. For the considered project, scenario 1 can therefore be regarded as the critical setting from an acoustical point of view.

5. CONCLUSIONS

In the current paper, the development of underwater noise with the increasing embedment of submerged skirt piles has been investigated. A comparison of the predicted SEL levels, which have been computed with a detailed numerical model before the offshore installation started, with measurement data recorded during piling of four skirt piles showed a very good agreement for the two different considered penetration depths. It has been shown that the applied numerical model is capable of accurately reflecting the effect of the decreasing free pile length in the water column on the noise levels.

The development of the SEL with penetration follows a certain systematic. Four dedicated phases could be identified, which are each characterised by typical effects. Based both on simulation and measurement, scenario 1 (pile head flush with the sea surface) in phase 4 could be identified as the critical scenario for noise prognosis in the regarded project. However, as the SEL difference of scenario 1 and 2 depends on the applied hammer energy profile, still both scenarios have to be analysed in future projects.

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