Industrial Learnings and Opportunities using Modelling for Prediction of Underwater Noise and Mitigation Measures

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Introduction

Over a number of years, DONG Energy has worked on applying and developing numerical modelling for prediction of underwater noise in connection with piling of large-diameter steel foundations. This has been done in collaboration with leading universities and consultants. Results from this work have provided valuable input to understanding and forecasting noise source strengths, transmission paths and far-field propagation. The understanding and estimation of the effect of the transmission through the soil is of particular importance for industrial applications. In addition, validation against field data has been performed. This contribution will present status of the work conducted and outlook for future use as well as further development points. Finally, it will explain and discuss a number of learnings that DONG Energy has taken away from our engagement in this important topic.

Borkum Riffgrund 1 offshore wind farm

This offshore wind farm in the German North Sea comprises of 77 monopile foundations. These were installed by impact hammering. based on prognosis an SEL around 175 dB at 750 m distance was expected. As this was exceeding the German regulation of underwater noise, mitigation was put into place to reduce the noise emissions. The noise mitigation was obtained using a double-wall screen, which surrounded the piles in the water column. The gap between the walls was filled by air and this effectively reduced the further transmission of noise going directly from the pile into the water column and made it possible to adhere to German regulations.

In connection with one of the piles in this wind farm, reference measurements were conducted by removing the noise mitigation screen during the last part of the piling sequence. The resulting effect on SEL and SPL can be seen in Figure 1.

The reference measurement was executed as part of the German research project BORA [1] that was supported in this way by DONG Energy. Detailed hydro-acoustic measurements were performed both in the near-field and in the far-field and results were compared with the modelling results. In this way, it was possible to validate modelling of noise generation in the near-field and noise propagation in the far-field separately:

- In the near-field a very good agreement between the predicted and the measured time signal can be observed. The corresponding delta in the SEL of the predicted and the measured sound pressure yields 0.5 dB.
- The associated sound propagation modelling for the far-field with the FE-WI model was able to predict the SEL at 750 m within 0.9 dB.

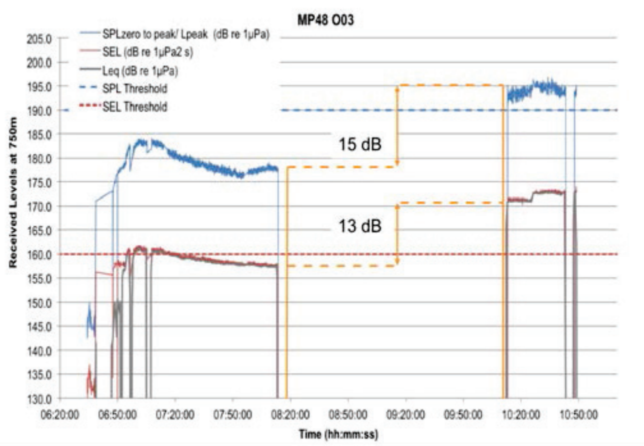

Figure 1: This graph shows time series of SEL (in red) and SPL (in blue) for the reference measurement. The noise mitigation screen was removed and an increase of 13 dB was observed for the SEL and 15 dB for the SPL

Reference measurements such as this are valuable for the development of accurate modelling of underwater noise as they allow very accurate method validation.

In connection with the piling of the foundations for the Anholt Offshore Wind Farm (OWF) in 2012 relatively detailed hydro-acoustic measurements were conducted by DONG Energy at a number of piles. These measurements included sound level recordings at several water depths at several distances in different directions. Measurements were conducted both inside the near-field and in the far-field region. In addition, acceleration measurements were performed at the seabed in several distances.

Overview of modelling methods

Near-field sound prediction by WEAP-FE

The measurement and far-field modelling work from the Anholt OWF case provided motivation for establishing an accurate near-field model. The classic geotechnical model approach used for driveability analysis "WEAP" (Wave Equation Analysis for Piles") was implemented [2]. The WEAP calculation includes details of all hammer components, including the ram profile and the helmet geometry - made here of an anvil and anvil ring. The stiffness data of the helmet – used as input in WEAP - was accurately determined using an external FE model. In the new WEAP-FE technique [6] WEAP estimates the hammer force onto the pile head, as well as the energy dissipated due to pile-soil interaction. These properties are introduced to a relatively simple linear-element, vibro-acoustic FE model that calculates the detailed sound field around the pile.

A particular benefit of WEAP-FE is an accurate mechanical and geotechnical representation of the entire hammer-pile-soil system in WEAP while maintaining computational effectiveness. This allows application to new sites without previous acoustic measurements.

As detailed in [5] WEAP-FE was validated against full-scale measurements for two cases: Vashon Island harbour piling, and the construction of the Anholt OWF.

For the Anholt case, the geotechnical site description was available for the 5.3 m diameter monopiles. However, the modelling was made difficult by the presence of the installation vessel hull (floating crane) between pile and the hydrophone, which was at a relatively large distance of 60 m. The vessel geometry was not included in the FE model, and as a consequence, certain acoustic interference features were not captured by the model as illustrated by the peak at 39 ms in Figure 2. Nevertheless, disregarding the interference events affecting upward moving wave fronts, a fair match in both time and spectral domain was achieved, and the overall SEL matched within +/-2 dB.

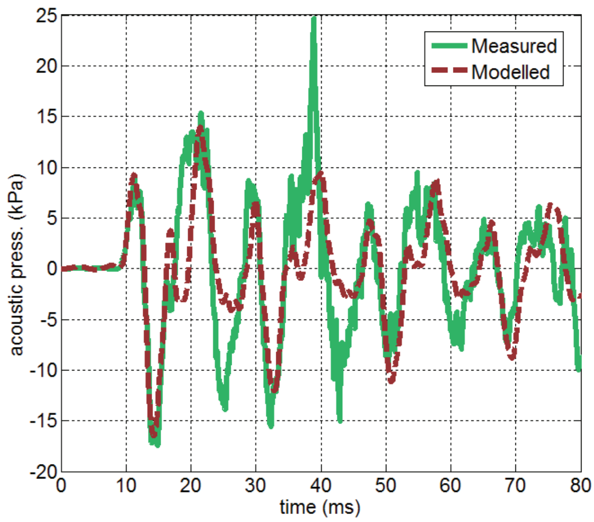

Figure 2: Example of near-field acoustic pressure time series at Anholt OWF from a single hammer impact, at 60 m range and 3 m off bottom for a pile penetration of 10 m: measured vs. modelled (WEAP-FE method).

In both case studies, the loading function supplied by WEAP seems to work remarkably well. The model of energy dissipation within the soil seems promising and functioning despite the simple fluid soil elements used in the FE model.

Near- and far-field sound prediction by a coupled FE-WI model with extended WEAP pre-calculation

As shown in [3], the analysis of offshore pile driving noise with a coupled WEAP and FE model seems to be very suitable, so this strategy has been further followed for setting up a coupled FE-WI model to cover both near- and far-field. In a first step, a similar approach has been carried out with an alternative method to determine the hammer force on the pile head, as, e.g., the shape of the ram mass and the helmet cannot directly be considered due to the one-dimensional wave equation approach of WEAP. Here, this shortcoming is eliminated by determining the excitation force on the pile head in a separate pre-calculation run, which is based on a 2D rotational-symmetric FE approach as presented in [4]. In this approach, a detailed discretization of the impact hammer is implemented and an accurate study of the contact properties including a comprehensive cross validation is accomplished.

After determining the exact pile head force within the pre-calculation run, it is implemented as a boundary condition to a WEAP code to compute the equivalent damping factors. Finally, both the excitation force from the pre-calculation and the equivalent damping factors of the WEAP analysis are used as input parameters for a further 2D rotational-symmetric acoustic FE model, which is optimized to efficiently predict the pressure levels in the surrounding water. With this acoustic FE model, that includes the pile, the water column and the (layered) soil, the propagation of the pressure waves in both the water column and the soil can be investigated. A detailed description of this modelling approach can be found in [5].

Depending on national regulations, a prediction of the resulting pile driving noise may be necessary up to distances of several km to the pile. To allow an evaluation of the noise levels far from the pile, the results of the acoustic FE model are coupled to a special propagation model based on Wavenumber Integration. For further details of the FE-WI propagation approach, see [6].

Beside this coupled FE-WI approach, which allows for the prediction of sound propagation over long ranges and the consideration of frequencies up to several kHz, the use of an extended acoustic FE model for predictions below 1km distance from the pile has proven to be very efficient for practical problems. Especially considering the German limit values, which are defined at 750 m distance to the pile, this approach gains in importance. Thereby, the idea is to coarsen the mesh of the acoustic FE model, allowing for a consideration of frequencies up to 1.5 kHz with at least six finite elements per wavelength. The limitation of the frequency range is reasoned by the finding that the relevant energy of offshore pile driving for wind energy plants is clearly below this frequency, with typical maxima of the underwater noise emission around 75 Hz to 200 Hz. This allows a computation of the resulting SEL und Lpeak values in a distance up to 750 m to the pile in an economically justifiable time, using a single acoustic FE-model, which is only combined with the two described pre-investigations (WEAP and FE modelling of the impact hammer).

One of the major advantages of this approach is that it allows for an implementation of possible sound mitigation measures into the model, both in direct vicinity to the pile, like cofferdams or small bubble curtains, or also further away, like big bubble curtains. Considering the existing limiting values for pile driving noise in the German EEZ, which can hardly be kept without noise mitigation, this is a tremendous advantage for the selection, dimensioning, and optimization of sound mitigation strategies for offshore wind parks.

Validation of this method at the Borkum Riffgrund 1 OWF is mentioned above. Figure 3 shows the agreement between measured and predicted pressure in the near-field.

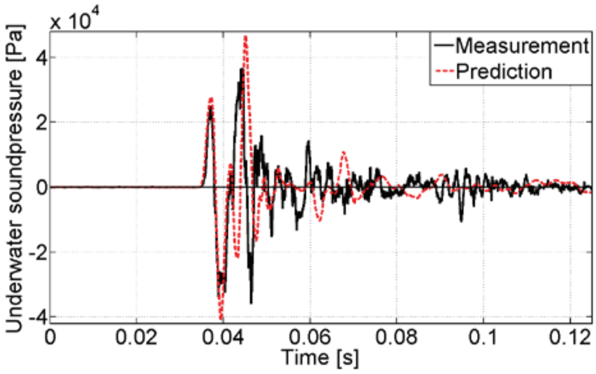

Figure 3 Predicted time signal of the underwater sound pressure in the near field and comparison with measurement data for Borkum Riffgrund 1. The corresponding ΔSEL is 0.5dB.

Efficient noise damping developments

The modelling and validation described so far has focussed on underwater noise from unmitigated piles. This is a prerequisite for being able to model accurately the effects of various mitigation systems. At the Borkum Riffgrund 1 OWF the IHC noise mitigation screen was used. This is a double-walled air-filled structure. According to reference measurements the system was capable of reducing the SEL at 750 m distance by around 13-15 dB, [7]. Modelling of a Borkum Pile including a generalised noise mitigation system similar to the IHC system showed a damping at the same level but also proved that the ground-borne sound becomes dominant already at this level of damping. Thus, there is a limit on the noise reduction that can be achieved by damping in the immediate vicinity of the pile – regardless of what system is being used. It is too early to say what the exact limit is as this may also depend strongly on soil parameters. Nevertheless, it is considered highly relevant to investigate the effects of combining several noise mitigation systems.
The FE-modelling of the near-field propagation clearly shows the presence of wave fronts reflected at the sea surface and at the interfaces at the seafloor and between the topmost layers of the seabed. This also indicates that there may exist optimal and sub-optimal geometries of far-field mitigation measures as 'Big Bubble Curtains' due to wave fronts passing 'beneath' a bubble curtain through a reflected wave path.
As the introduction of efficient damping of the energy path directly from the pile to the water causes the energy path through the soil to become dominant it is also evident that the geometry of the first up-going wave through the soil is relevant when selecting optimal geometry for a bubble curtain.
For a more detailed model-based discussion on the influence of different sound mitigation measures on the underwater sound pressure levels, see [5].

Conclusions

Carefully conducted validation experiments have shown that it is possible to accurately model the generation of underwater noise originating from offshore pile driving. The near-field behaviour can be described quite accurately in terms of the frequency spectrum, the arriving waveforms in the time domain and the emitted energy as given by the SEL metric. It is quite important that the near-field models also provide a good understanding of the different waveforms and propagation paths originating from piling.
The far-field propagation is subject to a larger variation partly because of the complex nature of the environment. However, if suitable approaches like the coupled FE-WI model or the extended acoustic FE model are used and comprehensive input parameters, especially regarding the soil, are available, predictions of high accuracy can be conducted. In this contex, in-situ estimation of the TL by measurement of air-gun shots is proposed as an efficient way of adjusting far-field model parameters.
With the mentioned modelling approaches, physical insight can be increased, which is instrumental in understanding how noise mitigation measures can be used.

References

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