



The Use of Numerical Modelling to Assist and Improve Industrial Understanding of Underwater Noise and Relevant Mitigation Measures

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Summary

This present paper summarises the results obtained through a research and development programme within generation and mitigation of underwater noise generated by pile driving. Modelling of the vibro-acoustic near-field has been performed using finite element (FE) modelling. The influence of various parameters has been examined. Propagation in the far-field has been modelled by wavenumber integration and by extended acoustic FE-modelling. The influence of seabed acoustic parameters has been examined by comparison with transmission loss estimated from recorded airgun shots. Modelling results in the near-field as well as in the far-field have been validated by comparison to reference measurements performed in connection to the installation of offshore wind farms.

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1. Introduction

Every year DONG Energy installs a large number of foundations for offshore wind turbines. For that reason, the company has an interest in understanding the details of how underwater sound during construction is generated and propagates. For some years an internal R&D project has been running, including the aim to develop accurate means for modelling underwater noise emissions. Focus is primarily on impactdriven piles.

Research activities have been conducted in cooperation with universities and leading consultants and comprise FE modelling of near field sound propagation as well as a novel integration of WEAP for quantifying the pile-soil interaction.

2. Numerical modelling

To understand in more detail how sound is generated from pile driving and how it propagates in the water column and the seabed, numerical modelling is required.

In connection with the piling of the foundations for the Anholt wind farm relatively detailed hydro-acoustic measurements were conducted 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.

To gauge the importance of various input parameters and system factors, numerical models were set up to describe the Anholt case and compare modelling results with the actual measurements. First, a relatively simple model was constructed which proved to be able to estimate the resulting long range noise levels to an acceptable high level of accuracy. Likewise, it was possible to estimate the frequency spectrum of the acoustic energy to a reasonable level of detail. Second, input parameters were then varied to investigate their sensitivity with the resulting quantities. As hydro-acoustic measurements were available, it was possible to perform the comparison and the evaluation of parameter variations separately in the near-field and at long range of the piles.

Key parameters and system factors were found to be:

- Detailed knowledge of the hammer-force curve,
- Attenuation of the compressional wave in the topmost seabed soil layers,
- Properties of the compressional and transversal waves in all layers around the pile,
- Geometry of soil layers around the pile,
- A requirement of more detailed representation of the interaction between pile and soil and associated soil damping quantities.

As an example, the kinetic energy of each impact hammer blow results in a hammer force and a certain radial displacement of the pile. Hammer force curves for 'slim' piles can be found in the literature but from numerical modelling, it became evident that it was necessary to model the sitespecific hammer systems comprising ram and helmet (helmet here refers to any component between the ram and pile head) in detail to obtain accurate hammer force curves. Here, the geometry of the helmet proved to have large influence on the hammer curve and therefore also on the force spectrum and ultimately on the noise spectrum.

The findings about the importance of soil parameters can be transformed into requirements to future site investigations in order to obtain knowledge of these parameters.

3. Near-field and far-field propagation

There are various numerical approaches for solving the fundamental Wave Equation for long ranges in an ocean environment. Examples of well-established numerical techniques include approaches based on Wavenumber Integration (WI), Parabolic Equations, Normal Modes as well as Beam Tracing. The outcome of such modelling is Transmission Loss data - which is a measure of the sound attenuation over distance in a defined environment – independently of the source characteristics.

3.1 Transmission Loss from empirical air-gun data

This first step aims at calculating the long range Transmission Loss data around the pile location as accurately as possible. Here, the idea is to match measured data while keeping a conservative approach, i.e. not underestimating the point source strength

For this purpose, a seismic air-gun was fired during the campaign when no hammering took place. An air-gun is useful as an underwater noise source since it is acoustically similar to a theoretical, omnidirectional point source. An empirically-based Transmission Loss (TL) can be derived using air-gun shot signals measured at several distances. Note the importance of the airgun deployment depth on the TL data with regards to sea surface reflection leading to interference patterns between direct and reflected sound field (so-called Lloyd mirror effect).

Figure 1 shows a comparison between TL data estimated from air-gun measurements and calculated by Wavenumber Integration.



Figure 1 Sound Transmission Loss (dB) per 1/3 octave (Hz) at range 1500 m ref@750 m. The red line shows the average of both empirical reference distances 750A and 750B. Calculated data are from Wavenumber Integration. 'Initial' designates results based on initial seabed acoustic parameters whereas 'adjusted' designates the results of a conservative parameter adjustment leading to better agreement between measured and calculated transmission loss.

The empirical and computed TL data can be compared, and the numerical input parameters to the model can be adjusted to improve the match.

3.2 Near-field sound prediction by WEAP-FE

The measurement and far-field modelling work from the Anholt 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 [1]. 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 [2] 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.

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

As shown in the previous section and in [2], 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 [3]. 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 both in the water column and the soil can be investigated. A detailed description of this modelling approach can be found in [4].

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 [5].

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 L_{peak} 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 described two preinvestigations (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.

4. Validation of detailed models

4.1. Validation of WEAP-FE

As detailed in [2] WEAP-FE was validated against full-scale measurements for two cases: Vashon Island harbour piling, and the construction of the Anholt Offshore Wind Farm (OWF).

The Vashon Island case [6] concerned small diameter piles driven with a diesel hammer. The paper describing the measurement case did not include geotechnical details. However, using generic properties for cohesive sand, WEAP-FE results were compared to measurements at 12 m distance. Good agreement in both time and frequency domain was achieved, and the overall SEL agreed within +/-1 dB.

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.

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.

4.2 Validation of the coupled FE-WI model for near and far-field

After the conduct of the numerical trial modelling of the Anholt case the next step was to examine the applicability of numerical modelling to asset projects. At the Borkum Riffgrund 1 OWF a reference test was performed where the last few meters of a pile were installed without noise mitigation measures in effect. The test was executed as part of the German research project



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).

BORA [7] that was supported in this way by DONG Energy. Detailed hydro-acoustic measurements were performed and results were compared with the modelling results.

The high prediction accuracy of the combined near-field – far-field modelling approach with the coupled FE-WI model is demonstrated with the validation of computed sound pressure levels with measurement data from the wind park Borkum Riffgrund 1.

In Figure 3, the underwater sound pressure levels of the acoustic FE model for the near-field with the described pre-investigation of the impact hammer is shown.



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 Δ SEL is 0.5dB.

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. It also showed a distance-dependent oscillation of the sound level as depicted in Figure 4, in which the results of the modelling by WI is shown together with a best-fit logarithmic curve.



Figure 4 Result of sound propagation modelling. Note the oscillatory pattern compared with the best-fit logarithmic curve.

Finally, an example of the extended acoustical FE model for far-field calculations with coarsened mesh parameters is demonstrated.

In Figure 5, a validation of predicted results with measurement data has been accomplished for the Anholt OWF. The results of the near- and far-field measurement are compared to the simulation results, yielding a delta in the far-field for the SEL and L_{peak} of 0.2dB in 750 m to the pile, while the difference of the near field prediction is slightly higher.



Figure 5 Predicted SEL and L_{peak} values over range in the near- and far-field computed with the extended acoustic FE model and comparison with measurement data for the Anholt OWF. At 750 m, the corresponding Δ SEL is 0.2 dB.

Special seismic measurements were performed as part of the BORA project [7], and results are expected to become accessible during 2015. When the actual seismic velocities become available it will be possible to re-run the model calculations. It is expected that this will lead to a further small increase in accuracy.

5. 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, [8]. 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 [4].

6. 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 quite accurately described in terms of the frequency spectrum, the arriving wave forms in the time domain and the emitted energy as given by the SEL metric. 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, insitu estimation of the TL by measurement of airgun 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. Especially the extended acoustic FE model that allows for predictions up to about 1 km distance to the pile, can be applied for the selection, design, and optimisation of sound mitigation strategies for offshore wind park projects.

7. References

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