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COMPUTATIONAL PREDICTION OF THE UNDERWATER SOUND PRESSURE DUE TO OFFSHORE PILE DRIVING

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The computation of the underwater sound pressure level due to offshore impact pile driving with numerical methods is an important chance to get a better understanding of the wave propagation in the soil and the acoustic emission to the water. In this contribution a finite element pile driving model to predict the underwater sound pressure in the area near the pile is presented. In this approach, the impact hammer is modeled explicitly and the importance of a detailed contact modelling with corresponding contact stiffnesses between the ram, the anvil and the pile is shown. A study of the contact stiffnesses is accomplished and the influence of these stiffnesses to the underwater sound pressure is investigated. Additionally an elasto-plastic soil model to take into account the losses due to plastic deformation of the soil has been integrated into the model. Finally the computed quantities of the finite element model are compared with corresponding values obtained in a measurement campaign. With the strain and the velocity signals measured at the pile top, the contact stiffnesses for the impact hammer are determined and the predicted underwater sound pressure is validated with measurement data. Hence, this is the first finite element model for acoustic purposes using a nonlinear soil material model, for which the input energy as well as the output data are validated.

1. Introduction

In a letter of intent, the German government decided in 2010 to decrease the greenhouse gas emission by 40% [1]. To fulfill this long-term goal of the turnaround in energy policy, offshore wind energy becomes a key role. During the construction of offshore wind parks, howeever, one of the major drawbacks is a possible negative influence to marine mammals, like the harbor porpoise. During the erection process a massive noise impact into the water is generated, since pile driving with an impact hammer is still the state of the art technology for wind turbine construction.

To preserve the underwater wildlife, limiting values for the sound exposure level SEL (160 dB) and the peak sound pressure level L_{peak} (190 dB) have been introduced by German authorities [1],[2]. By further measurements of the underwater sound pressure level it has been shown, that it is in most cases impossible to comply with these limits without a sound mitigation system [3]. Measures as a bubble curtain lead to a reduction of the sound pressure in the water due to the difference of the impedance of the water and the air bubbles [4]. The numerical prediction of the resulting underwater sound pressure level is an important way to comprehend the wave propagation both in the water and the soil. However they help to improve the sound mitigation system and to prevent cost-intensive offshore tests.

During the research project ”BORA”, funded by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, a comprehensive measurement campaign at the wind farm ”BARD Offshore 1” has been accomplished. This wind farm is located in the German exclusive economic zone, 90 km away from the island Borkum, in the German North Sea [5]. During the measurement campaign the pile dynamics, like the strain and the velocity at the pile top and the pile accelerations, and the acoustic response in the water in several distances were determined. The impact hammer used for the erection of the wind farm was of the type ”MENCK MHU 1900S” with a maximum blow energy of 1400 kJ. To repel and to avoid a negative influence to the marine mammals, the erection procedure starts softly, i.e. the energy of the impact hammer is raised from very low values until the maximum energy is reached.

In several previous publications by the authors, different aspects regarding the prediction of offshore pile driving noise have been discussed, see for example [6], [7], [8]. Steinhagen and Moosrainer have presented a finite element model to predict the sound pressure level in the water column [9]. They have taken into account the ram and the anvil of the impact hammer, the pile and the water, while the soil has been neglected. Reinhall and Dahl have developed a model, in which the soil has been discretized as an equivalent fluid [10]. Aside from the impact hammer this approach included the pile and the water, too. The ram and the anvil have been replaced by a force function similar to the analytical impact hammer models shown by Deeks et al. [11]. Milatz et al. have developed a first finite element model with a solid soil modelling [12]. The soil has been approximated as linear elastic. The impact hammer has been simplified by a mass falling on the pile; the anvil and the cushion have been omitted.

The finite element approach introduced in this contribution includes an explicitly discretized impact hammer and an elasto-plastic soil model. The needs of taking into account the full impact hammer, including the anvil and the ram, have been already shown by Deeks et al. [11], [13]. The nonlinear behavior of sand has been discussed for example in [14] and [15].

The results of the model suggested here are compared with data of the offshore measurement campaign at the wind farm BARD Offshore 1. The input energy of the impact hammer is observed with respect to the measurement of the velocity, the strain at the pile top and the acoustic energy obtained via the underwater sound pressure. Hence, this is the first finite element model for acoustic purposes using a nonlinear soil material model, for which the input energy as well as the output data are validated.

2. Finite Element Model

As discussed in the introduction the pile, the water, the soil, the ram, and the anvil are separately represented in this model. In order to reduce the computation time, a 2D axis-symmetric formulation has been chosen. By means of an explicit time integration scheme, brief transient dynamic events like the impact of the hammer on the pile can be reproduced in a computational model. A sketch of this model and the corresponding boundary conditions are visualized in figure 1.a). The pile, penetrated 15 m into the soil, has a total length of 80 m and an inner diameter of 3.2 m with a constant wall thickness of 0.07 m. The height of the water column is 40 m. First, a geostatic initial state of the vertical strain σ_2 is generated satisfying the following equation (see figure 1.b)):

$$\sigma_2 = \rho \cdot g \cdot h, \tag{1}$$

where h is the depth of the soil. In a finite element model, the need to fulfil the radiation condition leads to a choice of different non-reflecting boundary conditions for the soil and the water [16]. For the acoustic elements, which represent the water, an impedance boundary condition has been selected, while the soil domain is enclosed by infinite elements. To decrease the computation time even more, the air above the water is replaced by pressure boundary conditions. Here, the acoustical pressure is set to 0 Pa leading to a reflection factor of -1 corresponding to the small impedance of the air compared to the water. The material parameters for the different parts are summarized in table 1 [15]:

Table 1. Material properties of the soil and the pile.

Part	Material	Young's Modulus [$\frac{N}{m^2}$]	Density [$\frac{kg}{m^3}$]	Poisson's ratio [1]
Pile, Anvil, Ram	Steel	$210 \cdot 10^9$	7850	0.3
Soil	Dense Sand	10^8	2020	0.3

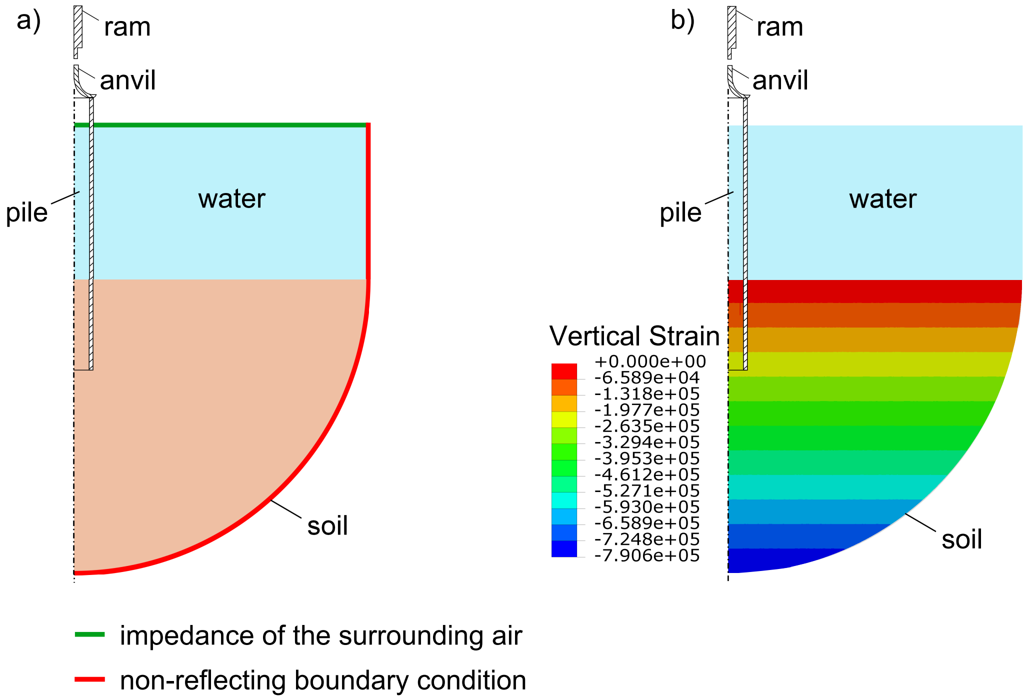

Figure 1. a) Geometry and boundary conditions of the 2D axis-symmetric time domain model, b) geostatic initial state of the soil.

For the soil, an elasto-plastic model with a Mohr-Coulomb yield-surface is implemented to take into account the energy dissipation due to plastic deformation of the sand. The Mohr-Coulomb parameters of dense sand are summarized in following table [17]:

Table 2. Mohr-Coulomb parameters of dense sand.

Friction angle	Dilation angle	Cohesion
$33°$	$10°$	0

Via structural acoustic coupling, the water is connected to the soil and the pile. The influence of the pile to the soil is modeled by a surface-to-surface contact with both normal and tangential behavior. This contact is enforced by a penalty based algorithm. To model the tangential behavior, the Coulomb friction law is chosen:

$$\tau = p \cdot \delta, \tag{2}$$

where τ is the resulting shear stress and p is the contact pressure. The friction coefficient is related to the friction angle of the soil Φ' and is set to $\delta = tan(\frac{2}{3} \cdot \Phi') = 0.4$ [18]. The normal behavior is described by a pressure overclosure relationship, which allows transmitting contact pressure with no limit, when the surfaces are in contact related to infinite contact stiffness.

The discretization of the pile and the impact hammer with the ram and the anvil is visualized in figure 2. Marked with blue is the contact of the ram and anvil, in the following called ”contact I”, and marked with yellow is the contact of the anvil to the pile, in the following called ”contact II”. In this model, a initial velocity v_r is assigned to the ram:

$$v_r = \sqrt{\frac{2 \cdot Q}{m_r}}, \tag{3}$$

where m_r is the mass of the ram and Q is the energy of the impact hammer. The velocities and energies according to the simulated blows of the impact hammer are summarized in table 3.

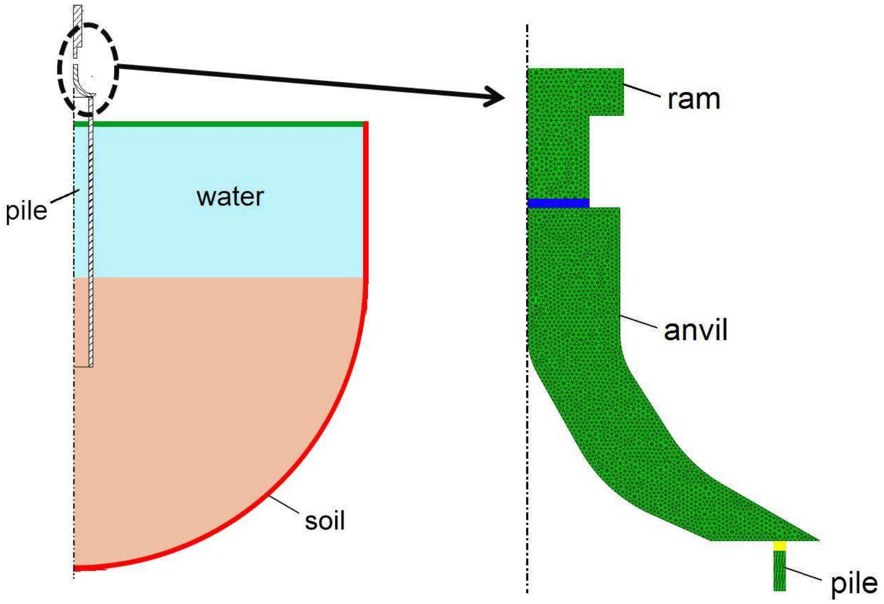

Figure 2. Discretization of the impact hammer and visualization of the contacts between the ram, the anvil, and the pile.

Both contacts, I and II, are enforced with a penalty contact algorithm, like the contact of the pile to the soil, and have both a normal and a tangential behavior. The tangential contact is defined by a friction coefficient of 0.15 (steel on steel). The difference to the other contact in the model is that the contacts of the impact hammer require a pressure overclosure with linear contact stiffness.

Both contact stiffnesses have a significant influence on the entire system. These quantities control and realize the energy transmitted from the impact hammer to the pile and so to the acoustic response inside the water. The sound pressure in the water for different stiffnesses of these contacts are shown in figure 3. It can be observed, that the stiffnesses of contact I and contact II have a massive influence to the sound pressure in the water. Thus, theses stiffnesses have to be determined accurately for the used impact hammer.

Table 3. Energy and initial velocity of the impact hammer.

Energy Q **[**kJ**]**	**Velocity** v_r **[**$\frac{m}{s}$**]**
430	3.1
1400	5.5

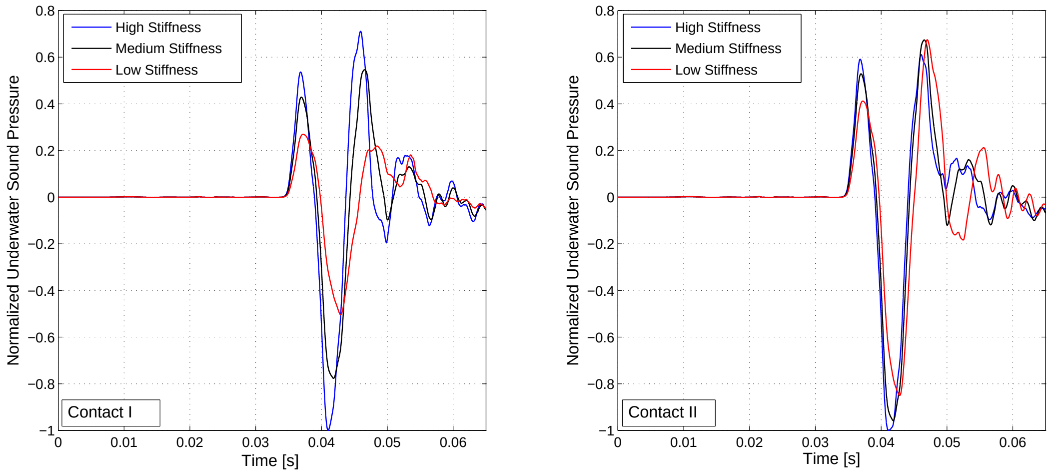

Figure 3. Comparison of the sound pressure in a distance of 30 m to the pile resulting from different contact stiffnesses. Left figure: variation of the stiffness of contact I, right figure: variation of the stiffness of contact II

3. Validation of the finite element model

To validate the pile driving model, the measurement data of the velocity v and the strain ϵ at the pile top and the underwater sound pressure 10 m above the soil in a distance of 30 m to the pile of two strokes were analyzed and compared to the simulation. With the strain and the velocity, the energy input can be validated. These quantities have the following relationship to the force F_p applied to the pile from the impact hammer [11]:

$$F_p = \frac{E_p \cdot A_p}{c_p} \cdot v = E_p \cdot A_p \cdot \epsilon, \tag{4}$$

where E_p is the Young's modulus of the pile, A_p is the cross section area of the pile and c_p is the longitudinal wave velocity. The stiffnesses of both contacts are determined with a gradient-based optimization. The goal of the optimization is to match the maximum of the velocity at the pile top. In figure 4, the measurement of strain and velocity at the pile top is compared with the simulation of a blow with 1400 kJ. A very good accordance can be seen. The maxima of the strain and the velocity of the simulation and the measurement agree very well.

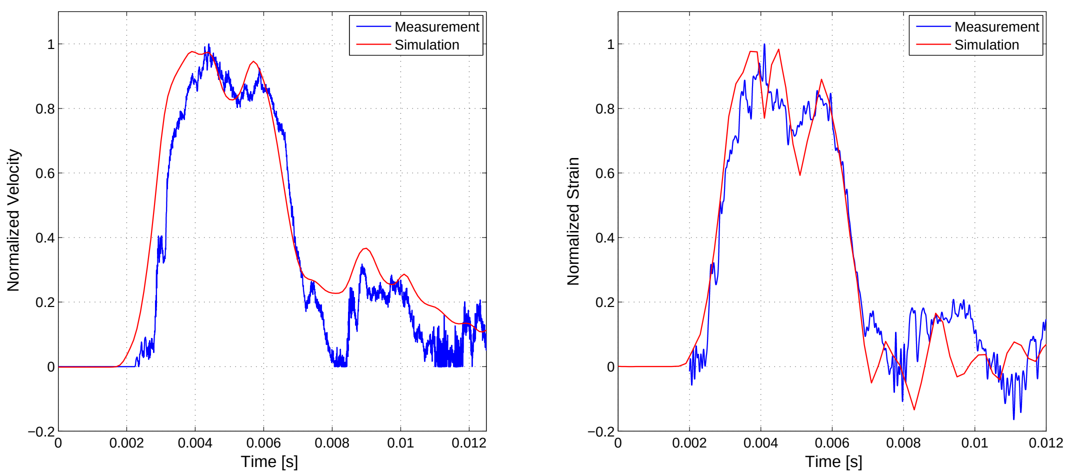

Figure 4. Left figure: comparison of simulated and measured velocity over the time, right figure: comparison of simulated and measured strain over the time.

The energy transmission from the pile and the soil into the water can be observed via the sound pressure level. First, the pressure over the time of two strokes with 400 kJ and 1400 kJ is visualized in figure 5. It can be seen, that the general shape of the simulation is matching quite well with the measurement. Only the high frequent oscillation of the measurement is not reproduced due to the numerical stabilization of the explicit time domain simulation. However, the energy transmission from the pile and the soil to water is simulated with good agreement with respect to the measurement.

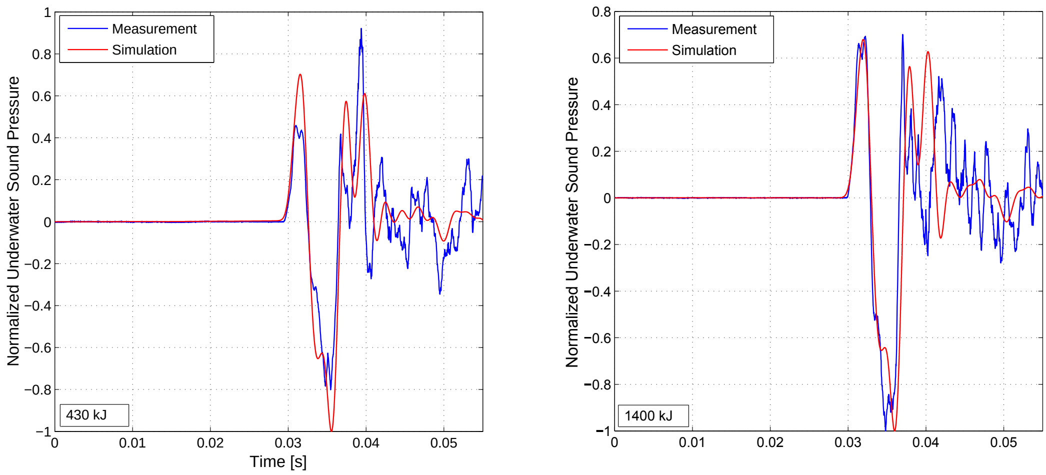

Figure 5. Left: comparison of pressure in the water in a distance of 30 m to the pile over the time resulting from a stroke of the impact hammer with 430 kJ, right: comparison of pressure in the water in a distance of 30 m to the pile over the time resulting from a stroke of the impact hammer with 1400 kJ.

The limiting value of the German authorities are formulated in SEL and L_{peak}. The SEL and L_{peak} of the measurements and the simulation are compared in table 4. With these results the suitability of the presented approach for the modelling of offshore pile driving is shown. The largest deviations are comparatively low with 1.3dB (SEL) and 1.4 dB (L_{peak}), which is an indication for the correct energy transmission discussed before. With respect to the given measurement uncertainty of +/-3 dB, a very well appropriate model is developed.

Table 4. SEL and L_{peak} of the measurements and the simulation.

Energy [kJ]	**measured SEL [dB]**	**simulated SEL [dB]**	**Δ [dB]**
430	184.2	184.8	0.6
1400	189.2	190.5	1.3
	measured L_{peak} [dB]	**simulated L_{peak} [dB]**	**Δ [dB]**
430	209.8	210.5	0.7
1400	214.0	215.4	1.4

4. Conclusion and Outlook

In this contribution, a finite element model for the acoustic response due to offshore pile driving is presented. The main focus has been the validation of the input energy and underwater sound pressure of the approach. To get a realistic input force applied to the pile, the anvil and the ram are discretized according to the geometry of an impact hammer.

The results of the model have been compared to the data of a measurement campaign in the German North Sea. The predicted values both for velocity and strain at the pile top showed a very good agreement with the measured values and validated the correct representation of the energy input. Furthermore, the underwater sound pressure has been evaluated. The very good accordance with the measurement data has shown the correct reproduction of the transmission paths of the energy into the water.

With these results the basis for the further research on developing a holistic simulation model for offshore pile driving noise is established. In the future a sound mitigation system will be implemented in the model. With such a system the modeling of the soil gets even more important than the direct coupling from the pile into the water decreases, such that the emission via the soil into water column becomes more pronounced. The use of a higher order soil model, like a hypoplastic model, will be required to have a realistic wave propagation in the soil.

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