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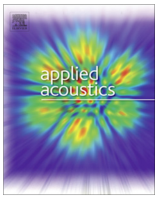

Numerical evaluation of pile vibration and noise emission during offshore pile driving

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ABSTRACT

When offshore structures like converter platforms or wind turbines are founded by pile driving, high noise level are emitted into the water. In this paper a numerical model will be presented and validated which is able to effectively predict the noise emission during pile driving under offshore conditions. It combines a Finite Element Method in the near field of the pile with a Parabolic Equation technique to compute the pressure spectrum, sound exposure and peak level in a certain distance of the pile. The results will be compared to measurements performed during two full scale offshore tests. Furthermore, a procedure for computing the acoustic properties of the sediment as a function of the frequency, depth and density is presented. This allows to represent the layered sediment at the construction site within the numerical methods.

1. Introduction

The most common technique to build offshore structures like converter platforms or wind turbines in medium deep water is by steel piles being driven into the ground by hydraulic hammers. This procedure causes high levels of noise emitted into the surrounding water. Those noise levels can cause damage to marine mammals living close to the construction sites [1]. For this reason, the German Federal Environment Agency enforced a restriction of noise level to 190 dB[1] peak and 160 dB Sound Exposure Level (SEL) in 750m distance of the pile [2,3].

In the recent past there have been a number of publications describing numerical models using the Finite Element Method (FEM) to predict the noise emission during pile driving. They all have in common, that the model is axial symmetric, the pile is modeled by structural plane elements and the solution is obtained in time domain. Reinhall and Dahl [4] solved and discussed the shape of the acoustic wave being emitted. The angle of the acoustic wave front caused by the difference in sonic speed between steel and water and sediment was compared to measurements. Additionally, the pressure spectrum was determined by solving the acoustic pressure filed using Parabolic Wave Equation (PE). The results were compared to FEM.

Zampolli et al. [5] compared the results of a near field FEM to measurements. He proved that the application of a model based on FEM is suitable for computing sound radiation during offshore pile driving. A similar model of the near field was used by Kim et al. [6]. The acoustic field surrounding the pile was determined by a transient FEM. A PE was applied to determine the pressure spectrum in larger distance to the pile than modeled by the finite element model. Alternatively to the PE, a combination of FEM with a wavenumber integration method can be applied [7–9].

In this paper, a detailed axial symmetric FEM model for solving the acoustic field close to the pile (Section 2) as well as a method applying PE for computing the pressure spectrum, peak and sound exposure level in a certain distance to the pile (Section 3) will be presented. By contrast to the approaches mentioned above, the geometry of the ram weight and the anvil will be considered. This allows to represent the loading of the pile in the time domain with high accuracy. Furthermore, the material properties of the layered soil at the site will be considered. In Section 4 a method will be presented to compute the acoustic properties (speed of sound and attenuation of the compressional and shear wave) from the mechanical values measured at the site. The representation of the layers will allow to consider the depth dependency of the radiation into the ground as well as reflections at the layers. Additionally, the layered properties are used for the far field propagation model.

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[1] All pressure level are given in dB re 1 µPa.

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The vibration of the pile, the pressure in close distance and the pressure spectrum as well as the peak and sound exposure level in 250 m and 750 m range will be compared to measurements in Section 5. The measurements were taken during two full scale offshore tests.

2. Finite element model

The finite element model applied here is an extension of Göttsche et al. [10,11]. The commercial software ANSYS version 15.0 is used. Pile, ram weight and anvil of the axial symmetric model shown in Fig. 1 consist of solid plane elements. They are connected by nonlinear frictional elements allowing separation of ram, anvil and pile after the strike. They represent the geometry of the parts used during the offshore test. Water and soil, shown in Fig. 1(b), consist of acoustical fluid elements solving the linear Helmholtz equation for compressional waves [12]. No damping effects are considered by the fluid elements, but spreading loss due to the axial symmetric character of the model. For the water, sonic speed and density are chosen to be constant for the entire domain. The dependency of the depth can be neglected due to the small water depth of 40 m. However, the dependency can be included if reliable measurements from the construction site are available.

Modeling the soil by fluid elements considering compressional propagation only is an approximation. Effects like the radiation of shear waves as well as frictional losses between pile and soil cannot be considered. In this paper the energy absorbed by shear waves and friction within the finite element model will be dissipated by additional dashpots located along the outer wall of the pile. The material properties of the layered soil including the dampers will be discussed in chapter 4.

The water surface is assumed to be fully reflective. Air is neglected as acoustic path, because the energy radiation in air and the transmission of airborne noise into water is negligible. A relative impedance of one is applied to the outer and lower boundary of water and soil in order to model an infinite domain. The impact of the hammer is generated by applying an initial velocity to the ram weight according to the desired kinetic energy.

In this model the water depth is 40 m and the pile has a length of 85 m. The simulation domain is 50 m wide and at the symmetry axis 100 m deep. Thus, the depth of the soil is much higher than the maximum penetration investigated. This ensures a realistic representation of the downward radiation and interaction of the wave front at the layers of the soil.

The simulation time is 100 ms and the time step size is 0.01 ms. An element size of 62.5 mm is applied in vertical direction. For the radial direction, the element length is 125 mm. This leads to about 490 000 elements in total. The upper frequency limit for radial direction is 2 kHz for a minimum of six elements per wavelength. This is satisfying, because the main contribution of the acoustic wave is supposed to be of less than 1 kHz. In vertical direction, the ratio of the element length and time step size ensures a value being slightly higher than the speed of sound in steel.

In order to determine if the results of the near field Finite Element Method depend on the discretization, the element size is varied. The model is slightly simplified and the size of the model is reduced in order to ensure a reasonable simulation time. The pile length above the water is shortened in order to reduce the time after the strike until the compression wave reaches the water. The depth of the water is limited to 30 m. Furthermore, the soil modeled by fluid elements as well as by dashpot elements are neglected. Instead of the soil, a fully absorptive boundary is arranged below the water. The pile is assumed to have a constant wall thickness of 50 mm. Furthermore, the pile is lengthened below the water in order to increase the time until the reflected compression wave reaches the measurement point. Since a refinement of the mesh by the factor of two and four will be investigated, time step size is reduced by the factor four as well for all three variations.

These modifications lead to results which cannot be compared to the measurements. However, they reduce the effects within the simulation to the most important: The propagation of the compression wave within the pile due to the impact of the ram, the free vibration of the pile and the radiation and propagation of the acoustic pressure wave.

Table 1 summarizes the element size of ram and anvil as well as of the fluid domain in vertical and radial direction. The element size of the pile in vertical direction equals the size of the fluid domain. In radial direction a number of element over the thickness is defined. The variation V1 equals the properties of the model described above. It can be seen that the number of elements as well as the simulation time are, with reasonable accuracy, reverse proportional to the square of the refinement.

Fig. 2(a) shows the normalized radial displacement of a node located at the outer edge of the pile in 10 m depth as a function of the normalized time. It can be seen that for $Time^* < 0.55$ no influence of the element size on the displacement is apparent. For $Time^* > 0.55$, the shape of the oscillation is in good agreement. However, the superposed oscillation differs slightly. The normalized pressure is determined in 10 m depth and 5 m distance from the axis. It is shown in Fig. 2(b). Again, no difference can be seen for $Time^* < 0.55$. Above this point in time, the difference between the three variations show very small differences.

It can be stated that the small influence of the refinement on the results does not justify the increase of the simulation time by a factor of up to 16. Furthermore, it has to be considered, that the decrease of the time step size by a factor of four already leads to an increase of the computational effort for all three configurations compared to the original model.

3. Far field propagation

In order to compare the simulation results to the legal limits [2,3] and to measurements the pressure spectrum, the sound exposure and peak level have to be determined in a certain distance to the pile. Therefore, receiving points in 250 m and 750 m are to be evaluated. There are a number of different models available [13]. For similar applications, the PE [4,6] and the wavenumber integration technique [7–9] were used. In this paper, the implementation of the PE in AcTUP v2.2 [14,15] will be used.

The time dependent pressure is determined at 65 receiving points in the finite element model. The points are located at 10 m distance from the pile axis and vertically equally spaced with 1 m. This leads to 40 points in water, and 25 below the mud line. The pressure can be transferred to 1 m distance from pile axis in the corresponding depth, because no attenuation but only spreading loss is considered in the finite element model. A logarithmic approximation of the loss within the finite element model lead to $11\log(10\,\text{m}/1\,\text{m})$ [dB] [16]. The acoustic pressure determined by FEM represents the radiation by cylinder of a certain length, whereas the PE assumes a spherical radiation from a point source. Therefore, the pressure is then modified, taking into account the difference between the surface of the represented part of the pile to the surface of the spherical point source. Then, a Fast Fourier Transform (FFT) is performed in order to consider the frequency dependance of the Transmission Loss (TL). Here, only the magnitude and not the complex character of the pressure is considered. A third octave pressure spectrum is computed for each point. This procedure leads to 65 sources distributed over the vertical length of the pile.

In order to determine the pressure spectrum at a certain distance to the pile, the TL has to be known. Due to the complexity