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Reducing offshore pile driving noise: Modification of the hammer impulse

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ABSTRACT

The foundation of offshore wind farm turbines using driven piles causes high levels of underwater sound emission during construction. The emitted sound levels are potentially harmful to marine mammals and other sea life. In order to protect the marine fauna, several countries have defined limitations for the sound pressure levels. Therefore, pile driving of state-of-the-art piles for offshore wind farms requires the application of noise mitigation systems, e.g. bubble curtains, to assure that sound pressure levels do not exceed official limits. Rapidly increasing dimensions of wind turbines with even higher pile diameters demand additional measures to comply with the official regulations. Therefore, the design of the hammer regarding its acoustic characteristics has recently gained attention.

Within this contribution, the driven pile as noise source and possible modifications of the pile excitation, i.e., the hammer impulse, to reduce sound emission, are discussed and first results towards a more silent hammer are presented.

Keywords: Offshore pile driving, vibroacoustics, underwater noise

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1. INTRODUCTION

The capacity of offshore wind parks has been rapidly increasing in the last decade. Even though offshore wind energy is an important source of renewable energy, every construction of a new offshore wind park causes high underwater noise levels, threatening to harm the marine fauna. Especially critical is the foundation of the wind turbines using piles. Here, an impact hammer is applied to drive the piles into the sea bed. Official limits of underwater sound pressure levels have been applied in several countries in order to protect marine mammals. To fulfil these regulations, noise mitigation systems, e.g. bubble curtains, hydro sound dampers, or noise screens, are usually applied. However, the dimensions of wind turbines and consequently pile diameters are increasing and require therefore more energy to be driven into the sea bed. As a consequence, sound pressure levels increase and additional sound mitigation systems have to be applied to fulfil regulations. In view of this, the modification of the sound source itself, i.e. the pile and the hammer, has recently gained attention.

The present contribution discusses how the driven pile emits sound with the aim to influence its noise emission towards lower sound pressure levels. The effect of modifications of the hammer impulse, i.e. its duration and frequency spectrum, are presented and discussed. Also, a parameter study on the influence of the mass and stiffness of the hammer on the sound pressure levels is presented.

2. NUMERICAL MODEL

Several approaches exist to model sound excitation and propagation as a result of pile driving, among them analytical and numerical models. For the range of interest (a prediction of sound pressure levels up to 750 m is crucial for the regulations of most countries), it is still possible to perform a detailed finite element (FE) analysis. A FE model provides the possibility to extract the underwater sound pressure but also gives information regarding the fluid structure interaction, i.e. the deformation of the pile.

The FE model applied here is axisymmetric, i.e. s2D. Although piles are also driven at locations with strongly asymmetric bathymetry, see e.g. [1], symmetry is an adequate assumption for the purpose of this manuscript that is discussing the driven pile as sound source and the modification of its sound emission.

As commonly applied, in a first step, one model is used to simulate the hammer impact on the pile and a second one to compute the sound emission and propagation. Here, the pile-head velocity caused by the impact is the output of the first and the input of the second model. The interaction of the two models is visualized in Figure 1. The separation of the modelling process into two models also allows for introducing a specific impact of a hammer without defining the corresponding hammer, that is especially useful for the purpose of this paper.

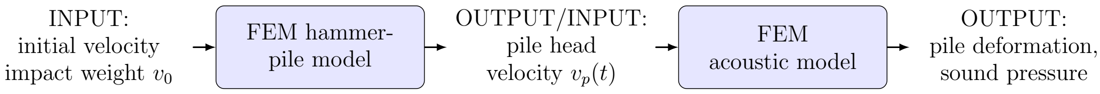


Figure 1: Modeling of underwater sound pressure and pile deformation as a result of pile driving.

In the present manuscript, a cylindrical pile with 70 m length, 6.5 m diameter and 80 mm wall thickness serves as an example. The embedded length of the pile is 35 m and the water depth is 30 m. The embedded pile is shown in Figure 2. The sea bed is modelled with different layers with exemplary values from the North Sea, originally provided in the context of the BORA project for the wind park BARD Offshore 1 [2]. Further specifications of the FE model can be found in [3].

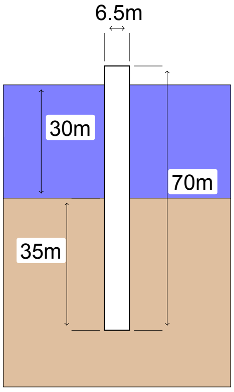


Figure 2: The exemplary pile used in the simulations.

The underwater sound pressure is evaluated based on two quantities, namely the sound exposure level (SEL) according to

$$\mathrm{SEL} = 10\,\log_{10}\left(\frac{1}{t_0}\int_{t_1}^{t_2}\frac{p(t)^2}{p_0^2}\,dt\right)\ [\mathrm{dB}] \tag{1}$$

and the peak sound pressure level ($\mathrm{SPL_{Peak}}$) given by

$$\mathrm{SPL_{Peak}} = 20\,\log_{10}\left(\frac{\max(|p(t)|)}{p_0}\right)\ [\mathrm{dB}], \tag{2}$$

where p_0 refers to the reference sound pressure for underwater sound, i.e. $p_0 = 1\,\mu Pa$, and t_0 to the reference time, i.e. $t_0 = t_2 - t_1 = 1\ s$.

3. THE PILE AS NOISE SOURCE

The hammer impact on the pile head causes a longitudinal deformation of the pile head travelling downwards until it is partly reflected at the end of the pile and travels upwards where it gets reflected again. The longitudinal compression causes radial expansion and thus excitation of sound waves in the surrounding water and soil. The sound waves in the soil leak partly into the water and therefore also increase the sound pressure levels [4].

This contribution focuses on the frequency components of the excited sound waves. They are analysed on the basis of an FE simulation of the exemplary pile and location as introduced in Section 2. A Gauss function

$$v_\mathrm{p}(t) = -a\,e^{b\,(t-t_0)^2} \tag{3}$$

is used to approximate the pile head velocity $v_\mathrm{p}(t)$ caused by a smooth hammer impact. The ram energy was set to 2000 kJ and the simulation time to 1 s.

The normalised magnitude of the energy spectral density of the sound pressure 2 m above the sea bed and in 750 m distance to the pile is shown in Figure 3. In comparison to the normalized energy spectral density, of the excitation, also shown in Figure 3, it is possible to recognize that some frequencies are transmitted stronger than others. Interestingly, it appears that these frequency peaks are close to the longitudinal resonance frequencies of a rod clamped at one side with the same diameter, length and material as the pile. The same observation has been made before in measured underwater sound pressure data by Siegl [5].

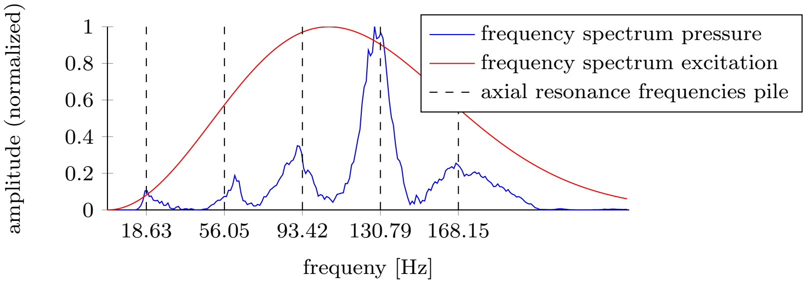


Figure 3: The frequency spectrum of the acoustic pressure 2 m over the sea bed and in 750 m distance to the pile.

The frequency spectrum of the pile deformation, shown in Figure 4, illustrates that these frequencies are also dominant in the axial acceleration in the pile covered with water as embedded in the sea bed. More surprisingly, however, the same frequencies are found to be dominant in the radial acceleration of the embedded part of the pile.

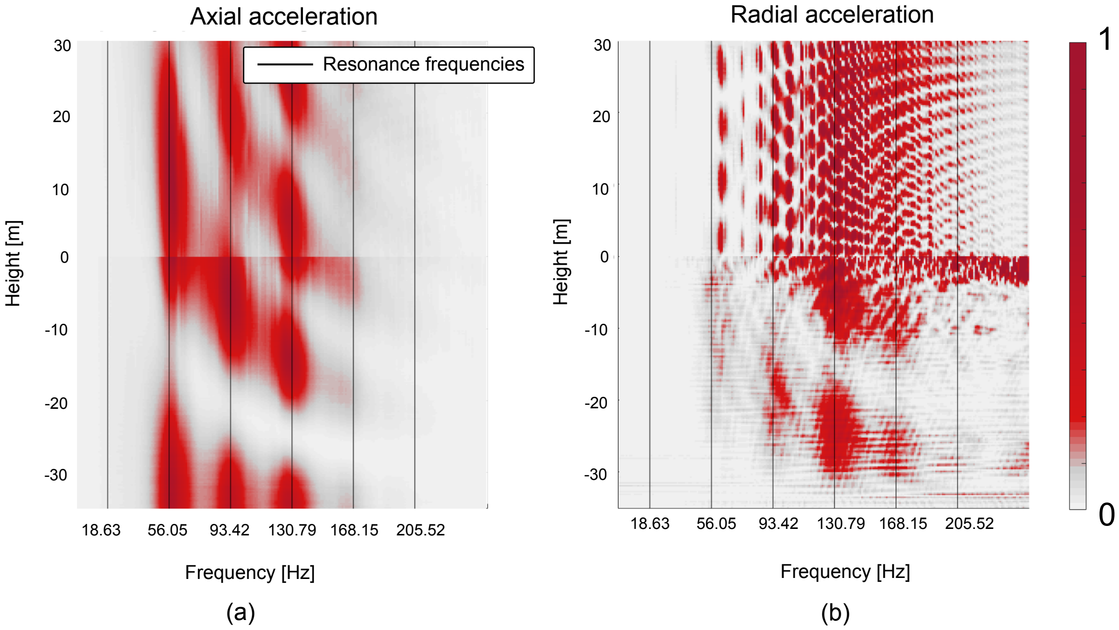


Figure 4: The normalized frequency spectrum of the axial and radial acceleration in the pile covered with water and embedded in the sea floor. The transition from the sea floor to water is at height = 0, while the sea level is at height = 30 m. The data is normalized with the maximal values of the axial/radial acceleration of the pile covered in water/embedded in the sea bed respectively.

The above presented results suggest that the resonance frequencies would be even more dominant if sound mitigation systems are applied, hindering the sound wave propagation in water. In summary, the longitudinal resonance frequencies of the pile appear to be relevant in the sound pressure in 750 m distance to the pile and these observations raise the question if it might be beneficial to avoid their excitation to reduce sound pressure levels.

4. MODIFICATIONS OF THE IMPULSE

In this section only modifications of the hammer impulse, independently of the hammer design itself, are considered.

4.1. Duration of the impulse

The first modification of the impulse to be discussed in this contribution is the length of the impulse. Therefore, the sound pressure levels as a result of impulses with different length but the same energy are presented in the following. As in Section 3, a Gauss function is used to approximate the pile head velocity v_p caused by the hammer impact according to

$$v_{\mathrm{p}}(t) = -a\, e^{b\,(t-t_0)^2}. \tag{4}$$

The parameter b is used to control the length of the impulse while the parameter a serves to keep the energy intake constant despite the changing length of the impulse. The energy is calculated based on the pile head velocity, as stated by,

$$E = \int_0^T v_{\mathrm{p}}(t)\, F_{\mathrm{p}}(t)\, dt = A_{\mathrm{p}}\, Z_{\mathrm{s}} \int_0^T v_{\mathrm{p}}^2(t)\, dt, \tag{5}$$

where E refers to the ram energy, T to the duration of the hammer impact, F_{p} to the force applied to the pile head, A_{p} to the cross section of the pile, and Z_{s} to the impedance of steel. The predefined impacts with different length are shown in Figure 5 (a).

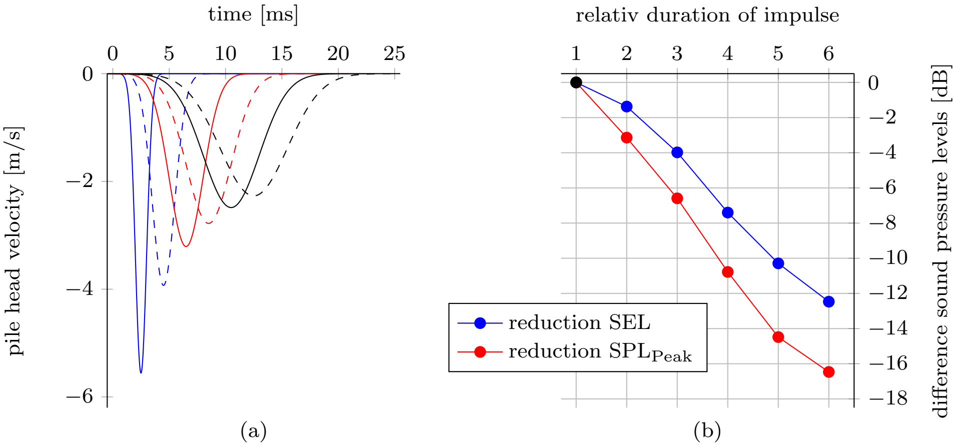


Figure 5: (a) 6 hammer impulses with different duration but the same energy. (b) The mean decrease of the sound pressure levels 2 m above the sea bed for a range from 700 to 800 m in comparison to the reference impulse 1.

A longer impulse is expected to decrease the amplitude and frequency of the quasi-longitudinal wave travelling down the pile and therefore to decrease the sound emission.

However, due to the complexity of system, it is not known beforehand how much the sound pressure levels decrease.

The results shown in Figure 5 (b) state that the sound pressure levels are monotonically decreasing with increasing length of the impulse, as expected. The difference between the second and first impulse is less than 2 dB for the SEL and less than 4 dB for the $\mathrm{SPL}_{\mathrm{Peak}}$. However, comparing the reduction caused by impulse 4, which is twice as long as impulse 2, one can observe that the difference in the SEL is about 6 dB and 7.6 dB for the $\mathrm{SPL}_{\mathrm{Peak}}$. The same can be applied for impulse 3 and 6, here the decrease in the SEL is 8.5 dB and in the $\mathrm{SPL}_{\mathrm{Peak}}$ the decrease is almost 10 dB. These results indicate that no simple rule of thumb can be established to link the decrease in sound pressure levels to the duration of the impulse.

4.2. Frequency Spectrum

Based on the influence of the longitudinal resonance frequencies of the pile on the sound pressure as presented in Section 3, possible sound reduction via omitting these frequencies is discussed next. In order to investigate the effect of resonance frequencies in the pile head excitation, two artificial pile head velocity profiles were created: One that only includes frequencies apart from resonance frequencies (impulse A) and another one that includes resonance frequencies (impulse B).

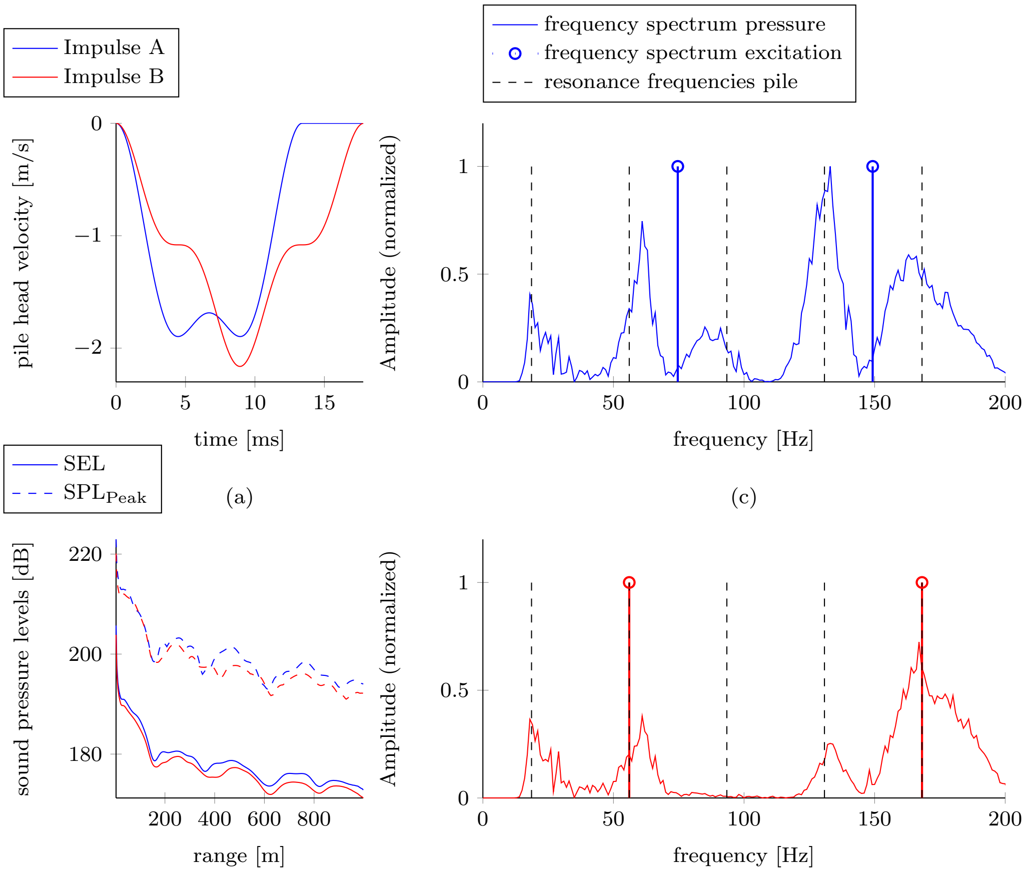
As introduced in Figure 3, the first five longitudinal resonance frequencies are 18.6, 56.0, 93.4, 130.8, 168.1 Hz. The acceleration of the first impulse (impulse A) is defined as

$$\mathrm{a}_{\mathrm{A}}(t) = \sin(2\pi\, 74.6\,\mathrm{Hz}\, t) + \sin(2\pi\, 149.2\,\mathrm{Hz}\, t), t \in [0, 1/74.6\, s]. \tag{6}$$

The frequencies $f = 74.6\,\mathrm{Hz}$ and $f = 149.2\,\mathrm{Hz}$ are chosen because each of them lies exactly between two resonance frequencies and moreover their periods have a common multiple of 1/74.6 s. The number of periods is therefore a natural number, allowing for an excitation that contains exclusively these frequencies. The second impulse (impulse B) is defined as

$$\mathrm{a}_{\mathrm{B}}(t) = \sin(2\pi\, 56.0\,\mathrm{Hz}\, t) + \sin(2\pi\, 168.1\,\mathrm{Hz}\, t), t \in [0, 1/56.0\, s], \tag{7}$$

a sum of two harmonic functions oscillating with exactly the 2nd and 5th resonance frequency. As before, the particular frequencies were chosen because of their advantage that their periods have a common multiple, here 1/56.05 s. The corresponding pile head velocities are shown in Figure 6 (a).



(a)

(c)

(b)

(d)

Figure 6: (a) The pile head velocity without resonance frequencies (impulse A) and with resonance frequencies (impulse B). (b) The resulting sound pressure levels for both excitations. (c) The frequency spectrum of the pressure 2 m above the sea bed and in 750 m distance to the pile resulting from impulse A. (d) Same as in (c), but for impulse B.

The results of the simulations, using impulse A and B as input respectively, are shown in Figure 6 (b) - (d). Despite the expectation to reduce the noise emission, the sound pressure levels as a result of Impulse A are higher than the sound pressure levels caused by impulse B. The frequency spectrum of the pressure as a result of impulse A, shown in Figure 6 (c), shows peaks close to the resonance frequencies even though the pile head excitation was carefully designed not to excite these frequencies. These results indicate that the longitudinal resonance frequencies are unavoidably dominant in the pressure and that their avoidance to reduce the sound is not as straight forward as expected.

5. MODIFICATIONS OF THE HAMMER COMPONENTS

A hammer for pile driving typically consists of two main components: the anvil and the impact weight. An exemplary simplified hammer is shown in Figure 7. During pile driving, the anvil rests on the pile head and the impact weight falls on the anvil which transmits the impact to the pile. This process is repeated about every two seconds several hundred times for every driven pile.

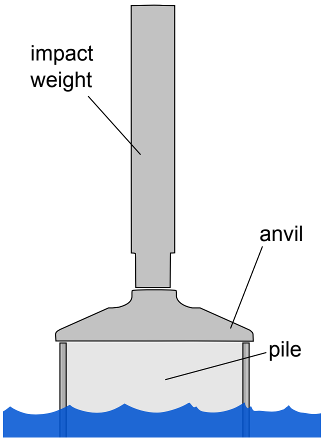


Figure 7: A simplified illustration of a hammer for offshore pile driving.

The acoustic characteristics of the hammer components can be modified changing either their material or shape. Although the material can be described easily with parameters, i.e. the density and the Young's modulus, there is no straightforward way to parameterize the shape. Subsequently it is even more challenging to describe the dependency of the sound pressure levels on the shape of the hammer components. Instead of relying on a particular parameterization of the shape of the components, and therefore already restricting the design possibilities, this contribution discusses merely the influence of two material parameters, the density and Young's modulus. This approach holds the advantage that the influence of only two parameters can be easily captured. Moreover, the density and Young's modulus also serve as a representation of the mass and stiffness of the components, respectively. The mass and the stiffness on the other hand can be also modified via the shape of the hammer. For example, a long impact weight with a small cross section has a lower stiffness than a shorter impact weight with a larger cross section. It is for these reasons that a parameter study on the hammer material also serves as a first rough assessment of the influence of the hammer shape on the sound pressure levels.

The parameter study is based on the same pile dimensions as applied in the previous sections. The ram energy is set to 2000 kJ and the simulation time to 1 s. As a starting point for the hammer, the hammer shape and material of the hammer MHU3500S from the company MENCK is used. Its original density and mass are varied within a range of ±50% for the impact weight and for the anvil individually. Variations of the density of the impact weight also change the energy impact on the hammer and pile. Therefore the initial velocity of the impact weight has been adapted for each scenario in the parameter study to maintain a ram energy of 2000 kJ. The adapted initial velocity v_0 of the impact weight was determined using the equation for the kinetic energy,

$$E = \frac{1}{2} \rho \, V \, v_0^2, \tag{8}$$

where ρ refers to the density of the impact weight and V to its volume. The sound pressure levels were evaluated at 2 m above the sea bed and in a distance of 300 m from the pile.

The results of both parameter studies, one for the impact weight and anvil each are shown in Figure 8 and Figure 9, respectively. Regarding the impact weight, the results show that sound pressure levels decrease with additional mass and increase with additional stiffness. The difference between the highest and lowest SEL is about 5.9 dB, i.e. a notable difference. Considering the results for the anvil, however, the difference in the sound pressure levels is small although the parameter space (variations of density and Young's modulus) is identical with the one applied for the parameter study of the impact weight material. The difference between the highest and lowest SEL is about 1.9 dB. These results indicate that modifications of the impact weight may bear significantly more potential to reduce sound pressure levels than modifications of the anvil. Nevertheless, these results should be considered cautiously, taking into account that the parameter study was based on merely two hammer components made of a homogeneous material each. Adding additional components to the hammer may hold even more potential for sound reduction.

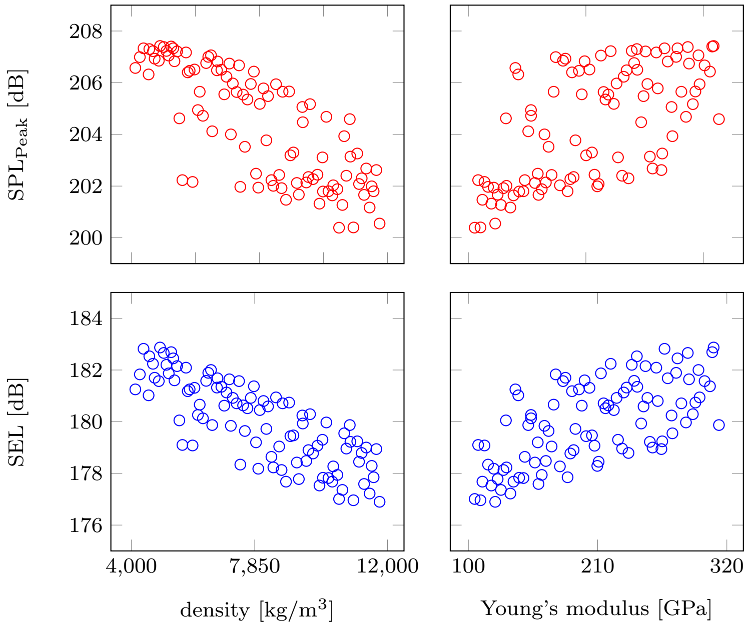


Figure 8: Results of the parameter study for the impact weight.

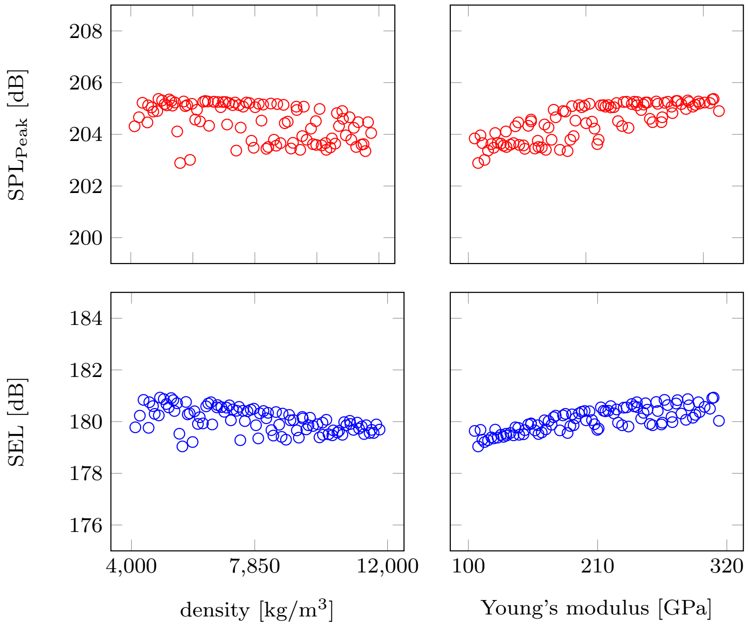


Figure 9: Results of the parameter study for anvil.

6. CONCLUSIONS

The pile as noise source and possible modifications of the hammer impact and the hammer itself were discussed. Prolonging the hammer impact caused a decrease in sound pressure levels, as expected, although no direct proportionality regarding the length of the impulse could be found. Despite the reasoned assumption that the longitudinal resonance frequencies of the pile are dominant in the underwater sound pressure, omitting these frequencies in the pile head excitation did not result in lower sound pressure levels. On the contrary, it appears that the resonance frequencies were dominant in the sound pressure although not existent in the excitation. The results of a performed parameter study on the mass and stiffness of the hammer components imply that, at least for the given hammer design, the sound pressure might be more sensitive to modifications of the impact weight than to the anvil. However, in both cases an increase in mass decreases sound pressure values while the stiffness needs to be lower in order to decrease noise levels. Overall, the underlying mechanisms of the dependency of the underwater sound pressure levels on the impulse upon the pile head appear to be complex. Future work will be directed towards the influence of the hammer shape on the sound pressure. The aim is to find other relevant factors than the duration of the hammer impact to decrease sound pressure levels.

7. ACKNOWLEDGEMENTS

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