Scaling offshore pile driving noise: examples for scenarios with and without a big bubble curtain

Jonas von Pein  
Institute of Modelling and Computation, Hamburg University of Technology: Technische Universitat Hamburg, Hamburg, 21073, GERMANY; jonas@vonpein.net

Tristan Lippert  
AqustIX GbR, Hamburg, GERMANY; lippert@aqustix.com

Stephan Lippert and Otto von Estorff  
Hamburg University of Technology: Technische Universitat, Hamburg, GERMANY; s.lippert@tuhh.de; estorff@tuhh.de

For the installation of offshore wind turbines, large pile foundations are driven into the seabed. The pile driving process can lead to high sound pressure levels in the water column. These levels can reach magnitudes that are potentially dangerous for the marine fauna. Therefore, in many countries the emitted sound pressure levels have to comply with limit values in order to protect the marine environment. Noise mitigation measures are usually necessary to fulfill these limits. Prior to wind farm construction, complex numerical models are often applied for a precise prediction of the occurring sound pressure levels to be expected. In order to allow a simplified first estimation even without such detailed calculation models, scaling laws provide an alternative approach. Within this contribution, already existing scaling laws for unmitigated pile driving are updated for scenarios including a big bubble curtain. The sound exposure levels of six different sites are estimated applying scaling laws for unmitigated and mitigated pile driving noise and compared to the actual measurements.
1. INTRODUCTION

Piles are commonly used for the installation of offshore wind farms. The standard installation procedure relies on percussive pile driving. Every single strike on the pile head leads to the emission of underwater noise with comparably high sound levels, when not properly mitigated. These noise emissions are potentially harmful to the marine environment.\textsuperscript{1,2} Therefore, many countries have defined limits for the emitted sound levels.\textsuperscript{3,4} To fulfill these, the application of noise mitigation has become a standard practice in many markets. A very important metric for pile driving noise is the sound exposure level (SEL). It is defined, with the sound exposure $E_p$ and the reference value $E_{p0} = 1 \mu \text{Pa}^2 \text{s}$ by

$$\text{SEL} = 10 \log_{10} \left( \frac{E_p}{E_{p0}} \right) \quad [\text{dB re } 1 \mu \text{Pa}^2 \text{s}] .$$  \hspace{1cm} (1)

The sound exposure can be computed with the pressure time series $p(t)$ by $E_p = \int_{t_1}^{t_2} p^2(t) \, dt$. The times $t_1$ and $t_2$ mark the beginning and end of the sound event.\textsuperscript{5}

The prediction of the SEL can be done by empirical or numerical models. A review of such models is e.g. provided by Tsouvalas.\textsuperscript{6} Most of the commonly used numerical models have been verified and validated with the pile driving noise benchmarks from the COMPILE and COMPILE II workshops.\textsuperscript{7,8}

Both modelling approaches, however, have the disadvantage of being only available to a few number of experts and institutions. Therefore, simple to apply scaling laws have been developed by von Pein \textit{et al.}\textsuperscript{9} for unmitigated pile driving noise. These have been derived with the application of a well validated pile driving noise model\textsuperscript{10} based on the finite element method (FEM) and validated with 21 publicly available measurement data sets.

The work at hand aims to demonstrate the application of scaling laws for unmitigated pile driving scenarios and the derivation of scaling laws for the scaling of scenarios with the application of a big bubble curtain (BBC) as noise mitigation measure.

The paper is organized as follows: Within Section 2 the used modelling approach with the combination of a FEM model combined with a Parabolic Equation (PE) model is briefly described. The considered scaling laws for unmitigated pile driving as derived by von Pein \textit{et al.}\textsuperscript{9} is provided in Section 3. The computed dependencies and their validation for pile driving with a BBC are described in detail in Section 4. The scaling laws for unmitigated and mitigated pile driving are discussed on the examples of six different sites with measurement data for mitigated and unmitigated pile driving in Section 5. A conclusion and an outlook on the next steps is provided within Section 6.

2. MODELLING APPROACH

The derivation of scaling laws for mitigated scenarios is done by a hybrid modelling approach. The close-range model is based on the FEM and the far-range model on the PE technique.\textsuperscript{11}

Within the FEM model the pile, soil, and water are discretized with a high level of detail. The pile head excitation is usually derived within a pre-calculation considering the original hammer component geometries. Within the acoustical model the derived pile head excitation is applied as a boundary condition at the pile head. At the lateral and lower end of the domain non-reflecting boundary conditions are applied. A detailed description and validation of this modelling approach is provided by von Pein \textit{et al.}.\textsuperscript{10}

The far-range model is a PE model. It is based on the split-step Padé approximation of the outgoing wave equation. For the following computations a coupling radius of 60 m is used. A description of detailed validation of the model is provided in von Pein \textit{et al.}.\textsuperscript{12}

Noise mitigation systems are included into the PE model by multiplying the pressure field in the frequency domain by a frequency dependent transmission coefficient at its dedicated position. The depth and
frequency dependent transmission coefficient of the BBC is derived with an approach suggested by Huisman 
et al.\textsuperscript{13} It is based on the differences of the impedance of the air water mixture and water as well as a first 
approximate of the bubble resonances. The bubble rise speed $v_r$, the width of the BBC at the sea surface $w_{\text{BBC}}(h_w)$ as well as the air supply $Q_{\text{atm}}$ are three parameters that need to be defined for the BBC model. Furthermore, the distance of the BBC $r_{\text{BBC}}$ to the pile is necessary for the computation.

3. SCALING LAWS FOR UNMITIGATED PILE DRIVING NOISE

The considered scaling laws for unmitigated pile driving noise are based on the dependencies derived 
and validated by von Pein \textit{et al.}\textsuperscript{9} These are based on the scaling of the strike energy $E$ by

$$\Delta \text{SEL}_E = 10 \log_{10} \left( \frac{E_i}{E_0} \right).$$

(2)

The influence of the pile diameter $d$ for unmitigated pile driving is scaled by

$$\Delta \text{SEL}_d = 16.7 \log_{10} \left( \frac{d_i}{d_0} \right).$$

(3)

The influence of the ram weight $m_r$ was investigated and derived to be scalable by

$$\Delta \text{SEL}_{m_r} = -10 \log_{10} \left( \frac{m_{r,i}}{m_{r,0}} \right).$$

(4)

The influence of the water depth on the SEL can be approximated with the damping term of the damped 
cylindrical spreading model\textsuperscript{14} and is defined with the reflection coefficient between water and soil $R$, in 
dependence on the water depth $h$, the propagation angle $\phi$, and the distance $r_i$ by

$$\Delta \text{SEL}_h = \left( \frac{10 \log_{10}(|R_i|^2)}{2 \cot(\phi) h_i} - \frac{10 \log_{10}(|R_0|^2)}{2 \cot(\phi) h_0} \right) r_i.$$

(5)

The propagation angle $\phi$ is approximately $17^\circ$ as shown by Reinhall and Dahl\textsuperscript{15} and the reflection 
coefficient can be computed with the acoustical parameters of soil and water. Within von Pein \textit{et al.}\textsuperscript{9} it is 
shown that these four effects can be added up to derive an estimate of the SEL by

$$\text{SEL}_i = \text{SEL}_0 + \Delta \text{SEL}_E + \Delta \text{SEL}_d + \Delta \text{SEL}_{m_r} + \Delta \text{SEL}_h.$$  

(6)

4. SCALING LAWS WITH A BBC

A. DESCRIPTION OF VARIATION RUNS

With the application of noise mitigation systems the importance of the soil conditions increases. This 
is due to acoustical energy tunneling the noise mitigation system and reentering the water behind it. Using 
just one general soil set-up is not considered sufficient here. Therefore, several runs have been conducted in 
order to derive trends not biased by the specific soil set-up.

The modelling of the BBC also adds parameters with uncertainty ranges. These are the air supply and 
the radius of the system.

In order to take these uncertainties into account the following approach is used: The variation runs of 
the strike energy, pile diameter, ram weight, and water depth are each conducted 50 times with different soil 
and BBC parameters. These parameters are derived by a latin hypercube sampling of the following realistic 
ranges:
The soil properties are varied around their nominal value with the following ranges: the compressional wave speed of the first three soil layers are in the ranges of $c_{p,1} = [1500, 1600] \text{ m/s}$, $c_{p,2} = [1600, 1775] \text{ m/s}$, and $c_{p,3} = [1800, 2050] \text{ m/s}$. The corresponding thickness of these layers is varied in the ranges of $\Delta z_1 = [1, 7] \text{ m}$, $\Delta z_2 = [4, 12] \text{ m}$, and $\Delta z_3 = [5, 15] \text{ m}$. Furthermore, the damping coefficient of the first two layers is varied in the ranges of $\alpha_1 = [0.15, 0.25] \text{ dB/} \lambda$ and $\alpha_2 = [0.3, 0.5] \text{ dB/} \lambda$.

The varied properties of the BBC are the air supply $Q_{atm}$, the bubble rise speed $v_r$, and the width of the BBC at the sea surface $w_{BBC}(h_w)$. These are varied in the ranges of $Q_{atm} = [0.25, 0.35] \text{ m}^3 \text{ min}^{-1} \text{ m}^{-1}$, $v_r = [0.25, 0.35] \text{ m/s}$, and the width $w_{BBC}(h_w) = [0.08h_w, 0.12h_w]$. The selection of parameters is similar to the parameters used by Huisman et al. Another important parameter is the distance between pile and BBC. The radius is in the range of $r_{BBC} = [70, 100] \text{ m}$.

B. DISCUSSION OF DEPENDENCIES WITH BBC

In the following, the computed dependencies of the SEL on the four varied parameters are shown. All of the presented results are derived with a BBC applied within the model. Despite the 50 different results a best-fit approximation of the mean value is derived and used to scale the according factor.

i. Strike energy

The variation runs show almost no differences between the individual runs. Therefore, the strike energy can be scaled in the same way as for unmitigated scenarios, see Equation (2).

ii. Pile diameter

The results of the different runs of the FEM/PE model with different diameters are displayed in Figure 1. Therein it can be seen that the variation is within a range of about 3 dB. A best-fit approximation of the mean of the 50 different runs results in

$$\Delta \text{SEL}_{d, \text{BBC}} = 18.3 \log_{10} \left( \frac{d}{d_0} \right)$$

with $d_0 = 2 \text{ m}$. This trend is slightly higher than the relation considered for unmitigated pile driving.

Figure 1: The computed dependency of the SEL on the pile diameter conducted with 50 different parameter combinations evaluated and averaged over the water depth at a distance of 750 m to the pile with a BBC.
The reason is that the presence of a BBC leads to a shift of the frequency spectra to lower frequencies as the BBC has a greater insertion loss at higher frequencies. Since the change in pile diameter also leads to a higher radiation efficiency especially at low frequencies, these effects are adding up and leading to the greater importance of the pile diameter with the application of a BBC.

iii. Ram weight

The influence of the ram weight has been conducted with the pile head excitation from Deeks and Randolph\textsuperscript{16} as described in von Pein \textit{et al.}\textsuperscript{9} The according results are displayed in Figure 2. Therein, only minor differences can be identified for the runs with different parameter combinations. The best-fit of the mean of the 50 runs is leading to a scaling of

\[
\Delta \text{SEL}_{m_r, \text{BBC}} = -9.2 \log_{10} \left( \frac{m_{r,i}}{m_{r,0}} \right).
\]  

This trend is slightly smaller than the trend derived for the unmitigated scenarios. This can, once again, be explained by the frequency ranges in which these effects occur. The changing ram weight has a greater influence on the higher frequencies. This leads in combination with a BBC to a slightly smaller dependence of the SEL on the ram weight.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{The computed dependency of the SEL on the ram weight conducted with 50 different parameter combinations evaluated and averaged over the water depth at a distance of 750 m to the pile with a BBC.}
\end{figure}

iv. Water depth

The greatest difference between the unmitigated and mitigated scaling laws can be found in the water depth dependency. For the unmitigated scenarios the water depth effect is mainly induced by the differences in propagation loss which can be computed with the damped cylindrical spreading model. This effect is still present in the BBC case. However, it is combined with the water depth dependent insertion loss behavior of the BBC. An important influence on the insertion loss of the BBC is the water depth dependent bubble size. It effects the volume fraction of air within the air-water mixture and the resonance effects. The variation of the soil parameters leads to differences of the reflection coefficient between water and soil and influences the amount of energy tunneling the BBC. The combination of these effects and their according uncertainties are also reflected in the large range of the results shown in Figure 3. A best-fit approximation of the mean of the uncertainty analysis results leads to a trend of

\[
\Delta \text{SEL}_{h_w, \text{BBC}} = 16.2 \log_{10} \left( \frac{h_{w,i}}{15 \text{ m}} \right).
\]  

\textbf{Figure 3:} The computed dependency of the SEL on the water depth conducted with 50 different parameter combinations evaluated and averaged over the water depth at a distance of 750 m to the pile with a BBC.
Figure 3: The computed dependency of the SEL on the water depth conducted with 50 different parameter combinations evaluated and averaged over the water depth at a distance of 750 m to the pile with a BBC.

C. VALIDATION WITH BBC

The validation is conducted with the following measurement data sets: The data of Sandbank (SB), Veja Mate (VM), Trianel (TR), and Deutsche Bucht (DB) are all taken from MarineEARS. Furthermore, data of Borkum West 2 (BW2) and Global Tech I (GTI) are used. The data sets are listed in Table 1. The data includes the number of piles installed with a BBC, the measured SEL, the according measurement range, the strike energy, pile diameter, water depth, and ram weight. All of these data sets have been measured with the application of a BBC.

Table 1: Measurement data derived with the application of a BBC.

<table>
<thead>
<tr>
<th>name</th>
<th>piles</th>
<th>SEL [dB]</th>
<th>range [m]</th>
<th>strike energy [kJ]</th>
<th>pile diameter [m]</th>
<th>water depth [m]</th>
<th>ram weight [t]</th>
<th>hammer type</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB</td>
<td>3</td>
<td>162-163</td>
<td>663-757</td>
<td>1013-1522</td>
<td>6.8</td>
<td>26.8-29.6</td>
<td>175</td>
<td>MHU 3500S</td>
</tr>
<tr>
<td>VM</td>
<td>1</td>
<td>171</td>
<td>803</td>
<td>1893</td>
<td>7.8</td>
<td>39</td>
<td>200</td>
<td>Hydrohammer S-4000</td>
</tr>
<tr>
<td>TR</td>
<td>1</td>
<td>163</td>
<td>749</td>
<td>1457</td>
<td>8</td>
<td>28.3</td>
<td>150</td>
<td>Hydrohammer S-3000</td>
</tr>
<tr>
<td>DB</td>
<td>1</td>
<td>168</td>
<td>749</td>
<td>2150</td>
<td>8</td>
<td>39.3</td>
<td>200</td>
<td>Hydrohammer S-4000</td>
</tr>
<tr>
<td>BW2</td>
<td>2</td>
<td>160-163</td>
<td>750</td>
<td>1200</td>
<td>2.44</td>
<td>30</td>
<td>60</td>
<td>Hydrohammer S-1200</td>
</tr>
<tr>
<td>GTI</td>
<td>2</td>
<td>163-164</td>
<td>600-700</td>
<td>583</td>
<td>2.48</td>
<td>40</td>
<td>66</td>
<td>MHU 1200S</td>
</tr>
</tbody>
</table>

To show that the dependencies found in Section 4 can also be identified within the measurement data of Table 1 the following approach is chosen: All data sets are scaled with three of the four developed dependencies to the parameters of the arbitrarily chosen site of TR. The differences between the actual measured value of TR and the scaled results are then plotted over the unscaled parameter. This can be seen within Figure 4. Furthermore, for the upper and lower limit of the resulting differences the according trend line of the scaling law is plotted. The difference between upper and lower limits of the plotted trends is around 7 dB and related to parameters that are not included within the simplified scaling laws such as the soil layering, the distance of the BBC to the pile, the actual air supply, and the pile hammer interaction. Additionally, measurement uncertainties have ranges of about ±2 – 3 dB. Keeping that in mind, the derived trends match very well with the trends of the measurement data. Furthermore, the range between upper and lower bound is in a similar range as for the unmitigated scenarios shown in von Pein et al. In the light of the higher number of uncertainties and simplifications, such as the neglect of the actual BBC radius...
and the actual BBC air supply, this outcome was not expected. To conclude, the validation shows that the derived trends can be used for the scaling of the SEL for scenarios with a BBC.

![Graphs showing the influence of pile diameter, strike energy, ram weight, and water depth on measured SEL with the application of a BBC.](image)

**Figure 4**: The influence of pile diameter, strike energy, ram weight, and water depth on measured SEL with the application of a BBC. For each of the four plots, the SELs have been scaled to the parameters of the TR site except for the parameter plotted on the x-axis. The plotted value is the difference of the actual measured SEL at TR and the scaled results of the other sites.

### 5. DISCUSSION

A common approach to estimate the SEL for mitigated scenarios is to derive an SEL for the unmitigated scenario and subtracting a noise mitigation specific insertion loss. With the newly derived approach it is also possible to directly derive an estimate for mitigated scenarios by applying the derived scaling laws for cases with a BBC.

The following approach is used to derive an estimated range of the SEL: The six sites of Table 1 are considered and five of the six sites are scaled to the site under consideration. The average is taken and displayed together with the minimum and maximum value of the five estimates, indicated by the error bar in Figure 5. These results are plotted right next to the actual measured SEL.

The SEL of the unmitigated scenario is estimated with the scaling laws provided in Section 3 and measurement data of 21 sites with unmitigated pile driving, as provided by von Pein et al. and not explicitly listed within this contribution. Within the data set of unmitigated pile driving also measurement data of the six sites of Table 1 are available. The estimate of the unmitigated SEL for the six considered sites is derived with 20 of 21 sites.

The comparison of the estimates of the mitigated and unmitigated scenarios to the actually measured values allows new insights into the measured data:

The estimations of the BBC results of SB show a very good agreement with the measurements and also indicate that the measurements were at the lower end of the considered data sets. At the same time the comparison of estimated and measured SEL for the unmitigated scenario shows that the measured SEL of the
unmitigated case of SB was the highest in the database. This new perspective allows a better classification of the actual BBC performance.

For VM the unmitigated SEL estimation matches the measured result very well. The comparison of the measured and estimated SEL with a BBC shows that the BBC performance is at the higher end of the range compared to the other sites.

The comparison of the TR results shows that for the unmitigated and the mitigated scenario the measured SEL is at the lower end of the scaled range. However, the cause of this comparably low noise site remains unclear.

These three comparisons demonstrate that the approach of directly scaling the SEL for scenarios with a BBC can provide new insights into the actual BBC performance and are another way of estimating the SEL with the application of a BBC.

![Graph](image)

**Figure 5:** The comparison of the scaled and measured SEL of six different sites with and without the application of a BBC.

6. CONCLUSION AND OUTLOOK

This contribution shows that the approach used for the derivation of scaling laws for the scaling of the SEL for unmitigated pile driving scenarios can be updated to include the influence of a BBC.

The consideration of a BBC leads to an increase of the number of parameters subjected to uncertainties. However, the range between upper and lower limit of the scaled data seen in Figure 4 is similar to the range derived for unmitigated scenarios.

With a decent database of measurements the derived scaling laws are a useful tool for the classification of the magnitude of the SEL for unmitigated as well as for mitigated scenarios with the application of a BBC.

The next steps in the development of scaling laws for offshore pile driving noise are the adaptation to scenarios with a noise mitigation system in the direct vicinity of the pile, a double big bubble curtain, and their combination. Furthermore, an investigation of the influence of each of the four parameters on the frequency spectra of the emitted noise and the SPL\text{peak} can be conducted.

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