COMPILE II: A real-life benchmark scenario for pile driving noise estimations

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Abstract: The effect of pile driving noise on the marine environment is an important factor in environmental impact assessment of planned marine structures, such as ports, bridges or offshore wind farms. Numerous models have been developed to predict the noise levels to be expected from such activities and to advise suitable mitigation measures to concur with different national and international regulation. A recurring problem in the validation of such models is the availability of acoustic measurements, as this is both costly to obtain and difficult to share across different research groups due to commercial sensitivity. To address this problem and compare a number of existing models, the first COMPILE workshop was organized by the Hamburg University of Technology (TUHH) and the TNO in 2014. A generic benchmarking case was then specified to compare various modelling approaches. Simulation results were compared at various depths and ranges between ten meters and fifty kilometres and the broadband results of all models were found to be in very good agreement, for this relatively simple case. In this contribution, the benchmark case for a second workshop (COMPILE II) is presented. The COMPILE II case was set up by TUHH, TNO and E.ON Climate & Renewables and is based on a real-life example, allowing for a model validation based on measurements. A detailed discussion of all relevant model parameters for the pile and the environmental conditions will be given as well as a description of the desired model outputs for later comparison to measured quantities.

Keywords: Pile Driving, Numerical Simulation, Benchmark, Validation
1. INTRODUCTION

Offshore pile driving is the state of the art foundation technique for many offshore structures, such as harbours, jettys, and offshore wind farms. The emitted noise levels from such marine pile driving activities are an environmental concern due to the potentially high encountered sound pressure levels, cf. de Jong and Ainslie [1], Lippert et al. [3], Halvorsen et al. [3], Dähne et al. [4], or Kastelein et al. [5]. To evaluate potential risks and to configure suitable mitigation measures, accurate noise level predictions for planned marine constructions are a key requirement.

Several numerical models have been developed for the prediction of the impulsive sound field from impact pile driving, see for example Reinhall and Dahl [6], Zampolli et al. [7], Tsouvalas and Metrikene [8], Lippert and von Estorff [9], or Fricke and Rolfes [10].

Comparing the different existing models is complicated by the absence of an analytical solution for the problem, on the one hand, and often the lack of available measurement data, on the other hand. The absence of measurement data is in large parts due to the fact that performing the offshore measurements needed to fully validate a numerical model is very cost intensive. In addition, the majority of the existing data on marine pile-driving noise have restricted availability for public use due to confidentiality agreements.

To compare the different existing models, the use of a generic benchmark case was a first step, which led to the definition of such an example and the organization of the first COMPILE workshop. In June 2014, the workshop took place at the Hamburg University of Technology (TUHH), with seven different models, contributed by international research groups from six different countries. The comparison was based on a generic benchmark case without noise mitigation, and the results of all presented models we found to be in remarkable agreement for this rather academical example. A case description, as well as a short description of each model and a comparison of the main results can be found in Lippert et al. [11].

At the end of the workshop, it was agreed by all participants that a real-life offshore example and actual measurement data would be the logical next step. Such data has now become available, provided by E.ON Climate & Renewables. It forms the basis for the COMPILE II case, which will be described in the following. Measurement data for model validation is available at the (in Germany) mandatory 250 m, 750 m, and 1500 m distances at a height of 2 m above the seafloor. Representative sound pressure time series, and one-third octave (base 10) (i.e., decidecade) band spectra will be derived from 25 consecutive hammer blows. Consequently, the series’ maximum, minimum, and mean SEL / SPL_{peak} as well as their standard deviation will be provided for model validation.

All relevant information will also be made available at https://www.tuhh.de/mub/compile.
2. DESCRIPTION OF THE COMPILE II CASE

In the present case, a real-life pile driving scenario without noise mitigation measures will be considered and measurement data will be used for validation of the final model results. The task focuses on calculating SELs and SPLs for a real-life pile driving configuration. Optionally, depth-dependent intensities and energy fluxes can be determined to provide a better model insight. In contrast to the first COMPILE case, cf. Lippert et al [11], many of the relevant modelling parameters are deliberately not explicitly dictated within this document.

Instead, participants have to decide on how detailed certain problem aspects should be modeled and derive the modeling input, which is required for their specific modeling approach, from information that is typically available for a noise prognosis prior to pile driving.

Pile geometry and used hammer

The general shape of the pile has been chosen corresponding to the real-life pile for which the measurements were taken. It consists of two cylindrical and one conical section and is schematically depicted in figure 1, alongside an indication of the bottom parameters. The geometric parameters are defined in table 1. The pile material is steel.

For those strikes that will be used for the validation of the modelling results, the pile was driven using the impact hammer Menck MHU-3500S, with an energy of 1525 kJ.

In contrast to the first COMPILE case, no specific forcing function is given for the second case, but only the used hammer type. The corresponding forcing functions can e.g. be derived using GRL-WEAP or similar models or by any other approach deemed to be appropriate by the participant. If participants do not have access to such models, Alexander Gavrilov from Curtin Universities Centre for Marine Science and Technology kindly offered to provide his Matlab code to derive an approximation of the forcing function (A.Gavrilov@curtin.edu.au).

![Fig.1: Schematic overview of the pile geometry and environmental parameters](image-url)
Table 1: Geometry parameters of the pile

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total pile length</td>
<td>$L$</td>
<td>m</td>
<td>75</td>
</tr>
<tr>
<td>Pile penetration depth</td>
<td>$L_p$</td>
<td>m</td>
<td>30</td>
</tr>
</tbody>
</table>

Pile segment 1

<table>
<thead>
<tr>
<th>Segment length</th>
<th>$L_1$</th>
<th>m</th>
<th>42</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile outer diameter</td>
<td>$D_{ap1}$</td>
<td>m</td>
<td>6.5</td>
</tr>
<tr>
<td>Pile wall thickness</td>
<td>$t$</td>
<td>m</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Pile segment 2

<table>
<thead>
<tr>
<th>Segment length</th>
<th>$L_2$</th>
<th>m</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile outer diameter</td>
<td>$D_{ap2}$</td>
<td>m</td>
<td>Linear interpolation (6.5-5)</td>
</tr>
<tr>
<td>Pile wall thickness</td>
<td>$t$</td>
<td>m</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Pile segment 3

<table>
<thead>
<tr>
<th>Segment length</th>
<th>$L_3$</th>
<th>m</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile outer diameter</td>
<td>$D_{ap3}$</td>
<td>m</td>
<td>5</td>
</tr>
<tr>
<td>Pile wall thickness</td>
<td>$t$</td>
<td>m</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Environmental conditions

The water depth at the pile is $H_{pile} = 39$ m. At the first sampling point at 245 m distance, the water depth is $H_1 = 39$ m, at the second sampling distance at 747 m the water depth is $H_2 = 37$ m and at the third sampling distance at 1481 m, the water depth is $H_3 = 32$ m.

For all depths further than Position 3 (for which no measurement data is available anymore), a generic constant depth of 32 m is to be assumed. In between the specified ranges, the depth can be obtained by linear interpolation. The water column can be assumed to have an iso-velocity profile.

From a geo-technical survey at the pile location, the soil data indicated in figure 1 and table 2 could be derived, given as qualitative description and measured cone resistance $q_c$. For a more detailed discussion of the properties of the different mentioned soil types, see Wentworth [12], Adeyeri [13], Shepard [14, p. 151-158] and Schlee [15].

Table 2: Geo-technical survey data

<table>
<thead>
<tr>
<th>Depth [m]</th>
<th>Type</th>
<th>Approx. $q_c$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 5</td>
<td>Loose to medium dense sand</td>
<td>0 - 10</td>
</tr>
<tr>
<td>5 – 6.5</td>
<td>Dense to very dense sand</td>
<td>10 - 40</td>
</tr>
<tr>
<td>6.5 – 9</td>
<td>Sandy clay</td>
<td>10</td>
</tr>
<tr>
<td>9 – 11.5</td>
<td>Dense to very dense sand</td>
<td>10 - 40</td>
</tr>
<tr>
<td>11.5 – 19</td>
<td>Sandy clay</td>
<td>10</td>
</tr>
<tr>
<td>19 – 35.5</td>
<td>Very dense, silty sand</td>
<td>&gt; 50</td>
</tr>
<tr>
<td>35.5 – 50.5</td>
<td>Medium dense to very dense silty sand</td>
<td>20 - 50</td>
</tr>
</tbody>
</table>
**Sampling points and quantities**

Mandatory sampling distances for this case have been chosen in accordance with the existing measurement data and are depicted in figure 2 (left side). Note that all depicted evaluation points are relative to the seafloor at each specific range. This is accounting for the fact that all measurements were taken 2 m above ground. Relative to the sea surface this means that at 250 m the receiver is located in a depth of 37 m, at 750 m it is in a depth of 35 m and at 1500 m and 5000 m distance it is in a depth of 30 m.

Sampling distances and sampling depths have been chosen according to relevant research and international offshore wind turbine foundation requirements. Following the conventions of COMPILE I, all distances and heights have been defined with respect to the pile center and seafloor (at the pile), respectively.

![Fig.2: Left: Mandatory sampling points / Right: Optional sampling points](image)

In figure 2 (right side), the optional sampling points are depicted. All participants are encouraged to also provide the quantities of acoustic time pressure $p(t)$, sound exposure level (SEL) and peak sound pressure level (SPL$_{\text{peak}}$) at these points.

The sound exposure level (SEL) is defined as

$$SEL = 10 \log_{10} \left( \frac{1}{T_0} \int_{0}^{\infty} \frac{p(t)^2}{p_0^2} \, dt \right) \, \text{dB}$$

with $p_0 = 1 \mu Pa$ and $T_0 = 1 \text{s}$. The zero to peak sound pressure level is defined as

$$SPL_{\text{peak}} = 10 \log_{10} \left( \frac{\max(p(t)^2)}{p_0^2} \right) \, \text{dB}$$

For the above equations, the sound pressure $p(t)$ is understood to be low-pass filtered in the frequency range 0-2.5 kHz. The time window should be long enough to contain most of the energy of a blow. At the same time, it should be kept to a minimum to prevent calculation times that are unnecessary long/impractical. From different measurement results it can be observed that the spectral density falls off quickly above 2 kHz. In order to capture information for acoustic frequencies at least up to 2 kHz, all models should yield pressure and velocity solutions with a time step of $1/5000 \, \text{s}$ (corresponding to a Nyquist frequency of 2.5 kHz) or smaller.
The sound pressure spectrum resulting from the Fourier transform

\[ P(f) = \int_{-\infty}^{\infty} p(t) e^{-2\pi if t} dt \]

should also be provided, as well as the SEL in decade bands (see ISO 18405 definition).

In addition to these quantities, all participants are encouraged to compute all or some of the following quantities. The particle velocities \( v_r(t) \) and \( v_z(t) \) and their frequency domain counterparts defined as,

\[ V_r(f) = \int_{-\infty}^{\infty} v_r(t) e^{-2\pi if t} dt \]

\[ V_z(f) = \int_{-\infty}^{\infty} v_z(t) e^{-2\pi if t} dt \]

In analogy to the first COMPIL case, it is also encouraged to compute the time-integrated intensity vector \( I \),

\[ I = \int_{0}^{T} p(t) v(t) dt \]

and the time-integrated equivalent plane wave Intensity \( I_{eq} \),

\[ I_{eq} = \int_{0}^{T} \frac{p^2(t)}{pc} dt \]

at the points specified in figure 2, and the energy flux through a cylindrical surface concentric with the pile \( E \),

\[ E = 2\pi R \int_{0}^{H} p(t) v_r(t) dt \, dh \]

and the time integrated equivalent plane wave energy flux (based on equivalent plane wave intensity) \( E_{eq} \),

\[ E_{eq} = 2\pi R \int_{0}^{H} \frac{p^2(t)}{pc} dt \, dh \]

at the ranges specified in figure 2.
3. SUMMARY

With this real-life benchmark case and the direct comparison of the modelling results to actual measurements, it is believed that valuable insights can be gained both on the underlying physics and the applicability and limitations of the different modelling approaches.

All interested institutions and companies are invited to join the workshop and submit results for the described case. Currently, the workshop is scheduled for 14 November 2017 in Hamburg, Germany. If you wish to receive further information or have any further questions please visit https://www.tuhh.de/mub/compile or send an email to s.lippert@tuhh.de, marten.nijhof@tno.nl, and tristan.lippert@tuhh.de.

REFERENCES
