Offshore Pile driving noise: Capability of numerical prediction models and ways to consider new technologies

Stephan Lippert
Hamburg University of Technology, Institute of Modelling and Computation

- Motivation
- Noise generation and transmission
- Modelling approaches / COMPILE
- Comparison to measurements
- Conclusions
Motivation

- **Typical characteristics** of current offshore wind park projects:
  - Locations *far at sea* (10-100km from coast)
  - Water depths 10-50m
  - Huge dimensions of the plants

- **Typical foundation types**:
  - Monopiles or tripiles
  - Tripods, jackets fastened by piles
  - Alternative concepts under investigation (gravity-based foundations, suction buckets, drilling of piles, etc.)

- **State-of-the-art technology**: Pile driving
  - Typical pile diameters 2-8m
  - Pile lengths up to 100m

→ High impact energy of the hammer results in considerable noise emission
Unmitigated source sound pressure levels clearly above 200dB are reached.

Trend towards larger turbines and thus increasing pile diameters will cause even higher noise levels.

In many countries, noise limitations exist to protect the marine wildlife.

Various mitigation measures are used to comply with the threshold values.

Accurate prediction of noise levels prior to construction is often mandatory and necessary to optimize the piling process and mitigation measures.

Several different approaches exist for the prediction of pile driving noise.
Numerical models have proven to be especially capable for the prediction of underwater pile driving noise

- **Detailed consideration** of:
  - Applied **hammer technology**
  - Exact **pile geometry**
  - Possible **noise mitigation measures**
  - **Site-specific propagation condition** in both water column and soil

- **Prognosis of the noise emission** and dimensioning of **mitigations measures**

- **High physical insight** regarding the **noise generation** and **propagation**

- **Focused** and **efficient optimization** of all components of the system

- **New technologies** (optimized impact hammers, BLUE piling, vibro hammers, alternative pile designs, new mitigation systems, etc.) can easily be **included** and **thoroughly investigated** before costly offshore testing
The **impact energy** of the hammer results partly in:
- pile penetration into the soil
- vibration of the pile
- vibration of the soil
- deformation (elastic/non-elastic)

Different **transmission paths** exist:
- Pile-to-water
- Pile-to-soil
- Soil-to-water

**Sound mitigation measures** may be used:
- Bubble curtains
- Cofferdam
- Etc.
Noise generation and transmission

Excitation force

Animated wave propagation in water and soil from numerical simulation model
Noise generation and transmission

Numerical simulation models allow for a high degree of physical insight!

Mitigation measures

Tunneling via the soil
Numerical simulation models allow for a high degree of physical insight!
Noise generation and transmission

Numerical simulation models allow for a high degree of physical insight!

Mitigation measures

Tunneling via the soil
Noise generation and transmission

Numerical simulation models allow for a high degree of physical insight!
Modelling approaches

- **Complicated task**, although different numerical **methods** are available
  - **Underwater acoustics** is a research topic since several decades
  - **Huge size** of the domain with **distances** of interest up to **several kilometres** and **frequencies** up to some kilohertz
  - Influence of **sea states** and related **damping effects** on the propagation model and **dispersion effects** for long range propagation
  - **Complex interaction** between the **pile** and the **soil**
  - **Thorough soil model** is very important, especially when using sound damping systems
  
  ➜ Often **hybrid models** instead of a single method with **dedicated approaches** for both near and far field
Modelling approach of TUHH

Tripartite global modelling approach with close range (CR) discretization method + long range (LR) propagation code:

- Far field model
- Coupling to far field
- Waves in the soil

- Near field model
- Coupling to near field
- Coupling
- Mitigation measures
- Waves in the soil

Coupling to near field

Pile dynamics and excitation
CR model consists out of **one** main model and **two** pre-calculations

**Pre-calculation 1** determines the forcing function of the impact hammer
- 2D-axisymmetric finite element model
- Explicit time integration

**Pre-calculation 2** determines an equivalent damping
- Equivalent damping takes into account the losses due to the plastic deformations of the soil (pile-soil-interaction)
- Extended 1D WEAP code

**Main model** consists out of the pile, the soil, and the water
- 2D-axisymmetric finite element model
- Explicit time integration
Modelling approach of TUHH

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- Pre-calculation 1 determines the forcing function of the impact hammer
  - 2D-axisymmetric finite element model
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  Possibility to include **new hammer technologies** (optimized impact hammers, BLUE piling, vibro hammers, etc.)

- Main model consists out of the pile, the soil, and the water
  - 2D-axisymmetric finite element model
  - Explicit time integration

  Possibility to include **alternative pile designs, new mitigation systems**, etc.
The COMPILE initiative has been founded by TUHH and TNO in 2014

- The **aim** of COMPILE was a **comparison** of the numerous models
- The **main goal** was to **increase** the exchange of ideas and **enhance** the different **numerical methods** → **LEARN FROM EACH OTHER**
- A **simplified test case** had been developed
- **Workshop** in **June 2014** at the Hamburg University of Technology with **9 participating institutions** from **all over the world** (Australia, Canada, Germany, South Korea, The Netherlands, United Kingdom)
- However, **rather empirical test case** with several **simplifications** (e.g. fluid soil without layering), many **predefined parameters** (e.g. given forcing function), and **no availability of measurement data**
COMPILE II has been launched by TUHH, TNO, and E.ON in 2017

- **Same aims** as COMPILE I, but much more **realistic and complex case**
- **Measurement data** from E.ON site available, but unknown to participants
- **Information** about hammer, pile, and site provided in a way as it is **typically available** in an offshore project **prior to construction**
- Many of the **relevant modelling parameters** have **not clearly** been **defined**, but have rather been **left open to be derived by the research teams** themselves, if needed for their modelling approach
- **Workshop** in **November 2017** at the Hamburg University of Technology
- **12 participating institutions** from **all over the world** (Australia, Canada, Denmark, Germany, South Korea, The Netherlands, UK, USA)
The COMPILE initiative: Benchmark test case

Conical pile in a layered soil, driven with MENCK MHU 3500S @1525kJ

<table>
<thead>
<tr>
<th>Depth</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 m</td>
<td>Water</td>
</tr>
<tr>
<td>39 m</td>
<td>Loose to medium dense sand</td>
</tr>
<tr>
<td>44 m</td>
<td>Dense to very dense sand</td>
</tr>
<tr>
<td>45.5 m</td>
<td>Sandy Clay</td>
</tr>
<tr>
<td>48 m</td>
<td>Dense to very dense sand</td>
</tr>
<tr>
<td>50.5 m</td>
<td>Sandy Clay</td>
</tr>
<tr>
<td>58 m</td>
<td>Very dense, silty sand</td>
</tr>
<tr>
<td>74.5 m</td>
<td>Medium dense to very dense silty sand</td>
</tr>
</tbody>
</table>

$L_1 = 42$ m
$L_2 = 20$ m
$L_3 = 13$ m
$D_{0.1} = 6.5$ m
The COMPILE initiative: Benchmark test case

Bathymetry and sampling points

**Mandatory**

- Sound pressure $p(t)$
- Sound exposure level $SEL$ and peak sound pressure level $SPL$

**Optional**

- Spectral sound pressure $P(f)$
- Sound particle velocity in radial and vertical direction $v_r(t)$, $v_z(t)$, $V_r(f)$, and $V_z(f)$
- Time integrated sound intensity vector $I$
- Time integrated energy flux $E$

Measurement data available!
The COMPILE initiative

- How to get an **accurate excitation force**?
  
  ![Analytical formula](image1.png)
  ![1D WEAP code](image2.png)
  ![Detailed FE model](image3.png)

- What about **damping**? **Losses** due to **soil deformation etc.**?

- Derivation of the **sound speed profile** for the **layered soil**?

- How to **consider** the **bathymetry** at the site?
Modelling approaches used within COMPILE II:

- **Numerical** model I (2 participants): Close range (CR) discretization method

- **Numerical** model II (1 participant): Long range (LR) propagation code

- **Numerical** model III (6 participants): CR discretization method + LR propagation code

- **(Semi-)Analytical** model (1 participant): Equivalent point sources + LR propagation code

- **Empirical** model (1 participant): Based on scaling laws and interpolation from huge set of measurement data
Comparison to measurements: COMPILE II

Sound exposure level (SEL)

- Spread of the predicted levels is quite moderate, many models match very well
- SEL is rather overestimated (conservative model assumptions, e.g. calm sea etc.)
- Many models reflect decay very well and will deliver reliable results also >1.5km

* Results updated after workshop
Comparison to measurements: COMPILE II

Peak sound pressure level (SPL)

- Generally **similar conclusion** for the SPL
- **Some models** match **very well**, although SPL is **much more difficult** to be predicted accurately than energy-averaged quantities like the SEL

*Results updated after workshop*
Comparison to measurements: Jacket piles

Normalized SEL over penetration depth for four jacket piles (● ○ ● ○) *

A: Pile head flush with sea surface  
B: Final penetration depth (pile head submerged)

- Application of a DBBC and an additional grout annulus bubble curtain (GABC)
- Predicted SEL for both penetration depths fit very well with on-site measurement
- Measured levels are slightly lower, as GABC (Δ=1..3dB) was not included in model

* Joint publication of TUHH, Novicos, and Heerema at UACE 2017, see Lippert et al., Prognosis of underwater pile driving noise for submerged skirt piles of jacket structures, Proceedings of UACE 2017, Skiathos, Greece (2017)
During offshore pile driving, **high underwater noise levels** are generated.

In many countries, **noise limitations** exist to **protect marine life**.

An **accurate noise prognosis** prior to construction is **often mandatory** and **necessary** to optimize the piling process and mitigation measures.

Numerical simulation models are capable to predict SEL and SPL levels that are clearly **within the confidence range** of the measurements.

Also **complex technical events**, like the **effect of noise mitigation measures** or the development of underwater noise for **submerged piles**, can be **correctly reflected by high-end models**.

Due to the **high physical insight** regarding **noise generation and propagation**, the computational models allow for a **focused and efficient optimization** of all components of the system.

**New developments** regarding hammer technology, pile design, or mitigation techniques can easily be **included** and **thoroughly investigated** before costly offshore tests are performed.
Thank you for your attention!

Contact:

TUHH
s.lippert@tuhh.de
+49 (0) 40 42878 4481

Novicos
lippert@novicos.de
+49 (0) 40 300 870 37