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

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

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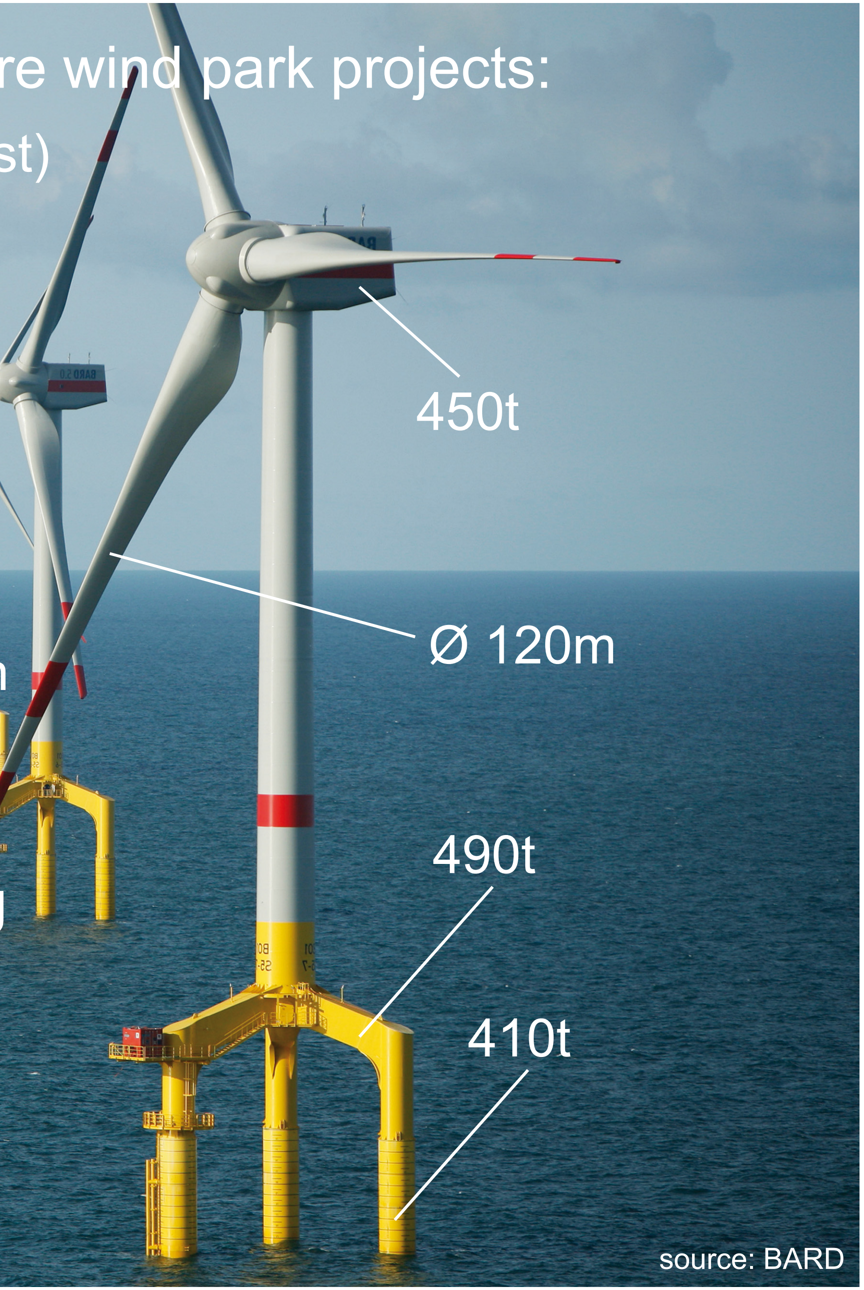
- Typical **characteristics** of current offshore wind park projects:
  - Locations **far at sea** (10-100km from coast)
  - **Water depths 10-50m**
  - **Huge dimensions** of the plants
- Typical **foundation types**:
  - **Monopiles** or **tripiles**
  - **Tripods, jackets** fastened by piles
  - **Alternative 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**



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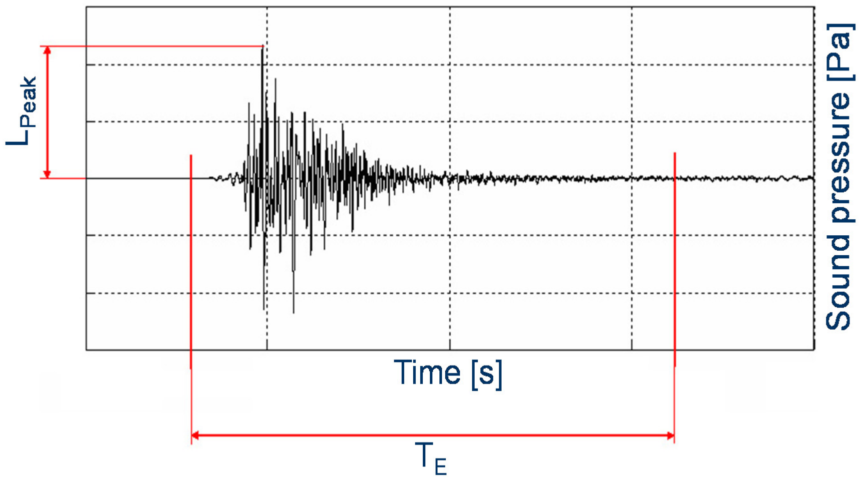
- Unmitigated source sound pressure levels **clearly above 200dB** are reached
- Trend towards **larger turbines** and thus **increasing pile diameters** will cause even **higher noise levels**
- In many countries, **noise limitations** exist to protect the marine wildlife
- **Various mitigation measures** 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

source: wikipedia



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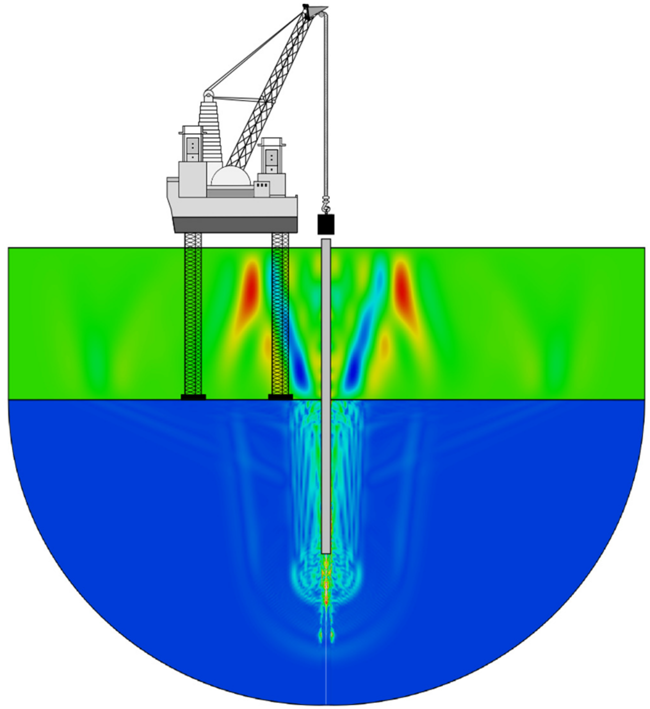
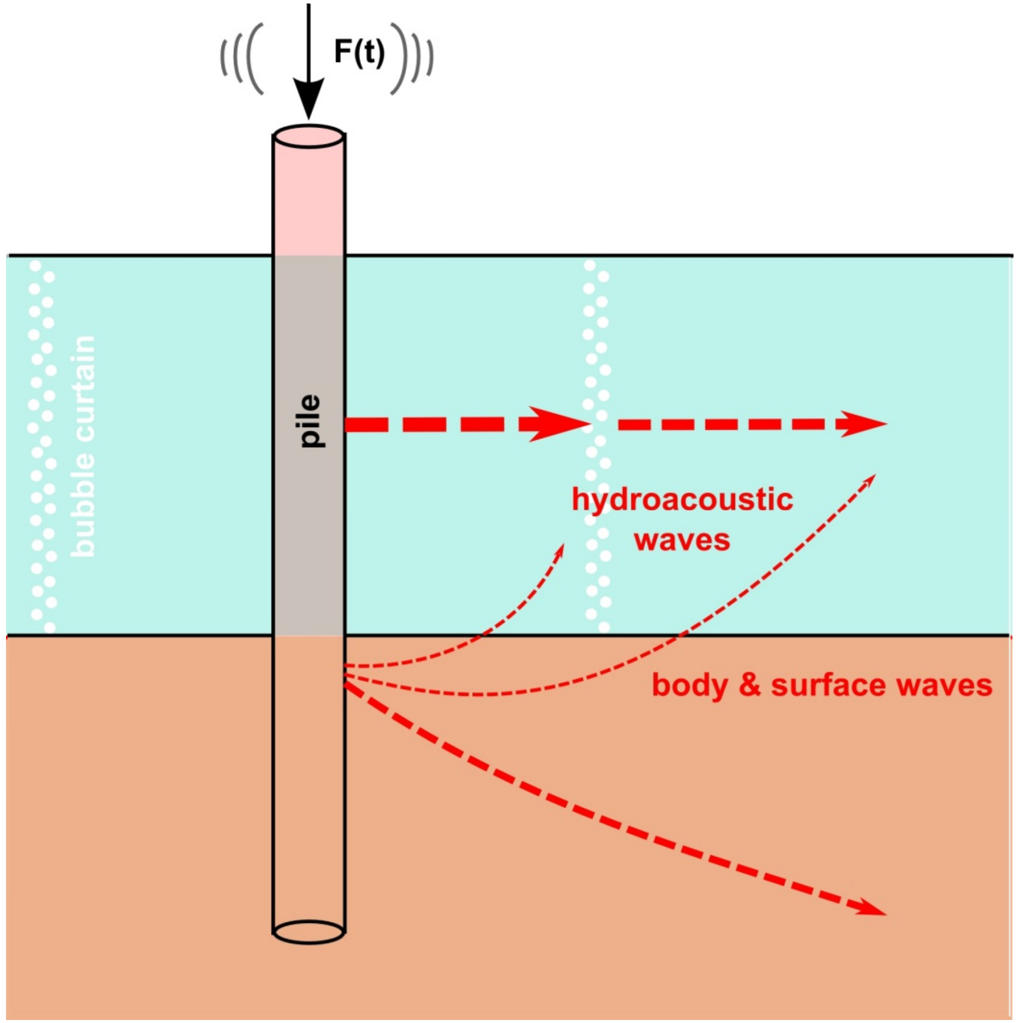
Numerical models have proven to be especially capable for the prediction of underwater pile driving noise

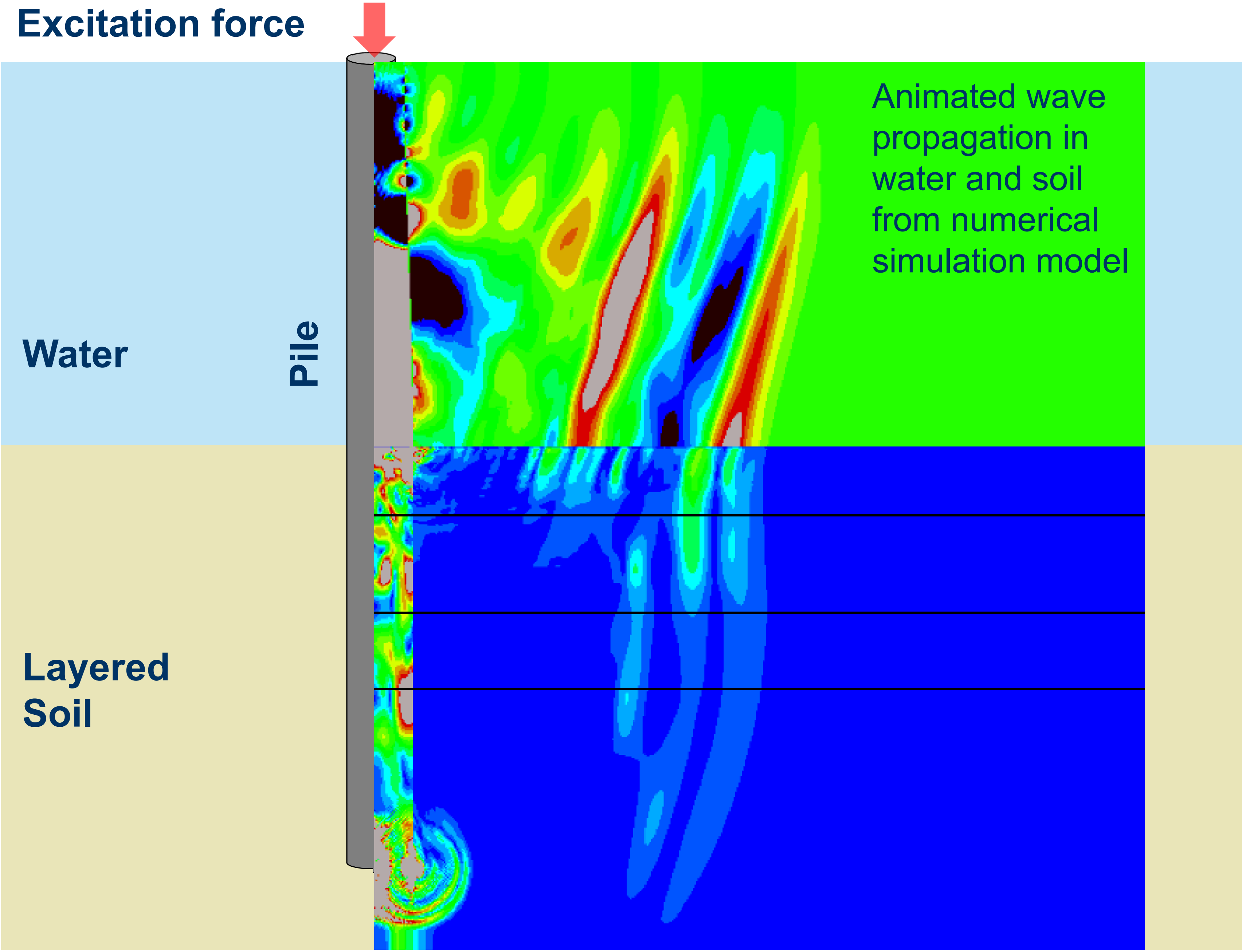


- **Detailed consideration** of:
  - Applied **hammer technology**
  - Exact **pile geometry**
  - Possible **noise mitigation measures**
  - **Site-specific propagation condition** in both water column and soil
- Prognosis of the **noise emission** and dimensioning of **mitigations measures**
- **High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



Noise generation and transmission

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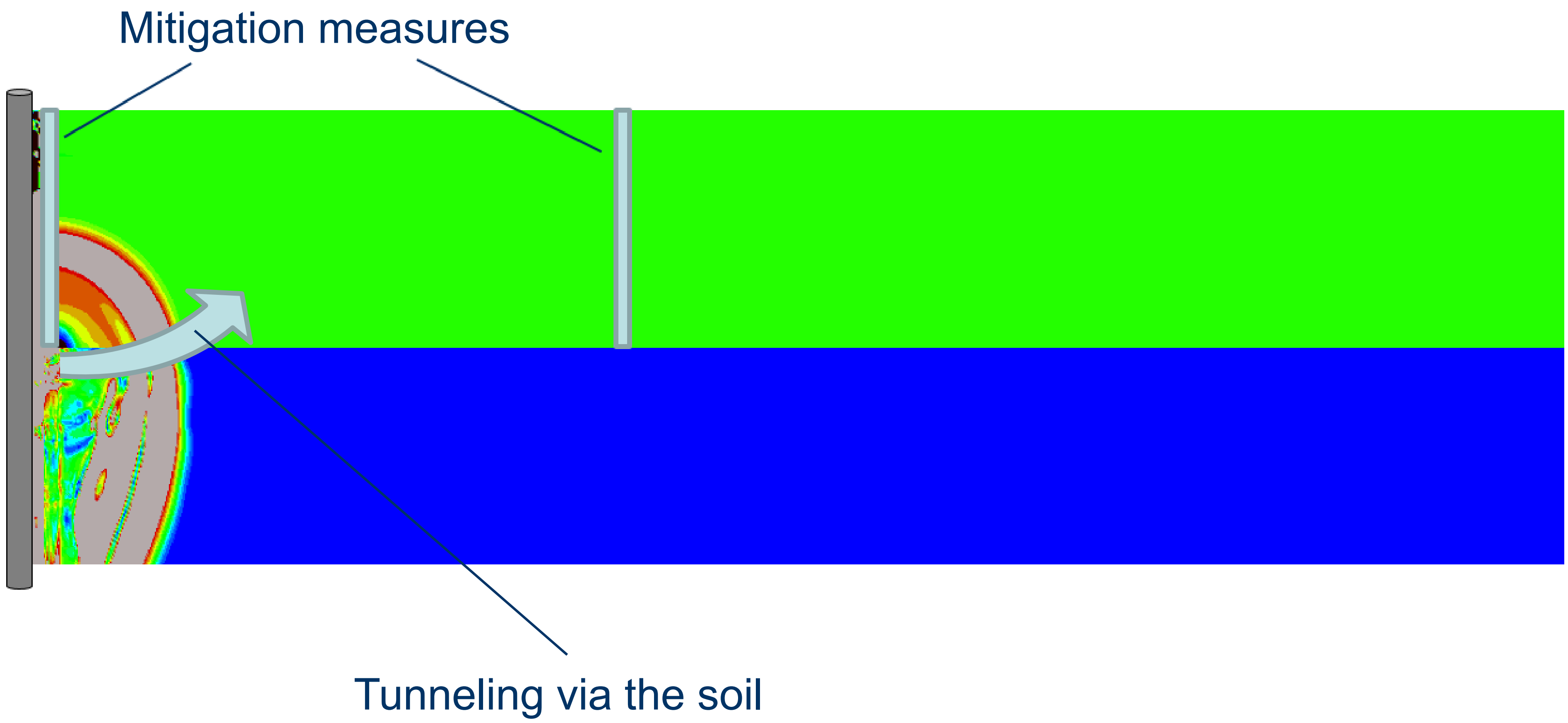
Numerical simulation models allow for a high degree of physical insight!



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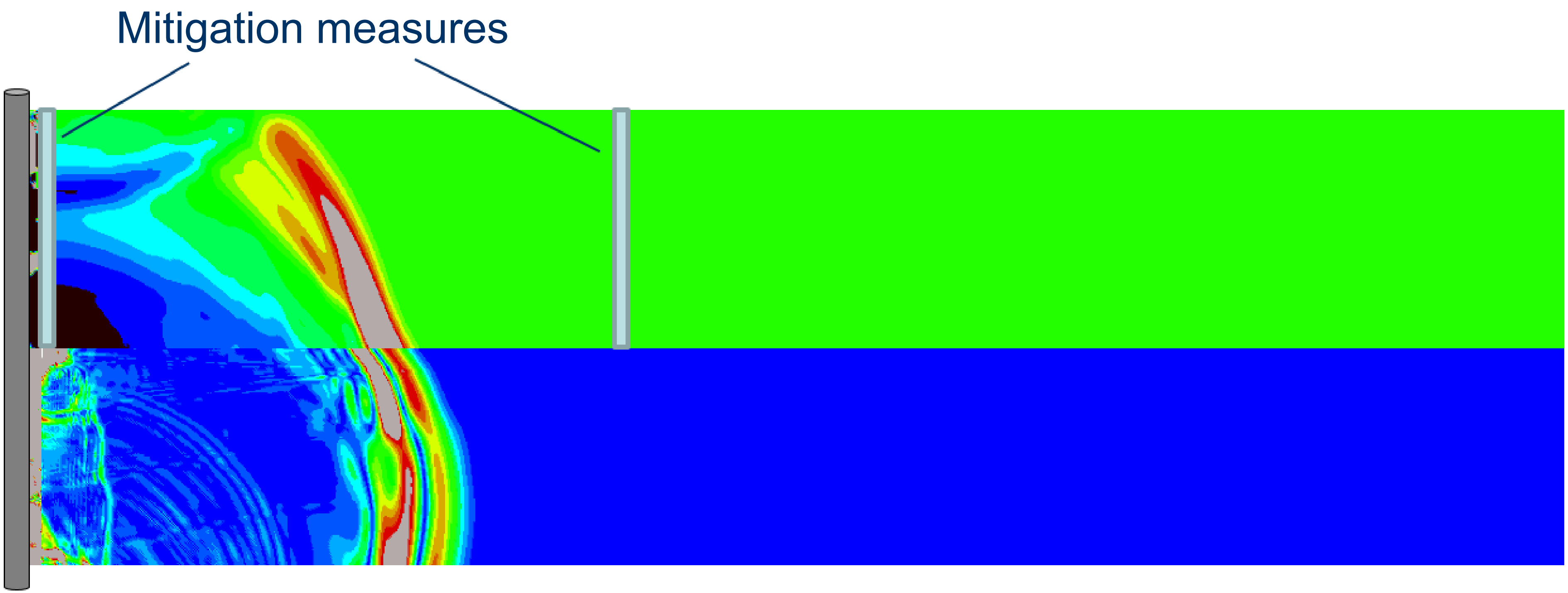

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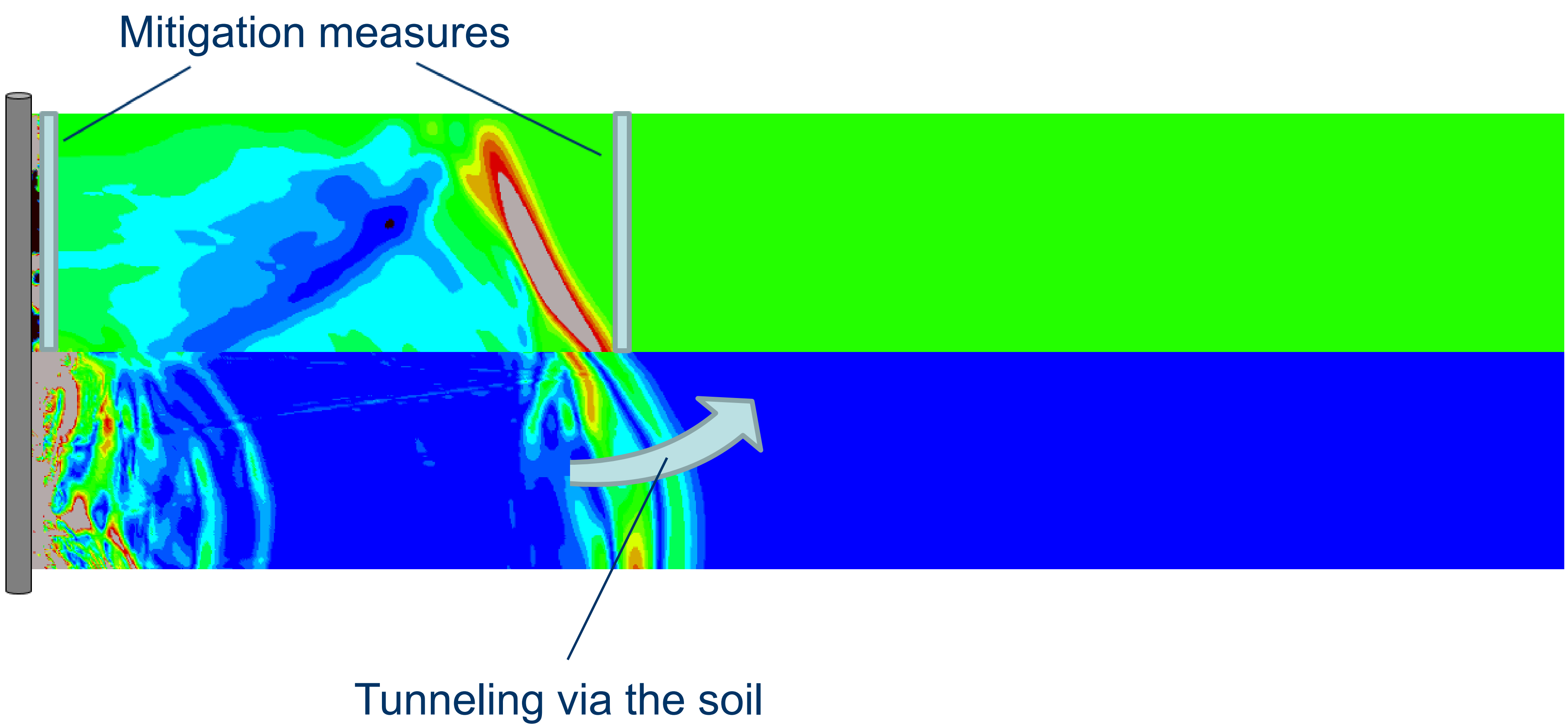

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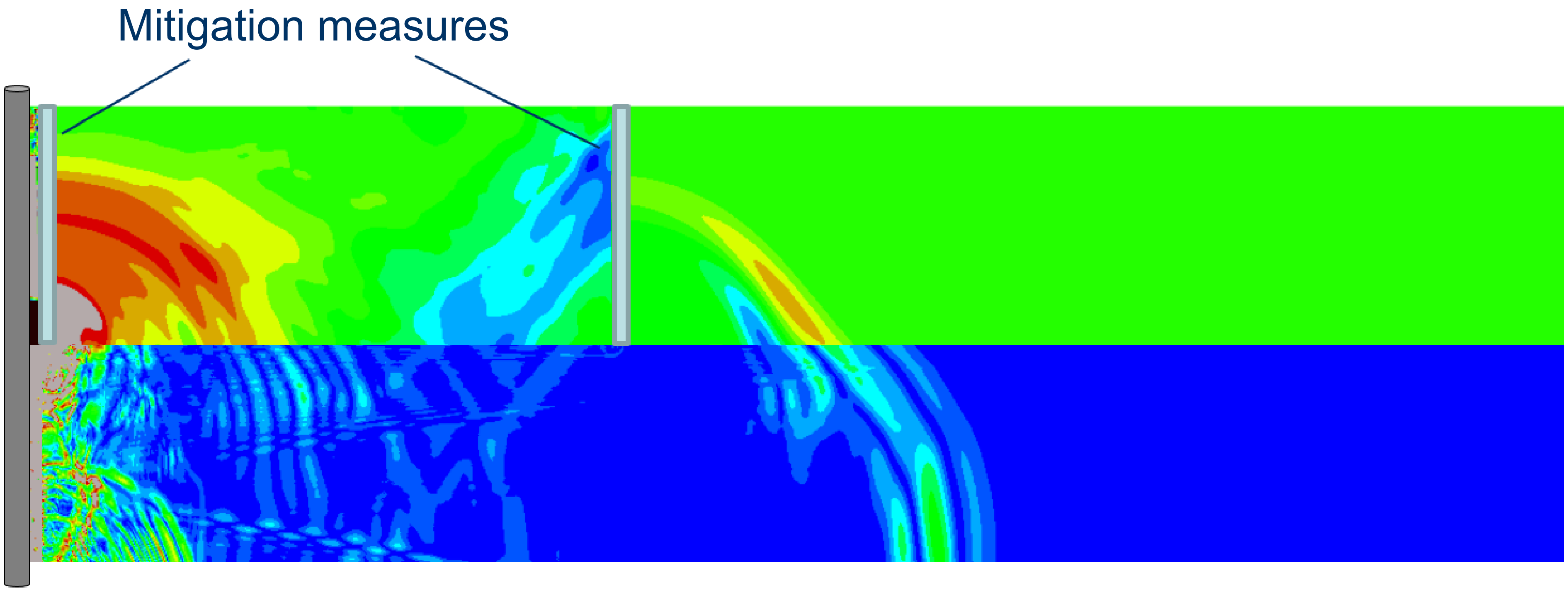

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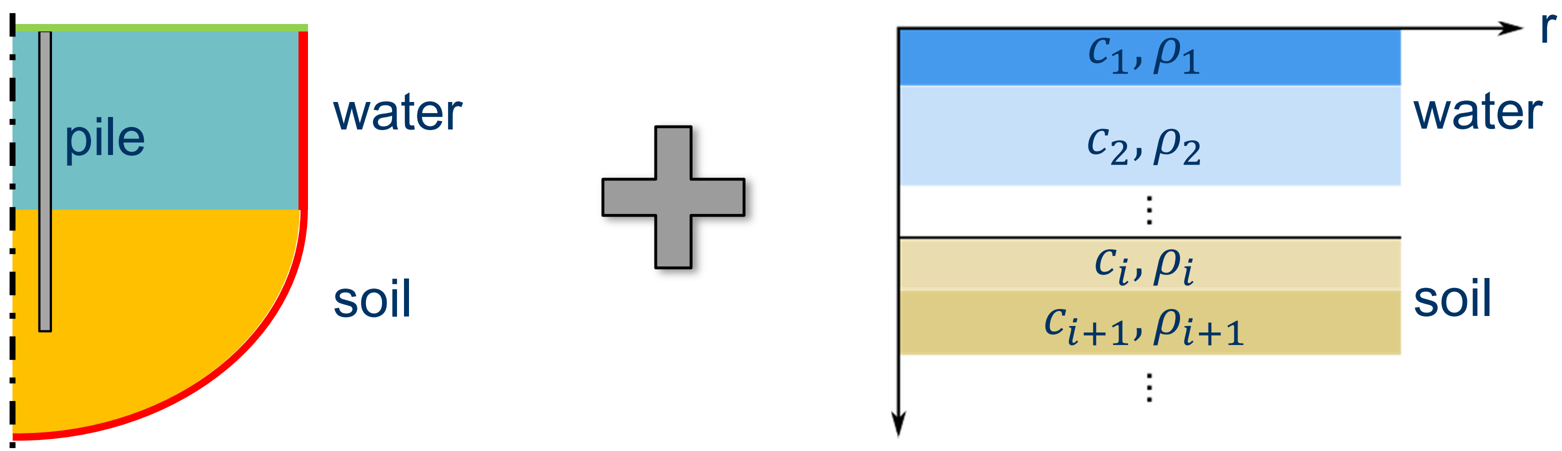
- **Complicated task,** although different numerical **methods are available**
  - **Underwater acoustics** is a **research** topic since **several decades**
  - **Huge size** of the domain with **distances** of interest up to **several kilometres** and **frequencies** up to **some kilohertz**
  - Influence 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**



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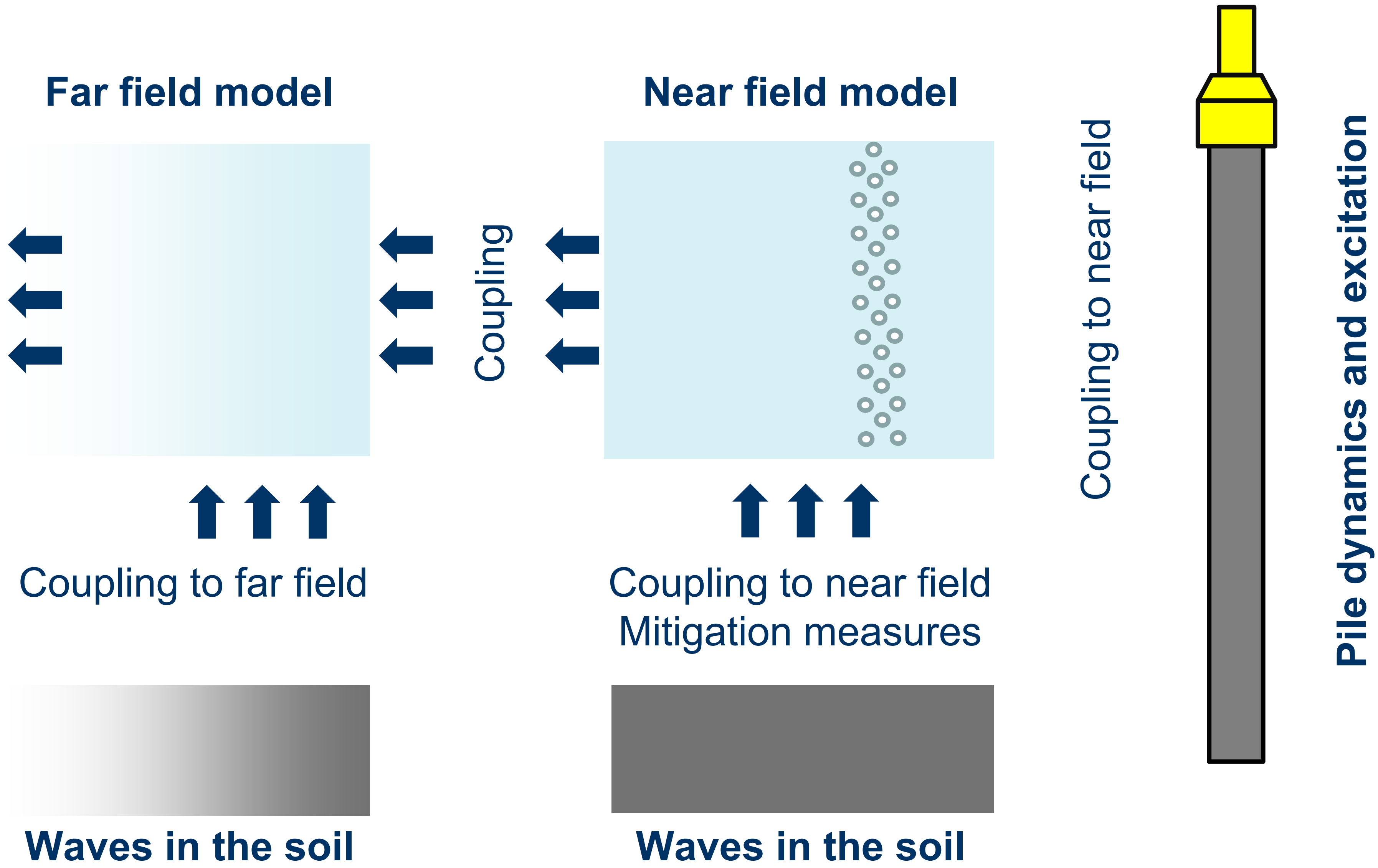
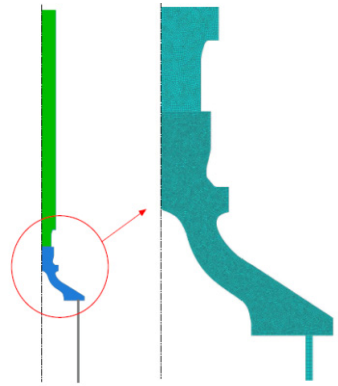
Tripartite global modelling approach with close range (CR) discretization method + long range (LR) propagation code:

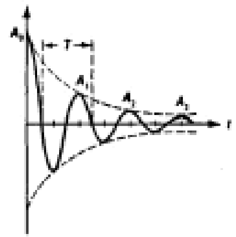


- **CR model consists out of one main model and two pre-calculations**

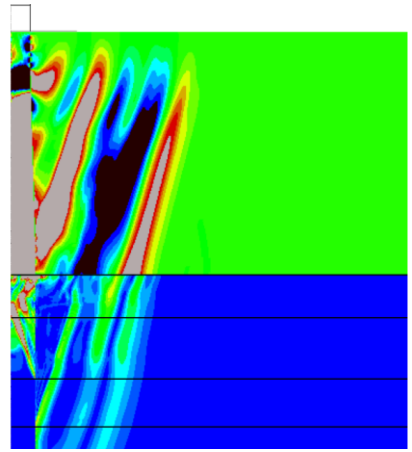
- **Pre-calculation 1 determines the forcing function of the impact hammer**
  - 2D-axisymmetric finite element model
  - Explicit time integration



- **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



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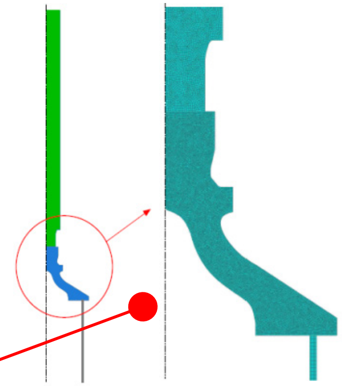
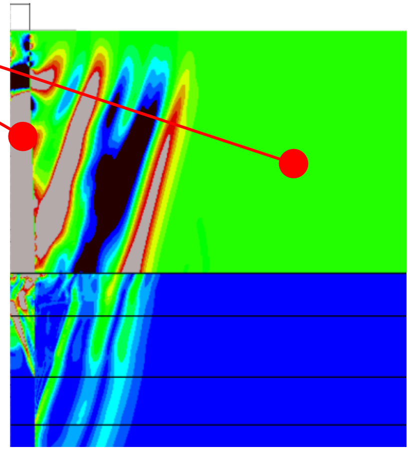


Possibility to include **new hammer technologies** (optimized impact hammers, BLUE piling, vibro hammers, etc.)

Possibility to include **alternative pile designs, new mitigation systems, etc.**



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  - 2D-axisymmetric finite element model
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The COMPILE initiative

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

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)

COMPILE II

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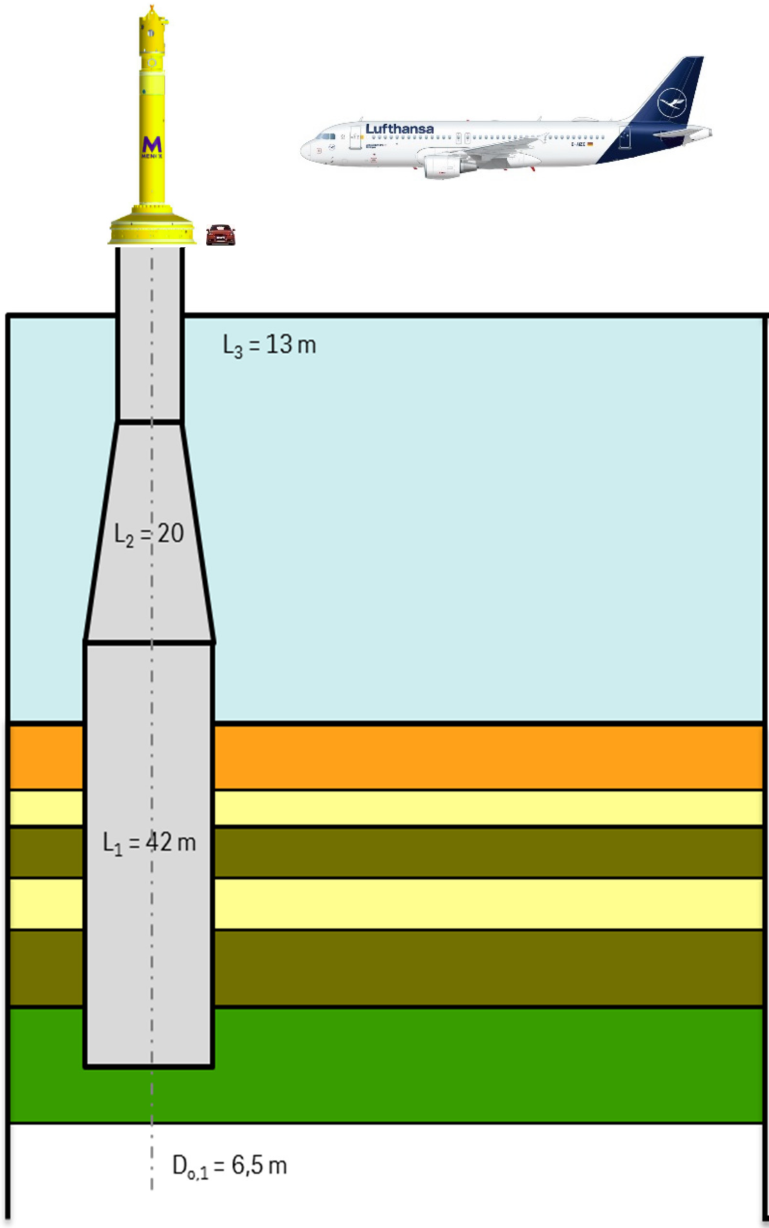
Conical pile in a layered soil, driven with MENCK MHU 3500S @1525kJ

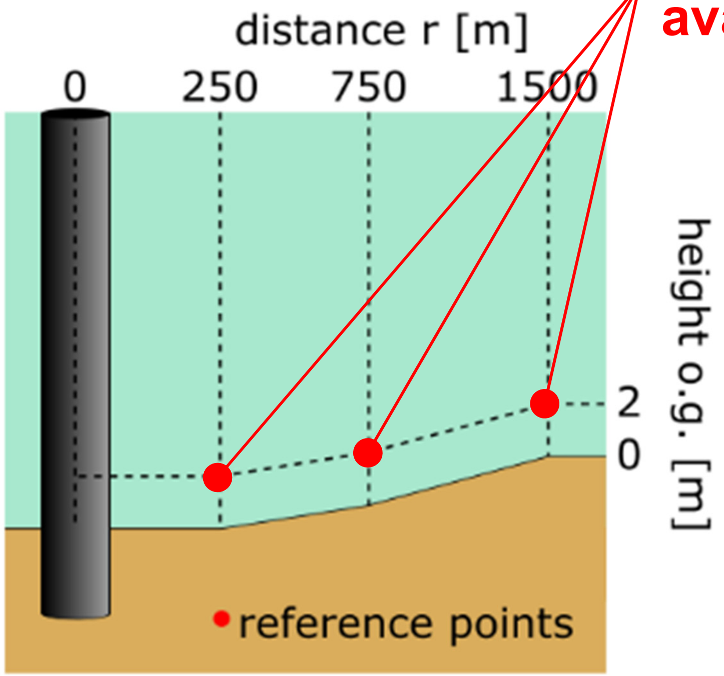


Depth	Type
0 m	Water
39 m	Loose to medium dense sand
44 m	Dense to very dense sand
45.5 m	Sandy Clay
48 m	Dense to very dense sand
50.5 m	Sandy Clay
58 m	Very dense, silty sand
74.5 m	Medium dense to very dense silty sand
0 m	

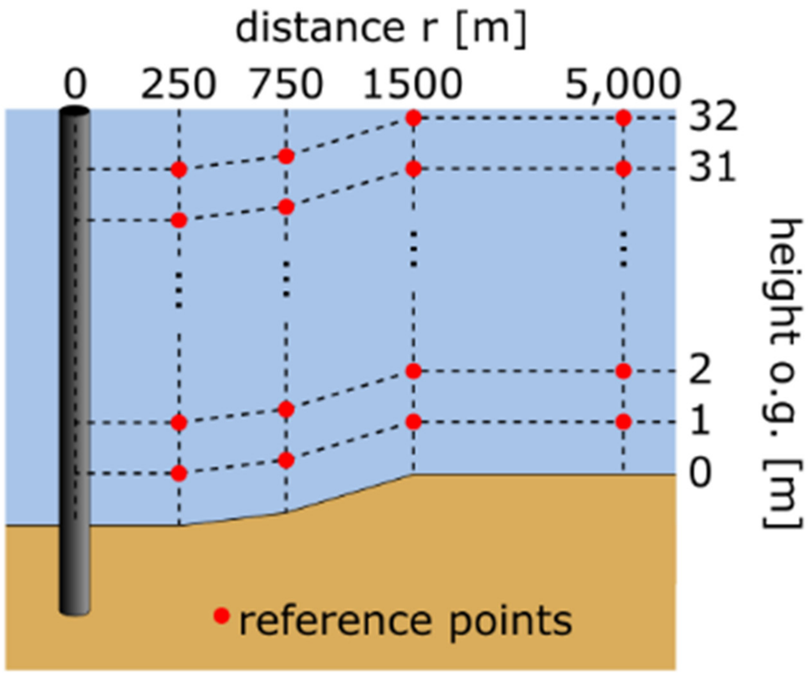
Bathymetry and sampling points

Mandatory

Measurement data available!



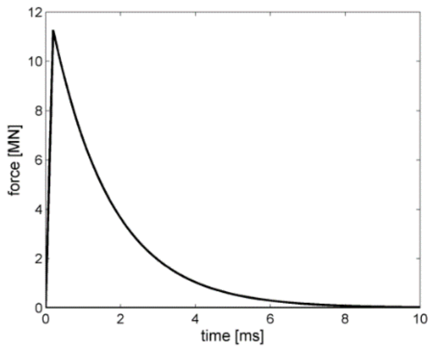
Optional



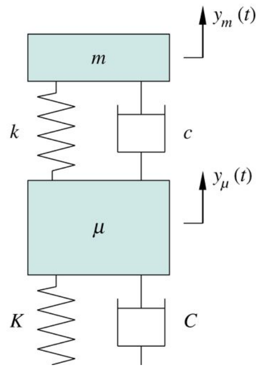
- **Sound pressure** $p(t)$
- **Sound exposure level** SEL and **peak sound pressure level** SPL

- **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

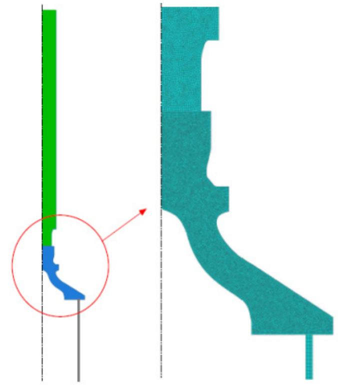
- How to get an **accurate excitation force?**



Analytical formula

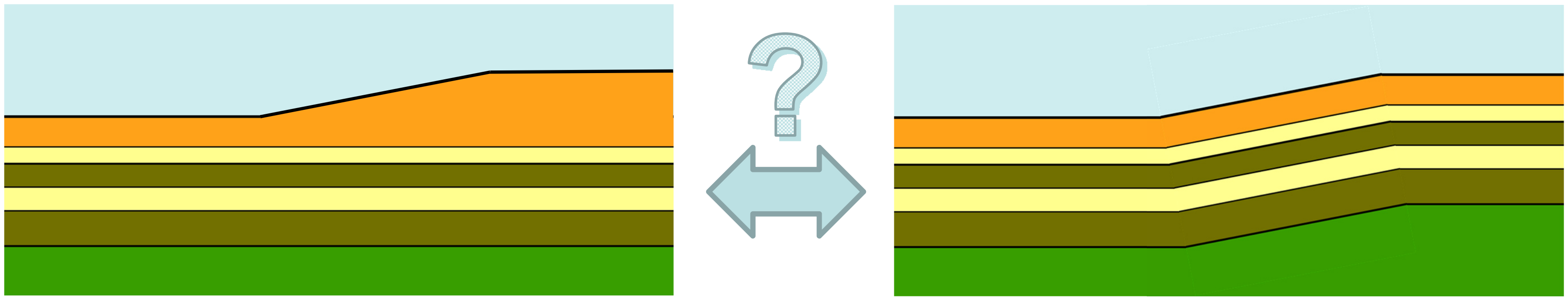


1D WEAP code



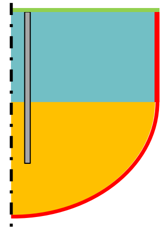
Detailed FE model

- 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?

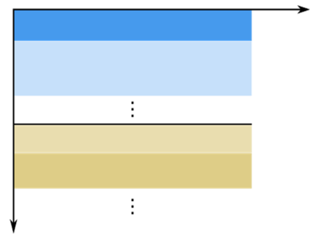


Modelling approaches used within COMPILE II:

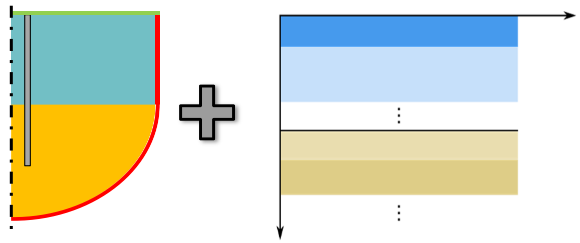
- **Numerical** model I (2 participants):
  Close range (**CR**) discretization method



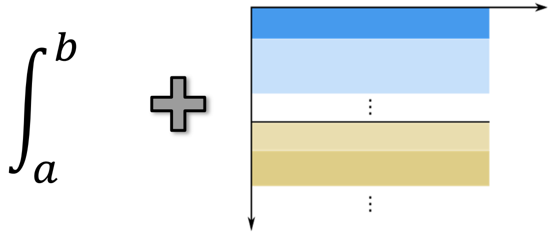
- **Numerical** model II (1 participant):
  Long range (**LR**) propagation code



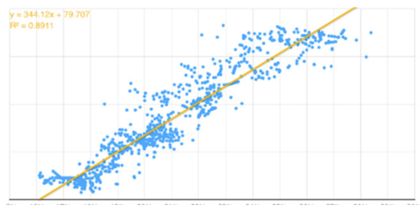
- **Numerical** model III (6 participants):
  CR discretization method **+ LR** propagation code



- **(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

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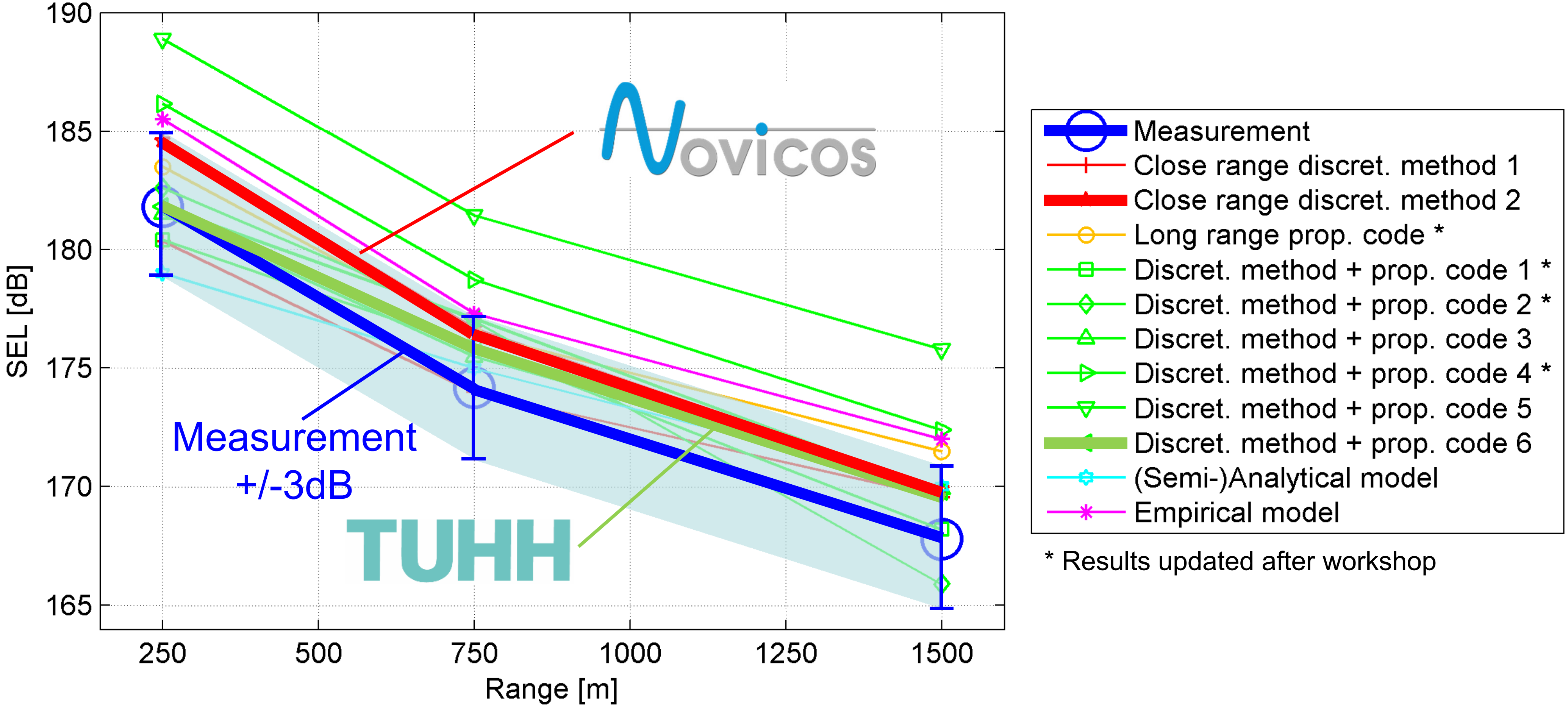
Sound exposure level (SEL)



- **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**

Comparison to measurements: COMPILE II

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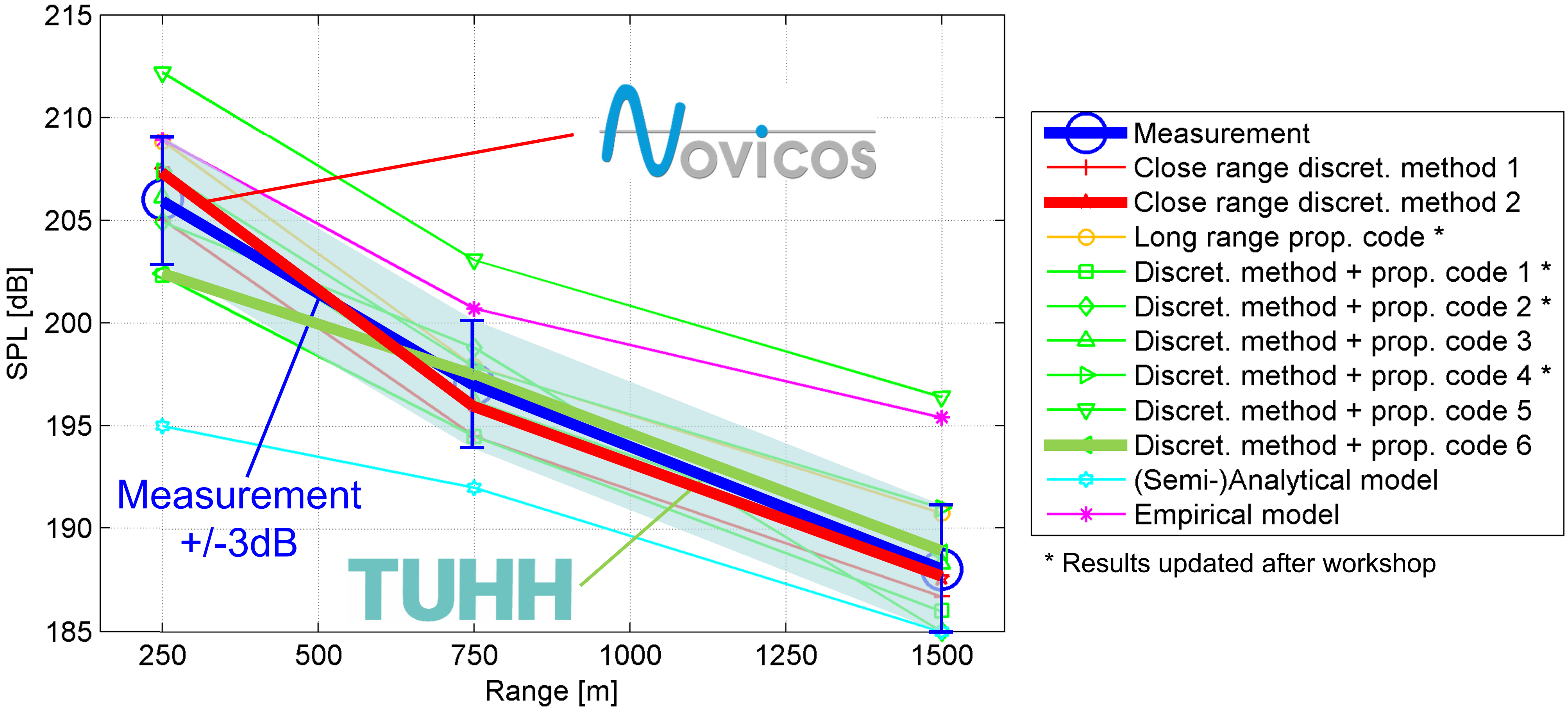
Peak sound pressure level (SPL)



- 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

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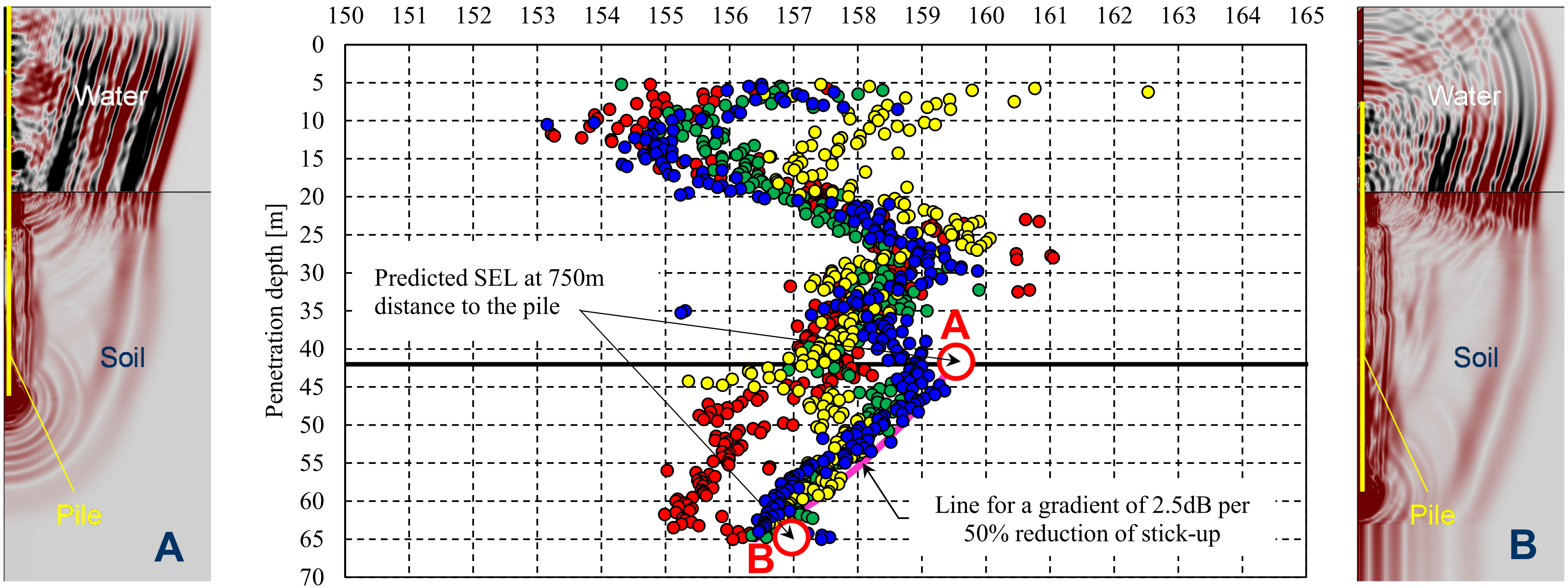
Normalized SEL over penetration depth for four jacket piles (●●●●) *

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)

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Conclusions

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- 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

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Thank you for your attention!

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