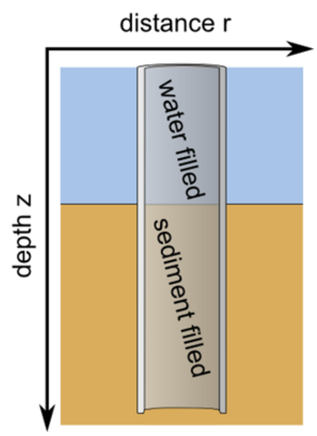
Case 1: Generic pile

Please note that participants in the COMPILE workshop are required to provide results for the generic pile.

Description

Case 1 consists of calculating SEL, SPL, depth dependent intensity and energy fluxes for a generic pile driving configuration under the following conditions:

- Sampling distances have been chosen in according to relevant research and international offshore wind turbine foundation requirements.
- Sampling depths have been chosen with respect to the water depth. It is expected (based on the results by Reinhall and Dahl [1] and Dahl et al. [2]) that the depths at which different phenomenon / regimes are observed scale with the height of the water column.
- Vertical arrays of sampling points have been defined for beam-forming. The given spacing of 0.2 m starting from the sea surface will ensure that the depth-integral of intensity can be approximated numerically using the points of the array at frequencies up to 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 (see e.g. [3,4]) it can be observed that the spectral density falls off quickly above 2 kHz. Therefore, model output in the form of pressure and velocity solutions with a minimum time resolution of 1/5000 s or smaller are required.

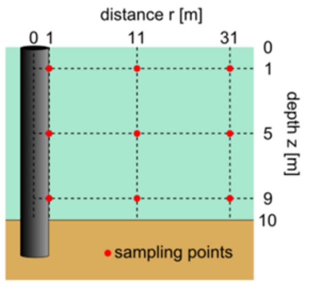
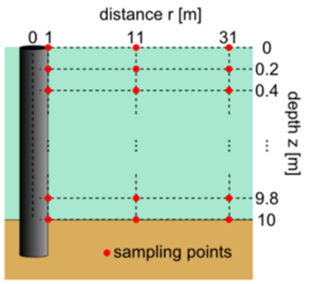


In this first and more general task, the pile to be modeled is embedded at a specific depth within the sediment (see Appendix). The lower part that lies underneath the seafloor is filled with sediment identical to the surroundings of the pile, whereas the upper part of the pile is filled with seawater.

Task

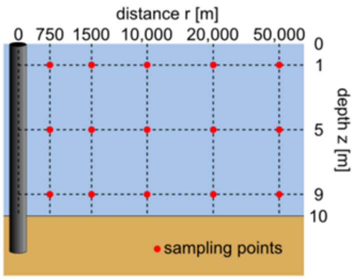
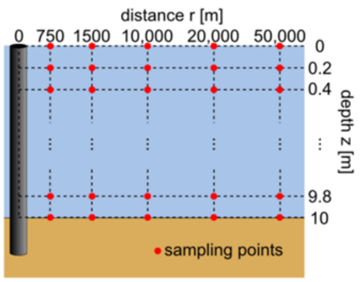
Close range

In the immediate surroundings of the pile, the following quantities have to be calculated at the specified sampling points:

Sampling distances and depths	Target quantities
	1) $p(t)$, $v_r(t)$, $v_z(t)$, $P(f)$, $V_r(f)$, $V_z(f)$ 2) SEL, SPL_{peak}
	1) $p(t)$, $v_r(t)$, $v_z(t)$, $P(f)$, $V_r(f)$, $V_z(f)$ 3) I, I_{eq}, E, E_{eq}

Far range

For the far field propagation, the following quantities have to be derived for the given sampling points:

Sampling distances and depths	Target quantities
	1) $p(t)$, $v_r(t)$, $v_z(t)$, $P(f)$, $V_r(f)$, $V_z(f)$ 2) SEL, SPL_{peak}
	1) $p(t)$, $v_r(t)$, $v_z(t)$, $P(f)$, $V_r(f)$, $V_z(f)$ 3) I, I_{eq}, E, E_{eq}

Explanation

1) Participants are encouraged to supply the pressure and velocity data as described below. Although these data will most likely not be used directly during the workshop, the quantities that will be discussed during the workshop that are listed at 2) and 3) are derived from them. For many models it holds that the underlying (pressure / velocity) data needs to be calculated by participants in the process of calculating the derived quantities, and they may be of use during discussions at a later stage.

   It is encouraged to sample the following quantities **at all sampling points**:
   - Sound pressure (p(t) [Pa])
   - Sound particle velocity in radial and vertical direction (v_r(t) [m s^{-1}] and v_z(t) [m s^{-1}])
   - Pressure (P(f) [Pa]) resulting from the Fourier transforms defined as:

$$P(f) = \int_{-\infty}^{\infty} p(t) e^{-2\pi i t f} df$$

   - Velocity in radial and vertical direction (V_r(f) [m s^{-1}] and V_z(f) [m s^{-1}]) resulting from the Fourier transforms defined as:

$$V_r(f) = \int_{-\infty}^{\infty} v_r(t) e^{-2\pi i t f} df$$
$$V_z(f) = \int_{-\infty}^{\infty} v_z(t) e^{-2\pi i t f} df$$

2) The following quantities are calculated from the pressure results **for the frequency band 0-2.5 kHz, at all points , excluding the points of the vertical arrays**:
   - Sound exposure level (SEL [dB re 1e-12 Pa^2s], i.e., $p_0 = 1\mu Pa; T_0 = 1s$)

$$SEL = 10 \log_{10}\left(\frac{1}{T_0} \int^{\infty} \frac{p(t)^2}{p_0^2} dt \right)$$

   - Zero to peak sound pressure Level (SPL_{peak} [dB re 1e-6 Pa])

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

   Note that in the equations for SEL and SPL_{peak}, the sound pressure $p(t)$ is understood to be low-pass filtered in the frequency range 0-2.5 kHz.

   Additionally, we encourage participants to provide SEL frequency “third-octave” band spectra. A base-ten system (‘decidecades’ rather than true third-octave bands) is required; see e.g. the ANSI S1.11-2004 specification. The corresponding center frequency of the n^{th} band is $f_n = 10^{n/10}$ Hz, and the lower and upper band edge frequencies are $f_l = 10^{-1/20} f_n$ and $f_u = 10^{1/20} f_n$.

3) The following quantities are calculated from the pressure/velocity results **at the vertical arrays**:
   - Time integrated sound intensity vector as a function of depth obtained by evaluating

     $$I = \int_{-\infty}^{\infty} p(t)v(t)dt$$

   - Time integrated equivalent plane wave intensity as a function of depth obtained by evaluating

     $$I_{eq} = \int_{-\infty}^{-\infty} \frac{p^2(t)}{\rho c} dt$$

   - Time integrated energy flux through a cylindrical surface concentric with the pile, ranging from water surface to seafloor having a radius R equal to the distance of the vertical element to the center of the pile, defined as:

     $$E = 2\pi R \int_0^H \int_{-\infty}^{\infty} p(t)v_r(t)dt\, dh$$

   - Time integrated equivalent plane wave energy flux (based on equivalent plane wave intensity) through a cylindrical surface concentric with the pile, ranging from water surface to seafloor having a radius R equal to the distance of the vertical element to the center of the pile, defined as:

     $$E_{eq} = 2\pi R \int_0^H \int_{-\infty}^{\infty} \frac{p^2(t)}{\rho c} dt\, dh$$

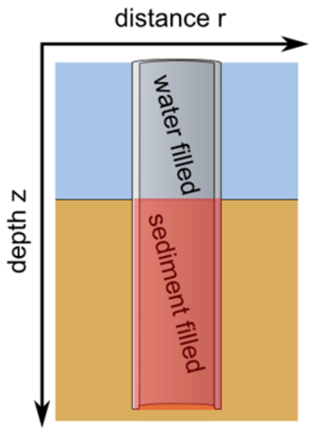
   The integrals over depth are to be taken with numerical quadrature (using the midpoint/rectangle rule) based on the points defined for the vertical arrays.

Pile Sediment friction

The main damping mechanism during impact pile driving is the friction between the pile and the surrounding sediment/soil. If damping is not properly modeled, predicted spectral density levels of the pressure in the water column exhibits sharp peaks and troughs associated with undamped resonances of the system which are not observed in measurement data (see for instance figure 4 of ref [3]).

A straight forward way to account for frictional damping is by using an equivalent damping in the definition of the material parameters for the portion of pile in contact with the sediment (see [3] and [6]). This approach is the proposed default method of accounting for frictional damping between pile and sediment. Using this method, both p-waves (pressure) and s-waves (shear) will be damped in the part of the pile that is surrounded by the sediment (indicated by red in the figure below). This can for instance be achieved by calculating a complex sound speed for these wave using the (frequency depended) damping coefficients for steel that are introduced below. Note that these coefficients and the associated damping parameters for steel that are given in the table below are only appropriate for the part of the pile in the sediment and only in case frictional damping is represented as an equivalent damping. **The upper part of the pile always remains undamped.**

It is encouraged to present results using other models/methods to account for the friction between pile and sediment if they are available. In such cases, it is preferred to present results using the proposed default method in addition to the available alternative method. In case of alternative methods, the damping parameters for steel given in the table below are most likely not sufficient/inappropriate to derive the necessary material/model parameters needed to describe pile-sediment friction. It is suggested that any non-prescribed parameters related to pile-sediment friction are chosen such that the resulting levels correspond well with the levels obtained using the proposed default method to account for pile-sediment friction. Note that if an alternative method is used to account for friction between pile and sediment, the damping values for steel should not be used for any part of the pile.



References

[1] P.G. Reinhall and P.H. Dahl, *Underwater Mach wave radiation from impact pile driving: Theory and observation*, J. Acoust. Soc. Am. 130(3), 2011.

[2] P.H. Dahl, P.G. Reinhall, D.M. Farrell, *Transmission loss and range depth scales associated with impact pile driving*, Proceedings of the 11th European Conference on Underwater Acoustics ECUA 2012, Edinburgh, UK, 2012.

[3] M. Zampolli, M.J.J. Nijhof, C.A.F. de Jong, M.A. Ainslie, E.H.W. Jansen, B.A.J. Quesson, *Validation of finite element computations for the quantitative prediction of underwater noise from impact pile driving*, J. Acoust. Soc. Am. 133(1), 2013.

[4] *Hydrosound measurements at BARD Offshore 1 using the small bubble curtain SBC2 developed by MENCK GmbH,* Technical Report, 2013 (in German; available via www.bora.mub.tuhh.de/pages/publications.html).

[5] M.A. Ainslie, *Principles of Sonar Performance Modeling*, Springer Praxis Books, 2010.

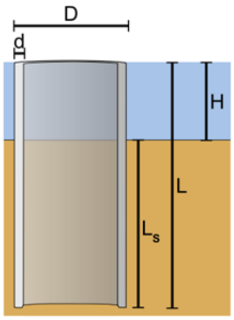
[6] M. Fritsch, "Zur Modellierung der Wellenausbreitung in dynamisch belasteten Pfaehlen (About the modelling of wave propagation in dynamically loaded piles)," Ph.D. dissertation, The Technical University, Braunschweig, Germany, 2008.

For further literature have a look at http://bora.mub.tuhh.de/compile, please.

Appendix: Parameters

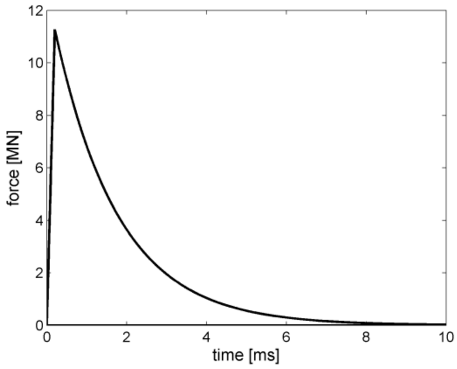
Geometry

Property	Symbol	Unit	Value
Water column height	H	m	10
Total pile length	L	m	25
Pile length in sediment	L_s	m	15
Pile outer diameter	D	m	2
Wall thickness of the pile	d	m	0.05



Forcing function

Following reference [1] and [3], the forcing function is defined as a linear increase of force during a short rise time, followed by exponential decay.



$$F = \begin{cases} F_p \dfrac{t}{t_r} & \text{for } t \leq t_r \\ F_p e^{-\frac{t-t_r}{t_d}} & \text{for } t > t_r \end{cases}$$

Property	Symbol	Unit	Value
Peak height	F_p	MN	20
Rise time	t_r	ms	0.2
Decay time	t_d	ms	1.6

Material

Material Property	Symbol	Unit	Value
Steel			
Young's modulus steel	E_p	GPa	210
Poisson ratio steel	ν_p	-	0.30
Density of steel	ρ_p	kg·m^{-3}	7850

Constant in absorption coefficient of p-wave[1]	γ_{pp}	Np·m^{-1}	3×10^{-5}
Constant in absorption coefficient of s-wave[1]	γ_{ps}	Np·m^{-1}	11×10^{-5}
Sediment			
Sound speed p-wave sediment	c_{sp}	m·s^{-1}	1800
Sound speed s-wave sediment	c_{ss}	m·s^{-1}	0
Density of sediment	ρ_s	kg·m^{-3}	2000
Constant in absorption coefficient of sediment[2]	γ_s	Np·m^{-1} Hz^{-1}	3×10^{-5}
Water			
Sound speed p-wave water	c_w	m·s^{-1}	1500
Density of water	ρ_w	kg·m^{-3}	1025
Absorption coefficient water	α_w	Np·m^{-1}	See equation (2)

The absorption coefficients for sediment, steel and water, defined as α_s, α_{pp}, α_{ps} and α_w, respectively, are frequency dependent. For the sediment and steel, the coefficient is linearly dependent on frequency:

$$\alpha_s = \gamma_s f, \qquad \alpha_{pp} = \gamma_{pp} f, \quad \alpha_{ps} = \gamma_{ps} f \tag{1}$$

In terms of neper per meter the absorption coefficient for water can be approximated as[3]:

$$\alpha_w = 1.40 \times 10^{-5} \frac{f^2}{f^2+f_1^2} + 5.58 \times 10^{-3} \frac{f^2}{f^2+f_2^2} \tag{2}$$

where

$$f_1 = 1.15 \times 10^3 \text{ Hz}$$
$$f_2 = 75.6 \times 10^3 \text{ Hz}$$

Note that the input for the expressions for α_s and α_w is frequency f in Hz. The absorption coefficients α_s and $\alpha_w$are given in neper per meter, implying (under the assumption of exponential decay) that the absorption coefficients are decay constants. Thus, for a plane wave in the frequency domain, the pressure P for a wave having unit amplitude at $x = 0$, can be expressed as[4]:

[1] These damping values for steel are only used for the pile section in the sediment in case an equivalent damping model is used to represent damping due to friction between pile and sediment.
[2] See equation (1)
[3] Note that the above equation is derived from the definition of α in reference [5] which is given in terms of neper per kilometer. The last term in the expression for α in reference [5] is dropped since it does not contribute significantly for the frequencies considered here.
[4] The sign of the first ± symbol depends on the direction of the wave. The second ± symbol depends on the sign chosen in the definition of the time dependence (being $\exp(i\omega t)$ or $\exp(-i\omega t)$).

$$P = \exp(\pm(ik \pm \alpha)x)$$

where $k = \omega/c$ with omega the angular frequency defined as $\omega = 2\pi f$. If attenuation coefficients in dB/m are preferred, these can be obtained by multiplying the calculated value of α_s and α_w by 20 $\log_{10}e \approx 8.686$. If attenuation coefficients in neper per wavelength are preferred, these can be obtained by multiplying α_s and α_w by c_s/f and c_w/f, respectively.

Converted properties

The values above have been converted for convenience to alternative units; the result is listed in this section. Note that there is no new information in this section, and it is not part of the scenario specification. In the event of inconsistencies between this section and the scenario specification above, the scenario specification prevails.

Property	Symbol	Unit	Value
Compressibility			
Bulk modulus steel	K_p	GPa	175.0
Bulk modulus sediment	K_s	GPa	6.480
Young's modulus sediment	E_s	GPa	NA
Bulk modulus water	K_w	GPa	2.306
Damping			
Absorption coefficient sediment	β_s	$dB \cdot \lambda^{-1}$	0.469
Absorption coefficient p-wave steel[5]	β_{pp}	$dB \cdot \lambda^{-1}$	1.564
Absorption coefficient s-wave steel[5]	β_{ps}	$dB \cdot \lambda^{-1}$	3.065
Sound speed			
Sound speed p-wave steel	c_{pp}	$m \cdot s^{-1}$	6001
Sound speed s-wave steel	c_{ps}	$m \cdot s^{-1}$	3208
Lamé-constants			
First Lamé-constant steel	λ_p	GPa	1212
First Lamé-constant sediment	λ_s	GPa	6.480
Second Lamé-constant steel	μ_p	GPa	80.77
Second Lamé-constant sediment	μ_s	GPa	0

[5] These damping values for steel are only used for the pile section in the sediment in case an equivalent damping model is used to represent damping due to friction between pile and sediment.

Property conversion

The material properties can be converted into other material parameters if needed using the table and equations below

	(K, E)	(K, λ)	(K, G)	(K, ν)	(E, G)	(E, ν)	(λ, G)	(λ, ν)	(G, ν)	(G, M)
$K =$	K	K	K	K	$\frac{EG}{3(3G-E)}$	$\frac{E}{3(1-2\nu)}$	$\lambda + \frac{2G}{3}$	$\frac{\lambda(1+\nu)}{3\nu}$	$\frac{2G(1+\nu)}{3(1-2\nu)}$	$M - \frac{4G}{3}$
$E =$	E	$\frac{9K(K-\lambda)}{3K-\lambda}$	$\frac{9KG}{3K+G}$	$3K(1-2\nu)$	E	E	$\frac{G(3\lambda+2G)}{\lambda+G}$	$\frac{\lambda(1+\nu)(1-2\nu)}{\nu}$	$2G(1+\nu)$	$\frac{G(3M-4G)}{M-G}$
$\lambda =$	$\frac{3K(3K-E)}{9K-E}$	λ	$K - \frac{2G}{3}$	$\frac{3K\nu}{1+\nu}$	$\frac{G(E-2G)}{3G-E}$	$\frac{E\nu}{(1+\nu)(1-2\nu)}$	λ	λ	$\frac{2G\nu}{1-2\nu}$	$M - 2G$
$G =$	$\frac{3KE}{9K-E}$	$\frac{3(K-\lambda)}{2}$	G	$\frac{3K(1-2\nu)}{2(1+\nu)}$	G	$\frac{E}{2(1+\nu)}$	G	$\frac{\lambda(1-2\nu)}{2\nu}$	G	G
$\nu =$	$\frac{3K-E}{6K}$	$\frac{\lambda}{3K-\lambda}$	$\frac{3K-2G}{2(3K+G)}$	ν	$\frac{E}{2G} - 1$	ν	$\frac{\lambda}{2(\lambda+G)}$	ν	ν	$\frac{M-2G}{2M-2G}$
$M =$	$\frac{3K(3K+E)}{9K-E}$	$3K - 2\lambda$	$K + \frac{4G}{3}$	$\frac{3K(1-\nu)}{1+\nu}$	$\frac{G(4G-E)}{3G-E}$	$\frac{E(1-\nu)}{(1+\nu)(1-2\nu)}$	$\lambda + 2G$	$\frac{\lambda(1-\nu)}{\nu}$	$\frac{2G(1-\nu)}{1-2\nu}$	M

K = bulk modulus, G = Shear modulus/second Lamé constant, E = Youngs modulus, ν = Poisson ratio, λ = first Lamé constant, M = p-wave modulus

Conversion to c_p, longitudinal speed of sound (p-wave), and c_s, shear speed of sound (s-wave) can be done using:

$$c_p = \sqrt{\frac{K + \frac{4}{3}G}{\rho}} = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}$$

$$c_s = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{2\rho(1+\nu)}}$$