Technische Universität Hamburg

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Scaling Laws for Offshore Pile Driving Noise and Bathymetry Induced 3D Effects

Band 35

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Hamburg, January 2024 Jonas von Pein

Abstract

The present thesis focuses on the investigation of the influence of bathymetry induced 3D effects on the sound levels and the derivation of simple to apply scaling laws for unmitigated as well as for mitigated pile driving scenarios. For this purpose, a hybrid pile driving noise model based on the finite element method and the Parabolic Equations (PE) is developed. The finite element model is used to derive the starting field for the computationally more efficient PE model, which is able to include horizontal diffraction and therefore allows for the investigation of bathymetry induced 3D effects. In addition, noise mitigation measures such as bubble curtains can be included in the model.

The developed modelling approach is validated with measurement data from three different wind farms including unmitigated and mitigated pile driving.

The location of the occurrence of bathymetry induced 3D effects is investigated with data of three real-life scenarios with dedicated water depth profiles. It is shown that sand dunes oriented in propagation direction are the main cause of 3D effects at the considered ranges. Furthermore, the influence of the sample size of the bathymetry data and the influence of uncertain acoustical parameters of the sea floor on the 3D effects are investigated and discussed.

The modelling approach is used to derive scaling laws for the influence of the strike energy, the pile diameter, the ram weight, and the water depth on the sound exposure level (SEL) and the peak sound pressure level (SPL_{peak}). This is done for mitigated and unmitigated scenarios.

The scaling laws for unmitigated pile driving are validated with 21 measurement data sets. Despite the four parameters that are usually publicly available, the influence of often non-public parameters is investigated. These are the penetration depth, the pile head diameter, and the wall thickness.

Scaling laws for mitigated pile driving are developed for four different kinds of noise mitigation systems. These are a big bubble curtain, a double big bubble curtain, a fully absorbing close range system, and the combination of a fully absorbing close range system with a double big bubble curtain. The main difference between the found dependencies is identified in the water depth trends. The scaling laws for scenarios with a big bubble curtain are validated with 17 measurement data sets.

It is demonstrated that the scaling laws can be used to derive estimates of the sound levels with deviations that are in the range of the variations occurring within the measurements of a single wind farm with several piles.

Contents

Nomenclature

Functions and scalars

c	sound speed
d	diameter
f	frequency
h	water depth
k	wave number
m_r	ram weight
p	pressure
r	range
t	time
z	depth
E	strike energy
R	reflection coefficient
Z	pile head impedance
λ	wave length
ρ	density
φ	Mach cone angle
ϕ	azimuth
ω	angular frequency

Matrices and vectors

$\boldsymbol{A}$	admittance matrix
$\boldsymbol{C}$	damping matrix
$\boldsymbol{F}$	load vector
$\boldsymbol{H}$	compressibility matrix
$\boldsymbol{I}$	identity matrix

$\boldsymbol{K}$	stiffness matrix
$\boldsymbol{M}$	mass matrix
$\boldsymbol{n}$	normal vector
$\boldsymbol{P}$	pressure vector
$\boldsymbol{Q}$	fluid mass matrix
$\boldsymbol{r}$	position vector
$\boldsymbol{X}$	depth operator
$\boldsymbol{x}$	displacement vector
$\boldsymbol{Y}$	azimuthal operator
$\boldsymbol{\sigma}$	stress tensor

Indices

d	diameter
i	index
l	longitudinal
p	pile
s	soil
t	wall thickness
w	water
z	depth
DCS	referring to the Damped Cylindrical Spreading model
N	of order N
NMS	referring to the mitigated case
ϕ	azimuthal
0	reference value

Operators and other symbols

∇	Nabla Operator
$\frac{\partial}{\partial x}$	partial derivative with respect to x
$\dot{(\cdot)}$	first derivative with respect to time
$\ddot{(\cdot)}$	second derivative with respect to time

Abbreviations

AL	Albatross (wind farm)
AN	Anholt (wind farm)
AR	Arkona (wind farm)
AW	Amrumbank West (wind farm)
BBC	Big Bubble Curtain
BO	Borssele (wind farm)
BORA	Berechnung Offshore Rammschall project
BO1	Bard Offshore 1 (wind farm)
BR1	Borkum Riffgrund 1 (wind farm)
BW2	Borkum West 2 (wind farm)
BU	Butendiek (wind farm)
CPII	COMPILE II benchmark scenario
CRS	Close Range System
CV	Coastal Virginia (wind farm)
DB	Deutsche Bucht (wind farm)
DBBC	Double Big Bubble Curtain
DCS	Damped Cylindrical Spreading
FE	Finite Element
FEM	Finite Element Method
GE	Gemini (wind farm)
GTI	Global Tech I (wind farm)
HRII	Horns Rev II (wind farm)
HS	Horn Sea (wind farm)
HSD	Hydro Sound Damper
IQIP-NMS	Integrated Monopile Installer of the company IQIP
ME	Merkur (wind farm)
MNRU	Menck Noise Reduction Unit
MP	Measurement Position
NM	Normal Modes
NMS	Noise Mitigation System
PA	Prinses Amaliawindpark (wind farm)
PE	Parabolic Equations
PTS	Permanent Threshold Shift
PULSE	Piling Under Limited Stress Equipment
RT	Ray Tracing
SB	Sandbank (wind farm)

SEA	Seastar (wind farm)
SEL	Sound Exposure Level
SPL_{peak}	Peak Sound Pressure Level
TL	Transmission loss
TR	Trianel (wind farm)
TTS	Temporary Threshold Shift
VM	Veja Mate (wind farm)
WEAP	Wave Equation analysis for Pile Driving
WI	Wavenumber Integration
2D	two-dimensional
3D	three-dimensional