Modelling Substrate-Borne Vibrations Generated by Offshore Monopile Installation

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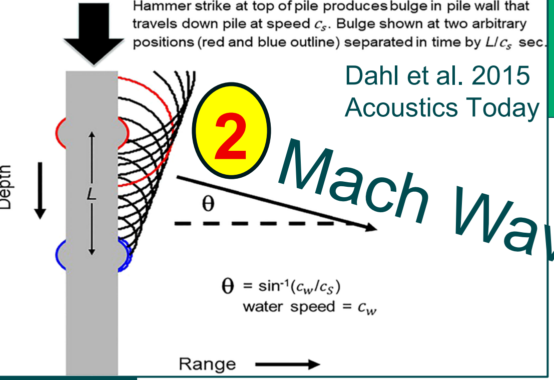
Outline

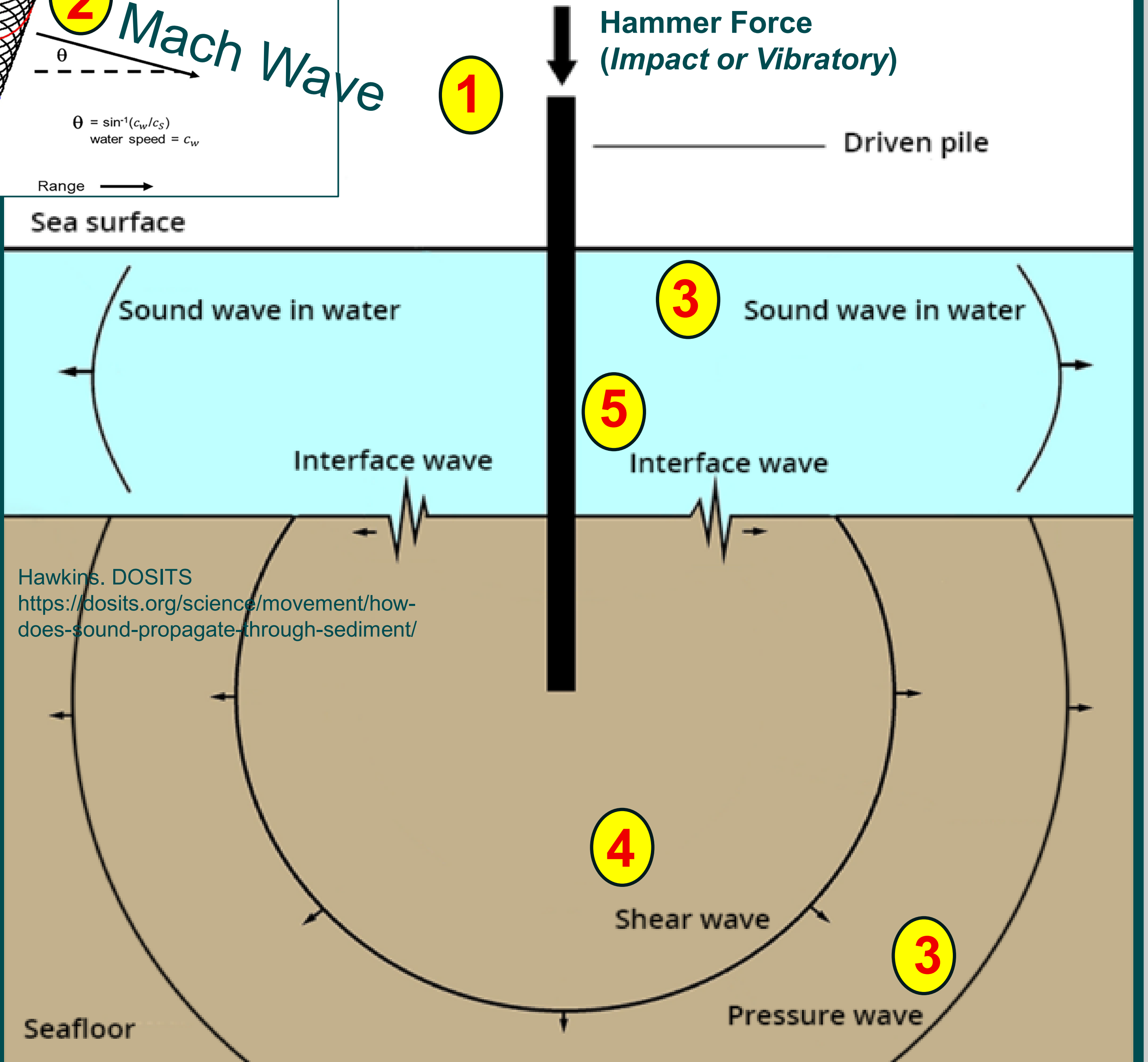
I. Background

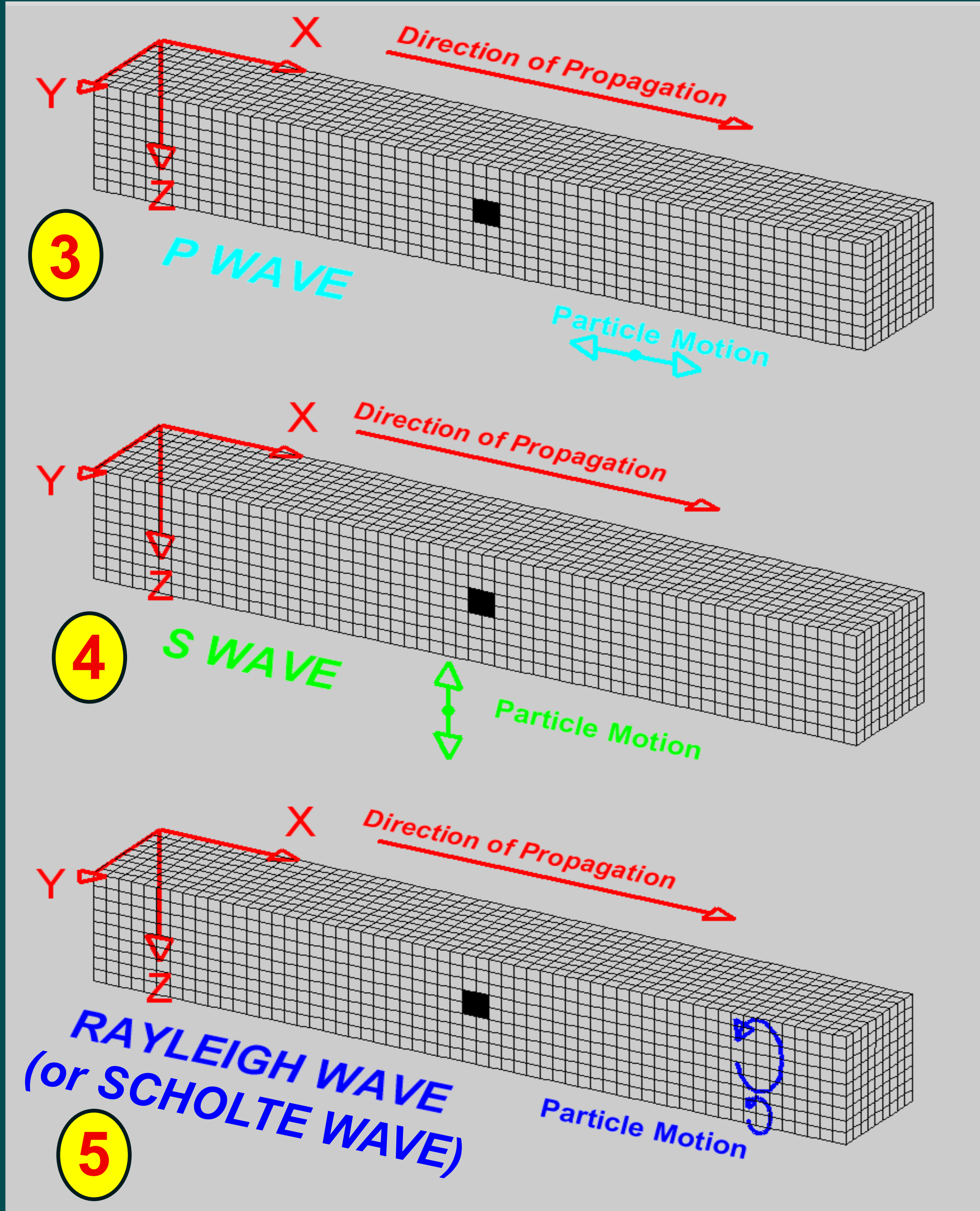
- Acoustic and elastic waves generated during pile driving installation of offshore wind monopiles

II. Research Objective: Create 3D vibroacoustics model

- 3D Modelling using SPECFEM3D
- 3D Meshing using GMSH
- Case Study: CVOW Pilot Project Monopile Installation

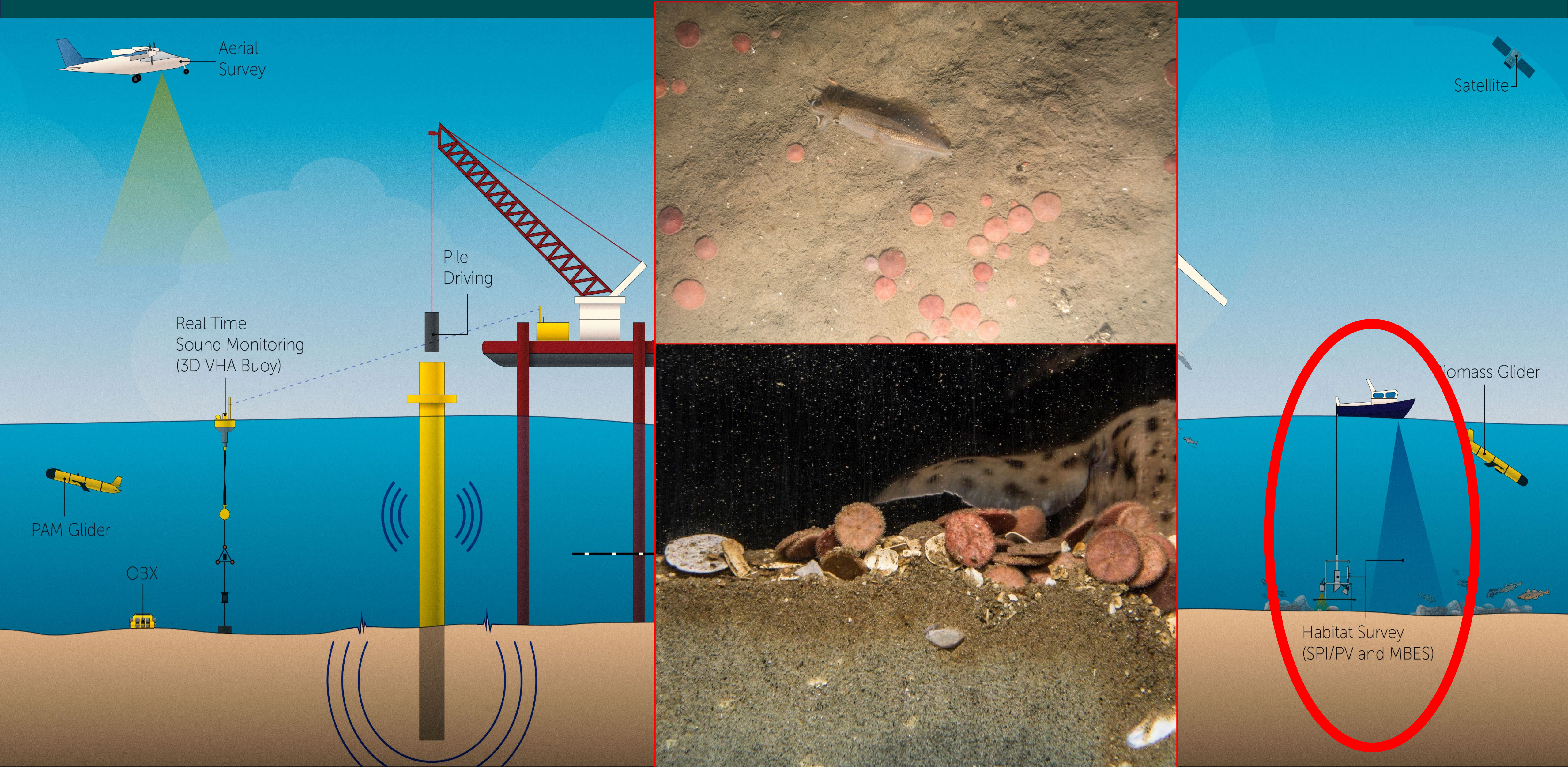




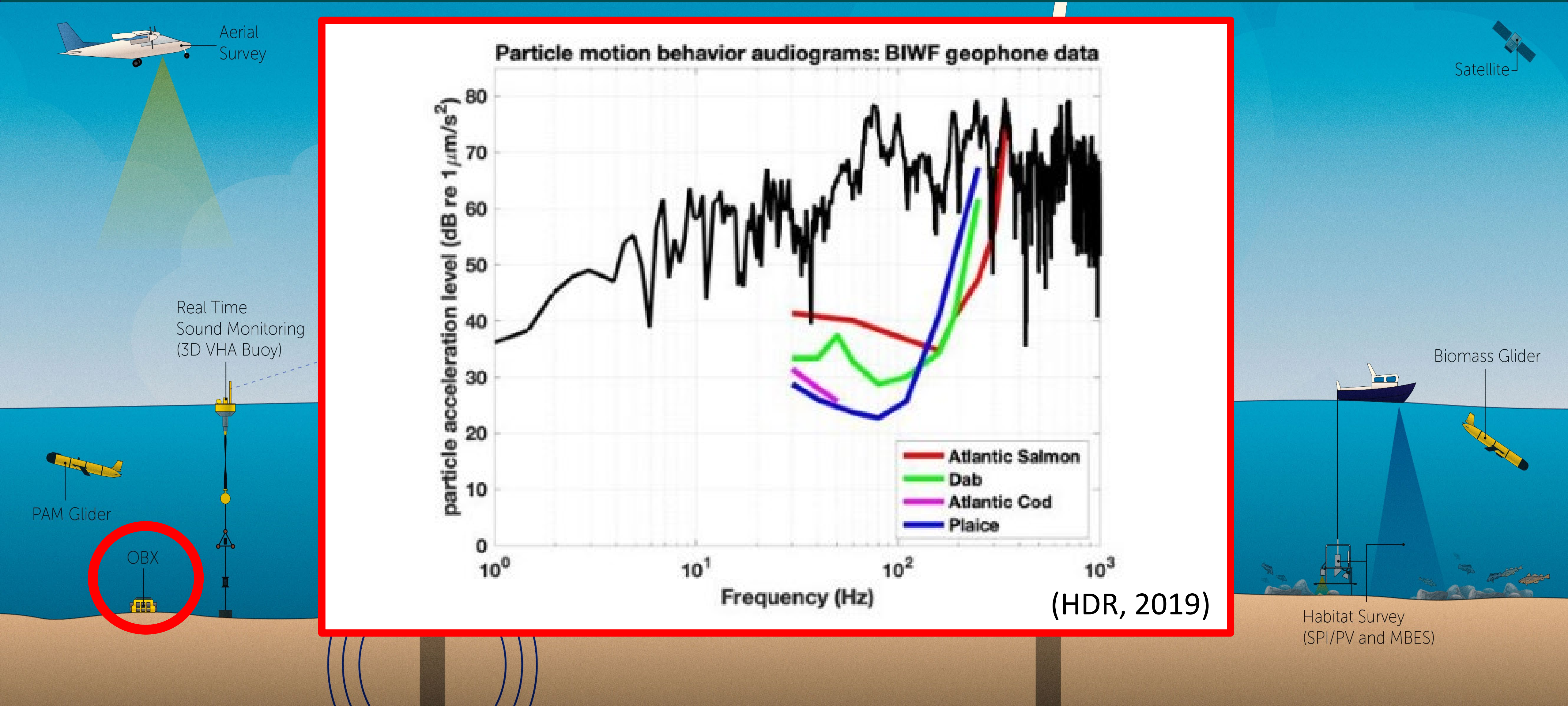


https://web.ics.purdue.edu/~braile/edumod/waves/WaveDemo.htm#P_S_R_L_Animations

Monitoring for Environmental Impacts of Wind Farms



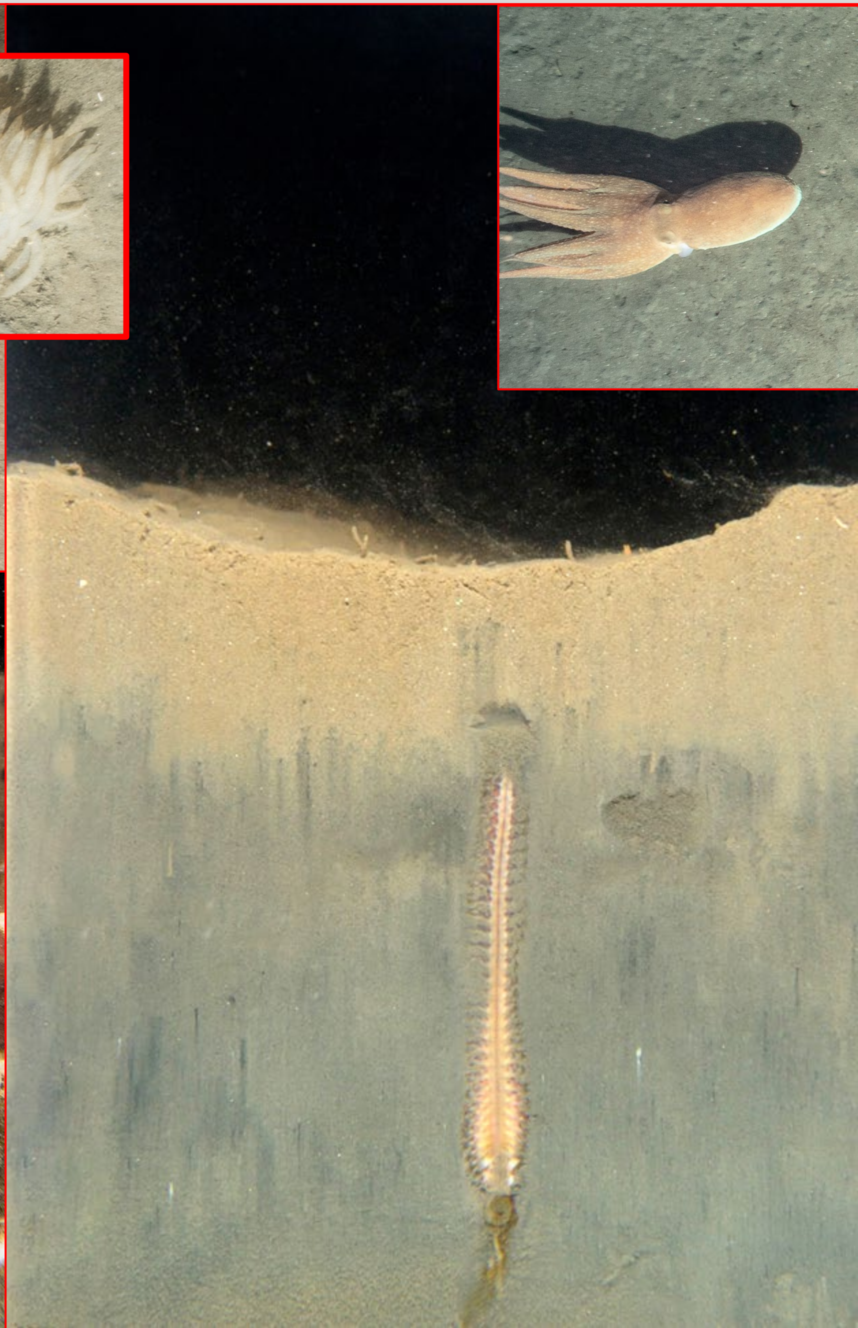
Measurements of substrate-borne particle motion during Block Island Wind Farm installation compared to hearing sensitivities of fishes



(HDR, 2019)

Research Objective

Develop high fidelity numerical model to predict substrate-borne vibroacoustic propagation for environmental impact assessment



3D Vibroacoustic Model

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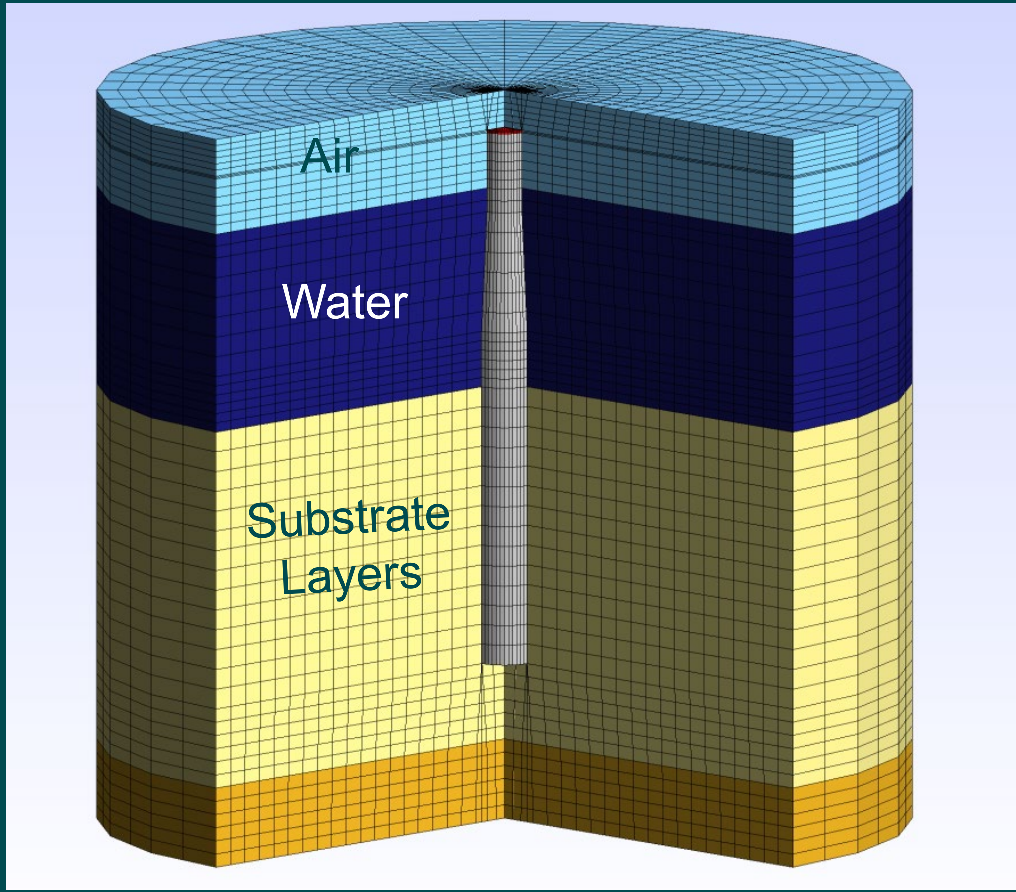
- Fully 3D Spectral Element Method, suitable for acoustic, elastic, and poroelastic wave propagation modeling
- Solves for coupled acoustic and elastic vibration, yielding pressure, particle motion, and stresses in 3D volumes
- Initialized with 3D meshing that has been optimized for thin walled, cylindrical monopiles with a taper, embedded in a layered substrate

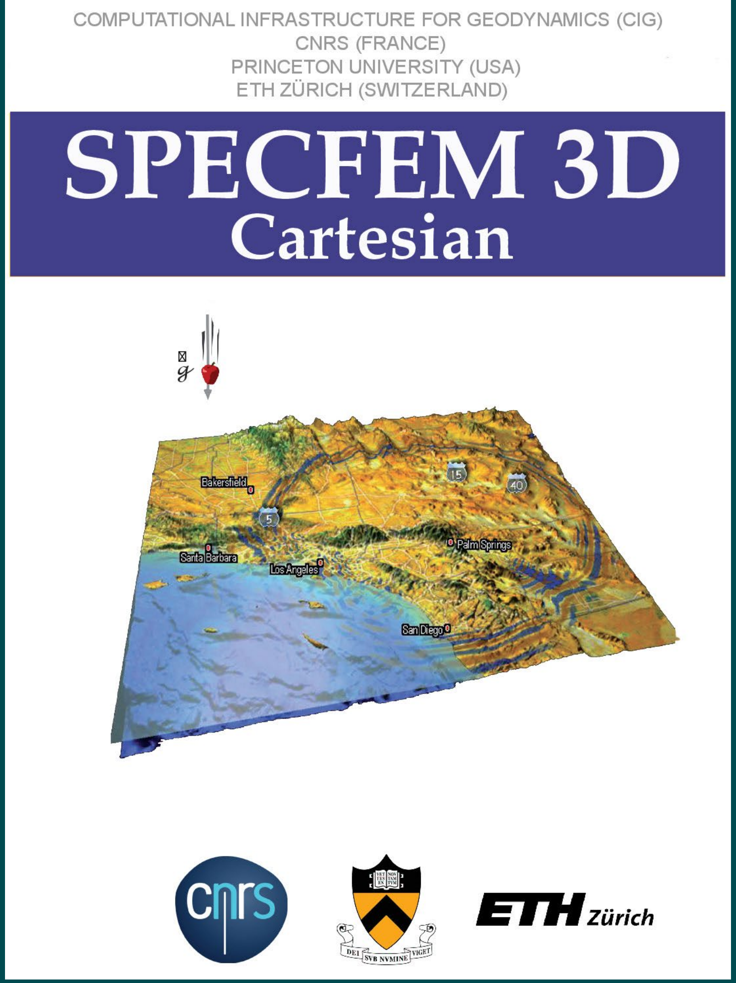


https://specfem3d.readthedocs.io/en/latest/

https://gmsh.info/

3D Model: SPECFEM 3D Cartesian

- Initially developed for computational fluid dynamics and adapted to seismic wave propagation (Komatitsch and Tromp, 1999)
- Has been applied to the case of offshore pile driving for 2D (Cristini et al. 2022) and simplified 3D cases (Jeong et al. 2020)
- Solves for coupled volumes, yielding pressure, particle motion, and stresses in 3D volumes
- Parallelized for CPU and GPU acceleration



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3D Meshing using GMSH

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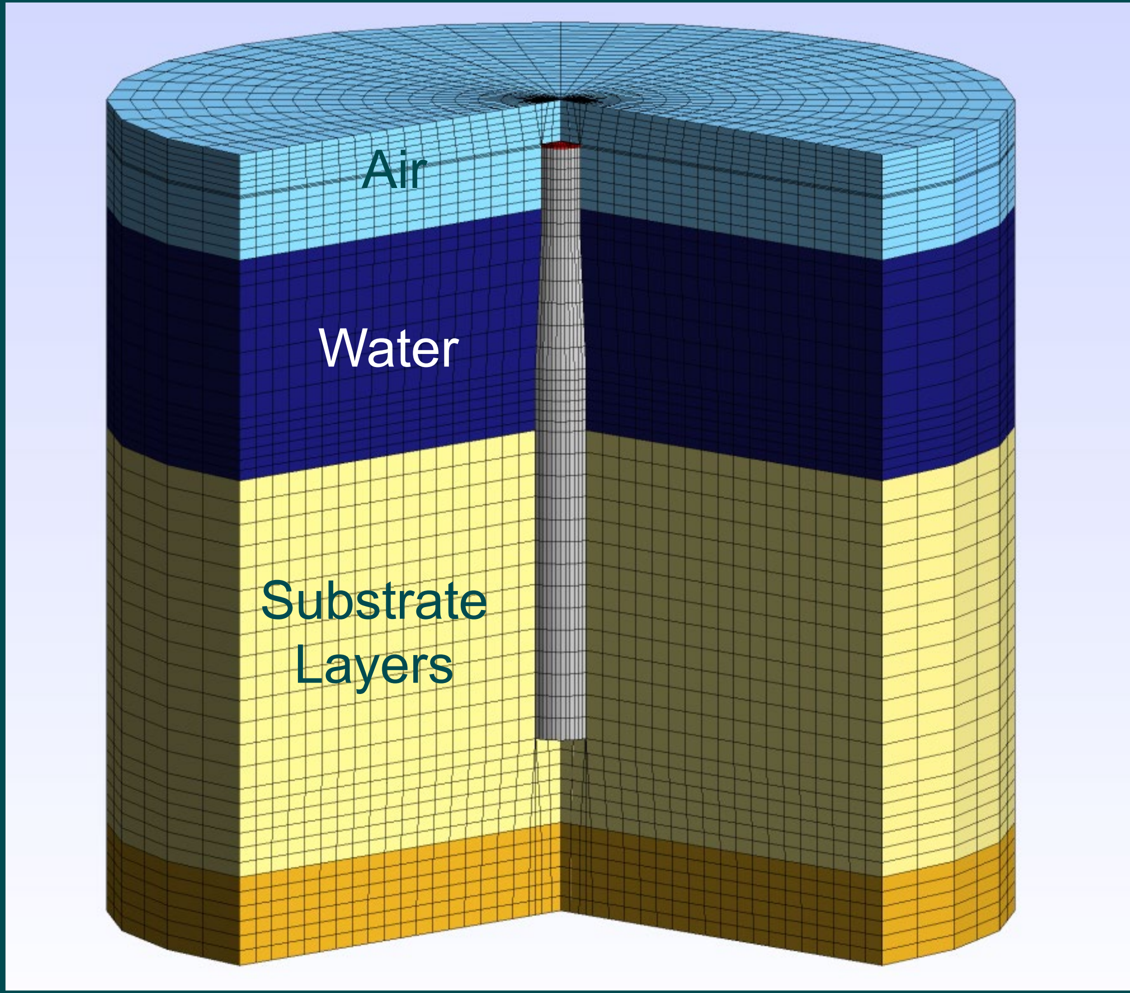
- Monopile and substrate layers created as structured 2nd order hexahedral elements
- Created by radial extrusion of a 2D surface mesh representing the profile of a tapered monopile coupled to acoustic, elastic, or poroelastic elements.
- Mesh element size in the radial direction is constant, with overall smaller elements near areas with high curvature.



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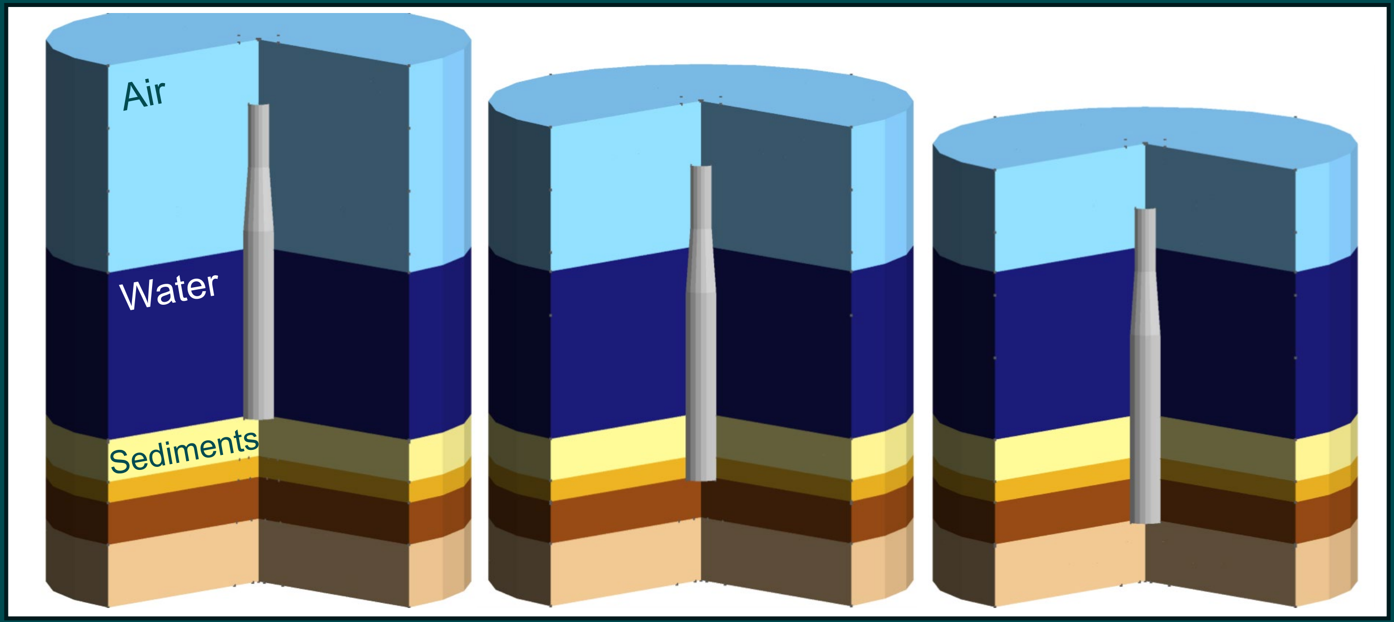
3D Vibroacoustic Model

Account for site-specific structural, environmental, and soil layer specifications



3D renderings of a common XXL monopile in a stratified substrate with different penetration depths

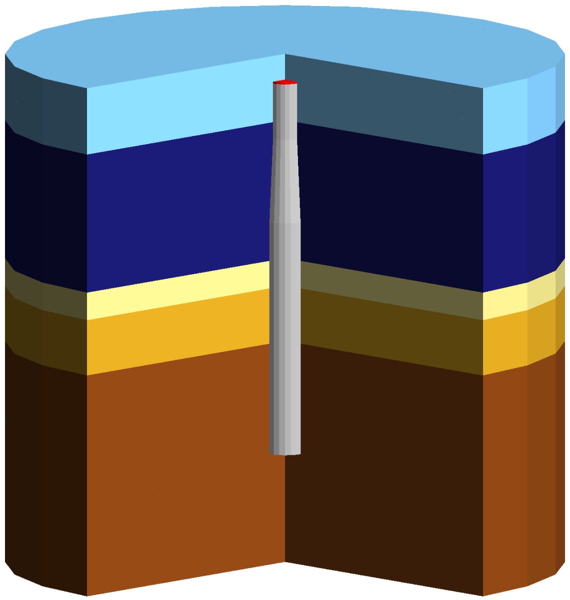
Monopile Specifications	Value	Unit
Top Radius	3.5	m
Bottom Radius	5	m
Wall Thickness	0.075	m
Pile Length	75	m
Knee 1	15	m
Knee 2	30	m
Penetration Depth	0.5, 15.5, 25.5	m

Environmental Specifications	Layer Depth (m)	Material
Top Buffer	15	Air
Surface	0	Air
Water Depth	-40	Sea Water
Sediment Layer 1	-50	Fine Sand
Sediment Layer 2	-55	Medium Sand
Sediment Layer 3	-65	Gravelly Sand
Sediment Layer 4	-80	Clay

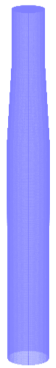
Material Specifications	$\rho\left[\frac{kg}{m^3}\right]$	$C_p\left[\frac{m}{s}\right]$	$C_s\left[\frac{m}{s}\right]$	Q_p	Q_s
Steel	8000	5600	3400	100	50
Air	1.25	343	0	100	100
Sea Water	1025	1500	0	100	100
Fine Sand	1600	1700	40	100	100
Medium Sand	1700	1800	60	100	100
Clay	2000	2100	500	100	130

Sound Fields Generated by Impact and Vibratory Piling

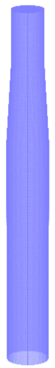
Specified Monopile



Impact Hammer



Vibratory Hammer



0.001 s

Layer Definitions

Surface	0	m	Air
Water Depth	-25	m	Sea Water
Sediment Layer 1	-30	m	Medium Sand
Sediment Layer 2	-40	m	Silt
Sediment Layer 3	-80	m	Silty Sand

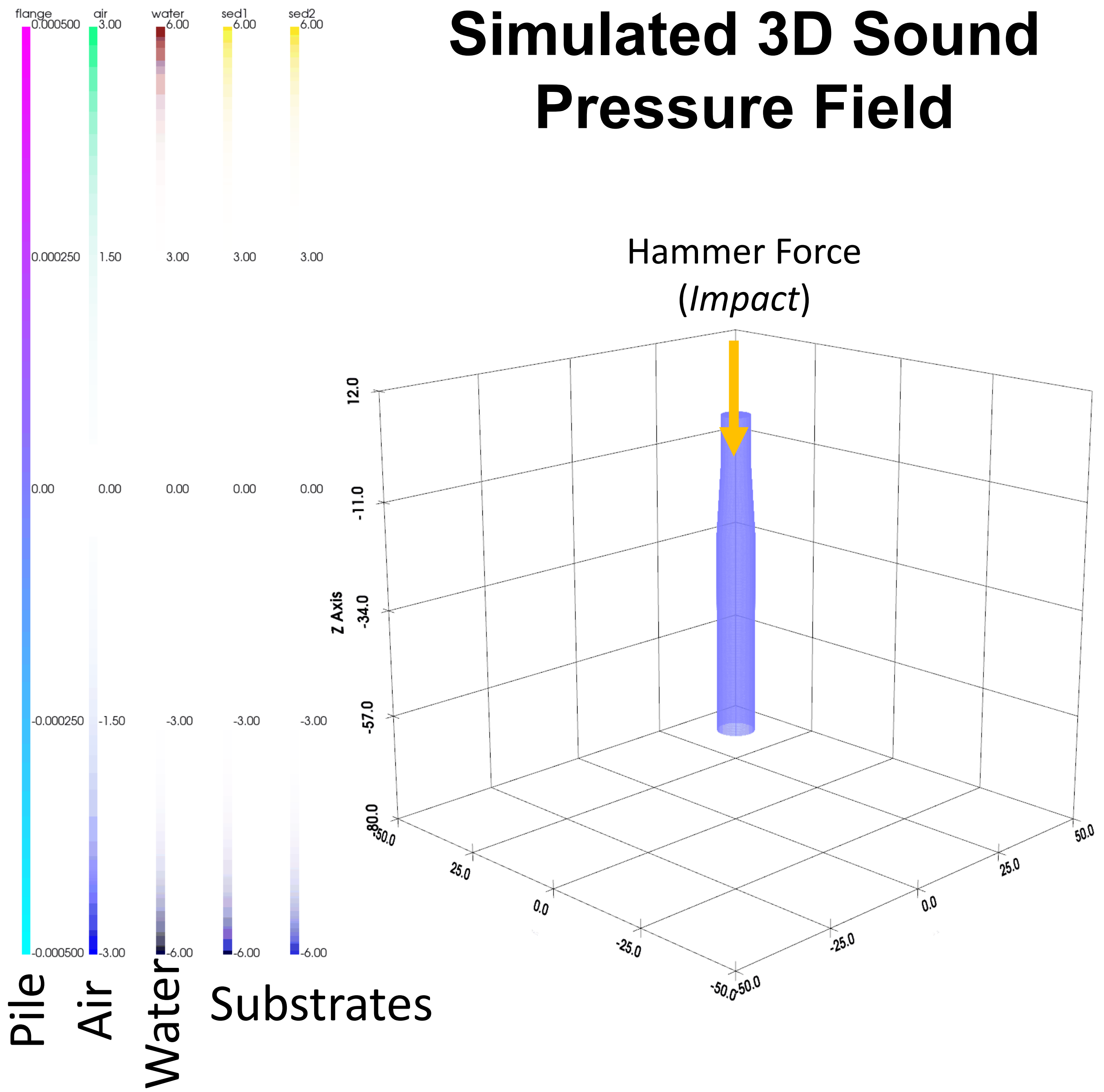
Impact Hammer Specifications

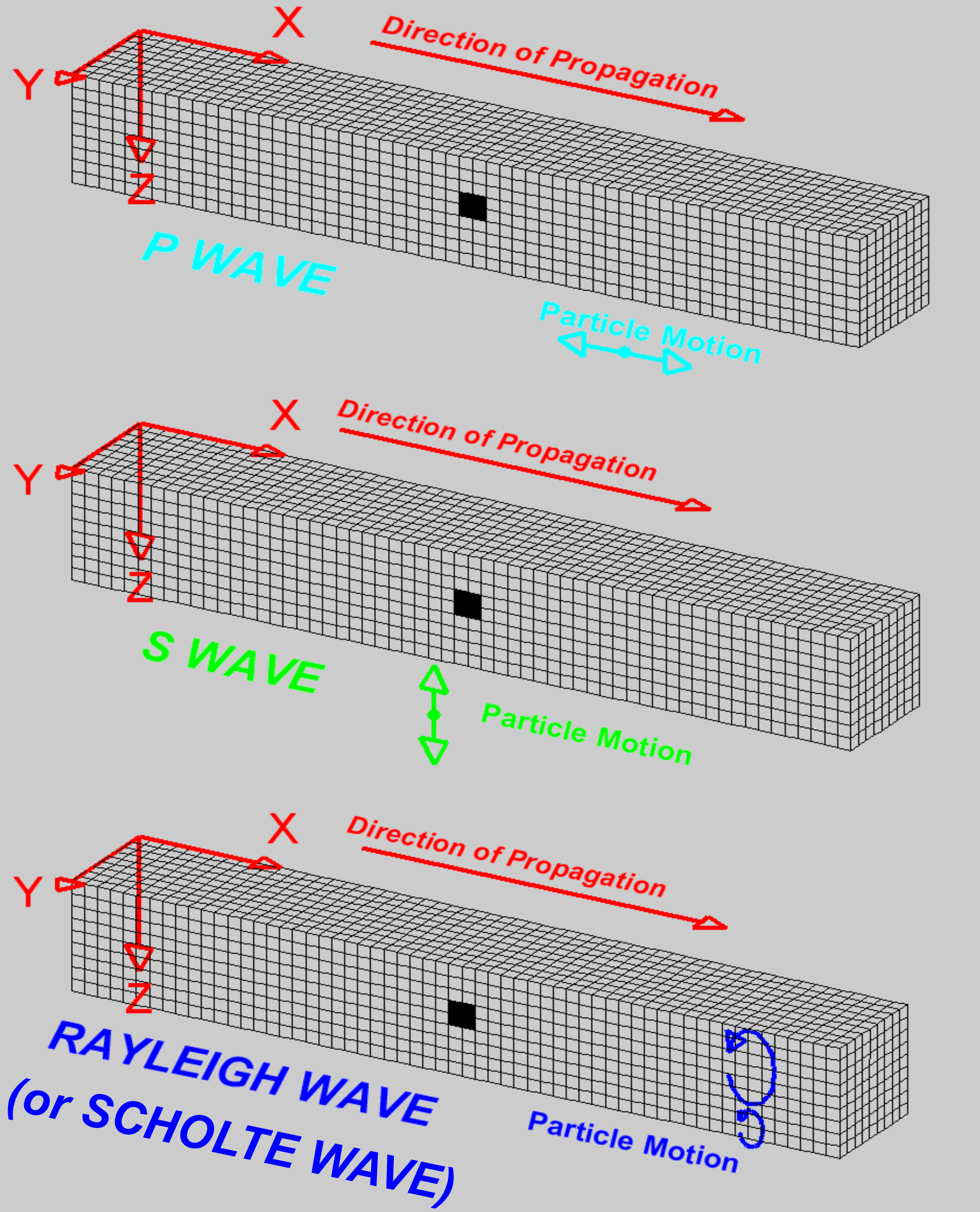
Hammer	IHC-S-3000	
Impact Energy	671	kJ
Weight	1479	kN
Dominant Frequency	500	Hz

Vibratory Hammer Specifications

Hammer	1363 APE 300VM	
Centrifugal Force	68.67	MN
Weight	1100	kN
Dominant Frequency	23	Hz

Simulated 3D Sound Pressure Field





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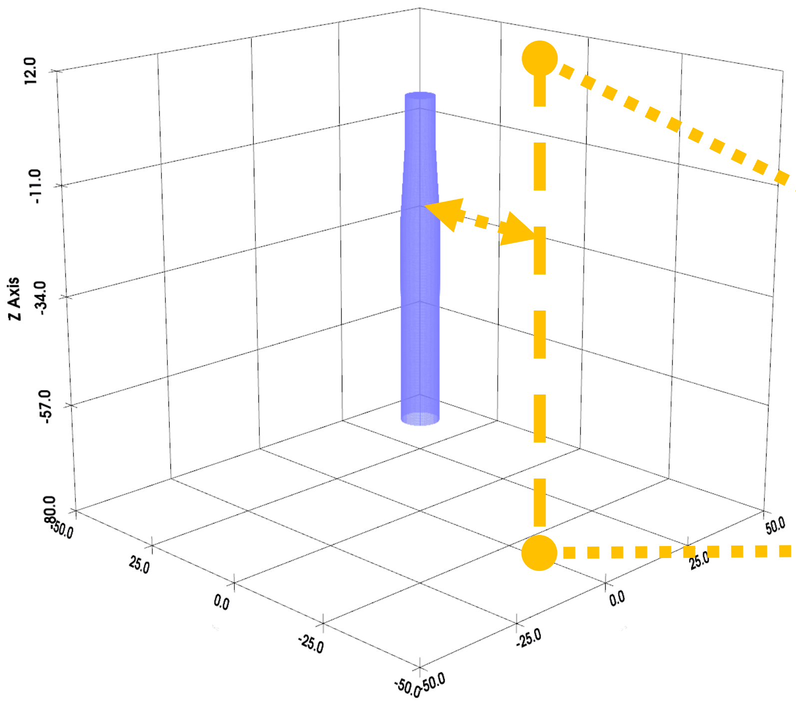
Simulated 3D Sound Pressure Field

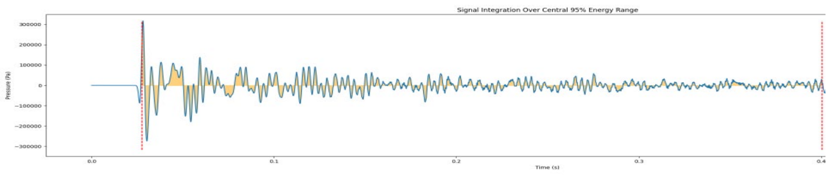


10 m

20 m

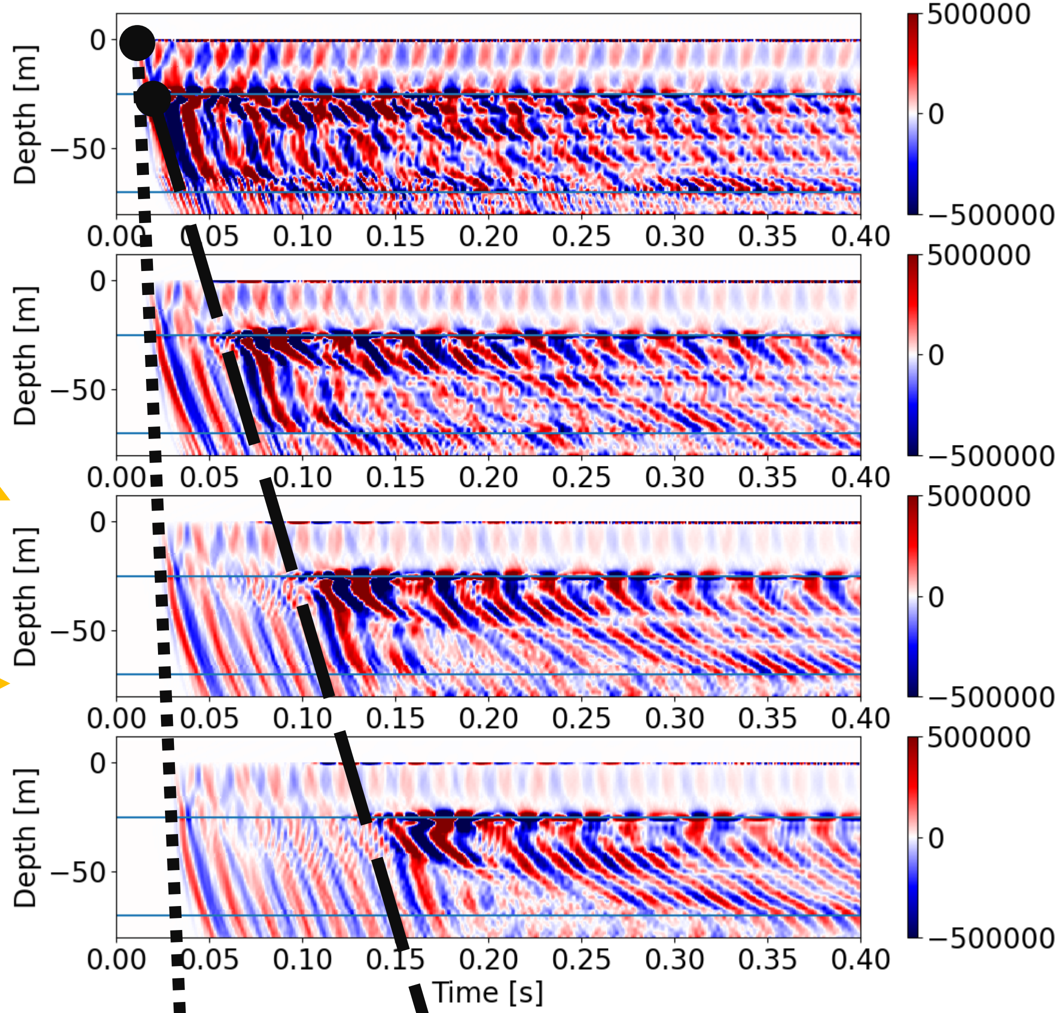
30 m

40 m



Simulated Waveform at r = 30 m, z = -12 m

Sound pressure sampled along vertical transects at ranges

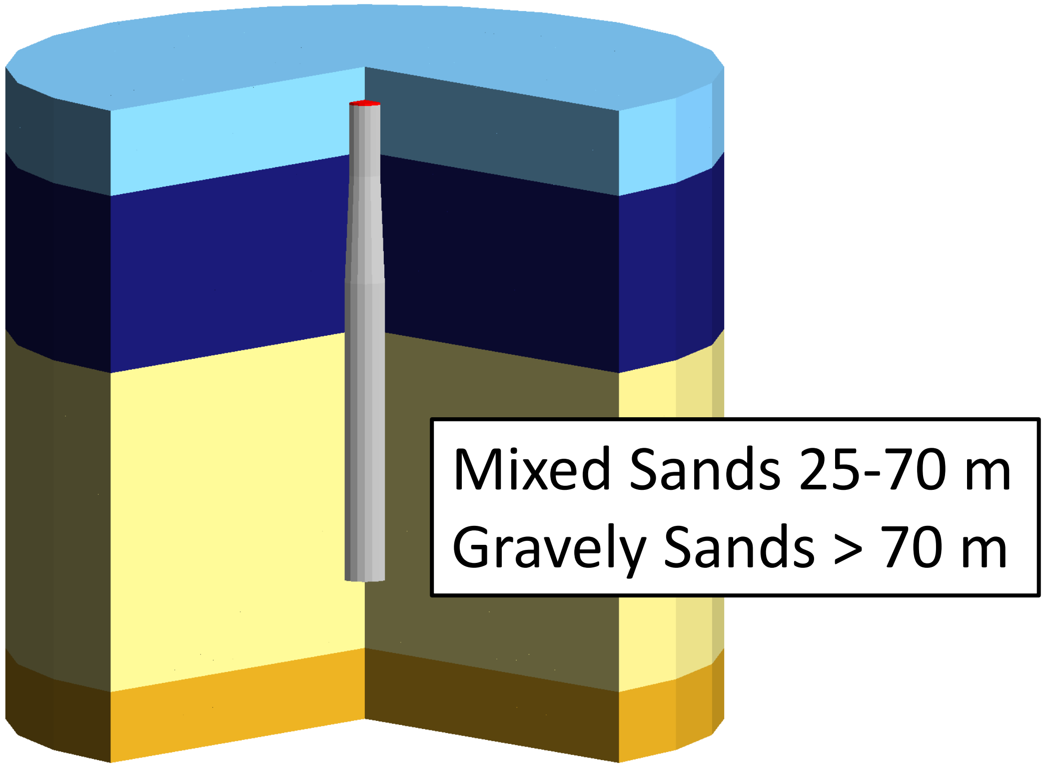


Mach Wave Scholte Wave

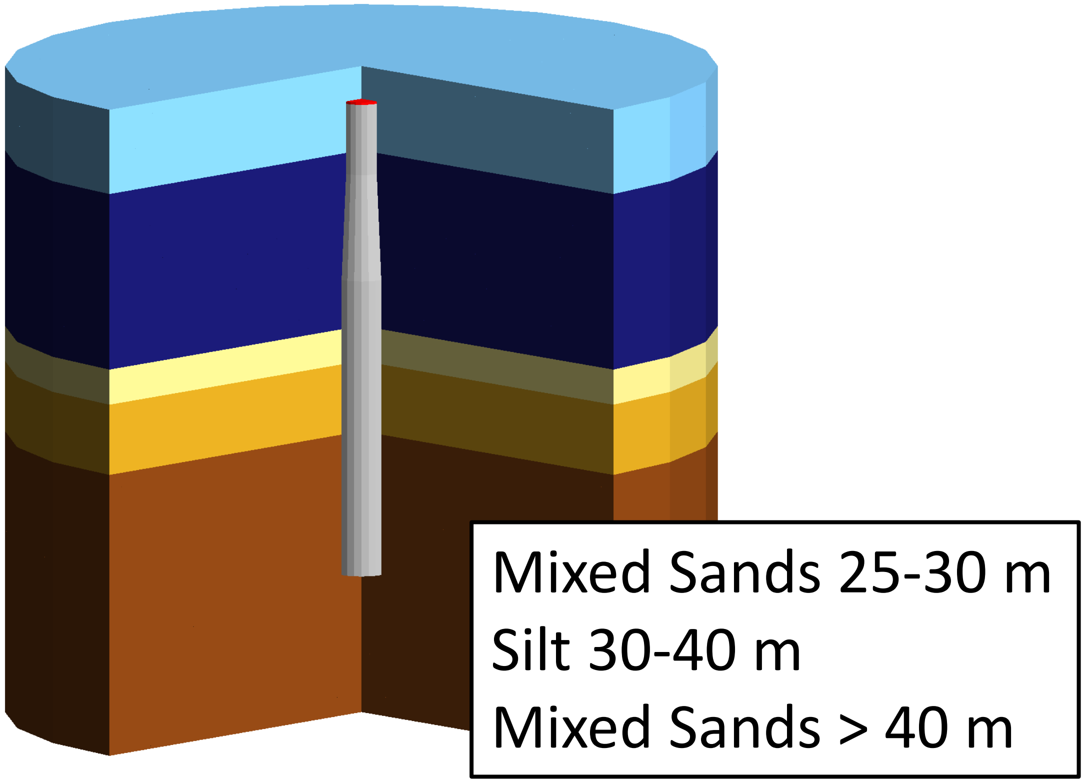
Effect of Substrate Layers on Sound Fields

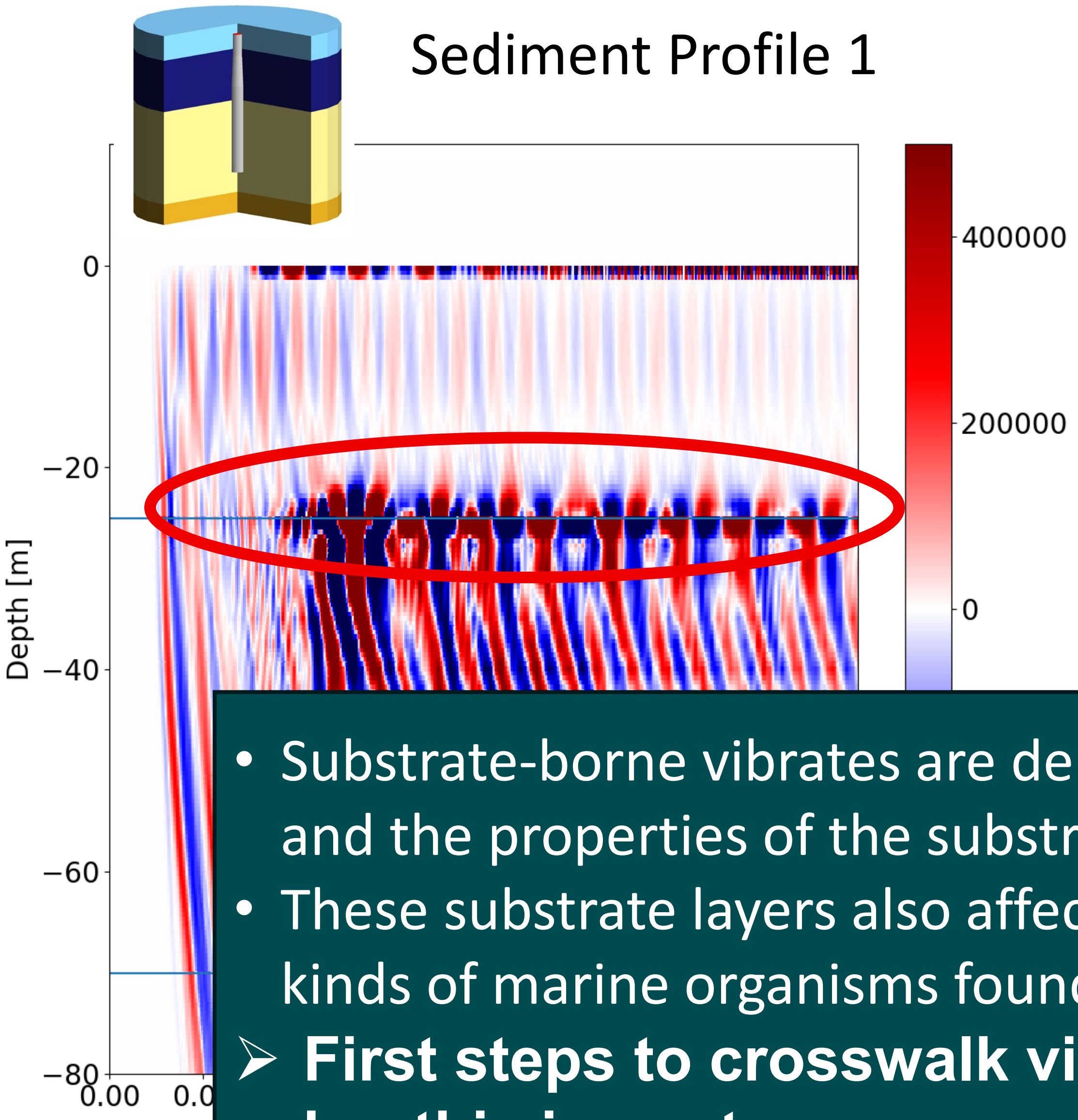
Same monopile geometry and hammer characteristics

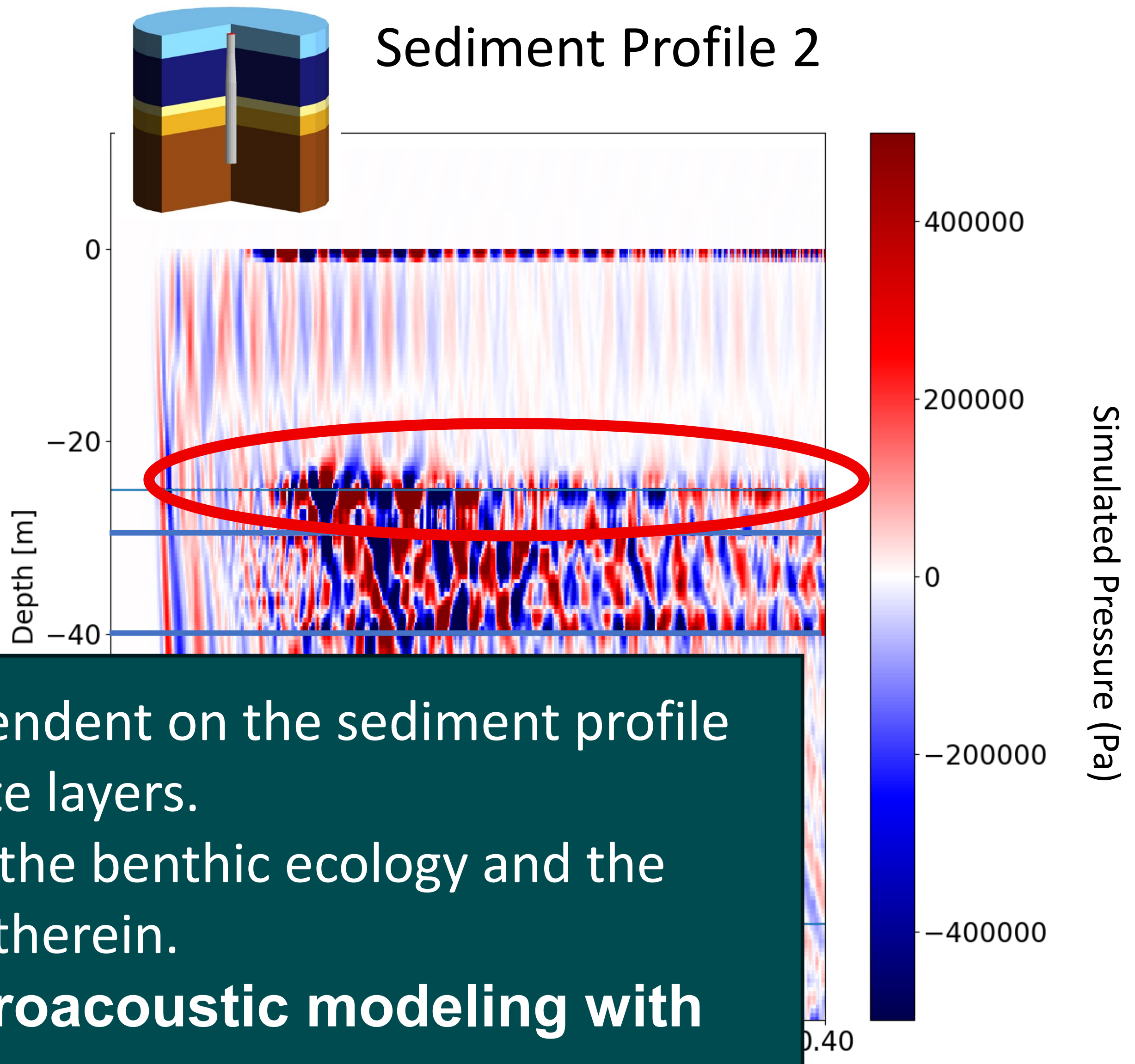
Sediment Profile 1



Sediment Profile 2



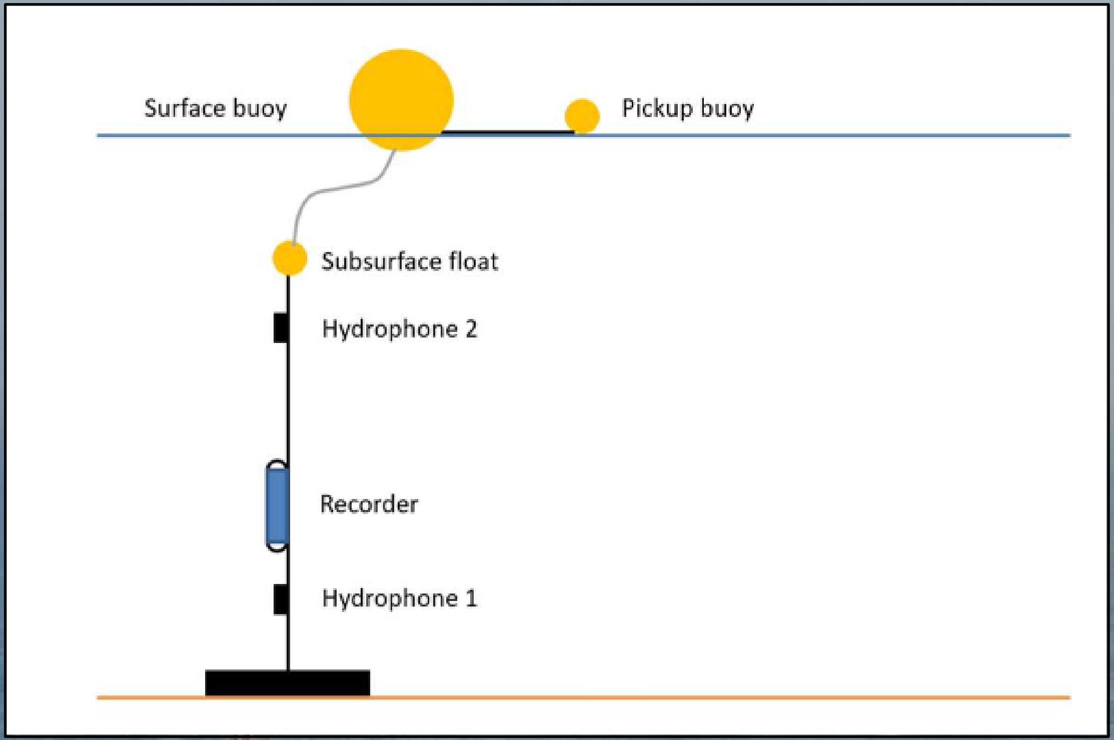




- Substrate-borne vibrates are dependent on the sediment profile and the properties of the substrate layers.
- These substrate layers also affect the benthic ecology and the kinds of marine organisms found therein.

➢ **First steps to crosswalk vibroacoustic modeling with benthic impact assessment**

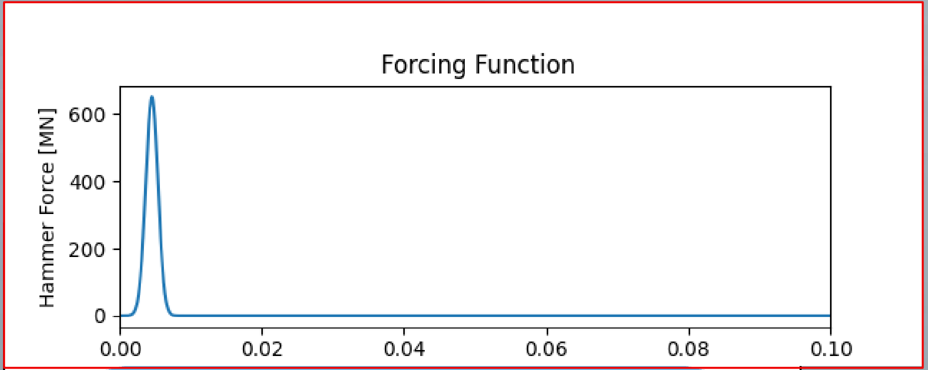
Case Study: Installation of the Coastal Virginia Offshore Wind (CVOW) Pilot Project

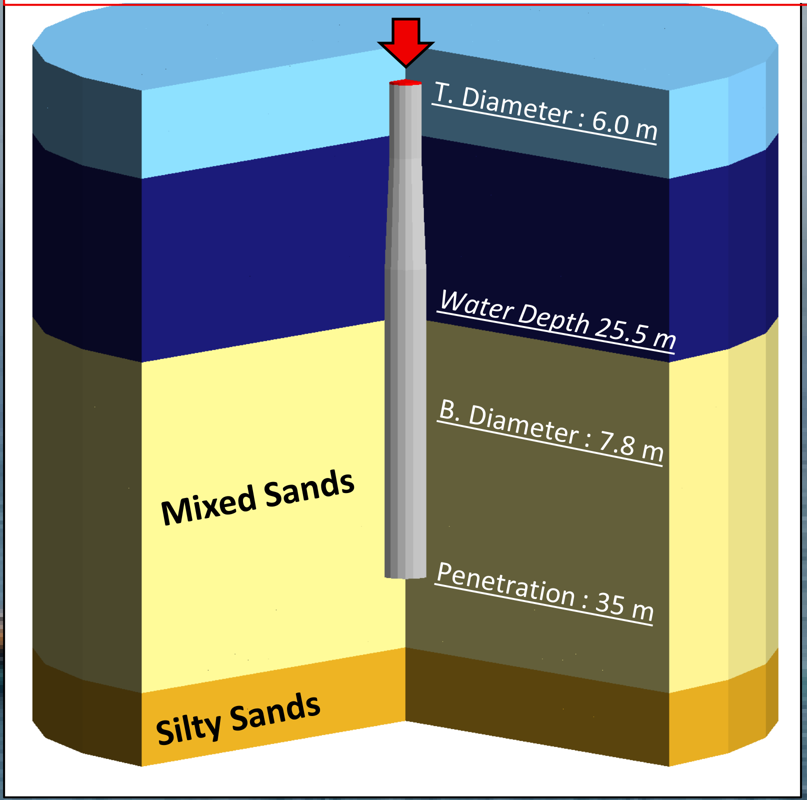


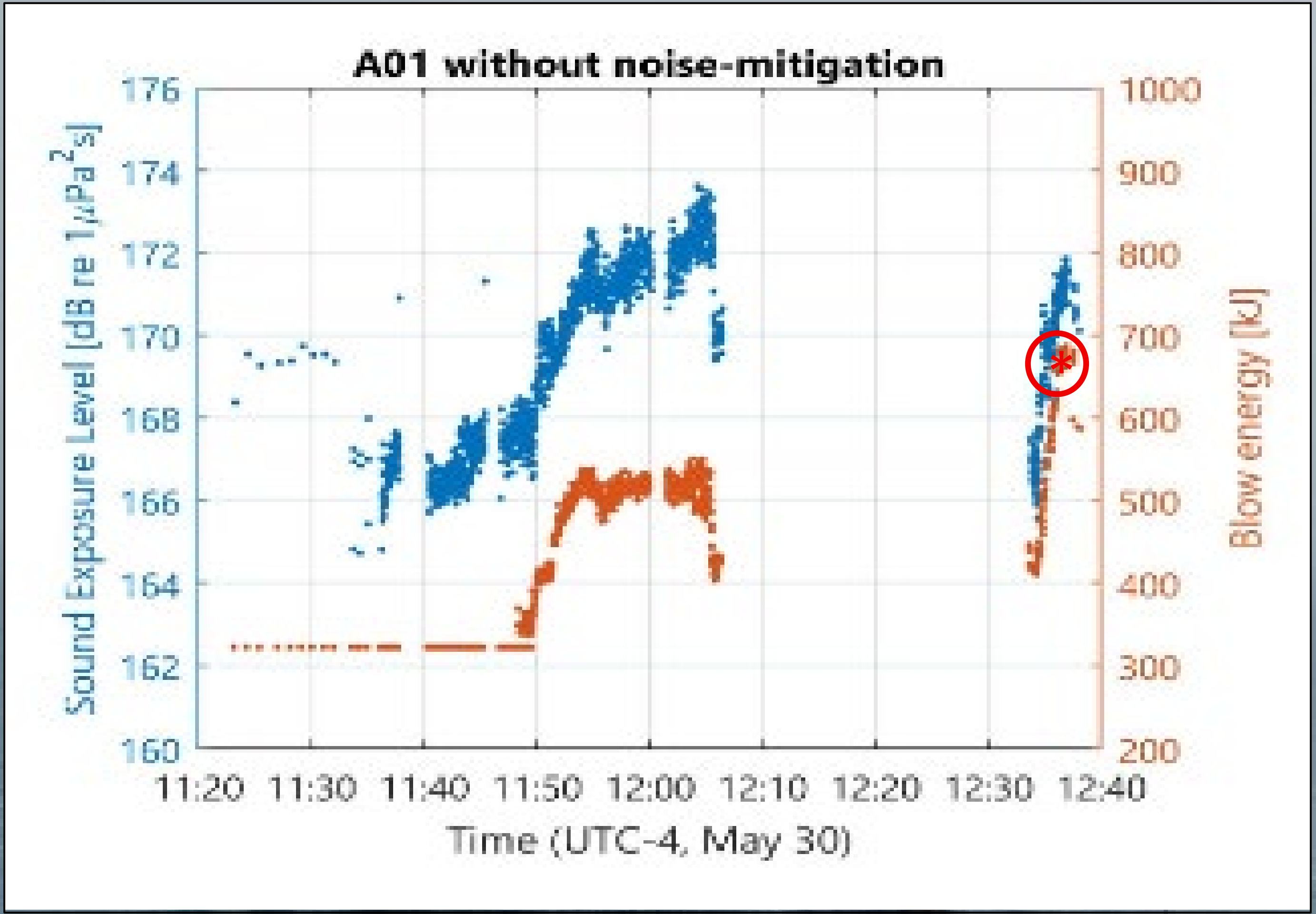
- IHC-S3000 Impact Hammer was used to install two large monopile foundations: A01 (without) and A02 (with) double Big Bubble Curtain noise mitigation
- Sound field measurements were reported

Data and Figures from:
https://tethys.pnnl.gov/sites/default/files/publications/coastal_virginia_offshore_wind_final_noise_and_pso_monitoring_report.pdf

Input Parameters for Sound Level Predictions







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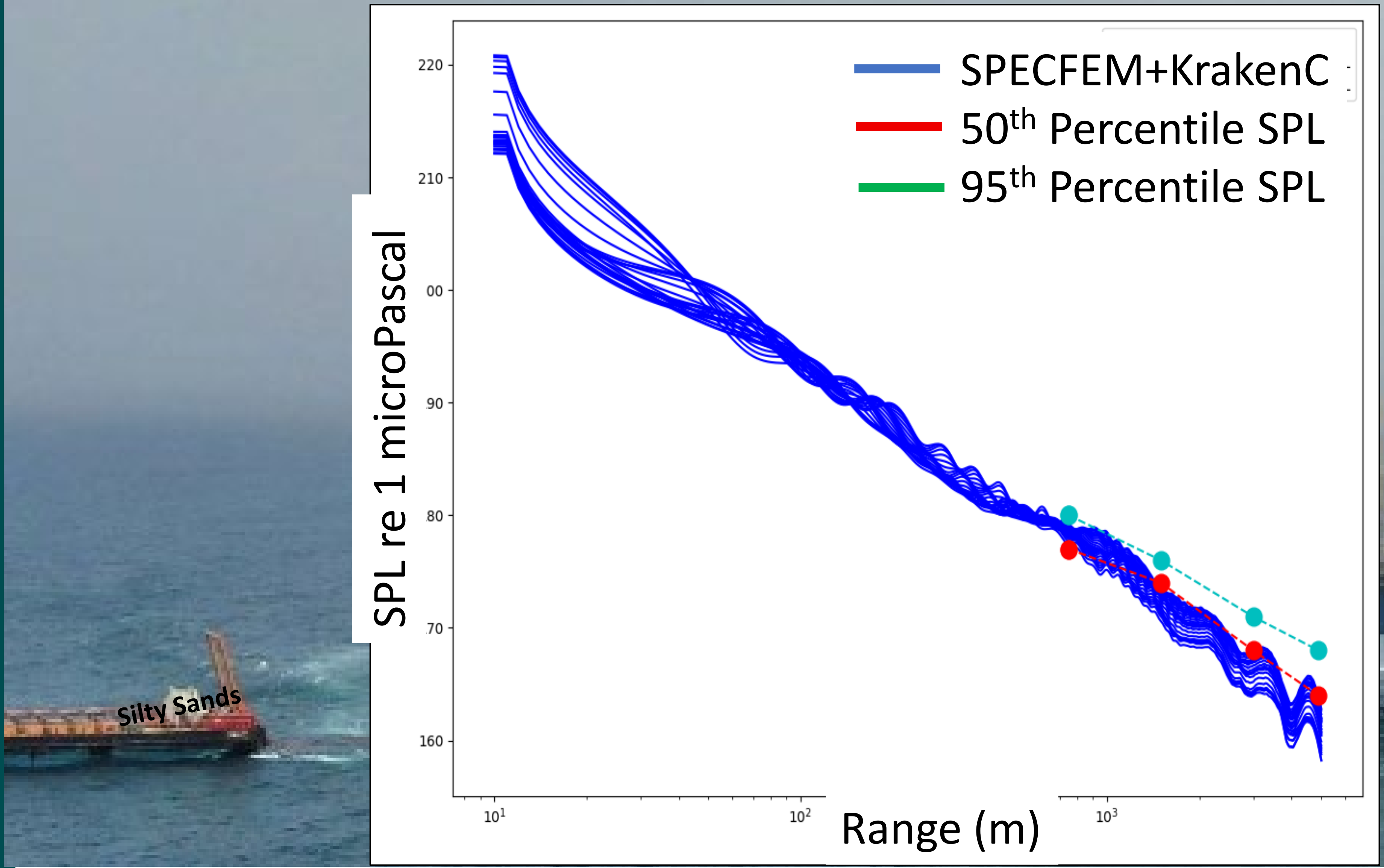
Sound Level Predictions with 3D Vibroacoustic Model



Summary

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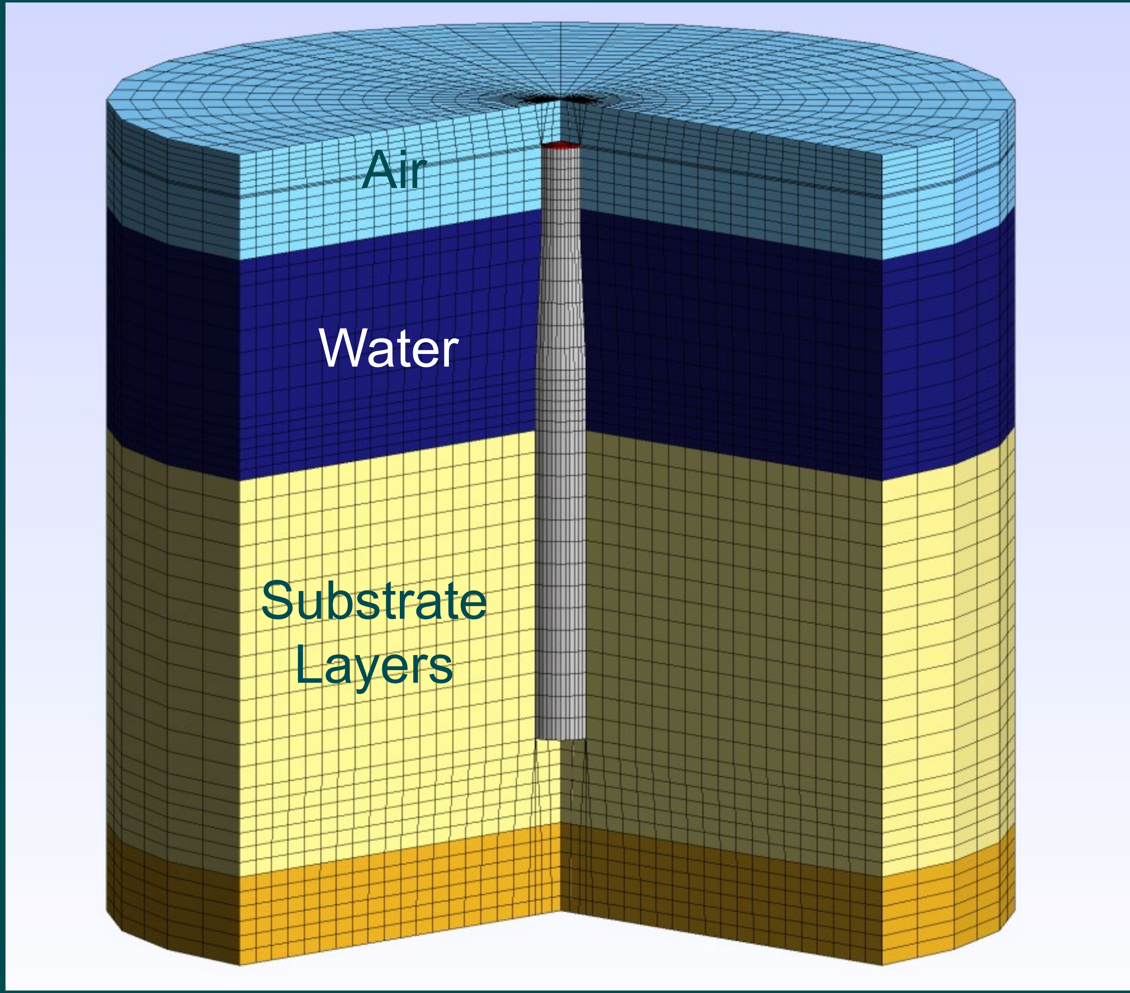
- Sound fields from offshore pile driving, including substrate-borne vibrations, are modeled using SPECFEM 3D Cartesian
- The vibroacoustic model is initialized with 3D meshes that have been optimized for thin-walled, cylindrical monopiles embedded in a layered substrate
- Far field modeling will be integrated with 3D PE that is being modified to include sediment propagation



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