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CFD analysis of sand and gravel filling in seabed socket for wind turbine tower

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cpfd

Aerotak in a nutshell

- Fluid mechanics consultancy
- Founded in 2017
- Team of 21 specialists located in two countries
- Clients in Europe, North America, South America, and Asia

Services

Design and optimization
Process and product design improvements

Computational Fluid Dynamics (CFD) analysis
Advanced simulations of gases, liquids, and solids

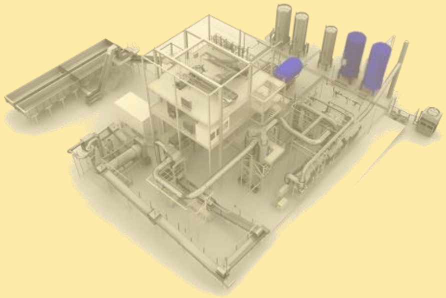
Thermal analysis
Advanced simulations of heat transfer and radiation

Experimental measurements
Pressure drops, velocity, and temperature distributions

Our core industries

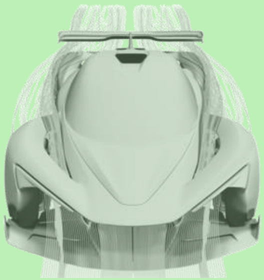
Process Engineering

Present in projects from start to finish, and beyond
60% of our total revenue



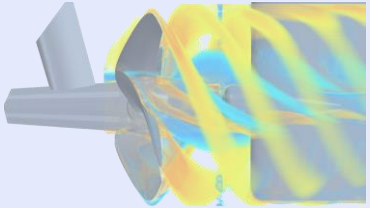
Automotive

Dedicated office in the UK
Industry-leading clients



Maritime

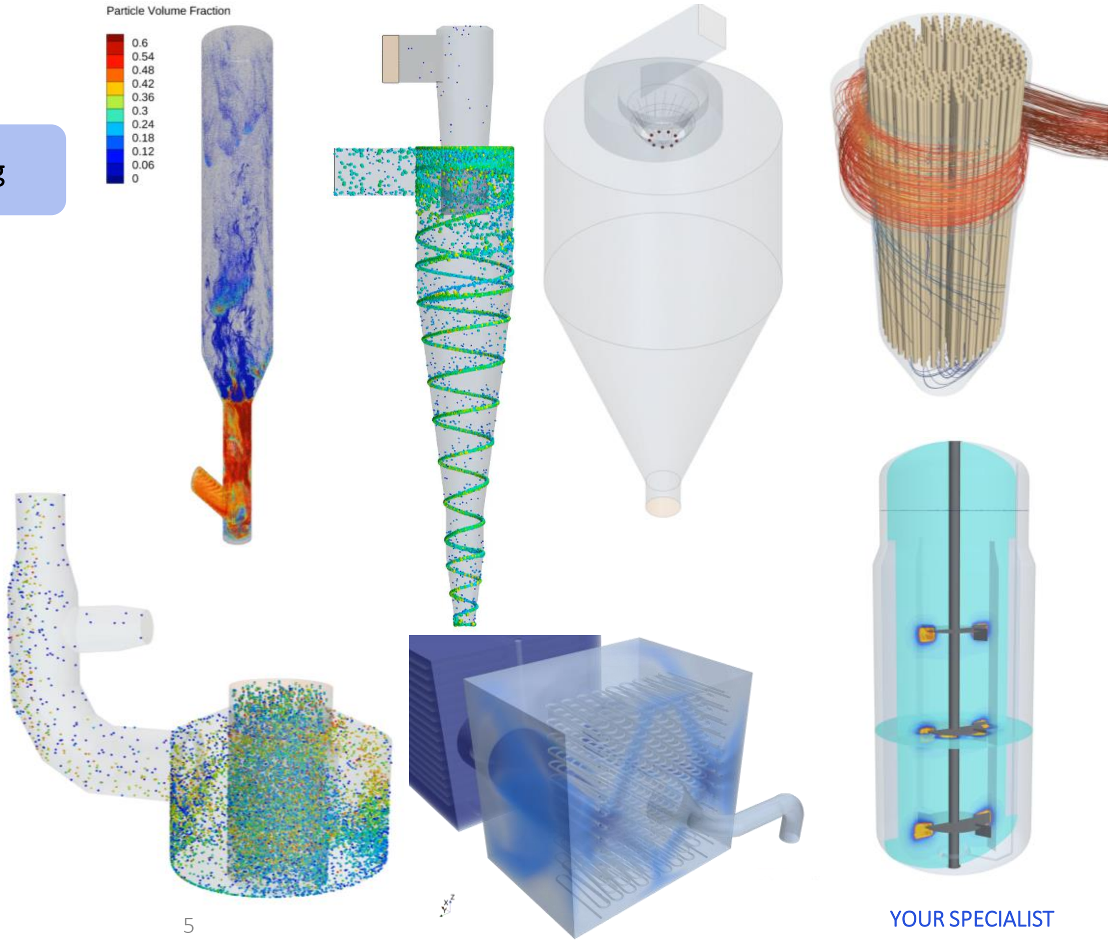
Extensively validated CFD models using tank tests, sea trials and in-service performance data



Core competencies: Process engineering

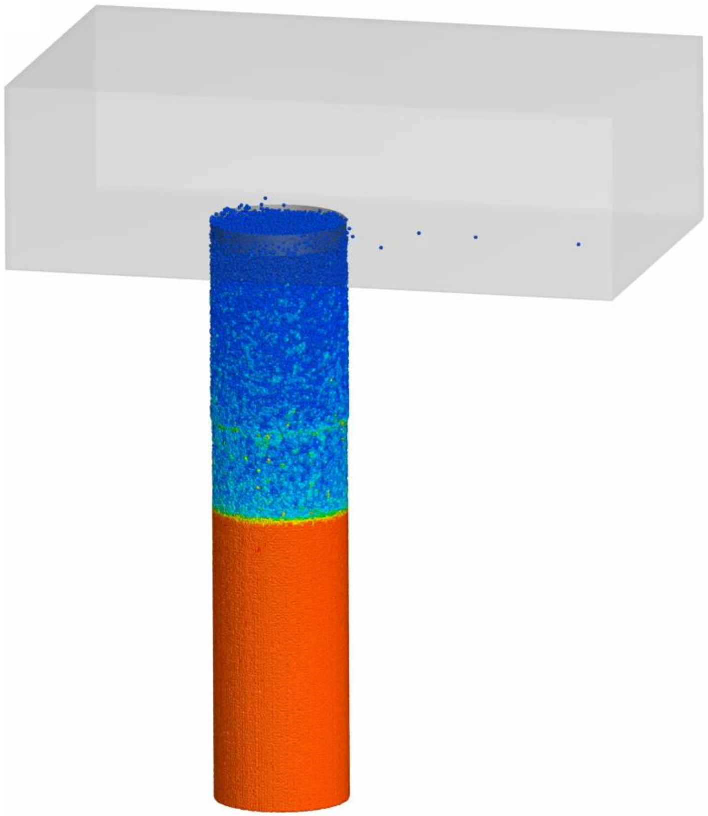
We specialize in simulating, designing, and optimizing

- Fluidized beds
- Spray dryers
- Bag filters
- Dry and wet cyclones
- Freeze dryers
- Mixing vessels



Use case

CFD analysis of sand and gravel filling in seabed socket



Introduction

Preparation of seabed for installation of wind turbines is required to ensure a strong foundation.

Drilled holes (sockets) are filled with sand and gravel to accomplish this.

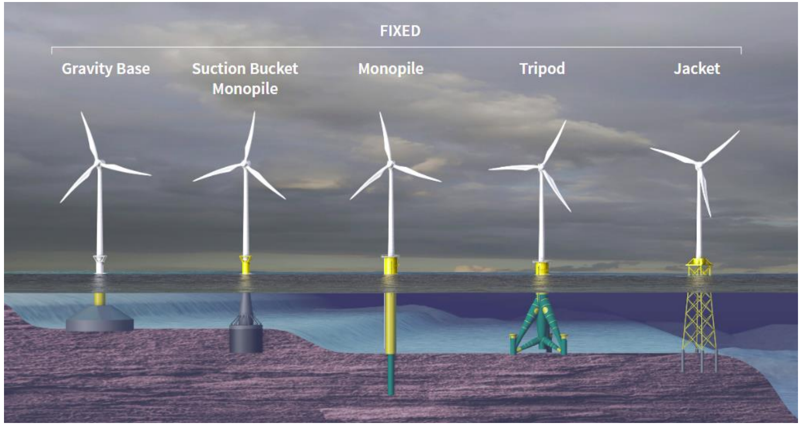
During filling of the sockets, proper distribution of the sand and gravel is necessary.

Numerous filling approaches, conditions, and methods can be used (some easier and cheaper than others) – but how to evaluate these?

Objective

Develop a CFD model that can be used to predict the filling behavior of sand and gravel into a seabed socket on the basis of the following performance parameters:

1) Uniformity in particle distribution within the socket at the end of the filling.
2) Surface contour of settled sand and gravel particles at the end of the filling.
3) Amount of sand and gravel lost to the surrounding water outside of the socket during filling.

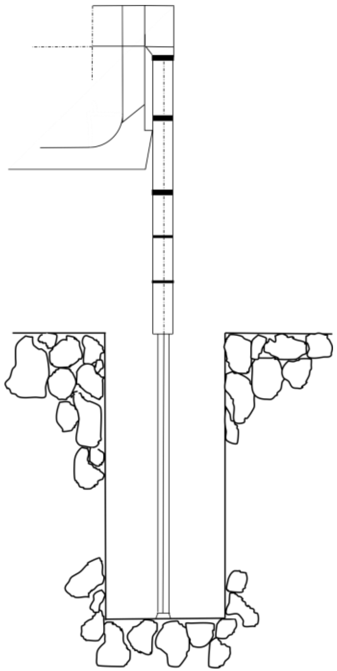


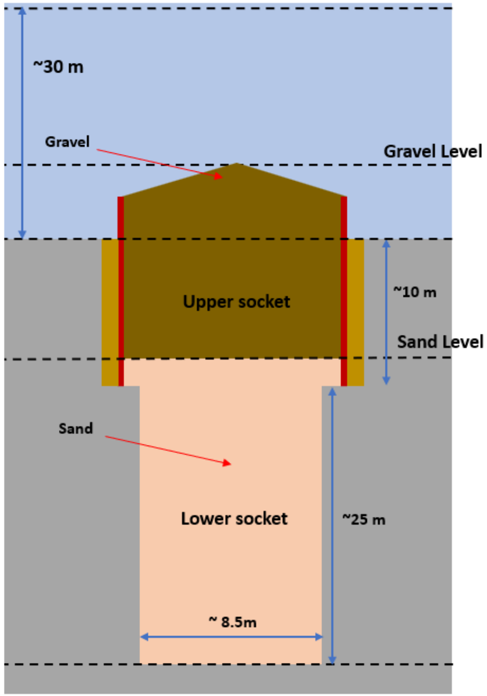
Introduction

- Sockets are 8.5 meters in diameter and roughly 35 meters deep and are to be filled first with sand (lower socket) and subsequently with gravel (upper socket).

- $D_{50,sand}$ = 0.425 mm, 2650 kg/m^3
  $D_{50,gravel}$ = 4.5 mm, 2650 kg/m^3

- Sand/gravel and are pumped with water through a vertical pipe (fall) at a total capacity of 3000 m^3/h with 450 m^3/h being solids.





Simulation approach

Simulation challenges:
- Large temporal scale
- Large physical scale
- Particle size distribution is of importance
- High and low local particle concentration

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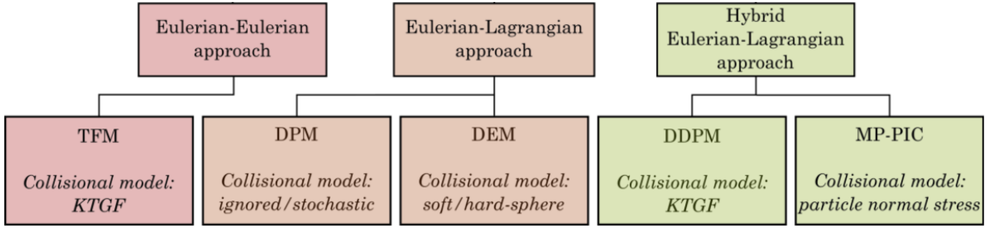
Possible simulation approaches:
- ~~Eulerian-Lagrangian~~
  - ~~Discrete parcel method (DPM)~~
  - ~~Discrete element method (DEM)~~
- ~~Eulerian-Eulerian~~
  - ~~Two-fluid model (TFM)~~
  - ~~Multi-fluid model (MFM)~~
- Hybrid Eulerian-Lagrangian
  - Dense discrete phase model (DDPM)
  - Multiphase particle-in-cell (MP-PIC)

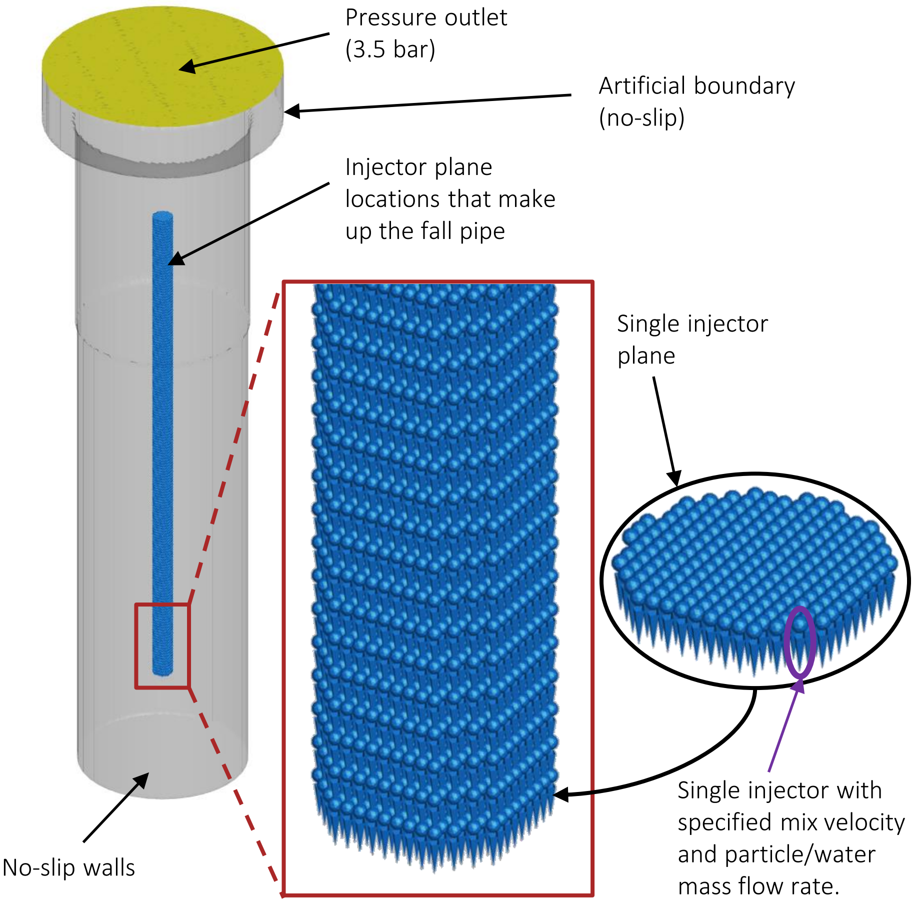


Model setup and conditions

Boundary conditions

Two methods of handling the fall pipe are simulated: "retraction filling" involves gradually retracting the pipe as the socket is filled, while "top filling" keeps the pipe constant at the top of the socket.

So-called injectors are used to feed particles and water to the domain, thus simulating the location of the bottom of the fall pipe.



Model setup and conditions

Simulation matrix

The table provides and overview of simulated cases, including specified boundary conditions.

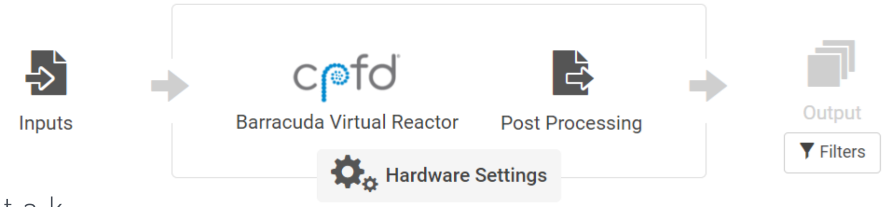
		Sand retraction filling	Sand top filling	Sand top filling at 2000 m³/h	Sand top filling at 20% solids content	Sand top filling with half-way pause	Sand top filling with casing	Sand top filling with casing and current	Gravel filling	Gravel filling at 4000 m³/h	Gravel filling at 20% solids content	Gravel filling with half-way pause
Particle type		Sand	Sand	Sand	Sand	Sand	Sand	Sand	Gravel	Gravel	Gravel	Gravel
Filling method		Retraction	Top	Top	Top	Top	Top	Top	Top/ retraction	Top/ retraction	Top/ retraction	Top/ retraction
Casing above seabed	m	0	0	0	0	0	1.4	1.4	1.4	1.4	1.4	1.4
Current, surrounding	m/s	0	0	0	0	0	0	0.5	0.5	0.5	0.5	0.5
Mix flow	m^3/h	3000	3000	2000	3000	3000	3000	3000	3000	4000	3000	3000
Solids	%	15	15	15	20	15	15	15	15	15	20	15
Solid flow	m^3/h	450	450	300	600	450	450	450	450	600	600	450
Solid density	kg/m^3	2650	2650	2650	2650	2650	2650	2650	2650	2650	2650	2650
Mix velocity	m/s	1.10	1.10	0.74	1.10	1.10	1.10	1.10	1.10	1.47	1.10	1.10
Filling speed	m/h	13.2	13.2	8.8	17.6	13.2	13.2	13.2	12.6	16.8	16.8	12.6
Filling time	h	1.96	1.96	2.94	1.47	2.51	1.96	1.96	0.95	0.71	0.71	1.23

Barracuda VR on Rescale platform

Simulations were carried out using a Barracuda Virtual Reactor license on Rescale's cloud solution platform.

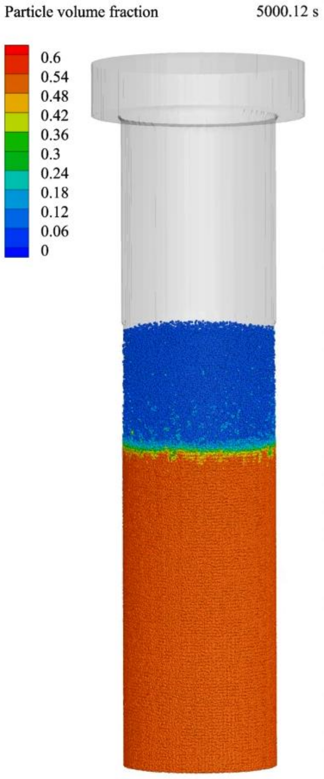
Workflow:

1) Upload inputs
    1) Barracuda license file
    2) Zip-folder with necessary files to run the simulation
2) Software settings
    1) Select software
    2) Write commands required to run the simulation
3) Hardware settings
    1) Select GPU (Intel Xeon E5-2690 v4 CPUs @ 2.6 GHz, Tesla V100)
    2) Select number of cores/nodes/GPUs and wall clock time (1 GPU with 6 cores)
4) Post processing
    1) If needed, add a post-processing script to process data upon completion of the simulation.
5) Simulation
    1) Simulation time varied between 6 and 18 hours at a cost of around 60 USD.
6) Data extraction

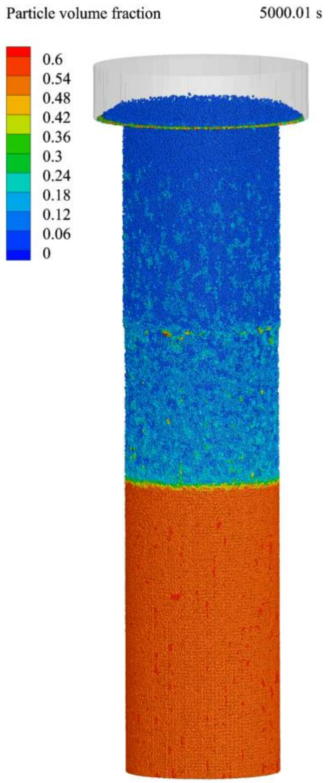


Sand filling method

- Results from the retraction (expensive and difficult to operate) and the top (cheap and simple) filling approaches are compared in the videos on the right.
- Injection and settling of sand particles are visualized as function of time and colored by particle volume fraction.
- The filling time is approximately 2 hours; reached using a time-step of 0.08 s – 0.25 s.
- Upon completion of the filling, 8.1 million computational particles have been injected.
- Biggest observable difference in the two methods in the amount of particles swirling around in the region of the socket not occupied by settled particles.
- Particles are observed to escape the upper socket for the top filling method.



Retraction filling



Top filling

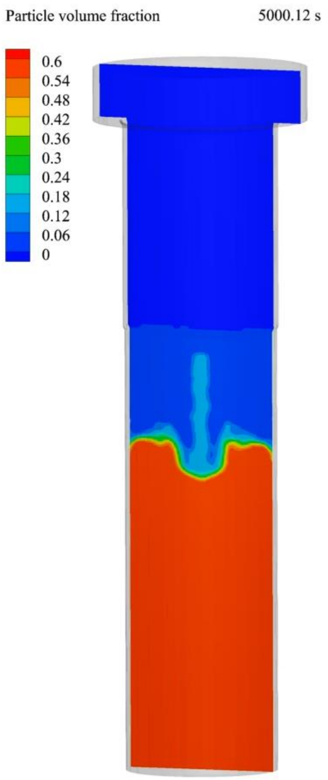
Sand filling method

Particle volume fraction visualized on a vertical plane through the center of the socket.

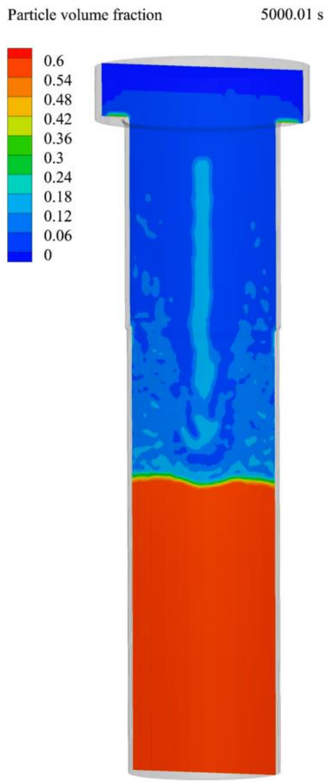
A bore in the settled particles is predicted to occur directly below the injection point due to the water and particle momentum.

Particle piling on the edge of the bore.

Upon completion of the filling, particles are allowed to settle, resulting in an almost completely horizontal contour/curvature of the settled particles.



Retraction filling



Top filling

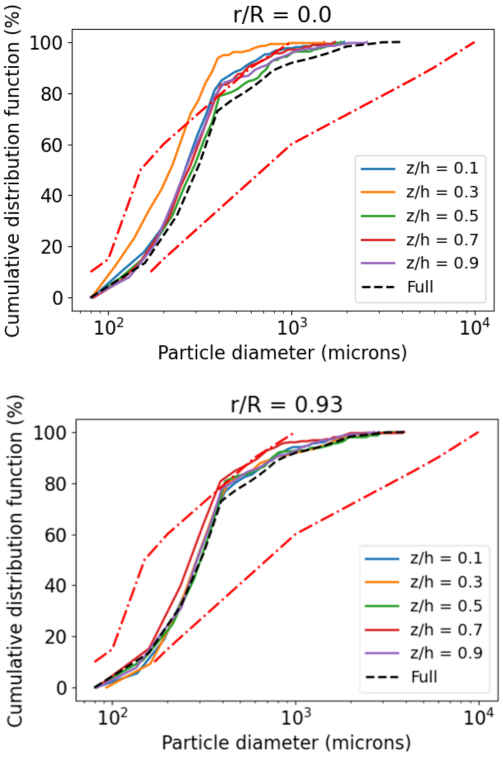
Sand filling method

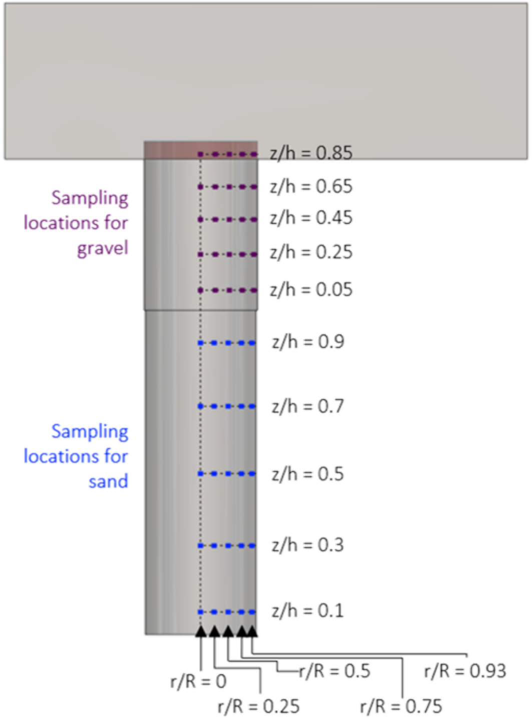
- Particle distribution in the socket can be quantified by exporting and post-processing detailed data on the position and size of the particles upon completion from Barracuda VR.

- Particle size distributions as function of axial location and plotted at specific radial locations for the retraction filling case.

- Limited axial segregation is observed to occurs, as the PSDs for each r/R-value are highly similar.

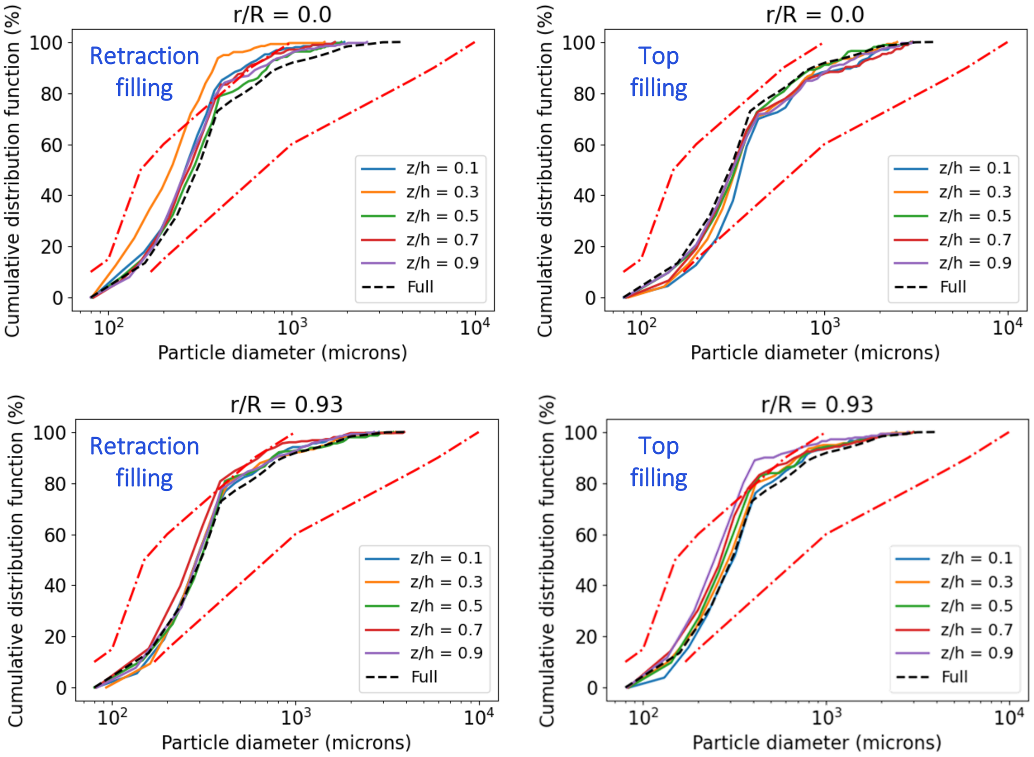
- Across the entire height, smaller particles are prone to collect in the center and particles outside the lower PSD bound can be expected here.





Sand filling method

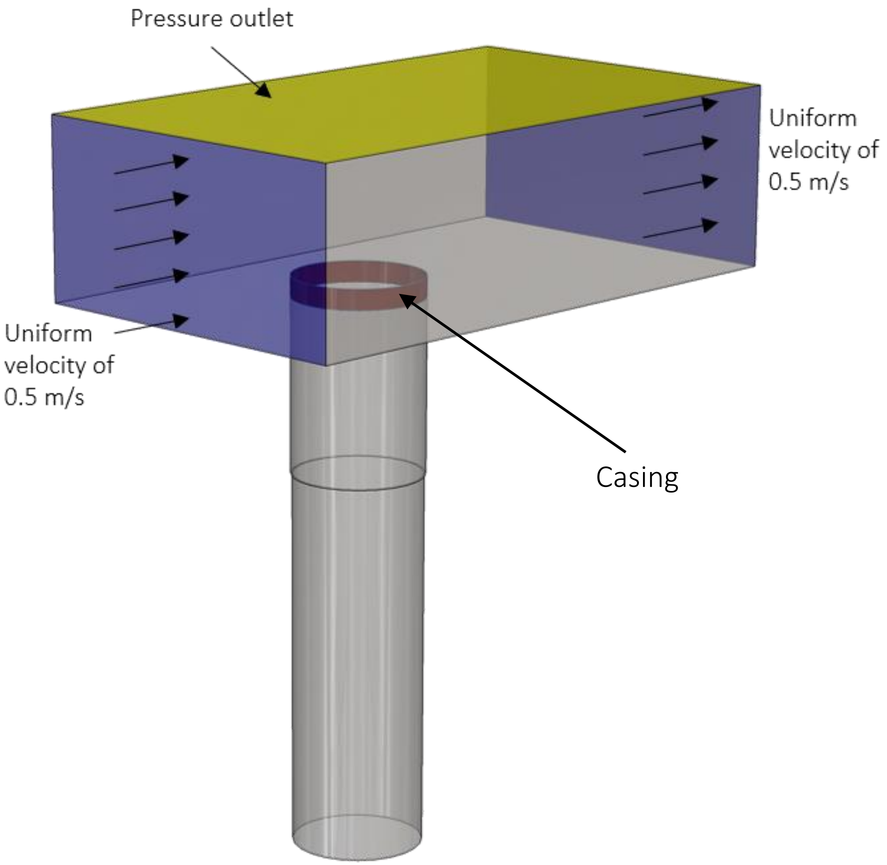
- Comparing the particle size distributions for a few of the sampling points for retraction filling and the top filling approach, minor differences are observed.
- Top filling gives a better distribution in the center, especially at the bottom of the lower socket.
- Top filling gives a slightly worse particle distribution near the wall, especially at the top of the upper socket.
- In general, the findings are highly similar for both the retraction filling and top filling approach, apart from higher risk of particles escaping the socket during filling for the latter.



Sand top filling with current

To further investigate and quantify the risk and amount of particles that are likely to escape the socket during sand filling, casing and current is included.

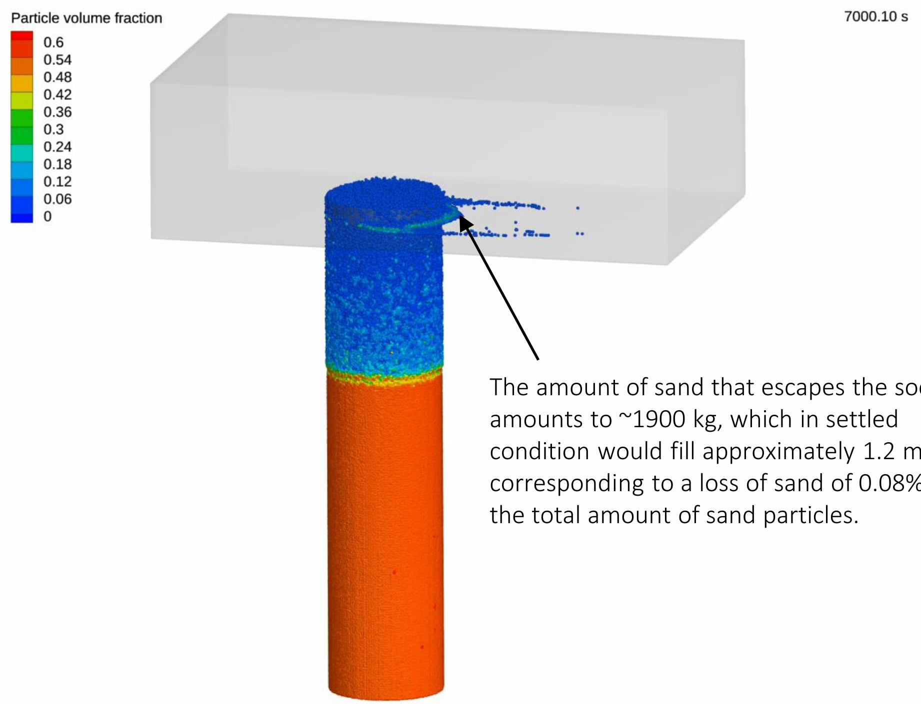
All operating conditions are identical to those of the sand top filling case.



Sand top filling with current

- The animations show isoview and topview of the sand filling of the socket with current and casing in place.

- The flow of water outside of the socket results a suction of particles out of the socket, which are being convected downstream.



The amount of sand that escapes the socket amounts to ~1900 kg, which in settled condition would fill approximately 1.2 m^3, corresponding to a loss of sand of 0.08% of the total amount of sand particles.

Isoview

Current

Topview

Conclusions and learnings

Technical highlights

- Sand and gravel filling in a seabed socket using computational fluid dynamics has been simulated. The objective was to assess the quality of the filling in terms of particle distribution uniformity within the socket, surface contour of settled particles, and particle loss to the surrounding water during filling.

- Sensitivity studies were conducted to analyze the impact of different operating conditions, filling methods, and external currents on particle loss to the surroundings.

- Key customer takeaway: The cost-effective top-filling method can replace the complex and costly retraction approach, with minimal particle escape from the socket.

Project management highlights

- By integrating Barracuda VR with Rescale, we expanded the project's simulation capacity from 5 (initial scope) to 12, enhancing our business proposition and delivering more valuable insights to the client.

- Leveraging Rescale's cloud-based simulations not only relieved strain on our local clusters but also reduced expenses associated with procuring and managing costly GPU resources.

- The exceptional support from CPFD Software and Rescale improved our project workflow, leading to substantial time and cost efficiencies.

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Appendix

Model setup and conditions

Simulation setup and parameters

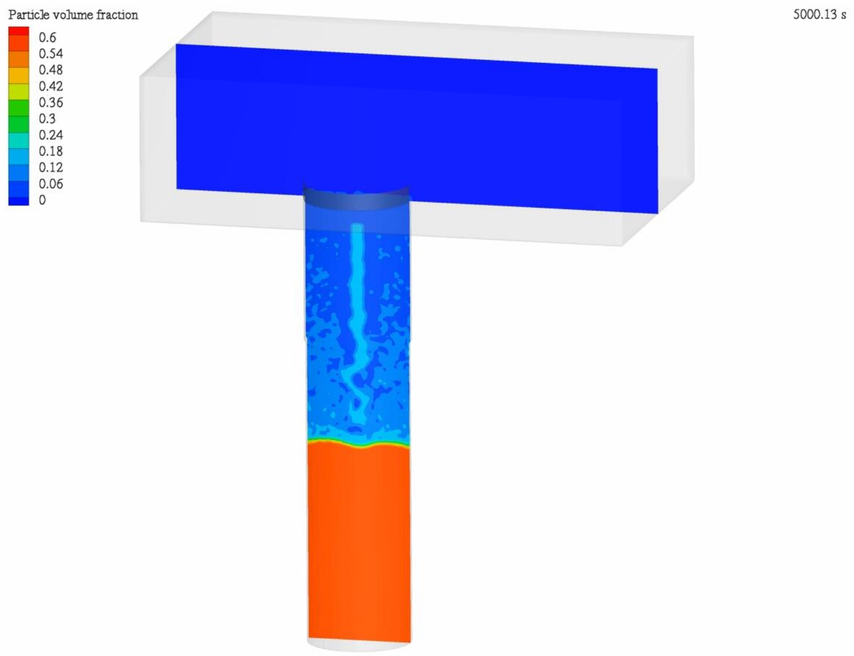
The table provides an outline and recap of the modeling parameters used to simulate the gravel and sand filling.
Detailed information on time-step, simulation time, geometry, cell count etc. will be provided for each of the simulated cases. The simulations matrix is included on the following page.

Solver	Barracuda Virtual Reactor 22.1.2, 3D, transient, Large Eddy Simulation (LES)
Turbulence model	Subgrid scale (SGS) turbulence model
Mesh	Cartesian, cut-cell mesh with 370,000-800,000 cells.
Inlet conditions	Fluid and particle injectors
Outlet conditions	Pressure outlet (top of fluid domain), reference pressure set at 3.5 bar
Wall boundary conditions	No-slip, normal-to-wall and tangent-to-wall retention coefficients of 0.85
Fluid properties	Incompressible, constant density (1025 kg/m^3)
Particle properties	Sand particles: D_{50} = 0.425 mm, 2650 kg/m^3, spherical, Wen-Yu Ergun drag model Gravel particles: D_{50} = 4.5 mm, 2650 kg/m^3, spherical, Wen-Yu Ergun drag model
Solver settings	Variable time-step = 0.08-0.25 s, CFL = 0.8-1.2, lift force, virtual mass forces

Sand top filling with current

Animations show particle volume fraction and water velocity magnitude on a vertical plane. Velocity vectors are shown on the animation with velocity magnitude to visualize the movement of the water within an in the vicinity of the casing.

A wake of recirculation flow at low velocity is observed downstream of the casing, as one would expect for the flow over and around an excerpt of cylinder at high Reynolds numbers.



Model setup and conditions

Modeling assumptions

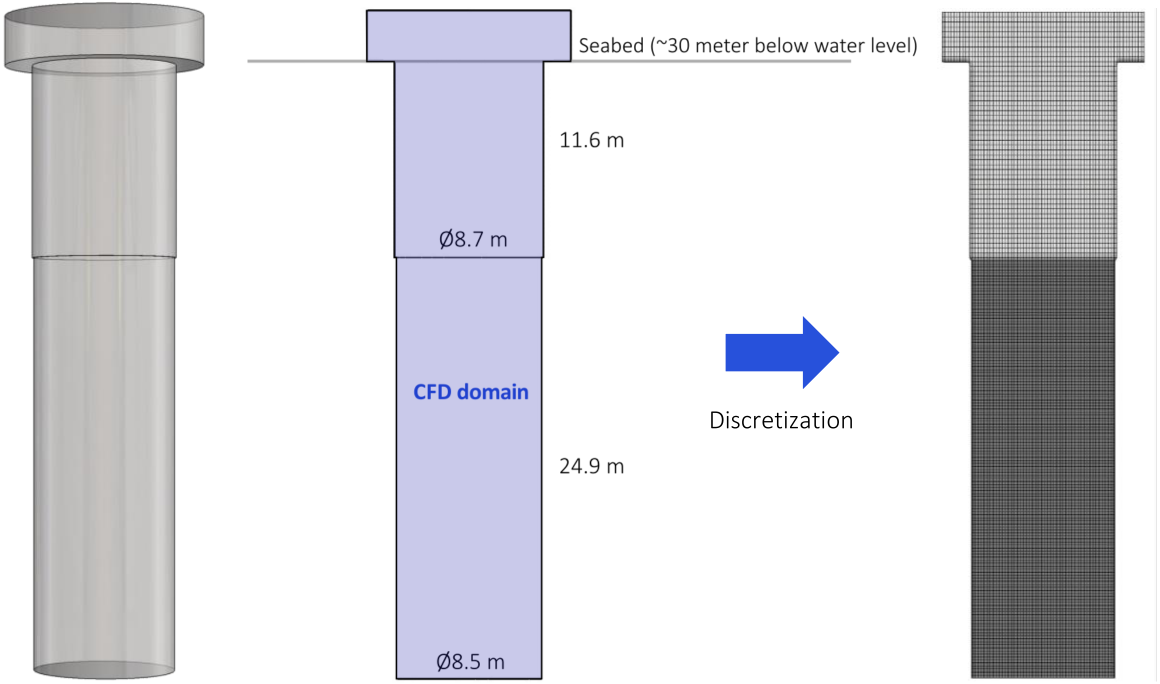
1. Sand and gravel particles are simulated as spherical with constant density.
2. Only the socket and an excerpt of the surrounding water is simulated.
3. Current and waves outside of the socket are neglected.
4. Casing is neglected for sand filling.
5. Water and particles are fed into the socket from the bottom of the fall pipe with a specified velocity (identical for water and particles) and solid content, and at a constant pipe diameter.
6. The fall pipe does not experience lateral movements within the socket and its geometry is neglected. Instead, a set of injectors are used to account for the water and particle feeding.
7. Solids settle into the socket with at a close-pack volume fraction of 60%.

On top of these follows a long list of assumptions related to the CFD modeling approach using the MP-PIC method, which will not be elaborated on here.

Model setup and conditions

Geometry and mesh

- The geometry consists of a lower and an upper socket.
- Only an excerpt of the ambient domain is included for the sand filling.
- A Cartesian cut-cell mesh with between 370,000 cells, depending on the geometry, is used to discretize the fluid domain.



Isoview   Sideview   Mesh

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