

CFD Modelling of Chain Induced Sediment Escape Out of Seabed Trenches

Hydrodynamic Analysis on Trench Evolvment
for Floating Wind Mooring Systems

Master Thesis ODE

Teun Slob



CFD Modelling of Chain Induced Sediment Escape Out of Seabed Trenches

Hydrodynamic Analysis on Trench Evolvment
for Floating Wind Mooring Systems

by

Teun Slob

to obtain the degree of Master of Science
at the Delft University of Technology,

Student Name	Student Number
Teun Slob	48776656

Project duration: February 3, 2025 – December 18, 2025

Company supervisor	Phd. P. Triantafyllos	
Thesis committee:	Dr. Ir. R.L.J. Helmons	TU Delft, supervisor
	Dr. Ir. G. Keetels	TU Delft, Chair



Preface

This thesis forms the closing part of my master in Offshore & Dredging Engineering at the TU Delft. The project arose from a difficult mechanism that had not yet been properly explained, which limited confidence in the seabed behaviour needed for floating wind development. What started as a simple question about trench behaviour developed into a wider exploration of sediment mobility, flow conditions, and the limits of stability inside these trenches. Working on this topic allowed me to combine physical intuition with numerical modelling in a way that fits well with the applied character of the programme while simultaneously giving me space to explore more unknown areas such as programming.

I am grateful to my supervisors for their guidance, feedback, and going out of their comfort zone to help me throughout the project. Their questions helped me refine the research direction, improve the analysis, plus strengthen the structure of the final document.

Completing this thesis has been an important step in my development as an offshore engineer, and I am grateful for the opportunity to work on a topic that challenged me both technically and personally.

*Teun Slob
Delft, December 2025*

Abstract

Mooring chains of floating offshore wind turbines generate cyclic seabed loading that excavates trenches and may transport sediment out of the trench. This thesis is the first to investigate the physical conditions under which such sediment escape ceases, using a Computational Fluid Dynamics (CFD) model that couples a Boussinesq-type incompressible flow solver with an immersed boundary method and suspended-sediment transport. Forty simulations were conducted across four trench depths (3–9 m), five grain sizes (0.0625–1 mm), and two inflow regimes (0.05–0.36 m/s) representing calm and storm conditions in the North Sea.

A new Escape Potential Index (EPI) was introduced primarily as a simulation prioritisation tool to identify edge cases and minimise the number of non-informative runs. Classical predictors such as the Rouse number were insufficient for this purpose as they do not include confinement or chain-induced uplift. The EPI therefore combines settling behaviour, chain forcing, and trench geometry into a single heuristic ranking. Although not a universal threshold, EPI correctly orders cases by mobility and, when combined with the Rouse number, defines a separation curve that distinguishes escaping from stable configurations and explains why classical suspension theory under predicts escape under cyclic chain forcing.

The results show that trench depth is the dominant control on sediment mobility. Shallow trenches strongly couple chain motion to the flow, producing intense suspension even under weak currents, while deeper trenches reduce uplift through geometric confinement and increased travel distance. A stabilisation threshold emerges: beyond approximately 5–7 m depth, all but the finest sands remain trapped. Grain size dependence follows classical settling behaviour, with fine material escaping across all depths and coarse fractions remaining largely immobile. When the depth–grain size limits are compared with North Sea bathymetry, extensive central and northern deep water areas appear suitable for floating concepts.

The study provides a mechanistic basis for predicting when sediment escape ceases, though limitations such as the rigid seabed, simplified chain geometry, and steady-state inflow imply that results represent upper bound mobility estimates rather than full morphodynamic evolution.

Summary

Floating offshore wind turbines rely on mooring chains that interact dynamically with the seabed. As floating platforms move, the cyclic loading produced disturbs the soil, excavates trenches, and may transport sediment out of the trench. These trenches can modify mooring-line geometry, alter anchor loading, and in extreme cases contribute to loss of station keeping.

This thesis investigates the physical conditions under which sediment escape from such trenches ceases. A Computational Fluid Dynamics (CFD) model was developed, coupling a Boussinesq-type incompressible flow solver, an immersed boundary method representing the moving chain, and suspended sediment transport.

Forty simulations were performed across four trench depths (3–9 m), five sediment sizes (0.0625–1 mm), and two representative North Sea flow regimes (0.05 and 0.36 m/s). To efficiently explore this large parameter space, a new Escape Potential Index (EPI) was introduced. EPI was developed to prioritise simulations near the expected transition between escape and no-escape behaviour, thereby avoiding unnecessary simulations of cases that are fully stable. Although the EPI correctly ranks cases by relative mobility, it does not yield a universal stability threshold. A direct comparison with the Rouse number shows that classical suspension theory alone underestimates the potential for escape inside a confined trench, as chain motion can mobilise grains even in regimes where the Rouse number predicts no suspension.

When plotted together, however, the combined Rouse–EPI space produces a clear logarithmic separation curve between escaping and stable configurations. This combined metric resolves why classical theory consistently under predicts sediment mobility in the presence of chain-induced turbulence and suggests that a practical threshold for trench elongation may exist. Further refinement is required to formalise this threshold and test its robustness across different geometries and sediment mixtures.

The results show that trench depth is the dominant control on escape behaviour. In shallow trenches, chain motion strongly couples to the surrounding flow, generating intense suspension even under weak currents. As depth increases, geometric confinement attenuates uplift and increases the travel distance required for escape. A stabilisation threshold emerges: beyond approximately 5–7 m trench depth, all but the finest sediments remain trapped across both sea states. Grain-size behaviour follows classical settling dynamics: fine material escapes at all depths, intermediate sands escape only under storm conditions or shallow confinement, and coarse sands remain largely immobile.

When these depth–grain-size limits are compared with North Sea bathymetry, extensive central and northern deep water areas emerge as suitable for floating concepts. Their combination of flow velocity and medium to coarse sediments naturally resists further trench deepening, reducing the risk of anchor exposure.

The study provides the first quantitative basis for predicting trench stabilisation, but also provides the works limitations: a rigid seabed, simplified chain geometry, suspended sediment only transport, and steady inflow conditions. These imply that the results represent upper bound mobility estimates rather than full morphodynamic evolution. Nonetheless, the framework offers a practical foundation for mooring design assessment, site selection, and future morphodynamic modelling of floating offshore wind systems.

Contents

Preface	i
Abstract	ii
Summary	iii
1 Introduction	1
1.1 Offshore Wind Energy and the Energy Transition	1
1.1.1 Transition Toward Floating Offshore Wind Turbines	1
1.1.2 Floating Platform Types	1
1.1.3 Mooring System Configurations	1
1.2 Problem Definition: Seabed Trenching under Mooring Lines	2
1.3 Research Objective and Research Question	3
1.4 Physical System Overview	4
1.5 Thesis outline	6
2 Background Theory	7
2.1 Mooring Chain Systems and Seabed Interaction	7
2.1.1 Overview of Mooring Configurations	8
2.1.2 Trenching Effects on Anchor Performance	9
2.1.3 Chain–Soil Interaction Mechanisms	10
2.2 In-Field trenches	10
2.3 Trenching in Different Seabed Types	13
2.3.1 Clay	14
2.3.2 Sand	15
2.4 Hydrodynamic Influence on Trenching and Erosion	17
2.4.1 Influence of Bottom Currents	17
2.4.2 Current-Induced Shear and Sediment Mobilisation	18
2.4.3 Suspension and the Rouse Number	18
2.5 Numerical Modelling Approaches for Trench Simulation	20
2.5.1 Two-Dimensional Model	20
2.5.2 Three-Dimensional Model and Current State of the Art	22
2.6 Related Phenomena and Knowledge Gaps	23
2.6.1 Cross-Study Observations and Remaining Gaps	24
3 Research Gap	26
4 Methodology	27
4.1 Research Scope	27
4.1.1 Scope of the Model	27
4.1.2 Parameter Space	27
4.1.3 Assumptions and Limitations	27
4.2 Numerical Background Theory	28
4.2.1 Basics of Computational Fluid Dynamics	28
4.2.2 Finite Volume Method	28
4.2.3 Soil as a Dispersed Phase	29
4.2.4 Pressure–Velocity Coupling Algorithms	29
4.2.5 Immersed Boundary Method: Numerical Concept	30
4.3 Numerical Model Framework	30
4.3.1 Single–Fluid Formulation with Buoyancy Coupling	30
4.3.2 Sediment Transport Equation	30

4.3.3	PIMPLE Coupling and Linear Solvers	31
4.3.4	Domain and Geometry Definition	31
4.4	Simulation Setup and Post-Processing	33
4.4.1	Simulation Configuration	33
4.4.2	Parameter Matrix	33
4.4.3	Data Sampling and Post-Processing	34
4.5	Preliminary Simulations	35
4.5.1	Steady-State Flow Fields.	35
4.5.2	Chain Motion in a Still Fluid.	36
4.5.3	Sediment Response to Flow and Chain Forcing.	36
4.5.4	Sediment Response to Injection Position	36
4.6	Validation and Sensitivity Analysis	36
4.6.1	Numerical Verification	36
4.6.2	Physical Validation	36
4.7	Simulation Strategy and Execution Plan	37
4.7.1	Escape Potential Index	38
4.7.2	Execution Logic	39
5	Results	41
5.1	Qualitative Results: Overview of Preformed Simulations	41
5.1.1	Calm Sea State Results	41
5.1.2	Storm Sea State Results	45
5.1.3	Combined Interpretation of Sea States	47
5.2	Quantitative Results: Metrics and Threshold Identification	48
5.2.1	Depth–grain size thresholds	48
5.2.2	Validation of EPI trends	49
5.2.3	Combined Rouse–EPI separation	50
5.3	Application to North Sea Development Potential	51
6	Discussion	54
6.1	Simulation Evaluation	54
6.1.1	Interpretation of Trench Behaviour	54
6.1.2	Evaluation of Predictive Metrics	55
6.2	Influence of Model Assumptions and Limitations	56
6.3	Comparison with Previous Studies	57
6.4	Implications for Offshore Mooring and Site Selection	58
7	Conclusion	59
7.1	Research Questions	59
7.2	Future Work and Recommendations	61
7.2.1	Model Development	61
7.2.2	Sediment Behaviour	61
7.2.3	Environmental Forcing	62
7.2.4	Engineering Application and Recommendations	62
7.2.5	Implementation Outlook	62
	References	63
	A Full Simulation Results	67
	Appendix A — Full Simulation Results	67
A.1	Flow-Field Results	67
A.1.1	Steady-State Flow Fields	67
A.1.2	Chain-Induced Flow Fields	70
A.2	Sediment Transport Results	72
A.2.1	Flow-Only Sediment Transport	72
A.2.2	Simulation Prioritisation Based on Rouse Number and EPI	76
A.2.3	Escape Evaluation Method	76
A.2.4	Edge-Case Strategy and Execution Order	77

A.2.5	Storm Sea State Case Results	79
A.2.6	Normal Sea State Case Results	82
A.2.7	Cases Observation and quantification	86
B	IbBousSoilFoam	88
B.1	Overview of Modifications	88
B.2	Replacement of Temperature by Sediment Concentration	89
B.2.1	Original thermal formulation	89
B.2.2	Modified sediment formulation	89
B.3	Summary of Solver Modifications	89
B.4	Buoyancy and Sediment Coupling	89
B.5	Settling Velocity and Slip–Flux Model	90
B.6	Immersed Boundary Implementation	91
B.7	Solver Flowchart	92
C	Numerical Implementation	93
C.1	Mesh Geometry Across Trench Depths	93
C.2	Discretisation Schemes	96
C.3	Linear Solvers and PIMPLE Configuration	97
C.4	Time Step and Courant Number Control	100
C.5	Post-Processing Scripts	101
C.6	Numerical Verification	102
C.6.1	Grid Refinement Study	102
C.6.2	Time Step Refinement Study	103
C.6.3	Turbulence Model Sensitivity	103
C.7	Comparison to DriftFlux-Type Two–Phase Solvers	103

List of Figures

1.1	Overview of offshore wind development and bathymetry in the North Sea. Shallow regions are nearly saturated with fixed-bottom wind farms, motivating expansion into deeper areas suitable for floating offshore wind. Taken from [3]	2
1.2	Overview of floating wind turbine platform types and corresponding mooring system configurations. The combination of platform concept and mooring design determines overall stability, cost, and seabed interaction.	3
1.3	Schematic overview of the physical system and resulting trench geometry. (a) Floating platform, mooring line, and anchor configuration illustrating cyclic chain motion and seabed interaction. (b) Detailed view of the trench region showing the main geometric parameters used in this study.	5
2.1	Typical configurations of catenary and taut mooring systems. Catenary moorings rely on heavy chain segments lying on the seabed, whereas taut moorings use synthetic ropes under near-constant tension. Semi-taut systems combine both behaviours by reducing chain length and steepening the line angle near the seabed. Based on [23].	8
2.2	Load vectors (in metric tonnes) at the anchor padeye for different floating offshore wind mooring designs. Catenary systems transmit primarily horizontal loads, while taut and tension-leg systems impose larger vertical components. Semi-taut moorings lie in between, combining moderate vertical and horizontal loading. Adapted from [4].	9
2.3	Results from Feng [9] showing that padeye depth has little influence on capacity, indicating that trenching severity is governed primarily by soil strength and seabed conditions.	10
2.4	Change in turbulence intensity for surge, sway, and heave motion at inflow velocities of 0.1–0.25 m/s. Heave motion produces the strongest amplification, with turbulence intensities up to 6.1 times higher than the baseline flow [12].	11
2.5	Top view of a trench width found in-situ by Bhattacharjee [2].	12
2.6	Longitudinal and transversal trench profiles in situ [6].	12
2.7	Stages of trench evolution in cohesive seabed clay, adapted from Rui et al. [30].	14
2.8	Axial effective width parameter for chain–sand interaction: interpretation of the resistance zone width ($E_{t,p} = 10.34$) for quartz sand [24].	15
2.9	Chain–soil interaction in sand under cyclic motion showing both side and plan views, adapted from [20].	16
2.10	Local turbulence near a moving mooring chain produces ripples and sand waves that mark the onset of trench formation [12].	17
2.11	Two-dimensional model predictions for trench depth compared with centrifuge test data (after Rui, 2023).	21
2.12	Normalised trench dimensions—(a) depth, (b) length, and (c) anchor–trench distance—computed as functions of soil strength ratio η_{su} and tension ratio η_T . As η_{su} decreases and η_T increases, trenches deepen, lengthen, and advance toward the anchor padeye, indicating a progressive loss of bearing resistance in weak soils.	22
2.13	Mechanisms governing trench formation in cohesive clays based on Rui et al. [29].	23
2.14	Typical trench geometries for steel catenary risers, showing bell- and ladle-shaped profiles (after Yu, 2024)[42].	23
2.15	Measured scour profiles for vibrating risers under different flow conditions (Li, 2017).	24
4.1	Overview of the computational domain and example case configuration used in the simulations.	32
4.2	Sediment transport regimes based on Rouse number ranges [22]. The fine particles switch from partial to full suspension when entering the storm sea state.	37

4.3	Escape Potential Index (EPI) distribution for all simulated configurations. Each grain size (d_{50}) shares one marker shape; lighter shades represent calm flow ($U = 0.05$ m/s), darker shades represent storm flow ($U = 0.36$ m/s). Depth increases from right to left.	39
4.4	Distribution of Escape Potential Index (EPI) values by trench depth and sea state (reversed X-axis). Higher EPI indicates greater escape potential.	39
5.1	Fine-sand sequence under calm flow ($d_{50} = 0.0625$ mm, $z = -3$ m): sediment escapes during the first upward chain motion.	42
5.2	Sequence of Case 4 soil movement: the soil escape happens due to downward motion.	43
5.3	Comparison of Cases 5 (top) and 6 (bottom) after the downward chain motion. The only difference is trench depth (-3 m vs. -5 m), which strongly affects the volume and height of soil mobilised. The shallow trench experiences much greater suspension because the chain occupies a larger fraction of the trench volume.	44
5.4	Representative storm case ($d_{50} = 0.0625$ mm, $z = -9$ m). Soil escapes vertically along the trench centreline. Red regions indicate concentrations above 10^{-5} . Current is from left to right	45
5.5	Outlet escape for a medium sand storm case ($d_{50} = 0.25$ mm, $z = -3$ m). Chain-induced motion couples with the background flow to eject sediment through the downstream outlet.	46
5.6	Escape rate shown for the storm cases. These lines define a stability boundary in (z, d_{50}) -space: trenches deeper than $5-7$ m retain all but the very finest material.	49
5.7	Escape ratio versus EPI for the storm cases, coloured by grain size and marked by trench depth. The plot shows that while higher EPI values correlate with larger escape ratios, escape does not occur consistently for a fixed EPI threshold.	50
5.8	Combined Rouse-EPI distribution of all cases on a log scale for y-axis. Green symbols indicate escape and red symbols indicate no escape. The yellow line marks the empirical transition band that separates most escape cases from non-escape cases.	51
5.9	Comparison of bathymetry maps for the North Sea. The black contour indicates the deep water region where floating foundations become necessary. Taken and altered from [3]	52
5.10	Median grain size (d_{50}) distribution. Coarser regions align with naturally stable trenches. Darkened area is not suitable for floating offshore wind due to anchor mooring trenches. Taken and altered from [3]	53
5.11	Comparison of projected Offshore wind projects planned up to 2035. Black contour marks areas suitable for floating wind parks without intervention. Taken and altered from [3]	53
6.1	EPI separation line with the dotted line showing all the depths of $z = -3$ m. Here the escape is partly due to the relative low travelling distance between the injected soil and the starting position of the chain resulting in a different escape mechanism than other depths.	56
A.1	Flow field visualizations at $z = -5$ m: (a) Calm sea state $t = 200$ and (b) storm sea state $t = 1200$	67
A.2	Stream tracer plots showing vertical flow velocity (colour) and flow direction (streamlines) at increasing trench depths for the storm seastate.	68
A.3	Stream tracer plots under calm conditions, showing vertical velocity and flow direction at increasing trench depths.	69
A.4	Time evolution of stream tracer plots under storm conditions at various time steps.	71
A.5	Time evolution of stream tracer plots under calm conditions from $t = 0$ to $t = 310$ s.	73
A.6	Final simulation results at $z = -9$ m under calm and storm conditions. Top row: only buoyancy soil concentration. Bottom row: vertical flow field, red is upwards and blue is downwards flow.	75
A.7	Edge-case logic used to evaluate sediment escape thresholds in the simulation campaign.	77
A.8	Final time step for Case 24. Soil is visibly concentrated near the top boundary, indicating significant vertical escape.	79
A.10	Case 33, soil escapes the trench via outlet flow.	80
A.9	Case 37, time step 48. Soil visibly exits through the outlet.	80
A.11	Case 28, final time step. Soil accumulates just outside the trench.	81

A.12 Case 17, soil remains on the trench bottom without suspension.	83
A.13 Case 13, soil temporarily on top of the chain during the first upward motion.	83
A.14 Case 5, soil escapes during the first upward chain motion.	84
A.15 Sequence of Case 4 soil movement: (a) initial upward motion, (b) downward chain motion, and (c) second upward motion causing soil escape.	85
B.1 Operational flowchart of the custom solver IbBousSoilFoam.	92
C.1 Annotated vertex map showing the trench vertices (A–D), the widening seabed vertices (E–H) and the vertices that make up the inlet the outlet and the top of the mesh (I–P). The second letter denotes the same point but at $y = 0$ instead of $y = 1$. These points define the mesh geometry consistently across all four trench depths.	94
C.2 Mesh for the $z = -7$ m trench geometry shown without the immersed chain. The fixed trench footprint and depth-dependent domain widening are apparent.	95
C.3 Same mesh as Fig. C.2, now including the immersed chain. The chain is handled by the immersed boundary method and refined dynamically during simulation.	96
C.4 Local refinement near the mooring chain. Cells within the IB-defined refinement band are refined by up to two levels, improving near-body resolution. It clearly shows that refinement is dependant on the original resolution.	96

Introduction

1.1. Offshore Wind Energy and the Energy Transition

Offshore wind energy plays a central role in Europe's transition toward a sustainable energy system. As global energy demand rises and carbon emissions must decline, the deployment of large-scale offshore wind farms provides a reliable path to expand renewable generation. Europe's offshore wind capacity surpassed 30 GW in 2024 and continues to grow rapidly, supported by ambitious national targets and technological advances that allow installation in increasingly deeper waters.

1.1.1. Transition Toward Floating Offshore Wind Turbines

The North Sea has long been the centerpiece of Europe's offshore energy and maritime activity. Its shallow continental shelf has made it an ideal location for fixed-bottom offshore wind farms, oil and gas extraction, while combined with dense shipping routes. Over the past decades, large portions of the southern and central North Sea have been increasingly occupied, or scheduled to be occupied, by offshore wind developments, as shown in Figure 1.1a. These shallow areas, typically less than 60 m deep, are now nearing spatial saturation. The limited availability of such sites pushes the next phase of offshore wind expansion toward deeper waters in the northern North Sea and Norwegian Sea, which can be seen in Figure 1.1b.

Figure 1.1b shows the bathymetry of the North Sea, with the red line marking the 60 m depth contour that separates shallow and deep regions. Beyond this boundary, floating offshore wind turbines (FOWTs) become necessary. Expanding into these deeper regions increases the potential construction area for offshore wind by more than 100%, significantly extending Europe's renewable energy potential. This transition marks a shift from conventional fixed-bottom systems to floating platforms, which are anchored to the seabed through mooring lines connected to anchors.

1.1.2. Floating Platform Types

Floating offshore wind turbines are typically mounted on platforms that provide stability through buoyancy and tension. The main platform types include spar buoys, semi submersibles, barge designs, and tension leg platforms (TLPs) [23], as shown in Figure 1.2a. Each concept has advantages depending on water depth and site conditions. Semi submersible and spar platforms currently dominate commercial development because they balance stability with manageable installation costs. Examples include projects such as Hywind Tampen in Norway and WindFloat Atlantic in Portugal, which demonstrate full scale operation at depths of 100 to 300 m. These platforms rely on mooring systems to maintain position under wind, wave, and current loading.

1.1.3. Mooring System Configurations

The mooring system provides the restoring force that limits platform motion. Three main configurations are used in practice: catenary, semi taut, and taut, see Figure 1.2b. Catenary systems, which is the conventional system, consist of long, heavy chains that rest partly on the seabed, providing stability

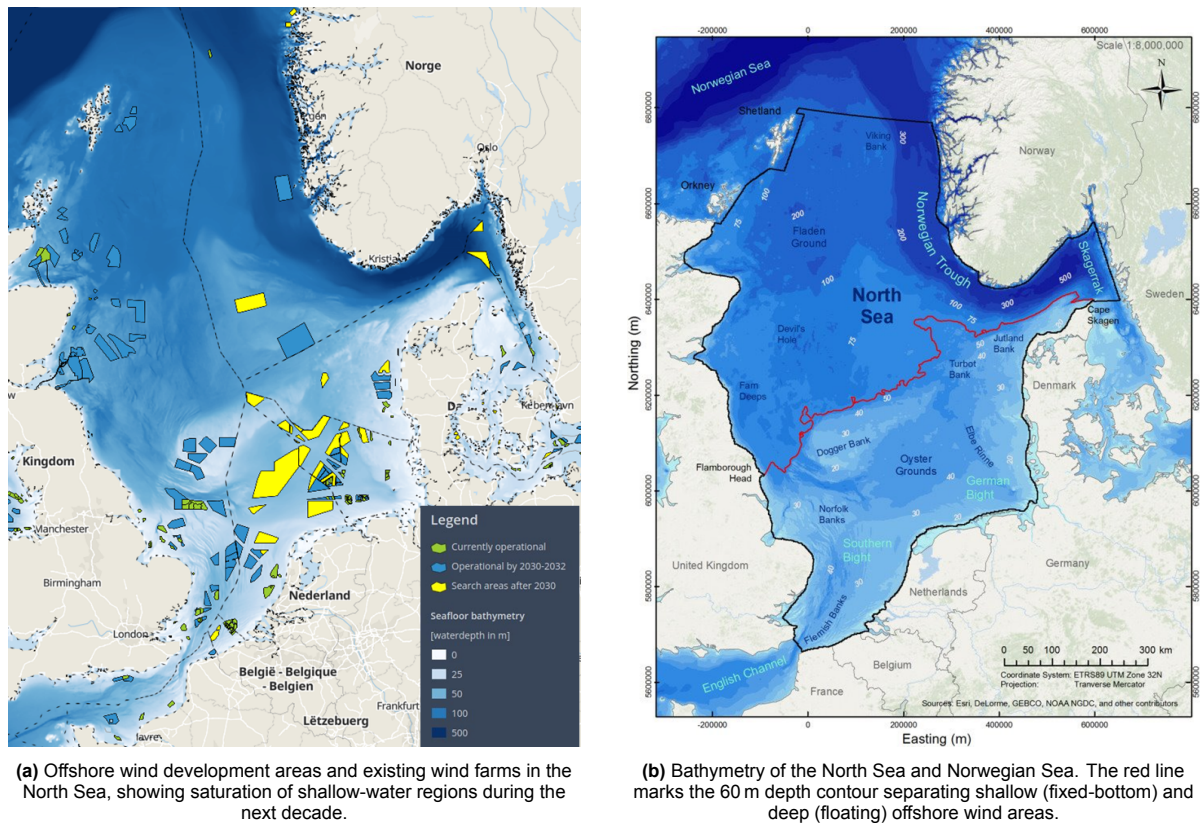


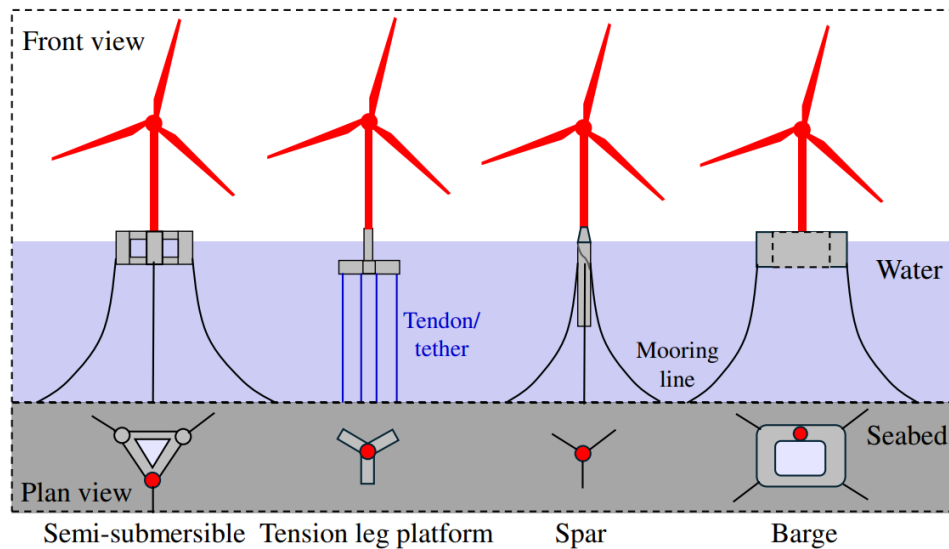
Figure 1.1: Overview of offshore wind development and bathymetry in the North Sea. Shallow regions are nearly saturated with fixed-bottom wind farms, motivating expansion into deeper areas suitable for floating offshore wind. Taken from [3]

through their horizontal weight component. They are simple and robust but require extensive seabed area and large amounts of steel chain, which increases cost and environmental footprint. Semi taut systems use shorter mooring lines at steeper angles and often combine steel chain with synthetic rope, reducing material demand and the overall footprint on the seabed [23]. Taut systems rely mainly on tensioned synthetic lines or tendons, minimizing lateral motion but increasing vertical load on the anchors. The semi taut configuration is particularly attractive for floating wind farms at intermediate depths between 80 and 200 m because it offers a balance between cost, stability, and anchor loading.

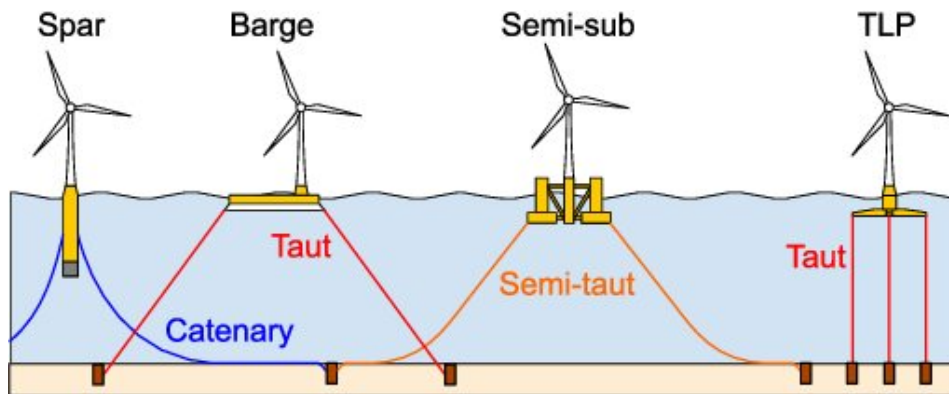
A comparative cost analysis by Cerfontaine et al. [4] reported that replacing a conventional catenary design with a nylon semi taut configuration can reduce mooring system capital expenditure by approximately 50 % (142 \$/kW), while total project capital expenditure decreases by around 4 %. Although installation duration increases slightly due to more complex tensioning procedures, the overall reduction in material and footprint makes semi taut mooring systems economically favourable for large floating wind farms at depths of 80 m and beyond.

1.2. Problem Definition: Seabed Trenching under Mooring Lines

While semi taut systems reduce cost and footprint, their steeper angles and dynamic motions cause more concentrated contact between the mooring line and the seabed, increasing the likelihood of local trench formation. The integrity of these mooring systems relies not only on their mechanical design but also on the stability of the surrounding seabed. Interactions between mooring lines, hydrodynamic forces, and sediment beds can reshape the seabed over time, leading to the formation of trenches. Field observations, such as those by Bhattacharjee [2], have reported trench formation near semi taut mooring lines in the Gulf of Guinea, showing that this process can significantly reduce anchor capacity [9]. During cyclic motion, each contact of the chain at the Touchdown Point, which is the location on the seabed where the mooring line or chain first comes into contact with the soil, disturbs the soil, loosening particles that are subsequently mobilized by near bed currents and vortices. Over time,



(a) Typical platform types for floating offshore wind turbines, including spar, semi submersible, barge, and tension leg platforms. Each concept achieves stability through a different combination of buoyancy and tension. Taken from [24]



(b) Typical mooring configurations: catenary, semi taut, and taut. The semi taut system reduces chain length and seabed footprint while maintaining sufficient restoring stiffness for floating wind applications. Taken from [5]

Figure 1.2: Overview of floating wind turbine platform types and corresponding mooring system configurations. The combination of platform concept and mooring design determines overall stability, cost, and seabed interaction.

this coupling between hydrodynamic shear and line motion excavates the seabed until erosion and deposition reach equilibrium. However, the mechanisms governing this stabilization process and the conditions under which trench growth ceases remain poorly understood [32, 36, 4, 24].

This knowledge gap limits the ability to predict long term seabed evolution and anchor performance in floating wind applications, where semi taut configurations are increasingly favoured for their reduced material requirements and smaller spatial footprint. Addressing this gap is essential for designing safe and cost efficient mooring systems that can operate reliably over decades.

1.3. Research Objective and Research Question

The objective of this work is to determine the conditions under which sediment motion within a seabed trench ceases and the system reaches a stable configuration. This leads to the following research question:

Under what conditions does sediment escape from a seabed trench cease, and how do trench geometry, sediment properties, and current velocity together establish this stabilization threshold?

To support the systematic answering of this question, the following sub-questions are formulated. To-

gether, they provide the scientific basis required to resolve the main research question:

- How does trench geometry influence internal vortex formation and sediment lifting potential?
- How sensitive is sediment escape to variations in current velocity near the seabed?
- How do different soil properties affect resuspension thresholds?
- How does turbulence enhancement caused by a mooring chain affect the onset of sediment resuspension?
- What are the critical stabilization thresholds for trench geometries under steady seabed flow, with and without chain dynamics?

Addressing these questions requires a numerical framework capable of simultaneously resolving the coupled interaction between flow turbulence, sediment transport, and the motion of the mooring chain. Since these processes influence one another dynamically, a Computational Fluid Dynamics (CFD) approach is necessary to capture the feedback between hydrodynamics and sediment response. Among available CFD platforms, *OpenFOAM* provides the required flexibility to modify governing equations, implement custom moving boundaries, and model multiphase flow within an open-source environment. It therefore forms the foundation for this research.

A transversal two dimensional CFD model is proposed to resolve turbulent flow, sediment resuspension, transport, and redeposition around an oscillating mooring chain. The framework is different from earlier longitudinal simulations, such as Rui made [25], by including the moving chain as a dynamic boundary that generates turbulence driven scour consistent with experimental observations as well as having sediment modelled. The sediment is treated as a dispersed phase within the carrier fluid, allowing a fully coupled representation of flow–sediment interaction. The model is implemented in a custom immersed boundary solver, *IbBousSoilFoam*, built within the *OpenFOAM* framework. High resolution simulations are conducted across a range of trench depths (3–9 m), sediment properties (0.0625–1 mm), and flow velocities (0.05 and 0.36 m/s) to determine the conditions under which sediment resuspension ceases and a stable trench geometry emerges. The resulting data yield quantitative stabilization curves for seabed trenches under mooring loads and improve predictive capability for floating wind design.

The findings are relevant for the safe and cost effective design of floating offshore wind systems. Improved understanding of trench formation and stabilization supports optimized mooring and anchor design, reducing conservative over dimensioning while minimizing seabed disturbance. By enhancing insight into these processes, this research contributes to the sustainable and reliable expansion of floating offshore wind energy.

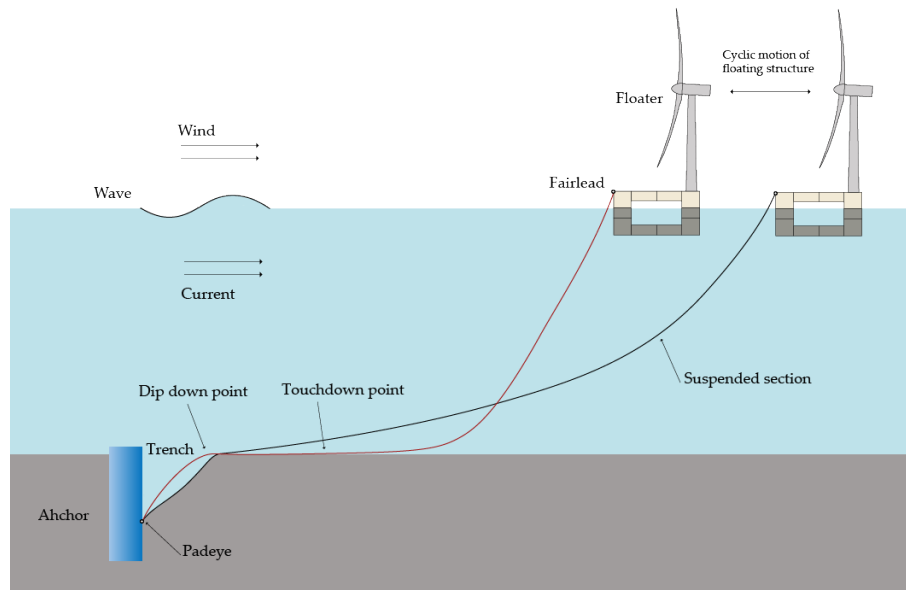
1.4. Physical System Overview

Trench formation beneath mooring lines is a gradual process driven by several physical mechanisms that act together over time. None of these mechanisms alone is sufficient to form a trench; only their continuous interaction can produce a stable seabed trench. All actors are shown in Figure 1.3 and explained below.

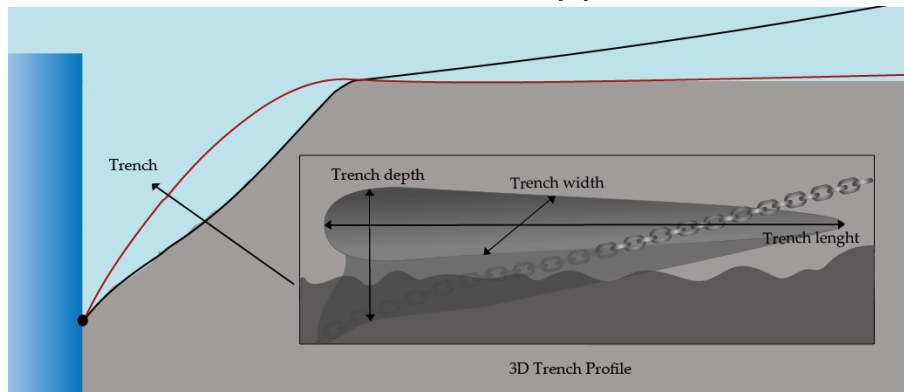
The sequence begins with the floating structure, which is continuously exposed to wind, waves, and current. These environmental loads cause motions in surge, sway, and heave. As the floater moves, its mooring lines experience variations in tension and angle. These variations are transferred to the seabed, resulting in time varying loads rather than static ones.

Next, the mooring line converts the floater motion into local forces on the seabed. At the *touchdown point*, where the chain first contacts the soil, the line repeatedly lifts off and settles again. Each contact cycle creates local stresses and shear, disturbing the upper layer of sediment. Through repeated loading, the soil gradually loses strength and a shallow trench begins to form.

The response of the seabed depends on its composition and mechanical behaviour, which is explained in chapter 2. Because the floater motion acts on the scale of seconds while soil consolidation takes hours to days, deformation accumulates gradually even when external forcing changes rapidly. Short storm events can therefore have lasting morphological effects through the cumulative disturbance of sediment and pore pressure.



(a) Overview of the physical system showing the floating platform, mooring line, and trench formation near the anchor. Cyclic floater motion, transferred through the mooring chain, initiates seabed deformation leading to trench formation. Based on [25].



(b) Zoomed view of the trench region near the anchor, illustrating the geometric parameters that define trench shape: depth, width, and length. The inset highlights the three dimensional trench profile caused by repeated contact of the mooring chain at the touchdown zone.

Figure 1.3: Schematic overview of the physical system and resulting trench geometry. (a) Floating platform, mooring line, and anchor configuration illustrating cyclic chain motion and seabed interaction. (b) Detailed view of the trench region showing the main geometric parameters used in this study.

At the same time, the moving chain interacts with the surrounding flow. Laboratory and numerical studies by Gao [12] and Rui [23] show that the oscillating chain generates turbulence and small vortices near the seabed. These vortical structures increase the effective shear stress on the soil surface and may momentarily raise pore pressure, enhancing sediment mobilization. The mechanical contact between chain and soil is thus tightly coupled to the hydrodynamic effects created by the chain motion.

A second location along the chain also plays a role: the *dip down point*, where the chain begins to descend into the seabed on its way to the anchor. Under typical long-chain catenary systems, this point is relatively static and does not produce significant seabed disturbance. However, in floating offshore wind systems the mooring lines are shorter and operate in a semi-taut configuration. This reduces the horizontal footprint of the catenary, bringing the touchdown point and the dip down point close together. When these points nearly coincide, the cyclic motions that normally occur only at touchdown propagate into the dip down region. Field studies and earlier numerical work have shown that it is this combined movement of a partially buried chain that produces the large and deep trenches observed in practice.

As the trench deepens, the changing geometry alters both the flow and the mechanical contact pattern.

Recirculating zones develop inside the trench, while stronger shear occurs along its shoulders. These local flow variations determine where sediment is eroded and where it is redeposited. When the rates of erosion and deposition reach equilibrium, the trench stabilizes and stops deepening.

In summary, trenching results from the combined action of four elements: the floating structure provides the motion, the mooring line transfers the load, the seabed governs deformation and resistance, and the surrounding flow redistributes sediment. Their continuous feedback explains both the gradual development and eventual stabilization of seabed trenches. The understanding presented in this chapter forms the physical foundation for the next part of this thesis, which describes the theoretical background and governing equations used to represent fluid, sediment, and their interaction in the numerical model.

1.5. Thesis outline

The remainder of this thesis is structured as follows. Chapter 2 reviews necessary background information, existing earlier research and modelling approaches. Chapter 3 identifies remaining gaps. Chapter 4 presents the numerical framework and simulation setup. The following two chapters, chapter 5 and chapter 6, discuss the results, interpret their implications for choosing a building project. Chapter 7 concludes this thesis and gives recommendations for future research.

2

Background Theory

This chapter reviews existing knowledge on seabed trench formation beneath floating offshore wind turbine (FOWT) mooring systems. It connects the mechanical, hydrodynamic, and geotechnical processes that drive trench initiation and evolution, before evaluating previous modelling approaches. The goal is to identify the knowledge gaps that motivate the numerical framework developed in later chapters.

2.1. Mooring Chain Systems and Seabed Interaction

Floating offshore wind turbines are kept in position by mooring systems that transfer environmental loads from the floater to the seabed. Each mooring line consists of a suspended section between the floater and the touchdown point (TDP) and a seabed-contact segment that extends to the anchor. Cyclic motion of the floater causes repeated lift-off and re-contact near the TDP, disturbing the soil and initiating trench formation.

This dynamic interaction, referred to as mooring line–seabed interaction (MLSI), is a key consideration in the geotechnical design of floating wind systems. Rui et al. [24] define MLSI as the coupled process through which hydrodynamic and mechanical loads are transmitted from the floating platform through the mooring line into the seabed. They show that this coupling affects not only trenching but also mooring stiffness, floater response, and anchor performance, underscoring the need for integrated analysis that combines hydrodynamics and soil mechanics.

Mooring layouts and anchor types are selected based on soil strength and water depth. Common anchors include suction caissons, drag-embedment anchors, and driven piles. Although their geometry differs, all are vulnerable to trench formation when the mooring line interacts dynamically with the seabed [46]. Field evidence summarised by Rui et al. [24] confirms that trenches are commonly found in front of suction caissons and pile anchors, especially when padeyes are positioned below the mudline. Reported trench dimensions range from 1 to 12 m in depth, 80–100 m in length, and up to 13 m in width. These deformations occur independently of anchor geometry and are primarily controlled by seabed strength and cyclic mooring motion. Numerical analyses have shown that slope-shaped trenches can reduce anchor pull-out capacity by approximately 5–9 %, with effects diminishing beyond five anchor diameters from the padeye [45]. When trenching coincides with local scour, capacity losses become even more pronounced, emphasising the need to assess combined seabed processes.

The way loads are transferred to the seabed depends on mooring configuration and stiffness, which determine the intensity of MLSI. Catenary systems allow a portion of the chain to rest on the seabed, dissipating energy through friction and horizontal movement. Semi-taut systems, by contrast, use shorter chains at steeper angles, transmitting higher dynamic loads to the TDP [4]. The mechanical sensitivity of this configuration is evident from numerical studies showing that shortening the line by only 1 % can increase failure probability by over 30 %, as this can change the line from a semi-taut to a taut mooring line [15]. More advanced designs attempt to mitigate these effects through variable-stiffness or multi-segment chains that redistribute loads [41, 30], or through shared-mooring layouts that reduce

the number of anchors and spread forces more evenly [18, 33].

Rui et al. [24] highlight that accurate prediction of trench development requires coupling hydrodynamic, structural, and geotechnical effects. Traditional design models often simplify this by prescribing static seabed boundaries or neglecting local sediment transport, which can lead to underestimation of trench growth and anchor capacity loss. This motivates the present study's CFD-based approach, which resolves the coupled flow–sediment dynamics governing trench stabilisation under mooring loads.

2.1.1. Overview of Mooring Configurations

Mooring systems are generally categorised as catenary, semi-taut, or taut, depending on how the line geometry balances weight and tension (Figure 2.1). Their configuration determines the platform's motion response, anchor loading, and degree of seabed contact.

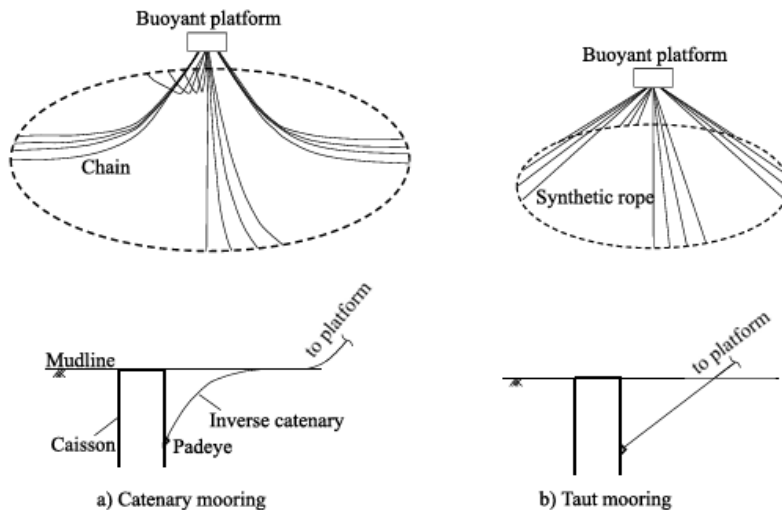


Figure 2.1: Typical configurations of catenary and taut mooring systems. Catenary moorings rely on heavy chain segments lying on the seabed, whereas taut moorings use synthetic ropes under near-constant tension. Semi-taut systems combine both behaviours by reducing chain length and steepening the line angle near the seabed. Based on [23].

In a catenary system, a large portion of the chain rests on the seabed, absorbing motion mainly through reconfiguration of its curved shape rather than stretching. The anchor padeye therefore experiences predominantly horizontal loads, while vertical forces remain limited. Although this layout provides excellent damping and robustness, it requires large amounts of heavy chain and occupies significant seabed area.

Taut systems, in contrast, employ synthetic or composite lines that remain under constant tension. The steeper inclination of these lines results in smaller platform excursions but increases vertical loads on the anchor, demanding stronger foundations and higher soil capacity. These systems are efficient in deep water but less forgiving to cyclic motion and seabed softening.

The semi-taut configuration offers a compromise between both extremes. It typically uses a shorter chain segment near the seabed and a synthetic rope above to reduce total weight. As chain length decreases, the horizontal distance between the dip-down point (where the line curves downward) and the touchdown point (where it first contacts the seabed) becomes smaller, often nearly coinciding. Rui et al. [24] note that this near-overlap concentrates cyclic contact and soil loading in a narrow region, making semi-taut systems more prone to trench formation. These systems are typically applied at intermediate water depths (80–200 m), where they balance cost and dynamic stiffness.

The differences between these systems are also reflected in the load orientation at the anchor. Figure 2.2 shows that catenary lines exert mainly horizontal forces, while taut and tension-leg systems produce steeper, more vertical loading. Semi-taut moorings fall between these extremes, combining moderate vertical components with a reduced horizontal footprint. The larger vertical load components in taut and semi-taut designs intensify seabed shear and contribute to trench initiation near the padeye.

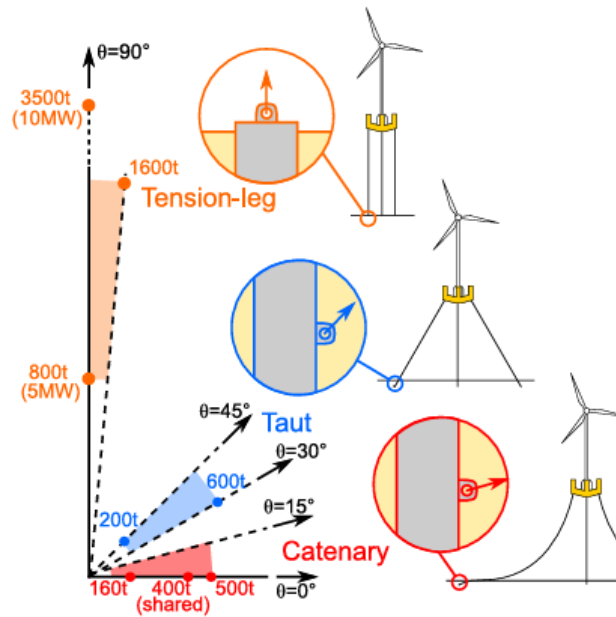


Figure 2.2: Load vectors (in metric tonnes) at the anchor padeye for different floating offshore wind mooring designs. Catenary systems transmit primarily horizontal loads, while taut and tension-leg systems impose larger vertical components. Semi-taut moorings lie in between, combining moderate vertical and horizontal loading. Adapted from [4].

Selecting an appropriate configuration therefore involves balancing hydrodynamic stability, mooring stiffness, and seabed interaction. As water depths increase, the shift from catenary to semi-taut or taut layouts reduces material demand but introduces greater geotechnical complexity.

2.1.2. Trenching Effects on Anchor Performance

Trenching has been observed in front of suction and pile anchors in multiple field and laboratory studies, yet it is not tied to anchor geometry. The underlying cause is cyclic interaction between the moving chain and the seabed, which progressively removes material near the padeye [37, 46]. Any configuration with an embedded padeye is therefore prone to trenching when exposed to long-term dynamic loading.

Feng [9] quantified the impact of trenching on suction caisson capacity. Vertical resistance decreased by roughly 10 % when suction at the caisson–soil interface was maintained and by much more when suction was lost, as trench width increased. Horizontal capacity was reduced by 40 % with suction and up to 70 % without suction when the trench width equalled the caisson diameter ($w/D = 1$). Inclined capacity also fell as the load angle decreased, especially for semi-taut systems where the mooring angle is below 60° . These reductions are mainly due to loss of shaft friction and changes in soil failure mode.

Follow-up work by Sassi et al. [32] demonstrated that once a trench extends to the anchor pile, system capacity can decrease by at least 10%. These results agree with Feng et al. [9], who found capacity losses up to 70% in extreme cases where trench width equals the anchor diameter. As the seabed erodes, the line angle steepens and axial load at the padeye rises, increasing anchor tension even though forces at the floater remain nearly constant [39, 40]. The combined influence of erosion, soil yielding, and geometric feedback explains how trenching progresses toward a stable configuration while still compromising long-term anchor reliability.

Figure 2.3 illustrates that changing the padeye location offers limited benefit. Moving the connection upward reduces trench depth but simultaneously promotes rotational failure, leaving the overall capacity nearly unchanged. Restoring the design capacity would require larger caisson dimensions, which is economically unfavourable. From a design perspective, catenary moorings distribute load more horizontally, while semi-taut and taut layouts focus forces near the padeye, accelerating trench growth. These findings confirm that trenching is a coupled soil–structure problem that must be addressed in

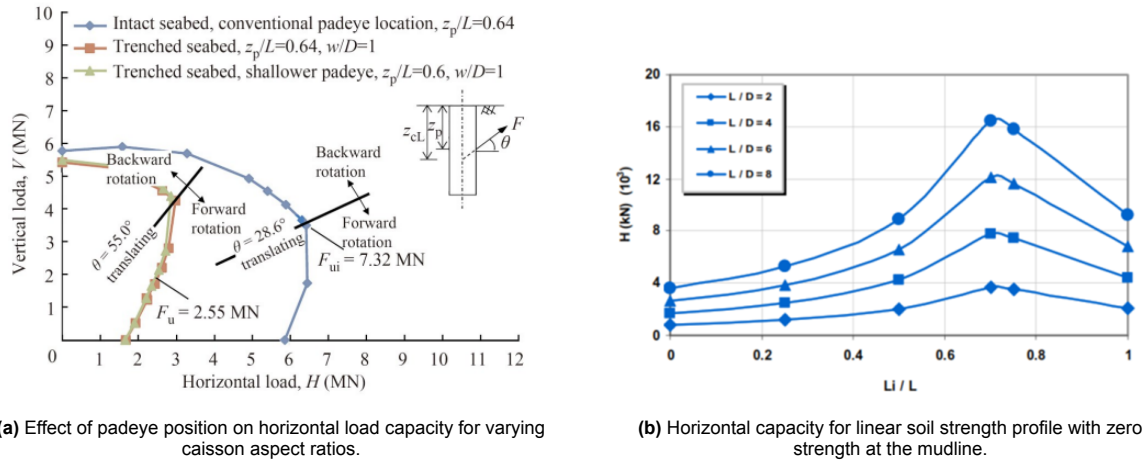


Figure 2.3: Results from Feng [9] showing that padeye depth has little influence on capacity, indicating that trenching severity is governed primarily by soil strength and seabed conditions.

mooring design.

2.1.3. Chain–Soil Interaction Mechanisms

Trench evolution is strongly influenced by the local interaction between the mooring chain and the seabed, where cyclic contact and hydrodynamic effects act simultaneously. Rui et al. [24] describe this process as a continuous feedback between mechanical penetration, soil remoulding, and near-bed flow acceleration that progressively reshapes the surface layer.

In centrifuge tests with calcareous sand, Frankenmolen et al. [11] observed that the friction coefficient of the embedded chain section was initially lower than that of the exposed section but increased with successive loading cycles. This cyclic hardening behaviour results from gradual soil densification and surface roughening, which cause the chain to embed more firmly over time. The repeated contact created shallow depressions that eventually stabilised into permanent trenches.

Shen et al. [34] extended these insights through finite-element simulations in both clay and sand. They showed that cyclic loading drives a progressive “dig-in” process, where the chain penetrates deeper with each motion cycle and the mean line tension decreases as resistance redistributes along the embedded portion. This alters the stress field near the seabed and promotes local turbulence, linking mechanical and hydrodynamic influences on sediment mobilisation. This is explained in more detail in subsection 2.3.2.

The role of turbulence was investigated experimentally by Gao et al. [12], who found that chain motion amplifies near-bed turbulence intensity by more than six times, depending on motion mode and flow velocity. The effect is strongest for vertical heave motion, which generates vortices that lift sediment from the trench bed and enhance local scour. These findings highlight that trench development cannot be explained solely by soil deformation: it arises from the coupled action of cyclic loading, sediment disturbance, and turbulence generated by the moving chain.

2.2. In-Field trenches

Since 2014, several detailed offshore investigations have confirmed the occurrence of seabed trenches around mooring systems, all located in soft, normally consolidated clay. The three best-documented cases; the Serpentina FPSO, the AH001 FPSO, and the multiple OLTs nearby the Serpina, they span water depths from 140 m to over 1,300 m and represent the benchmark observations based on many experiments and numerical models.

Case 1: Serpentina FPSO, Gulf of Guinea [2] At a water depth of approximately 475 m, the Serpentina FPSO was moored using nine suction piles in very soft, normally consolidated clay typical of the Gulf of Guinea. The soil exhibited low undrained shear strength ($s_u < 15$ kPa near the mudline) and

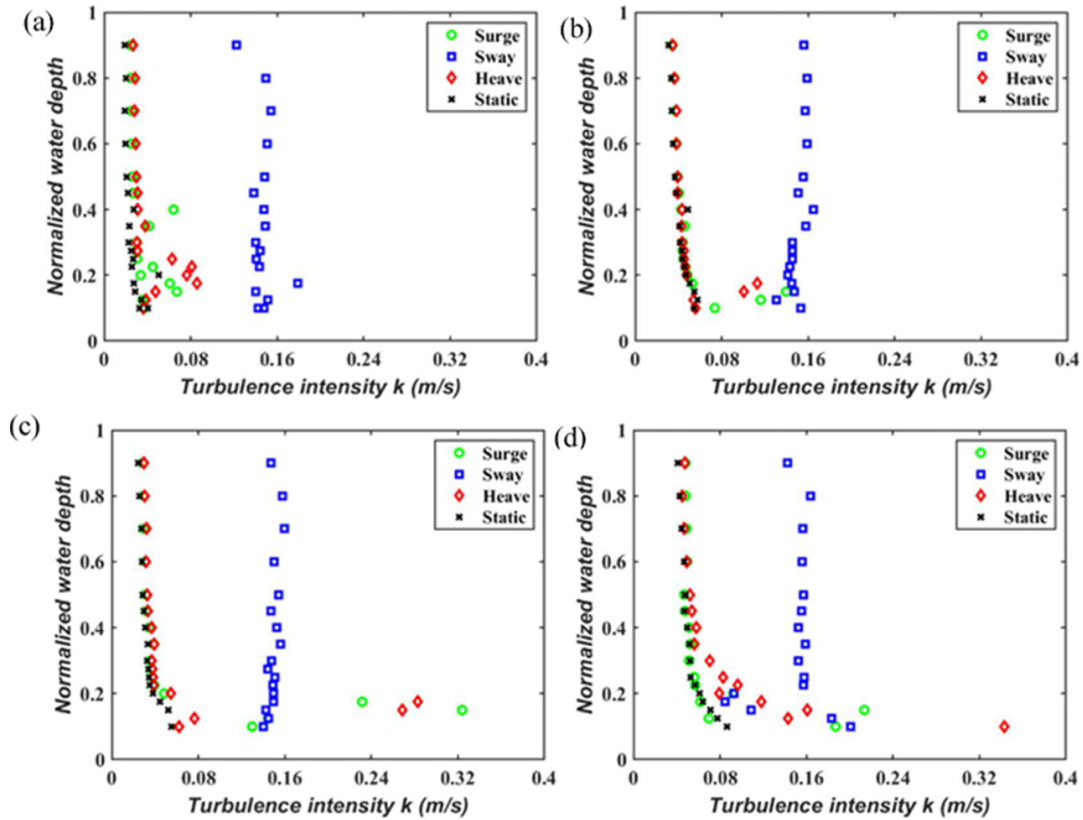


Figure 2.4: Change in turbulence intensity for surge, sway, and heave motion at inflow velocities of 0.1–0.25 m/s. Heave motion produces the strongest amplification, with turbulence intensities up to 6.1 times higher than the baseline flow [12].

a strength gradient of roughly 1.3–1.5 kPa/m, combined with high water content and low permeability. Figure 2.5 and Figure 2.6 show how during routine ROV surveys, nine distinct trenches were discovered around the touchdown areas look like. Trench depths ranged from 4–7 m, lengths from 25–40 m, and widths from 4–10 m. The trenches formed within months of installation due to large-amplitude chain oscillations during swell conditions. Cyclic loading caused excess pore-pressure accumulation, progressive remoulding, and local soil loss, reducing the suction piles' bearing capacity and prompting full mooring replacement within six months. This case highlighted how low-strength, high-plasticity clays are highly susceptible to rapid trench development when exposed to repeated chain motion.

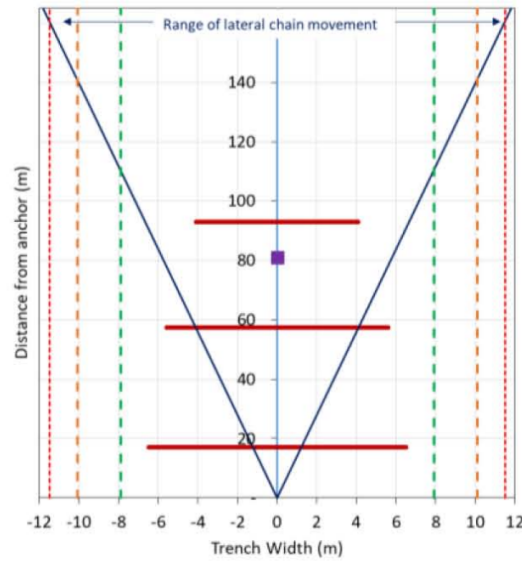


Figure 2.5: Top view of a trench width found in-situ by Bhattacharjee [2].

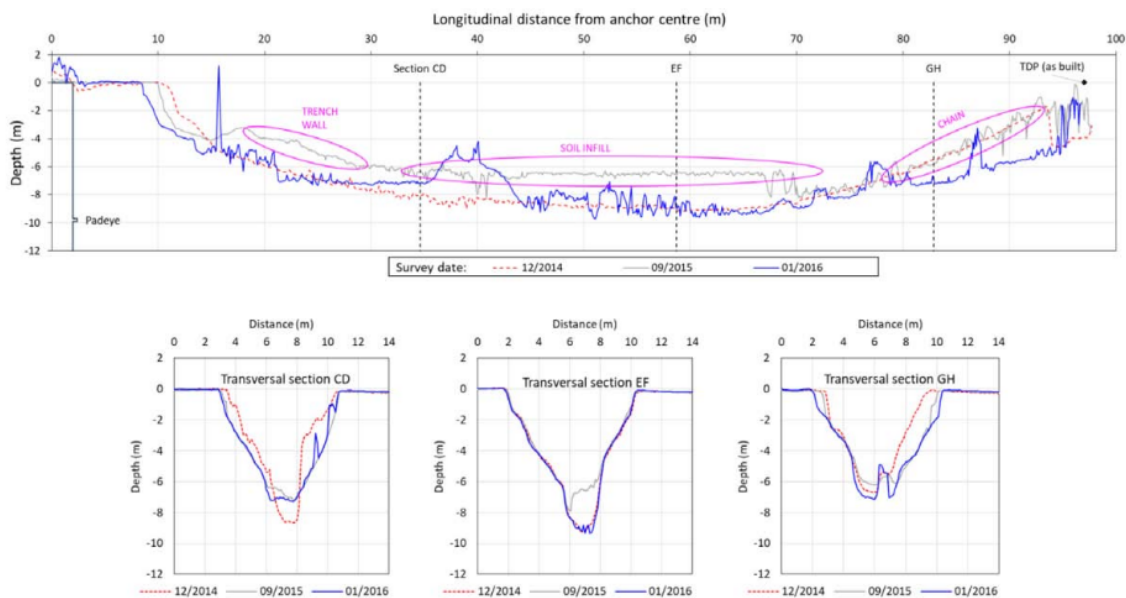


Figure 2.6: Longitudinal and transversal trench profiles in situ [6].

Case 2: AH001 FPSO, North Sea [8] The AH001 FPSO operated in 140 m of water over soft silty clay with undrained shear strengths of 10–25 kPa. Although the soil was stiffer than tropical clays, it remained plastic and fully saturated, allowing strain accumulation under cyclic shear. Twelve trenches were detected in front of the pile anchors, extending 135–166 m in length, up to 10 m in depth, and 25–35 m in width. The wide and shallow geometry indicates progressive wall collapse and lateral displacement rather than rapid fluidization. The high length-to-depth ratio ($\approx 15:1$) suggests that low drainage capacity and cyclic softening governed trench growth, with shear strain concentrating along weak planes close to the touchdown points.

Case 3: OLTs, neare the Serpina FPSO [6] At water depths approaching 1 300 m, multiple off-loading terminal buoy systems developed extensive seabed trenches along their mooring lines. The

seabed consisted of soft, high-plasticity clay (unit weight $\approx 14\text{--}16\text{ kN/m}^3$, undrained shear-strength gradient $\approx 1.3\text{--}1.5\text{ kPa/m}$), normally consolidated and sensitive with limited drainage capacity. Each site exhibited several trenches that deepened from $\approx 2\text{--}4\text{ m}$ after a few years to $\approx$ padeye depth (10 m) after 8–10 years, with widths up to 2–3 times the anchor diameter. Slow consolidation and cyclic degradation of the clay led to wall instability and progressive trench advance toward the anchors. Combined vertical and lateral chain motions, together with the soft soil response and weak currents, prevented natural backfilling, leaving persistent seabed depressions.

Table 2.1: Summary of documented field observations of seabed trenching.

Study	Location / Sedi- ment	Depth (m)	Length (m)	Remarks
Bhattacharjee (2014)	Gulf of Guinea, soft normally consolidated clay	4–7	25–40	Nine trenches near suction-pile moorings; cyclic loading caused soil loss and reduced holding capacity.
Hess (2015)	North Sea, soft silty clay	up to 10	135–166	Twelve trenches in front of pile anchors; cyclic softening and lateral deformation of cohesive soil.
Colliat et al. (2018)	Offshore Western Africa, soft high-plasticity clay	1–12	80–90	30–45 trenches around OLT moorings; progressive trench deepening over 8–10 years.

Bathymetric and ROV imagery from these sites show that trenches follow the curvature of the mooring lines and are deepest near the touchdown point. Profiles are often asymmetric, with a steeper wall on the tension side and a gentler slope toward the anchor, reflecting the direction of cyclic chain motion and flow-induced shear. The Gulf of Guinea cases further demonstrate that long-period swell excitation, low clay strength, and poor drainage can drive sustained trench deepening long after installation.

Across all documented sites, trench formation occurred in soft, normally consolidated clays with low undrained shear strength ($5\text{--}25\text{ kPa}$), high plasticity, and limited drainage capacity. These mechanical properties favour cyclic remoulding and prevent rapid pore-pressure dissipation, leading to progressive trench deepening rather than quick stabilization. The consistent occurrence of such soils at trenching sites underlines the strong mechanical dependence of trench evolution on clay strength, permeability, and cyclic mobility.

To date, no in-situ cases of mooring-induced trenching have been documented in sandy seabeds. This likely reflects the higher permeability and shear strength of sand, which promote rapid pore-pressure dissipation and limit plastic deformation compared to clay. Observed trenching in sandy environments has so far been restricted to controlled laboratory and numerical studies [12, 25, 20], explained in detail in subsection 2.3.2. The absence of field evidence therefore represents a significant knowledge gap in understanding sediment–mooring interactions under non-cohesive conditions.

2.3. Trenching in Different Seabed Types

Trench formation strongly depends on the mechanical and hydraulic behaviour of the seabed material. In cohesive clays, trenching is governed by cyclic softening and remoulding, while in sandy seabeds it is dominated by sediment transport and turbulence-induced scour. This section summarises both mechanisms and highlights how differences in permeability, strength, and pore-pressure response control trench evolution.

2.3.1. Clay

In cohesive clays, trench formation develops gradually through cyclic shear, pore-pressure build-up, and loss of soil strength. Rui et al. [30] described this as a continuous sequence that begins with small shear planes beneath the moving chain and evolves into larger wall collapses and trench elongation toward the anchor. Figure 2.7 schematically illustrates the process. During early loading cycles, the chain disturbs the surface layer and increases excess pore pressure near the mudline. As effective stress decreases, the clay softens and remoulds, allowing deeper penetration of the chain. Subsequent cycles trigger local wall failures, while bottom currents remove loosened material, slowly extending the trench toward the padeye. This combination of cyclic softening and hydrodynamic erosion explains the progressive trenching behaviour often observed in long-term field data.

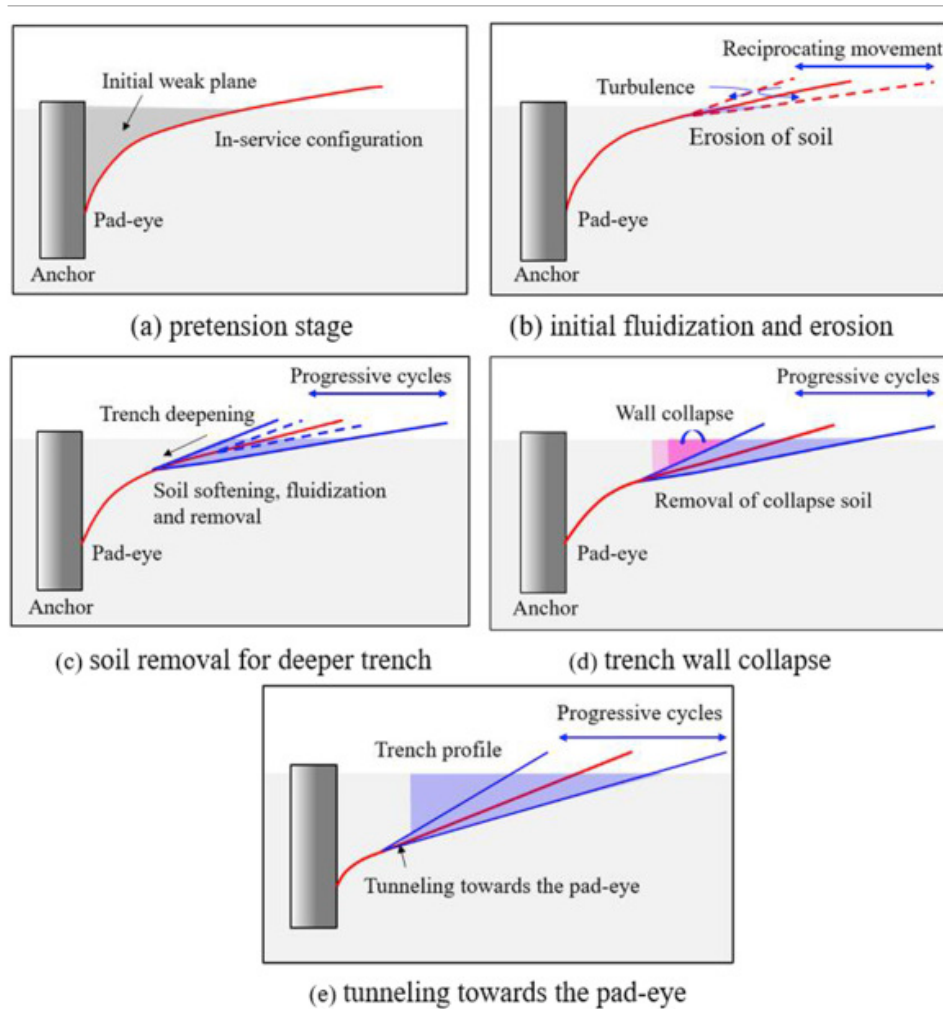


Figure 2.7: Stages of trench evolution in cohesive seabed clay, adapted from Rui et al. [30].

A complementary explanation by Sun [36] focuses on the spatial distribution of soil resistance beneath the chain. The model distinguishes three overlapping zones: a trenching zone where the soil is repeatedly displaced, a tunnelling zone with reduced strength, and an outer remoulding zone where gradual degradation occurs. Initially, uplift resistance dominates near the surface, but as cycles continue, deformation transfers to deeper layers, expanding the weakened zone laterally. This behaviour explains why clay trenches often widen over time even when depth growth slows. For the trench to elongate further, the remoulded material must be removed by near-bed flow, linking mechanical softening to hydrodynamic transport.

The low permeability of clay promotes pore-pressure accumulation, leading to progressive weakening under cyclic motion. As the trench deepens, wall collapses and material removal allow the cavity

to extend toward the anchor. This process can continue for years and often produces deep, narrow trenches that reach the padeye level, substantially reducing anchor capacity.

2.3.2. Sand

Trenching in sandy seabeds is primarily governed by sediment transport and turbulence rather than plastic soil cutting, as the high shear strength and drainage capacity of sand restrict chain penetration. The interaction between the mooring chain and sand is dominated by frictional resistance, which depends strongly on chain inclination and motion amplitude [24]. Rui et al. showed that axial resistance mobilises rapidly during the first few cycles and stabilises once chain displacement reaches roughly one chain diameter. Smaller displacements (less than $0.5 d_b$) result in stable resistance after only a few cycles, while larger motions cause limited particle breakage and gradual densification of the surrounding sand. The soil-arching effect behind the chain generates a short plateau of nearly constant resistance during unloading and reloading, reflecting temporary stress release. Compared with clay, cyclic loading in sand produces densification rather than softening, leading to shallow, stable trenches once equilibrium is reached.

The stabilisation of axial resistance is illustrated in Figure 2.8, which presents the measured axial effective width parameter $E_{t,p}$ from laboratory tests on quartz sand [24]. The tests show that $E_{t,p}$ converges to an average value of about 10.3, indicating that the resisting soil zone around the chain extends over approximately ten chain diameters. Once this width is mobilised, further cyclic loading causes little additional penetration or resistance change, confirming that trench evolution in sand quickly reaches mechanical equilibrium when flow is neglected.

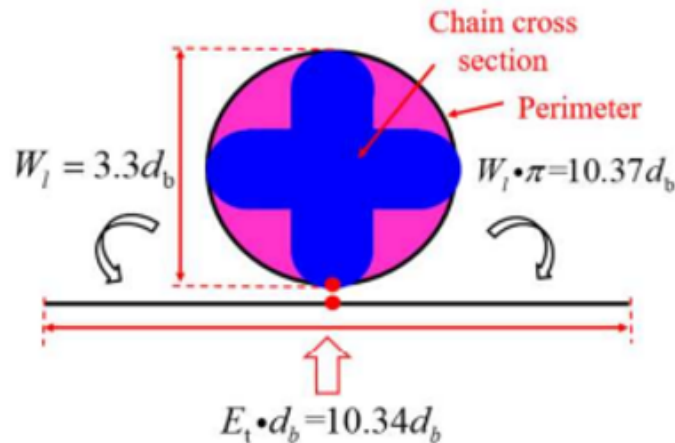


Figure 2.8: Axial effective width parameter for chain–sand interaction: interpretation of the resistance zone width ($E_{t,p} = 10.34$) for quartz sand [24].

Experimental observations by Lu et al. (2021) [20] confirm that cyclic motion of a taut mooring chain in sand can disturb the seabed and initiate shallow ruts, even in the absence of flow. Under repeated oscillation, the chain lifts and drops the sand, forming local plumes that resettle when no current is present. This behaviour represents the incipient stage of trenching. The study also identified a ratcheting effect, in which the mooring line progressively mobilises toward the fairlead, reducing padeye tension and modifying line geometry. This is in line with the trenches found in the experiment by Gao for heave motions [12]. These results highlight that in sandy seabeds, mechanical uplift and cyclic chain motion alone can initiate small trenches, while hydrodynamic scour is required for further trench development.

As illustrated in Figure 2.9, the chain's impact against the seabed pushes sand upward and over the links, ejecting plumes irrespective of grain size or current. These plumes settle back into place without horizontal transport, resulting in stable, shallow depressions. The findings indicate that in sandy seabeds, cyclic chain motion alone can initiate small trenches, while sustained hydrodynamic scour is needed for deeper trench development.

Flow induced processes further influence how trenches develop in sandy seabeds. Gao et al. [12]

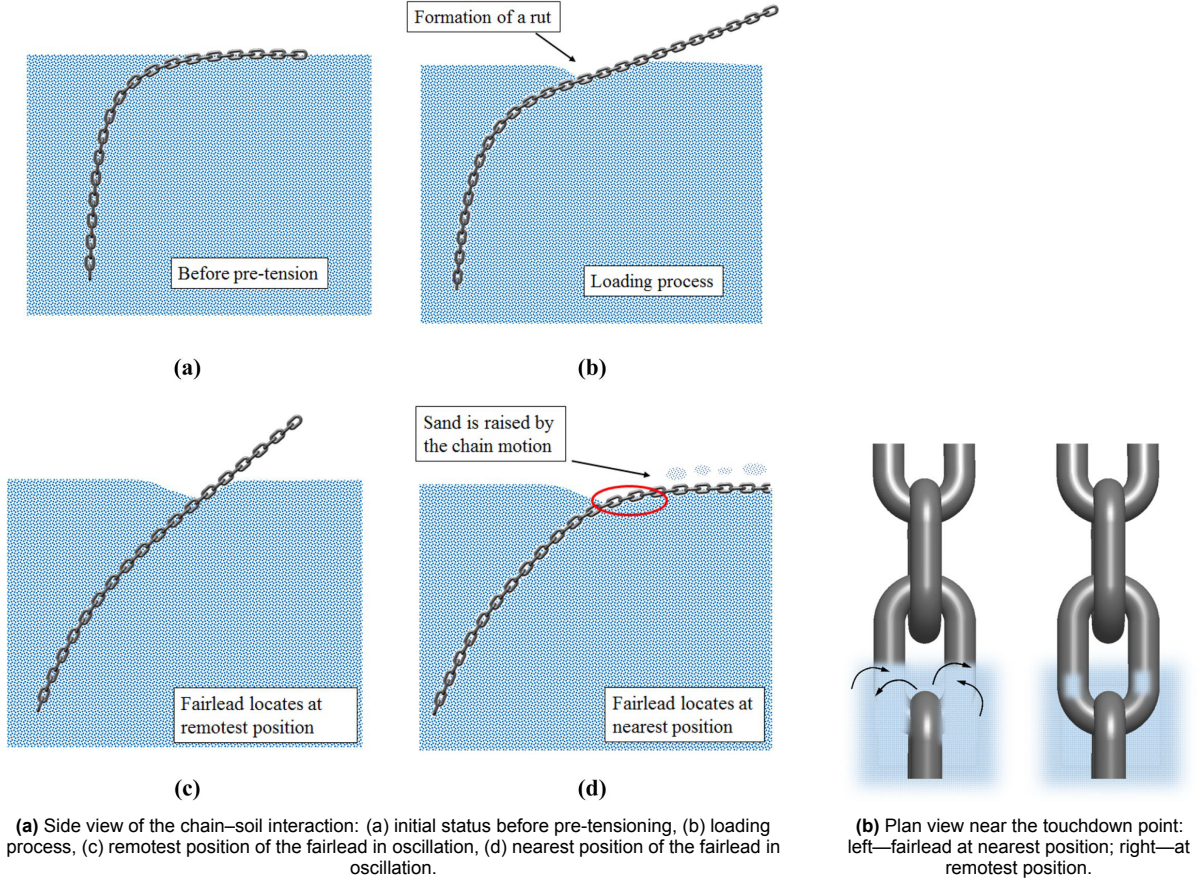


Figure 2.9: Chain–soil interaction in sand under cyclic motion showing both side and plan views, adapted from [20].

demonstrated that when near-bed flow velocity exceeds the threshold U_{cr} for sediment motion, bedload transport intensifies and deposition rates rise sharply. The critical velocity can be estimated using the formulation of Soulsby (1997):

$$\bar{U}_{cr} = 7 \left(\frac{h}{d_{50}} \right)^{1/70} [g(s-1)d_{50}\theta_{cr}]^{1/2} \quad (2.1)$$

$$\theta_{cr} = \frac{0.30}{1 + 1.2D_*} + 0.055 (1 - \exp(-0.020D_*)) \quad (2.2)$$

$$D_* = \left[\frac{g(s-1)}{\nu^2} \right]^{1/3} d_{50} \quad (2.3)$$

where D_* is the dimensionless grain size, s the sediment-to-water density ratio, θ_{cr} the critical Shields parameter, and ν the kinematic viscosity of water.

When these conditions are met, turbulence generated by the oscillating mooring chain enhances near-bed shear and drives local ripple and sand-wave formation, as shown in Figure 2.10. Gao et al. observed that turbulence intensity during lateral (sway) and vertical (heave) motion can reach values multiple time the mean current, substantially increasing sediment mobilisation, as explained in subsection 2.1.3. These findings confirm that trench initiation in sandy seabeds is governed by the combined effects of turbulence-driven sediment transport and limited cyclic densification, rather than by continuous mechanical cutting as observed in cohesive soils.

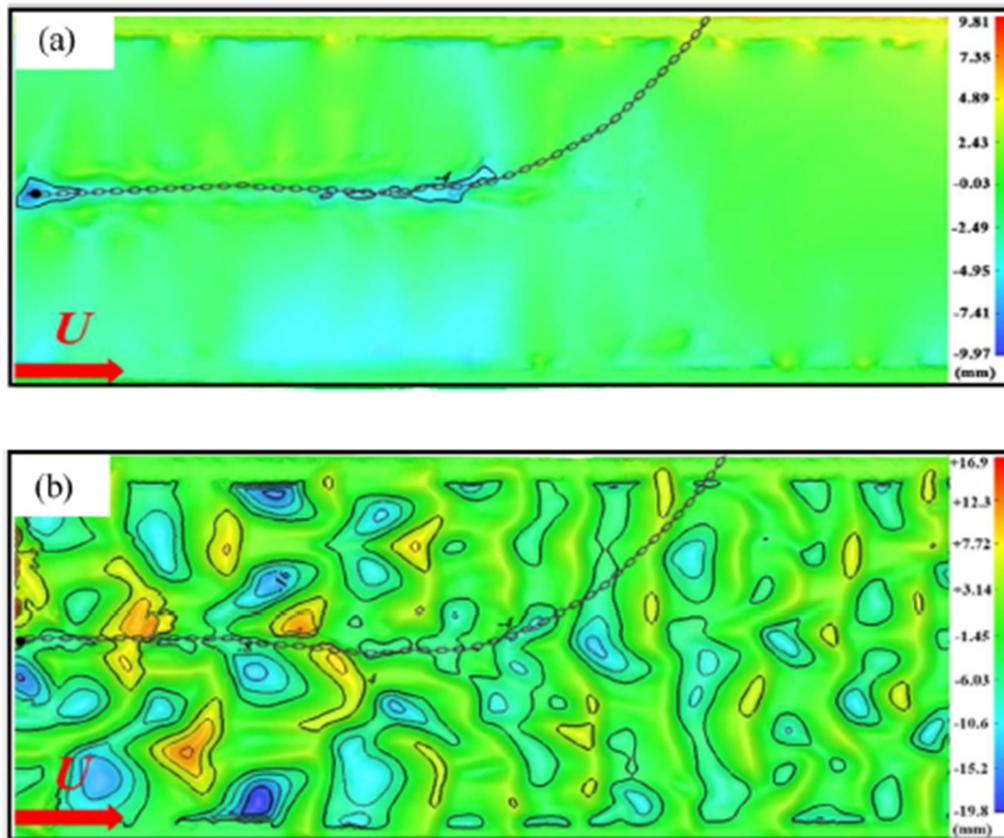


Figure 2.10: Local turbulence near a moving mooring chain produces ripples and sand waves that mark the onset of trench formation [12].

2.4. Hydrodynamic Influence on Trenching and Erosion

2.4.1. Influence of Bottom Currents

Bottom currents play a central role in the long-term evolution and morphology of seabed trenches. Even when mooring-induced motion initiates trenching, the continuous shear stress exerted by ambient currents determines whether the excavated material is removed or redeposited. As flow passes over an uneven seabed, velocity gradients intensify along trench shoulders and decrease inside the cavity, creating local circulation patterns that promote both erosion and infill. Over time, these hydrodynamic feedbacks reshape the trench profile and control its equilibrium depth.

The strength of this process depends on the magnitude and direction of the near-bed current relative to the mooring line. When the current aligns with the trench axis, sediment is transported efficiently along the trench floor, while cross-flow components enhance sidewall erosion through secondary vortices. In cohesive clay, such currents remove remoulded material and prevent self-healing of the trench surface, allowing gradual deepening. In sandy seabeds, they govern the balance between erosion and deposition by redistributing suspended particles around the trench margins.

At low flow velocities, bottom currents mainly maintain a thin mobile layer that limits further deepening once the trench reaches hydraulic equilibrium. During storm or high-current events, however, the increased shear stress can resuspend sediment from both the trench base and its shoulders, temporarily accelerating erosion. The combined influence of steady currents and episodic energetic events thus determines whether a trench stabilises, infills, or continues to expand over time. This hydrodynamic component is therefore critical to any accurate representation of trench formation and evolution under floating mooring systems.

Lu et al. (2021) [20] performed cyclic mooring-line tests in quiescent water without an imposed current.

The observed sand plumes and shallow ruts confirm that mechanical chain motion alone can disturb the seabed, yet in the absence of flow, the displaced sand resettles, preventing full trench development. This gives a bases for research on how the addition of a current could potentially result in trenches for clay

2.4.2. Current-Induced Shear and Sediment Mobilisation

The ability of bottom currents to erode or reshape a trench depends on the bed shear stress they impose on the seabed. When the near-bed shear stress exceeds the critical threshold for sediment motion, particles begin to move as bedload or suspension depending on their size and density. This threshold is typically expressed using the non-dimensional Shields parameter θ , which represents the ratio between the applied shear stress and the submerged weight of the sediment grains. Sediment motion starts when θ exceeds the critical value θ_{cr} , as defined in the Soulsby formulation introduced in the previous section.

In steady conditions, the critical shear stress is rarely reached in deep offshore environments, but even modest background flows can interact with local flow acceleration around the trench and the mooring chain. The combined effect can temporarily raise the effective shear stress above the critical limit, mobilising sediment that would otherwise remain stable. As the current passes over a trench, the velocity increases along the upper shoulders and decreases inside the cavity, establishing zones of erosion at the edges and deposition within the centre. These gradients drive slow but continuous trench adjustment toward an equilibrium profile.

The direction and variability of the current further influence this process. Along-trench currents tend to flush sediment out of the depression, while oblique or cross-flow conditions generate asymmetric side-wall erosion and lateral infill. When coupled with cyclic chain motion, these shear variations enhance resuspension near the touchdown point, producing local pulses of sediment flux. Consequently, even low-energy flows contribute to cumulative morphological change when they interact with the mechanical disturbance from the mooring system.

This interaction between ambient flow and mooring-induced turbulence is seldom captured in existing numerical or experimental trench studies. Most models approximate the flow field as steady or neglect hydrodynamic coupling entirely, which limits their ability to reproduce observed erosion–deposition patterns. The few exceptions, such as the work by Gao et al. (2022), demonstrate that including realistic flow conditions is essential for predicting how trench geometry evolves under combined current and mooring effects.

2.4.3. Suspension and the Rouse Number

Sediment transport near the seabed depends on two coupled mechanisms: the initiation of particle motion and the subsequent mode of transport. The onset of motion is governed by the bed shear stress, while the type of transport, bedload or suspension, is determined by the relative balance between settling and turbulent uplift.

Critical Shear Stress for Bed Initiation

The initiation of motion occurs when the bed shear stress, τ , exceeds a critical value τ_{cr} . This threshold represents the shear force needed to overcome the submerged weight of a particle and initiate movement along the bed. It is often expressed in dimensionless form using the Shields parameter θ , defined as:

$$\theta = \frac{\tau}{(\rho_s - \rho_w)gd_{50}}. \quad (2.4)$$

At the threshold of motion, $\theta = \theta_{cr}$, which can be estimated empirically following the relationship proposed by Soulsby [35] and is defined in Equation 2.2 and Equation 2.3.

The critical shear stress then becomes:

$$\tau_{cr} = \theta_{cr}(\rho_s - \rho_w)gd_{50}. \quad (2.5)$$

Here, ρ_s and ρ_w are the densities of sediment and water, respectively, ν is the kinematic viscosity, and

g is gravitational acceleration. The associated critical shear velocity u_{cr} can be obtained from:

$$u_{cr} = \sqrt{\frac{\tau_{cr}}{\rho_w}}. \quad (2.6)$$

The Shields framework therefore provides the threshold conditions under which sediment begins to move along the bed surface. It has been widely used to describe incipient motion for sandy and silty soils, including offshore environments such as the North Sea. However, it does not describe whether the entrained grains remain in motion or resettle onto the bed, which depends on vertical turbulence and settling velocity.

Suspension Potential and the Rouse Number

Once sediment is mobilised, its transport mode is determined by the balance between upward turbulent diffusion and downward settling. This balance is expressed by the dimensionless *Rouse number*, P , defined as:

$$P = \frac{w_s}{\kappa u_*}, \quad (2.7)$$

where w_s is the particle settling velocity, $\kappa \approx 0.41$ is the von Kármán constant, and u_* is the shear velocity representing near-bed turbulence intensity.

The Rouse number categorises transport regimes as follows:

$P < 1.2$: full suspension, $1.2 < P < 2.5$: partial suspension, $P > 2.5$: bedload or no suspension.

Low Rouse numbers ($P < 1$) indicate strong turbulence relative to settling, causing sediment to remain suspended in the water column. High Rouse numbers correspond to weak turbulence, leading to near-bed motion or deposition. In this way, the Rouse number complements the Shields parameter: the former controls the mode of transport, while the latter defines when motion begins.

In the context of seabed trenching, these two parameters jointly describe how sediment is mobilised and redistributed by flow. The Shields parameter defines the onset of erosion at the trench shoulders, whereas the Rouse number determines whether mobilised sediment remains aloft and escapes the trench or settles back into it. Turbulence generated by chain motion or strong bottom currents can temporarily have an increasing effect on u_* , lowering P and thus might promote sediment suspension. This mechanism explains how even fine-grained materials can remain entrained during storm events or near oscillating mooring chains.

Although these relationships are well established in river and coastal morphodynamics, they are rarely applied to offshore mooring problems, as most trenching models neglect hydrodynamic coupling and suspended-load transport, focusing instead on mechanical chain–soil contact. Only Gao et al. [12] included flow-driven turbulence and suspension effects in their trench experiments, showing that near-bed turbulence around the chain governs both initiation and stabilisation. In subsequent sections, the theoretical thresholds introduced here are used as reference points for analysing sediment behaviour under simulated flow conditions.

Settling Velocity

The settling velocity, w_s , represents the terminal fall speed of a sediment grain through still water when the downward gravitational force equals the upward drag force. Its value depends primarily on the grain diameter d , the relative density contrast between sediment and water, and the kinematic viscosity ν . For natural sands and silts, w_s can vary over several orders of magnitude, from 10^{-4} to 10^{-2} m/s.

For spherical particles, w_s can be obtained from the equilibrium of forces:

$$\frac{1}{2} C_D \rho_w A w_s^2 = (\rho_s - \rho_w) g V, \quad (2.8)$$

where C_D is the drag coefficient, A the projected area, and V the particle volume. Combining these terms leads to the implicit relationship:

$$w_s = \sqrt{\frac{4(\rho_s - \rho_w)gd}{3C_D\rho_w}}, \quad (2.9)$$

with C_D being a function of the particle Reynolds number $Re_p = w_s d / \nu$. For natural sediments, this expression is typically solved using an empirical fit rather than iteration.

A convenient explicit formula was proposed by Soulsby, valid for particle diameters from fine silt to coarse sand:

$$w_s = \frac{\nu}{d} \left(\sqrt{10.36^2 + 1.049 D_*^3} - 10.36 \right), \quad (2.10)$$

where the dimensionless grain size D_* is given by Equation 2.3.

For example, for quartz grains in seawater ($s \approx 2.65$, $\nu = 1.0 \times 10^{-6} \text{ m}^2/\text{s}$, $\rho_w = 1025 \text{ kg/m}^3$):

$$\begin{aligned} d_{50} = 0.0625 \text{ mm} &\Rightarrow w_s \approx 0.003 \text{ m/s}, \\ d_{50} = 0.25 \text{ mm} &\Rightarrow w_s \approx 0.03 \text{ m/s}, \\ d_{50} = 0.375 \text{ mm} &\Rightarrow w_s \approx 0.054 \text{ m/s}, \\ d_{50} = 0.5 \text{ mm} &\Rightarrow w_s \approx 0.07 \text{ m/s}, \\ d_{50} = 1.0 \text{ mm} &\Rightarrow w_s \approx 0.12 \text{ m/s}. \end{aligned}$$

These values are then inserted into the Rouse number (Equation 2.7) to assess whether the grains remain suspended under a given shear velocity u_* . Smaller particles, having lower w_s , yield lower Rouse numbers and thus remain in suspension longer under equivalent flow conditions.

2.5. Numerical Modelling Approaches for Trench Simulation

Over the past decade, multiple researchers have sought to replicate the mechanisms of trench formation using both numerical and experimental approaches [10, 16, 17, 18, 28, 36, 44]. Among these, the two- and three-dimensional finite-element models developed by Rui and co-workers have become the benchmark for predicting trench geometries in clay. Their work aims to capture the final equilibrium trench shape rather than its full temporal evolution, linking soil properties and line loading to the resulting morphology.

2.5.1. Two-Dimensional Model

Rui's initial two-dimensional model was designed to reproduce field observations of trench formation near moored structures, such as those in Equatorial Guinea (Sassi et al., 2017[32]). The model predicts the final trench profile based on soil strength and line tension ratios and compares its results with centrifuge experiments. Figure 2.11 shows that while the model successfully replicates overall trench trends, it slightly overpredicts depth due to a simplification: all disturbed soil is deleted rather than being allowed to refill the cavity. Consequently, the model cannot simulate partial backfilling or sediment redistribution. Furthermore, the vertical scale in the centrifuge tests was amplified while the lateral scale remained unchanged, limiting the ability to reproduce dynamic chain response. As a result, the static prediction underestimates trench length (approximately one-third of field value) and locates the trench farther from the padeye.

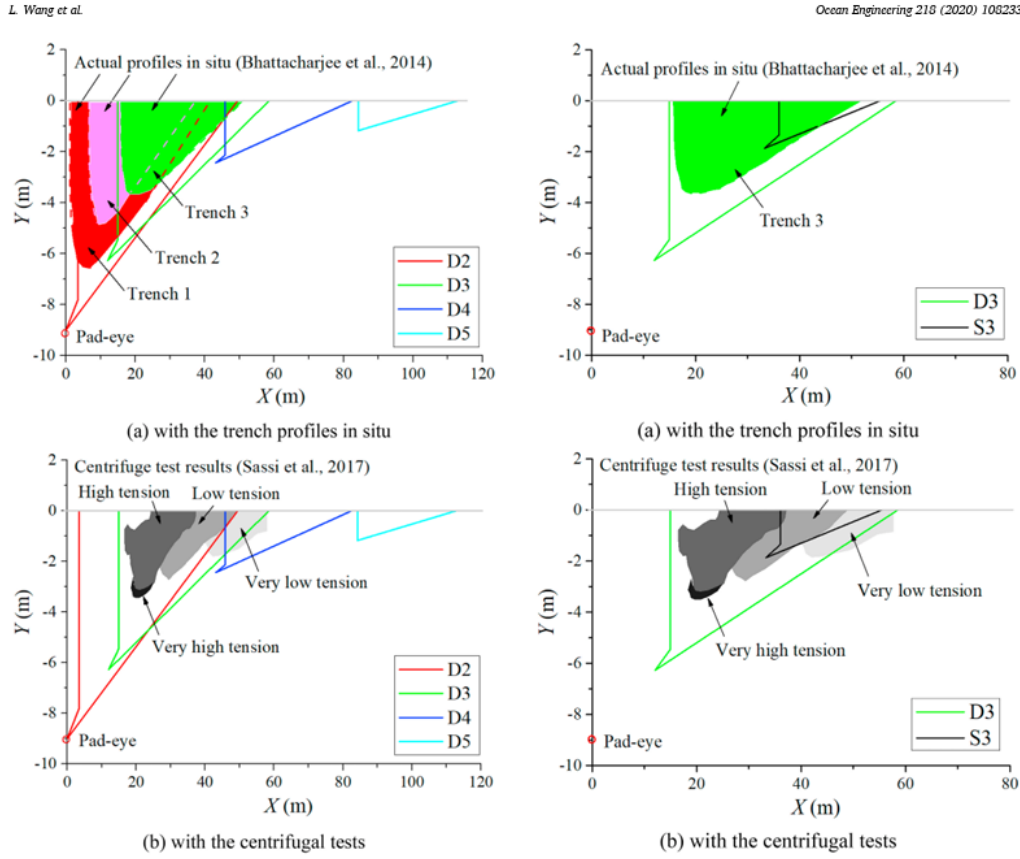


Figure 2.11: Two-dimensional model predictions for trench depth compared with centrifuge test data (after Rui, 2023).

To generalise these results, Rui introduced the following non-dimensional parameters:

$$d_{\text{final}} = \frac{d_n}{d_{\text{pad}}}, \quad l_{\text{final}} = \frac{l_n}{d_{\text{pad}}}, \quad s_{\text{final}} = \frac{s_n}{d_{\text{pad}}},$$

which normalise trench depth, length, and anchor-trench distance by the anchor padeye diameter d_{pad} . Figure 2.12 illustrates how these quantities vary with soil strength ratio η_{su} and tension ratio η_T . As η_{su} decreases (weaker soil) and η_T increases (higher load), both trench depth and length increase substantially. Maximum depths occur near $\eta_{su} \approx 0.5$ and $\eta_T \approx 1.5$, beyond which very soft soils or extreme loading trigger collapse and limit further deepening. The trench length shows a similar trend, forming a plateau at high tension ratios. Conversely, the normalised anchor-trench distance s_{final} shrinks from about $3 d_{\text{pad}}$ in stiff soils and low loads to as little as $0.3 d_{\text{pad}}$ under high loads and weak soils. This indicates that intense mooring forces in soft seabeds draw the trench front closer to the anchor padeye, reducing holding capacity and potentially affecting anchor stability.

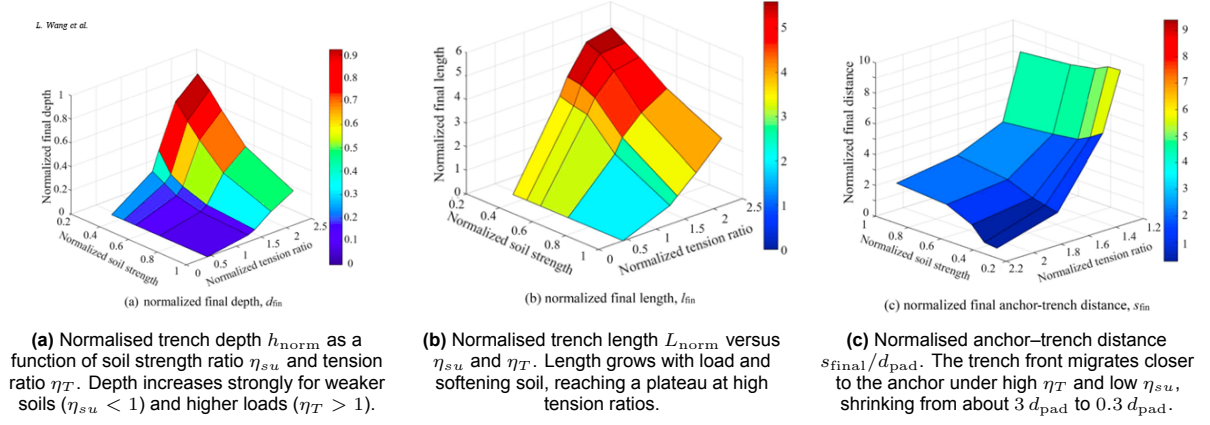


Figure 2.12: Normalised trench dimensions—(a) depth, (b) length, and (c) anchor-trench distance—computed as functions of soil strength ratio η_{su} and tension ratio η_T . As η_{su} decreases and η_T increases, trenches deepen, lengthen, and advance toward the anchor padeye, indicating a progressive loss of bearing resistance in weak soils.

2.5.2. Three-Dimensional Model and Current State of the Art

Building on this work, Rui et al. (2023) [30] coupled a three-dimensional dynamic mooring-line model with an iterative soil-removal algorithm to predict equilibrium trench shapes beneath oscillating chains in clay. This model is now widely used as the state-of-the-art tool for assessing trench risk in cohesive seabeds.

A simplified view of the three-dimensional trench geometry is shown in Figure 2.13a. Together these figures clarify how mooring line geometry, oscillation characteristics, and seabed strength jointly determine the equilibrium trench profile. Soft clays subjected to large cyclic loads lead to short anchor-trench distances and deep cavities, while stiffer soils or smaller oscillation amplitudes restrict trench development. These insights underpin present design strategies for semi-taut mooring systems and form the numerical foundation on which the current study builds.

The influence of soil strength on trench geometry is shown in Figure 2.13b. The simulations reveal that fairlead tension decreases as the touchdown point moves away from the anchor, which highlights the sensitivity of trench development to mooring line geometry. Oscillation periods of 100–200 s produce the deepest and widest trenches, while higher-frequency motions near 50 s limit chain excursions and suppress trench formation. Larger motion amplitudes lead to proportional increases in trench depth together with trench width. Soil strength gradients also influence the morphology. Mild gradients near 1.25 kPa per metre have little effect, while steeper gradients near 2 kPa per metre trigger wall collapse, limiting trench depth yet leaving the width almost unchanged due to persistent lateral chain sweep.

While Rui's models provide a comprehensive framework for cohesive clays, no equivalent three dimensional description exists for sandy seabeds. The present study therefore extends this line of research to non-cohesive soils, where hydrodynamic processes together with sediment transport dominate the behaviour. An initial attempt to adapt Rui's clay-based model to include fluid-driven sediment motion was not possible due to limited access to the commercial version of the code. For this reason a new computational framework has been developed in this thesis to study trench evolution in sand using a fully coupled hydrodynamic approach, which addresses a clear gap in the existing modelling literature.

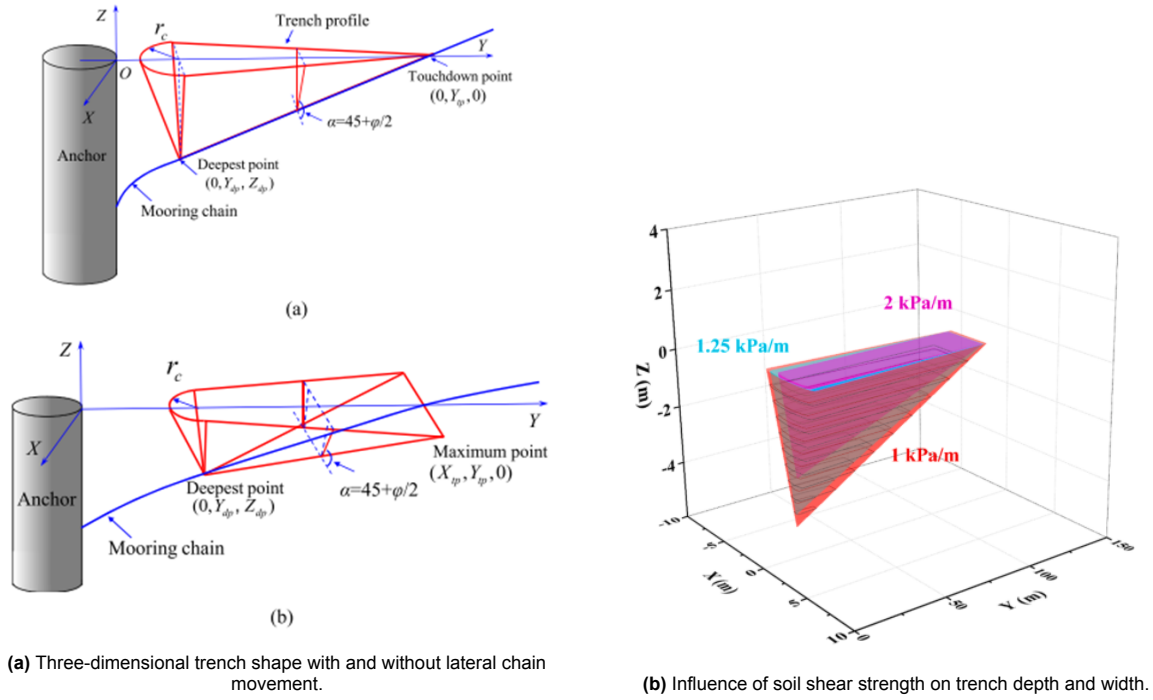


Figure 2.13: Mechanisms governing trench formation in cohesive clays based on Rui et al. [29].

2.6. Related Phenomena and Knowledge Gaps

Yu (2024)[42] investigated the dynamic response of a steel catenary riser in the touchdown zone. Although risers and mooring chains share similar cylindrical geometry, their scale and motion differ substantially. The study demonstrated that trenches also form beneath risers, with depth and length primarily governed by soil stiffness and cyclic motion amplitude. Wang (2017)[38] and Yu (2023)[43] reported comparable trench morphologies, observing so-called *bell* and *ladle* shapes that closely resemble those formed beneath mooring chains (Figure 2.14). These results indicate that trenching is controlled less by component type and more by the mechanics at the touchdown point, where repeated contact and local stress redistribution occur. All of the reported riser experiments were, however, performed without background flow, meaning that purely mechanical effects dominated the observed deformation.

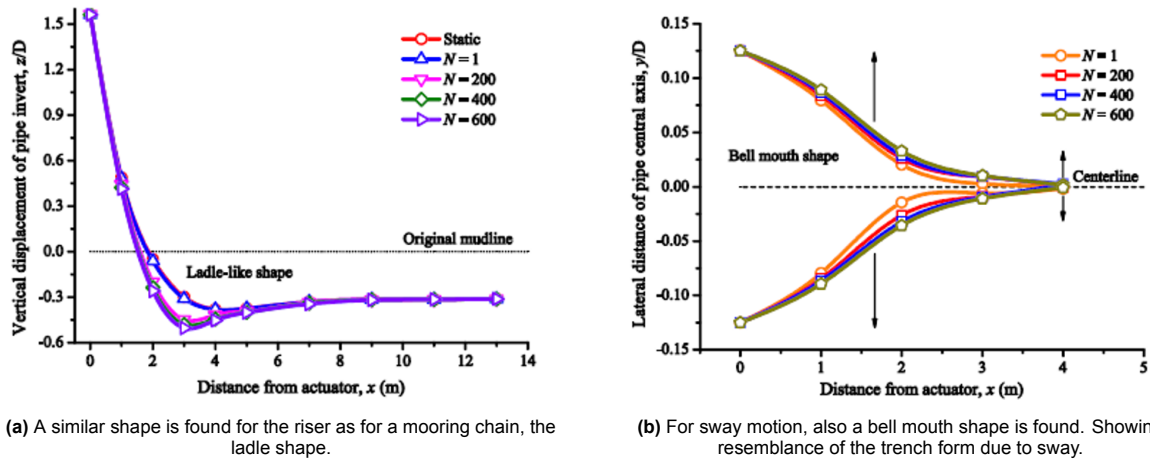


Figure 2.14: Typical trench geometries for steel catenary risers, showing bell- and ladle-shaped profiles (after Yu, 2024)[42].

Li (2013)[19] extended this work by examining scour around a riser subjected to a cross-flow while

2.6.1. Cross-Study Observations and Remaining Gaps

Across multiple studies, similar trends emerge. Rui et al. (2021)[27] showed that cyclic chain motions with amplitudes smaller than one chain diameter lead to stable trench formation, whereas larger amplitudes cause continued deepening and elongation. Guo et al. (2022) [12] found that carbonate sands resist penetration more strongly than quartz sands under identical loading, confirming the importance of grain mineralogy and angularity. In addition, Rui (2023) [25] demonstrated that trench width scales linearly with the horizontal sweep of the chain, while trench depth decreases with increasing distance from the anchor.

were conducted under no water or quiescent water conditions, neglecting flow or the full fluid–structure interaction. The erosion and transport of particles within the trench due to steady or oscillatory flow therefore remain poorly quantified. While existing metrics provide useful predictive relationships for trench geometry, they are largely based on mechanical interaction alone or limited to catenary configurations and a clayey type soil.

In summary, current research has established the main mechanisms governing trench initiation and shape, but the combined influence of hydrodynamic forcing, chain-induced turbulence, and long-term seabed response remains unresolved. No integrated framework yet captures how these factors interact, particularly for sandy seabeds where fluid motion dominates sediment behaviour. Building a model containing all of these variables can be done via Computational Fluid Dynamics (CFD), this will be explained in the following section. In chapter 3, the knowledge gaps will be synthesized and the specific limitations in existing approaches that motivate the development of the new CFD-based model presented in this thesis will be outlined.

3

Research Gap

Previous studies have established a foundation for understanding seabed trenching beneath mooring lines, particularly under catenary configurations. However, these trench models are all build for clay whereas sand is left out.

This literature review reveals four key gaps that limit the predictive accuracy and applicability of existing models:

1. **Main focus on old catenary systems.** Most work concentrates on catenary configurations, while modern floating wind increasingly applies semi taut or taut lines. These configurations lead to steeper line angles, more localized seabed loading, and therefore different trench initiation mechanisms.
2. **Neglect of hydrodynamic forcing.** Near bed currents and flow induced erosion are rarely included, despite their recognized role in sediment mobilization in related hydraulic settings. Lu [21] found that chain in sand could produce sand plumes ejected from the seabed, but settled down due to no flow. So apart from the experiment by Gao [12], existing trench models, numerical or experimental, do not explicitly include hydrodynamic effects.
3. **Limited treatment of long term evolution.** Cumulative effects over a typical 25 year operational life, such as progressive scour, soil softening, and particle transport, remain largely unaddressed. This restricts reliability assessments at project timescales.
4. **Simplified chain motion and turbulence.** Local turbulence generated by chain geometry and motion is insufficiently represented. Gao [12] showed that trench form in sand depends on chain induced turbulence and motion, while Rui [23, 24] demonstrated that chain links increase turbulence intensity. These insights have not been carried through into predictive models.

These gaps highlight the need for modelling approaches that couple hydrodynamic forces with sediment dynamics, account for prolonged environmental loading and explicitly represent chain-induced turbulence especially in a sand type like soil, as the experiments done in the past have found trenches, but only stable ones as was found that without flow no deep trenches occur [27, 12, 20]. So there is no model that fully grasped all the separate influencers such as settling motion, trench geometry, chain motion and induced current and bottom current.

To address these limitations, it is proposed to develop a transversal two dimensional Computational Fluid Dynamics model that resolves turbulent flow, sediment resuspension, transport, and redeposition around an oscillating mooring chain. In contrast to earlier two dimensional *longitudinal* simulations that did not reproduce trenching in sand [25]. The proposed framework includes bottom current and the moving chain as a dynamic boundary to generate turbulence driven scour consistent with experiments as the two key factors for flow inside the trench. Sediment is represented as a dispersed phase within the carrier fluid. By focusing on cross sectional trench geometry, the model aims to quantify how lateral flow–sediment interactions govern trench formation and stabilization in sandy seabeds, thereby improving predictive capability for design.

4

Methodology

This chapter outlines the methodological framework adopted to investigate sediment resuspension and escape mechanisms from seabed trenches under hydrodynamic forcing. Building on the theoretical background presented in the previous chapter, the methodology describes how the governing equations are implemented numerically, how the computational domain is defined, and how the simulations are designed, executed, and analysed.

4.1. Research Scope

The objective of this research is to investigate sediment resuspension and escape behaviour from seabed trenches influenced by hydrodynamic flow and mooring-chain motion. To achieve this, high-resolution numerical simulations are performed using a custom OpenFOAM solver, *IbBousSoilFoam*, which couples incompressible flow, suspended sediment transport, and immersed boundary motion. The study aims to isolate the dominant physical mechanisms that govern trench stability under varying flow and soil conditions, rather than to reproduce a specific field case.

4.1.1. Scope of the Model

The computational model represents an idealised two-dimensional vertical cross-section of a seabed trench. Flow, sediment transport, and chain-induced turbulence are resolved using a transient Reynolds-Averaged Navier–Stokes (RANS) formulation under the Boussinesq approximation. The sediment phase is treated as a dispersed scalar field, governed by an advection–diffusion–settling equation. Sediment–fluid density coupling is included via buoyancy, but drag feedback, particle collisions, and hindered settling effects are neglected. The mooring chain is represented by an immersed boundary (IB) mask that allows vertical oscillation within a stationary mesh, capturing fluid–structure interaction without mesh deformation.

4.1.2. Parameter Space

The simulations cover a range of conditions representative of offshore mooring environments. The inflow current is steady and homogenous over a height of 2 m starting at the sea bottom. The flows are incorporated, 0.05 and 0.3 m/s, representing a calm and a storm sea state. Trench depth varies between 3 m and 9 m with fixed sidewall angles of 63°, based on in-situ geometries reported by Bhattacharjee [2]. Sediment grain sizes of $d_{50} = 0.0625, 0.25, 0.375, 0.5, \text{ and } 1.0 \text{ mm}$ are considered to evaluate size-dependent resuspension thresholds. The flow field is driven by steady inlet velocities, while the chain motion follows a prescribed vertical displacement with varying amplitude and period. This motion is steady and equal for the up- and downwards motion, 0.1 m/s (calm) – 0.3 m/s (storm).

4.1.3. Assumptions and Limitations

To maintain computational tractability, several simplifying assumptions are applied:

- The domain is two-dimensional, three-dimensional flow and vortex dynamics are neglected.

- The flow is incompressible and isothermal, excluding temperature or salinity gradients.
- The sediment concentration remains below 6%, consistent with the Boussinesq approximation.
- Soil–chain contact mechanics and erosion of cohesive seabed layers are not modelled explicitly.

4.2. Numerical Background Theory

4.2.1. Basics of Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) is the numerical solution of the governing equations of fluid motion, which express conservation of mass, momentum, and, when relevant, scalar quantities such as sediment concentration. For an incompressible Newtonian fluid, the Navier–Stokes equations can be written as

$$\nabla \cdot \mathbf{U} = 0, \quad (4.1)$$

$$\rho \left(\frac{\partial \mathbf{U}}{\partial t} + \mathbf{U} \cdot \nabla \mathbf{U} \right) = -\nabla p + \nabla \cdot (\mu \nabla \mathbf{U}) + \rho \mathbf{g}, \quad (4.2)$$

where $\mathbf{U}$ is the velocity vector, p the pressure, ρ and μ the fluid density and dynamic viscosity, and $\mathbf{g}$ the gravitational acceleration. Each term in the momentum equation (4.2) corresponds to a distinct physical mechanism. The term $\rho (\partial \mathbf{U} / \partial t)$ represents the local (time-dependent) acceleration of the flow, which is relevant because both the background current and the chain motion produce unsteady velocity fields. The convective term $\rho (\mathbf{U} \cdot \nabla) \mathbf{U}$ describes the transport of momentum by the flow itself and is responsible for the development of vortices and upward jets inside the trench.

Pressure forcing enters through $-\nabla p$, driving the flow from high to low pressure while also enforcing incompressibility. Momentum diffusion is represented by $\nabla \cdot (\mu \nabla \mathbf{U})$, which accounts for viscous and turbulence-induced smoothing of velocity gradients, particularly near the chain surface and trench walls. Finally, the gravitational body force $\rho \mathbf{g}$ acts on the flow and provides the basis for buoyancy effects.

Together, these terms balance acceleration, pressure, diffusion, and gravity, forming the foundation of the CFD formulation used in this study.

In practice, the instantaneous turbulent flow field is too complex to resolve directly for engineering-scale domains, such as seabed trench simulations. Therefore, the present study applies the Reynolds-Averaged Navier–Stokes (RANS) formulation, in which each variable is decomposed into a mean and fluctuating component:

$$\mathbf{U} = \bar{\mathbf{U}} + \mathbf{u}', \quad p = \bar{p} + p'.$$

Substituting these into the Navier–Stokes equations and time-averaging yields an additional term representing the turbulent stresses. These stresses are modelled using an eddy-viscosity hypothesis, which relates them to the mean velocity gradients. This approach captures the mean effect of turbulence on sediment suspension and near-bed shear without resolving the full turbulent spectrum.

All equations are solved in transient form to account for the time-varying flow field around the moving mooring chain and the evolving sediment concentration.

4.2.2. Finite Volume Method

OpenFOAM and the solver developed in this study, `IbBousSoilFoam`, employ the finite volume method (FVM), which ensures strict local and global conservation of transported quantities. The general transport equation for a variable ϕ is integrated over each control volume V :

$$\int_V \frac{\partial \phi}{\partial t} dV + \int_S \phi \mathbf{U} \cdot \mathbf{n} dS = \int_S \Gamma \nabla \phi \cdot \mathbf{n} dS + \int_V Q dV, \quad (4.3)$$

where Γ represents the diffusion coefficient, Q a source term, and the surface integrals are evaluated over the control volume faces.

The equations are discretised using second-order accurate central differencing for diffusive terms and bounded upwind schemes for convective fluxes, which balance accuracy and numerical stability. Temporal discretisation is performed implicitly using a first-order Euler scheme, suitable for transient RANS

simulations with small Courant numbers ($Co < 0.4$). Linearised algebraic systems are solved iteratively using OpenFOAM's matrix solvers (e.g. GAMG for pressure and PBICG for velocity and scalar fields), with under-relaxation to ensure stability of the coupled solution.

4.2.3. Soil as a Dispersed Phase

Sediment is treated as a dispersed scalar field transported by the carrier fluid. This Eulerian–Eulerian representation is valid for dilute suspensions ($C < 0.06$), where particle–particle interactions and hindered settling can be neglected. The sediment concentration C satisfies the advection–diffusion–settling equation

$$\frac{\partial C}{\partial t} + \nabla \cdot (C \mathbf{U}) + \nabla \cdot (C \mathbf{w}_s) = \nabla \cdot (\mathbf{D}_{eff} \nabla C), \quad (4.4)$$

where w_s is the settling velocity (computed using the Soulsby formulation; see Equation 2.10) and D_{eff} the sediment diffusivity. Each term reflects a distinct physical process acting on the concentration field C . The term $\partial C / \partial t$ represents the local temporal change in sediment concentration, while the advective flux $\nabla \cdot (C \mathbf{U})$ describes transport of sediment by the mean flow, including the recirculation inside the trench and the upward jets generated near the chain.

Gravitational settling enters through the slip flux $\nabla \cdot (C \mathbf{w}_s)$, which moves particles downward relative to the surrounding fluid at a rate determined by the Soulsby settling velocity. Diffusion is represented by $\nabla \cdot (D_{eff} \nabla C)$, combining molecular and turbulence-induced mixing that smooths concentration gradients, especially near the trench walls and in the shear layer above the chain.

Together, these terms model the competition between upward transport by the flow, downward settling under gravity, and lateral mixing by turbulent diffusion, allowing the solver to capture the spatial and temporal evolution of suspended sediment within the trench. More details in Appendix B.

Although the flow is solved under an incompressible constraint, the mixture density varies with sediment concentration. For dilute mixtures this dependence is linearised through a Boussinesq-type approximation:

$$\rho(C) = \rho_f [1 - \beta C], \quad (4.5)$$

where ρ_f is the clear-fluid density and $\beta = (\rho_s - \rho_f) / \rho_f$ is a dimensionless density ratio derived from the solid and fluid densities.

In the momentum equation, density variations enter only through the buoyancy term, while inertial and pressure terms are evaluated using a reference density. This preserves the incompressible character of the velocity field while capturing the first-order buoyancy effects associated with suspended sediment.

4.2.4. Pressure–Velocity Coupling Algorithms

For incompressible flow, the pressure field is not solved directly but instead appears implicitly through the continuity constraint ($\nabla \cdot \mathbf{U} = 0$). To enforce mass conservation, pressure and velocity are coupled iteratively using the PIMPLE algorithm, which is a hybrid of the SIMPLE (steady) and PISO (transient) schemes.

Each PIMPLE iteration begins with a momentum predictor step, solving the discretised momentum equation for a provisional velocity $\mathbf{U}^*$ using the previous pressure field. A pressure-correction equation is then derived from the continuity constraint:

$$\nabla \cdot \left(\frac{1}{a_P} \nabla p' \right) = \nabla \cdot \mathbf{U}^*, \quad (4.6)$$

where a_P is the diagonal coefficient of the momentum equation and p' the pressure correction. The updated pressure and velocity fields are corrected until the divergence-free condition is satisfied to within the solver tolerance. This approach allows stable transient convergence in RANS flows with moderately large time steps, balancing computational efficiency with accuracy.

4.2.5. Immersed Boundary Method: Numerical Concept

The immersed boundary (IB) method enables the representation of solid bodies inside a fixed Eulerian mesh without the need for mesh deformation or body-fitted grids. Instead of reshaping the mesh around the object, the IB framework imposes the effect of the solid through a forcing term or a blending field that locally modifies the momentum equation.

In the diffused-interface IB formulation used in this study, the solid body is represented through a mask field $\gamma(\mathbf{x})$, which varies smoothly between 0 and 1:

$$\gamma(\mathbf{x}) = \begin{cases} 1, & \text{fluid region,} \\ 0, & \text{solid region,} \\ 0 < \gamma < 1, & \text{interface region.} \end{cases}$$

The mask defines a transition layer in which fluid and solid velocities are blended. A weighted reconstruction enforces the no-slip condition on the immersed surface:

$$\mathbf{U}(\mathbf{x}) = \gamma \mathbf{U}_f + (1 - \gamma) \mathbf{U}_s,$$

where $\mathbf{U}_f$ is the fluid velocity and $\mathbf{U}_s$ is the local solid-body velocity.

This diffused interface avoids sharp discontinuities in velocity and pressure and prevents numerical oscillations when the immersed object moves relative to the mesh. Because γ is updated every time step, arbitrary body motion can be imposed without modifying mesh connectivity.

The IB method is therefore particularly suited for problems involving moving structures embedded in the flow, such as oscillating mooring chains, where imposing accurate boundary conditions would otherwise require costly mesh motion or overset-grid interpolation.

4.3. Numerical Model Framework

This section explains how the governing equations and concepts introduced in Section 4.2 are implemented in the custom OpenFOAM solver `IbBousSoilFoam`. Where the previous section provided the theoretical background, the focus here is on the practical formulation, coupling strategy, and solver configuration used in the simulations.

4.3.1. Single-Fluid Formulation with Buoyancy Coupling

Although water and sediment are present as two physical components, the solver treats the mixture as a single incompressible fluid with a density that depends on the local sediment concentration. Only one momentum equation is solved, and sediment affects the flow solely through buoyancy, consistent with the Boussinesq-type density relation in Eq. (4.5). The buoyancy differences due to the soil are calculated via an extra forcing term added to the momentum equation and with this formulation, the incompressible momentum equation solved by `IbBousSoilFoam` becomes

$$\rho_f \left(\frac{\partial \mathbf{U}}{\partial t} + \mathbf{U} \cdot \nabla \mathbf{U} \right) = -\nabla p + \nabla \cdot (\mu_{\text{eff}} \nabla \mathbf{U}) - (\rho(C) - \rho_f) \mathbf{g}, \quad (4.7)$$

here the resulting buoyancy force added to the momentum equation is the last term in (4.7)

$$\mathbf{f}_b = -(\rho(C) - \rho_f) \mathbf{g}, \quad (4.8)$$

This is done so that density variations modify vertical momentum without affecting incompressibility or the pressure-velocity coupling. This captures the first-order feedback between suspended sediment and the flow inside the trench while avoiding the complexity of a fully coupled multiphase formulation.

4.3.2. Sediment Transport Equation

Sediment concentration is calculated using an advection-diffusion-settling equation consistent with Eq. (B.3). In the solver, gravitational settling is represented through a prescribed slip velocity field

$\mathbf{V}_{dj} = -w_s \hat{\mathbf{z}}$, which appears in the flux term of the transport equation. Diffusion is modelled by a constant eddy diffusivity D_s , following the simplified scalar transport approach used in OpenFOAM.

The sediment equation is solved in conservative form using the mixture mass fluxes, which ensures consistency with the finite volume discretisation. Field relaxation are applied to maintain numerical stability under the steep shear gradients near the trench walls and around the immersed boundary.

4.3.3. PIMPLE Coupling and Linear Solvers

All simulations are performed using the PIMPLE algorithm, which combines the transient accuracy of PISO with the iterative stability of SIMPLE. This makes it well suited for moving-body problems with strong local shear, such as the immersed mooring chain. Each time step consists of:

1. Momentum predictor — computation of a provisional velocity field using the current density, buoyancy force, and immersed boundary forcing.
2. Pressure–velocity coupling — four pressure-correction steps to enforce incompressibility and stabilise the solution.
3. Sediment transport update — solution of the concentration equation using the updated velocity field and slip velocity.
4. Immersed boundary update — application of forcing terms, mask reconstruction, and chain-motion corrections.

Pressure is solved using the GAMG multigrid algorithm, while velocity and scalar fields use Krylov solvers (PBiCG or BiCGStab) with ILU preconditioners. More details can be found in Appendix C.3. A fixed time step is used throughout the simulations, with constraints defined by the Courant-number analysis in Appendix C.4. A full schematic of the solver execution sequence, including the IBM update, momentum predictor, PIMPLE corrections, and sediment transport step, is provided in Appendix B.

4.3.4. Domain and Geometry Definition

Computational Domain and Meshing

The computational setup represents a two-dimensional cross-section of the seabed trench and surrounding flow region. Each geometry is generated using OpenFOAM's `blockMesh` utility, with a single cell extrusion in the y -direction and `empty` patches applied at the front and back to enforce two-dimensionality. Trench depths between 3 m and 9 m and a sidewall angle of 63° are used, see Figure 4.1, consistent with the field geometry introduced in Section 4.1. Rounded transitions are implemented at the wall–bed intersections to avoid velocity singularities and improve numerical stability.

The mesh consists of six structured hexahedral blocks forming the trench base, sidewalls, and surrounding seabed. Refinement is concentrated near the trench floor and walls to resolve vertical shear and sediment gradients, while coarser spacing is applied farther from the active flow region. Typical mesh sizes range from 15,000 to 40,000 cells, with a maximum non-orthogonality of 67° and skewness below 3, both within OpenFOAM's stability limits. The trench region maintains 15–20 cells across its depth, ensuring spatial convergence without excessive computational cost.

Mesh grading is controlled through `simpleGrading` with factors between 0.5 and 2.0, providing fine spacing near the trenchwalls and a gradual coarsening towards the middle, here the chain is placed which has its own refinement, see Figure 4.3.4. Curved edges are defined using the `arc` command to represent rounded trench corners and smooth inflow–outflow transitions. Mesh quality is verified using `checkMesh`, confirming appropriate aspect ratios and cell orthogonality across all trench depths. An overview of all differences in sizes of the domains are given in section C.1

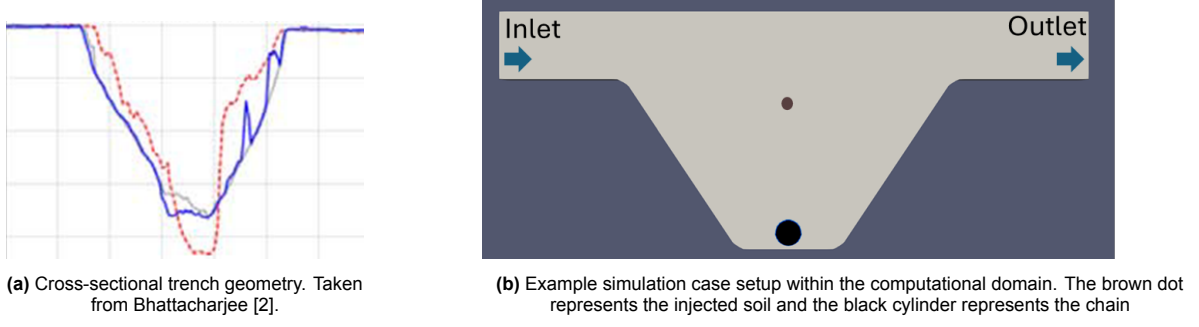


Figure 4.1: Overview of the computational domain and example case configuration used in the simulations.

Immersed Boundary and Motion Handling

The oscillating mooring chain is represented in the solver using the `immersedBoundaryDynamicRefineSolidBodyMotionFvMesh` class from `foam-extend 5.0`. This framework combines a prescribed solid-body motion, a diffused-interface immersed boundary mask, and automatic mesh refinement based on the chain's proximity.

IB mask and velocity enforcement. A scalar mask field $\gamma(\mathbf{x}, t)$ is constructed every time step by `updateIbMasks.H`. This field identifies which cells lie inside the chain, within the diffused interface, or in the fluid. Using this mask, the solver reconstructs the velocity in IB-affected cells:

$$\mathbf{U} = \gamma \mathbf{U}_f + (1 - \gamma) \mathbf{U}_s,$$

thereby enforcing the no-slip condition on the chain surface while keeping the mesh stationary. The routines `updateIbPatchFields.H` and `updateIbMasks.H` update the local mask and boundary fields each time step as the chain moves.

Prescribed chain motion. Chain motion is defined via the `graphVelocity` motion function, which reads a user-specified displacement–time curve. Only heave motion is applied; all other degrees of freedom (surge, sway, roll, pitch, yaw) are constrained to zero. The dynamic mesh class computes the solid-body velocity $\mathbf{U}_s$ at each time step directly from this input.

Immersed boundary driven mesh refinement. Adaptive mesh refinement is activated to maintain high resolution around the chain. Cells within approximately 0.08 m of the immersed boundary are refined up to two levels, while cells farther away are unrefined. Refinement and unrefinement occur every two time steps, using buffer layers to ensure smooth transitions. This approach keeps the mesh aligned with the effective IB interface while limiting the overall cell count to roughly 20,000 per simulation.

Flux handling and stability. During mesh motion the solver switches between absolute and relative flux formulations using `fvc::makeAbsolute()` and `fvc::makeRelative()` for consistency between velocity, fluxes, and pressure. A dedicated IB Courant number check (`immersedBoundaryCourantNo.H`) ensures stable time stepping in regions affected by rapid IB motion.

Parallel execution. Simulations are decomposed using the `simple` method (e.g. a (2×3) subdivision). Both refinement and IB mask updates operate locally within each processor domain, enabling efficient parallel computation.

This IB implementation allows the chain to move freely within a fixed mesh while maintaining accurate momentum exchange and stable coupling with the transient RANS solver.

Boundary Conditions

Boundary conditions match those described in Section 4.1 but are implemented numerically as shown in Table 4.1.

Boundary	p	U	C
Inlet	zeroGradient	fixedValue U_{in}	zeroGradient
Outlet	fixedValue 0	zeroGradient	zeroGradient
Seabed / Walls	zeroGradient	fixedValue (0 0 0)	zeroGradient
Top (Free Surface)	zeroGradient	zeroGradient	zeroGradient
Front / Back	empty	empty	empty
Mooring Chain (IB)	zeroGradient	prescribed motion	zeroGradient

Table 4.1: Boundary conditions applied to pressure, velocity, and sediment concentration fields. U_{in} is either 0.05 or 0.36 [m/s] depending on the sea state and the soil is added to the mesh via the SetFieldsDict.

This configuration ensures stable inflow, smooth outflow, and accurate near-bed resolution within the trench region. For more detail on schemes and turbulence handling, time control and more, see section C.2.

4.4. Simulation Setup and Post-Processing

4.4.1. Simulation Configuration

All simulations are performed in transient mode to capture the unsteady interaction between the incoming flow, sediment transport, and mooring-chain motion. Each case is initialised from a still flow field and advanced until a statistically steady state is reached. The time step is set constant while maintaining a Courant number below unity ($Co_{max} < 0.5$), resulting in Δt values between 10^{-3} and 10^{-2} sec depending on flow conditions. The total simulated duration ranges from 250 to 1100 simulation seconds, ensuring that one and a half chain oscillation cycles are resolved in the dynamic cases.

Simulations are executed in parallel using six processors with domain decomposition defined in the decomposeParDict using 3 cores for the x-axis (width) and 2 for the z-axis (depth). Residual convergence is monitored at every time step, and a solution is considered converged when all residuals fall below at least 10^{-6} . More details can be found in Appendix C.3.

4.4.2. Parameter Matrix

The study considers two steady inflow conditions representative of calm and storm sea states. Steady inflow velocities of $U_{in} = 0.05$ m/s and $U_{in} = 0.36$ m/s correspond to mild and energetic flow regimes, respectively. The mooring chain motion follows prescribed vertical oscillations with amplitudes between 5 and 11 m and characteristic velocities of 0.1 or 0.3 m/s. Both inflow and chain motion are coupled to the sea state: under calm conditions, the inflow velocity and chain motion are set to 0.05 m/s and 0.1 m/s, respectively, while storm conditions use 0.36 m/s and 0.3 m/s. Sediment behaviour is analysed across five median grain sizes ($d_{50} = 0.0625, 0.25, 0.375, 0.5$, and 1.0 mm), covering very fine to coarse marine sands. The settling velocity that comes with these grain sizes are given in Table 4.2

d_{50} (mm)	w_s (m/s)
0.0625	0.003
0.25	0.03
0.375	0.054
0.5	0.07
1.0	0.12

Table 4.2: Settling velocities corresponding to the grain sizes used in this study.

This parameter matrix enables a systematic exploration of how trench geometry, sediment size, and hydrodynamic forcing interact to control resuspension and sediment escape. The complete set of simulated cases combines variations in trench depth, sediment class, and flow intensity, as summarised in Table 4.3.

Table 4.3: Matrix of all simulation cases showing variations in flow velocity, sediment size, and trench depth. Category 1-5 are the calm sea state, category 6-10 are the storm sea state.

Category	Case	Flow Speed [m/s]	d_{50} [mm]	Trench Depth [m]
1	1	0.05	0.0625	-3
	2	0.05	0.0625	-5
	3	0.05	0.0625	-7
	4	0.05	0.0625	-9
2	5	0.05	0.25	-3
	6	0.05	0.25	-5
	7	0.05	0.25	-7
	8	0.05	0.25	-9
3	9	0.05	0.375	-3
	10	0.05	0.375	-5
	11	0.05	0.375	-7
	12	0.05	0.375	-9
4	13	0.05	0.5	-3
	14	0.05	0.5	-5
	15	0.05	0.5	-7
	16	0.05	0.5	-9
5	17	0.05	1.0	-3
	18	0.05	1.0	-5
	19	0.05	1.0	-7
	20	0.05	1.0	-9
6	21	0.36	0.0625	-3
	22	0.36	0.0625	-5
	23	0.36	0.0625	-7
	24	0.36	0.0625	-9
7	25	0.36	0.25	-3
	26	0.36	0.25	-5
	27	0.36	0.25	-7
	28	0.36	0.25	-9
8	29	0.36	0.375	-3
	30	0.36	0.375	-5
	31	0.36	0.375	-7
	32	0.36	0.375	-9
9	33	0.36	0.5	-3
	34	0.36	0.5	-5
	35	0.36	0.5	-7
	36	0.36	0.5	-9
10	37	0.36	1.0	-3
	38	0.36	1.0	-5
	39	0.36	1.0	-7
	40	0.36	1.0	-9

The simulation times of the cases are given in Table 4.4 and are estimated by running the first 10 simulation seconds and extrapolating that number for the whole simulation.

4.4.3. Data Sampling and Post-Processing

Post-processing is performed using OpenFOAM's built-in `sampleDict` and `probes` utilities, complemented by `ParaView` for flow field visualisation. Velocity, pressure, and sediment concentration fields are exported at 1 s intervals for temporal averaging and spatial profiling.

Sediment escape is quantified by integrating concentration flux through the outlet of the mesh. Multiply this flux and the total sediment mass leaving the mesh through the outlet provides an escape index

Table 4.4: Simulation duration for different flow velocities and depths. Difference is due to number of cells per depth and the travelling distance and velocity of the chain per sea state.

Flow Velocity (m/s)	Depth (m)	Time (min)
0.05	-3	40
0.05	-5	60
0.05	-7	120
0.05	-9	150
0.36	-3	30
0.36	-5	45
0.36	-7	90
0.36	-9	120

used to assess trench stability. Visual inspection of vorticity and concentration contours complements these quantitative metrics, enabling identification of coherent flow structures responsible for sediment entrainment.

4.5. Preliminary Simulations

Before executing the full set of coupled simulations, a series of preliminary cases were conducted to verify solver behaviour and to understand the fundamental flow and sediment mechanisms in isolation. These tests served two purposes: (i) to confirm that the solver produced physically realistic velocity and shear stress fields, and (ii) to identify characteristic flow structures that influence sediment mobilisation within the trench. Detailed results and visualisations are provided in Appendix A.

4.5.1. Steady-State Flow Fields.

Eight steady state flow fields were analysed: four depths under two sea states. Table 4.5 shows the simulation time required to reach steady flow. Longer times result from higher inflow velocities and deeper trench geometries, which require more time for flow stabilization. Simulations start with a zero flow mesh, gradually ramping up to the target velocity.

Table 4.5: Steady-state simulation time (in seconds) for different flow velocities and depths.

Flow Velocity (m/s)	Depth (m)	Steady-State Sim Time (s)
0.05	-3	200
0.05	-5	300
0.05	-7	200
0.05	-9	200
0.36	-3	1600
0.36	-5	2800
0.36	-7	1600
0.36	-9	1600

The results confirmed that the RANS–PIMPLE framework produces stable velocity fields and physically consistent near-bed shear stresses. Flow organisation within the trench evolved from weak separation zones in shallow geometries to well defined vortices in deeper ones, resulting in an average wall shear velocities of 0.0045 and 0.013 m/s, for a calm and a storm sea state, respectfully. In storm conditions, recirculation intensified, generating upward jets consistent with enhanced sediment resuspension potential, whereas calm flows favoured stable, depositional conditions. The influence of the chain lying on the seabed on the vortex driven flow inside the trench got less and less impactful as the trench got deeper and at a trench depth of $z = -5\text{m}$, the time to reach the steady state was for both sea states significantly longer, denoting the transition depth from a weak to a stronger vortex region.

4.5.2. Chain Motion in a Still Fluid.

To isolate the influence of chain motion, vertical oscillations were imposed without background current. The immersed boundary framework reproduced realistic wake formation and periodic vortex generation during upward strokes, confirming accurate momentum forcing near the moving body. Local wall shear stresses increased significantly around the chain, reaching up to 0.45 Pa in storm conditions and up to 0.0062 Pa in calm sea state. This shows that only in the storm sea state the chain motion has a significant increase the overall wall shear stress inside the trench. This shows the increase in suspension capability of the overall flow in the trench.

4.5.3. Sediment Response to Flow and Chain Forcing.

Sediment transport was assessed through an buoyancy only and combination with settling velocity tests under both calm and storm flows. In the absence of settling velocity, suspended material followed streamlines and some escaped the trench under strong flow conditions, while most still settled against the left trench wall. When a small settling velocities was included, sediment remained suspended but trapped within the recirculating vortex, confirming that background flow alone cannot cause net sediment loss. Chain motion induced local resuspension even without ambient currents but did not sustain long term escape without additional flow energy.

4.5.4. Sediment Response to Injection Position

Sediment was injected at the mid-trench horizontal position because sensitivity tests showed that the right hand side consistently forces particles into a downward jet, artificially suppressing escape. The centre location avoids this bias, ensures comparability across cases, and better reflects the assumption that suspended sediment largely follows the local flow. This provides a neutral and physically representative starting condition for evaluating escape thresholds.

These preliminary simulations demonstrate that each sub-process, hydrodynamic flow, chain motion, and sediment transport, behaves in line with theoretical expectations. They provide physical confidence in the solver's predictive capability and form the foundation for the subsequent coupled trench simulations. More detail on each of these simulations are given in Appendix A.

4.6. Validation and Sensitivity Analysis

4.6.1. Numerical Verification

Numerical consistency was confirmed through grid and time-step refinement tests. A sequence of meshes with increasing resolution near the trench floor showed less than 2% variation in mean near-bed velocity and sediment concentration, confirming spatial convergence. Reducing the time step from 1×10^{-2} to 2.5×10^{-3} s did not significantly alter velocity or concentration profiles, verifying temporal stability. The adopted discretisation and time control therefore provide sufficient accuracy for all simulated conditions. Switching from the $k-\epsilon$ turbulence closure to a $k-\omega$ SST model caused less than 4% deviation in velocity. More detail on numerical verification is given in Appendix C.

4.6.2. Physical Validation

The simulated physical system was designed to represent realistic seabed and hydrodynamic conditions typical of the North Sea. Sediment and fluid properties were based on literature values for marine sands, and the imposed flow velocities (0.05–0.36 m/s) fall within observed near-bed current ranges from the Copernicus Marine Service [7]. The mooring chain dimensions (diameter 0.23 m) correspond to those used in commercial floating wind systems [13], ensuring that the flow–structure interactions are physically representative. Two representative chain velocities were applied to capture realistic environmental conditions in the North Sea. A velocity of 0.1 m/s represents a *calm sea state*, where chain motion is limited to slow oscillations induced by mild currents. In contrast, a velocity of 0.3 m/s corresponds to a *storm sea state*. These values fall within the range inferred from dynamic mooring analyses in offshore environments, where displacements of several metres over wave periods of approximately 10 s yield segment velocities between 0.1 m/s and 1.0 m/s [14].

The computed wall shear stresses from the CFD simulations were compared with theoretical sediment mobility thresholds. The average stresses of $\tau_{\text{calm}} = 0.02$ Pa and $\tau_{\text{storm}} = 0.17$ Pa correspond to shear velocities of 0.0045 and 0.013 m/s, respectively, as mentioned in subsection 4.5.1. These values

indicate that sediment motion should be negligible under calm flow but possible for fine sands during storm flow, consistent with field expectations. Further comparison using the Rouse number confirmed that fine particles transition from partial to full suspension as flow intensity increases, see Figure 4.2, while coarse material remains immobile, as expected when taking the Rouse number per d_{50} value into account, see Table 4.6. The simulated flow fields displayed the expected near-bed shear patterns and recirculation zones, confirming that the solver captures realistic hydrodynamic and transport behaviour.

Table 4.6: Rouse number for various sediment sizes and trench flow regimes based on CFD-derived shear stress.

d_{50} [mm]	w_s [m/s]	Sea State	u_* [m/s]	Rouse Number
0.0625	0.003	Calm	0.0045	1.63
		Storm	0.0130	0.56
0.25	0.030	Calm	0.0045	16.3
		Storm	0.0130	5.63
0.375	0.052	Calm	0.0045	28.2
		Storm	0.0130	9.76
0.5	0.070	Calm	0.0045	38.0
		Storm	0.0130	13.2
1.0	0.120	Calm	0.0045	65.9
		Storm	0.0130	22.5

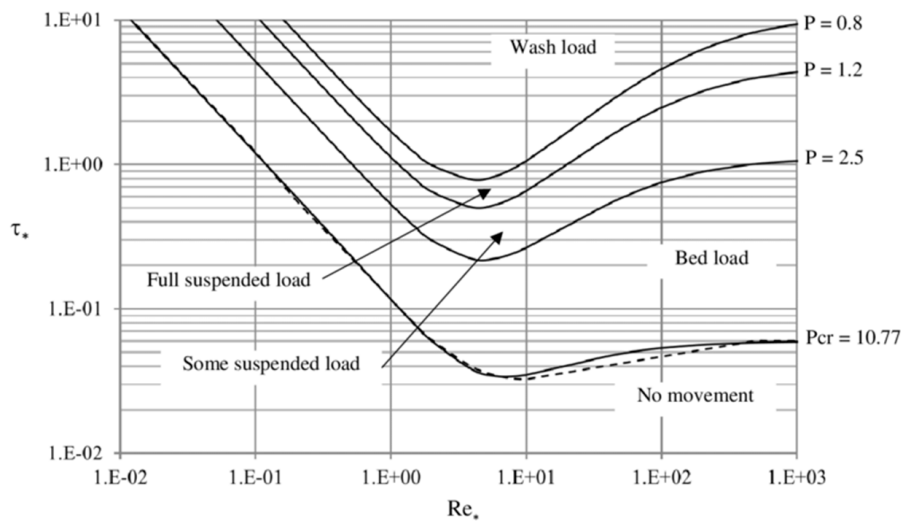


Figure 4.2: Sediment transport regimes based on Rouse number ranges [22]. The fine particles switch from partial to full suspension when entering the storm sea state.

4.7. Simulation Strategy and Execution Plan

Following the verification of flow behaviour and sediment mobility thresholds, a structured simulation campaign was designed to determine the conditions under which sediment escapes from the trench domain. The objective was to identify transition points between no escape, partial escape, and full suspension, using a computationally efficient and adaptive approach.

A traditional Design of Experiments (DoE) approach was considered but found unsuitable for this problem. DoE methods typically aim to explore the full parameter space in a uniform or statistically balanced manner, which is unnecessary in this study because large regions of the parameter space do not contribute meaningful information. Specifically, cases in which no sediment escape occurs do not influence the establishment of the stabilization threshold. What is required instead is an efficient method for locating the narrow set of edge conditions where the system transitions from no escape to escape.

To address this, a targeted simulation prioritisation method was developed. Rather than sampling the entire domain, simulations were iteratively directed toward the regions in which the transition behaviour was expected to occur, based on intermediate results from earlier runs. This adaptive approach allowed the identification of the critical boundary between escape and non-escape with far fewer simulations than a conventional DoE would require. This simulation method is based on the escape potential of each case.

4.7.1. Escape Potential Index

To efficiently explore the parameter space without exhaustively simulating all configurations, a heuristic index was developed to rank cases by their expected likelihood of sediment escape. The resulting *Escape Potential Index* (EPI) combines the dominant physical controls governing suspension, upward transport, and trench confinement. It is defined as

$$\text{EPI} = 100 \cdot \frac{1}{P} \cdot \frac{v_{\text{chain}}}{v_{\text{up,max}}} \frac{H_{\text{ref}}}{|D|}, \quad (4.9)$$

where v_{chain} is the imposed vertical chain velocity, $v_{\text{up,max}}$ the maximum upward velocity in the trench under background flow, P the Rouse number, and D the trench depth. The reference height $H_{\text{ref}} = 2$ m represents the distance travelled by the chain above the original sea floor. The reference height $H_{\text{ref}} = 2$ m was chosen as a representative distance at which the chain has fully exited the trench and begins to interact with the overlying flow field. Although the actual chain excursion varies with sea state and does not always reach exactly 2 m, the purpose of H_{ref} in the EPI is to provide a consistent and physically meaningful reference for comparing different sediment-flow regimes rather than reproducing case specific motions.

Figure 4.3 shows the full distribution of EPI values for all grain sizes and trench depths. Higher EPI values correspond to stronger escape potential. Each term in the index reflects a specific physical mechanism:

- A higher ratio $\frac{v_{\text{chain}}}{v_{\text{up,max}}}$ increases the potential; slower chain motion relative to upward flow reduces escape likelihood.
- The Rouse number appears in the denominator: larger P indicates dominant settling over shear-driven suspension, lowering escape potential.
- Dividing by $|D|$ accounts for confinement; deeper trenches reduce the effective influence of chain motion and thus reduce the index.

To better illustrate how escape potential varies systematically with depth and sea state, Figure 4.4 shows the depth averaged EPI for calm and storm conditions. A notable feature is the pronounced dip at $z = 5$ m under storm flow. This anomaly corresponds to a locally reduced upward velocity in the trench (see chapter 6), which also caused this depth to require a longer time to reach steady state (Table 4.5). This depth marks a transitional regime between weak and strong vortex shedding, as further examined in Appendix A.

The complete EPI-based ranking used to guide simulation order is provided in Appendix A, Table A.1. Importantly, the EPI was not intended as a deterministic predictor of escape, but as a practical mechanism to identify the most informative “edge-case” configurations early in the simulation campaign, but after its initial use as a prioritisation metric, the EPI also proved physically meaningful, helping to interpret why certain configurations escape while others remain stable. This will be explained further in subsection 5.2.3

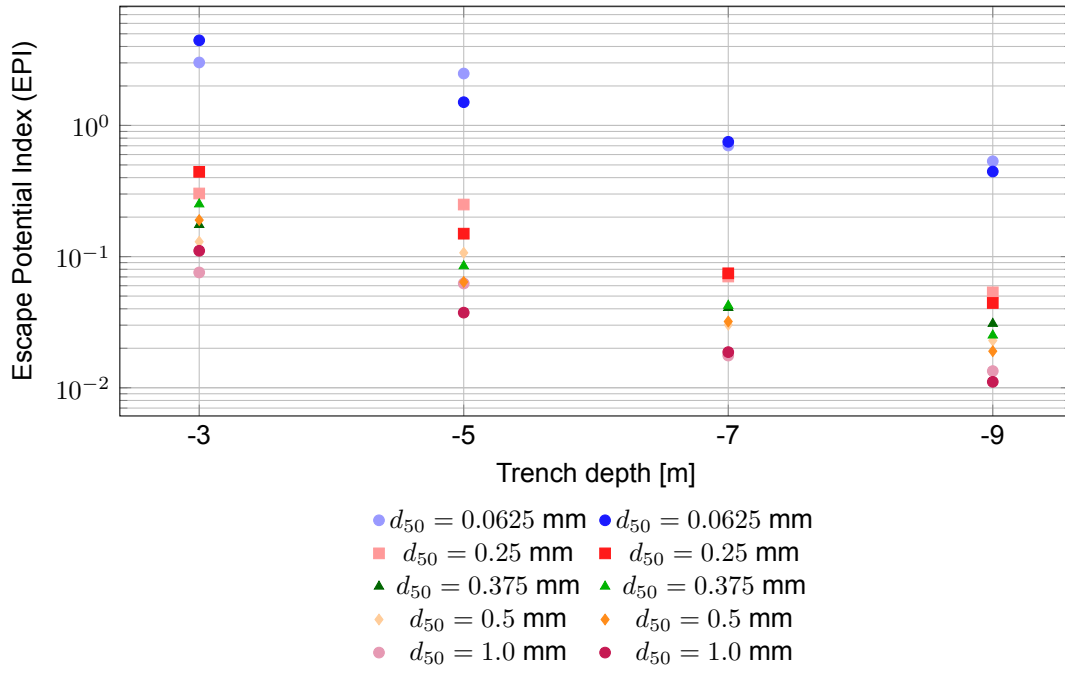


Figure 4.3: Escape Potential Index (EPI) distribution for all simulated configurations. Each grain size (d_{50}) shares one marker shape; lighter shades represent calm flow ($U = 0.05$ m/s), darker shades represent storm flow ($U = 0.36$ m/s). Depth increases from right to left.

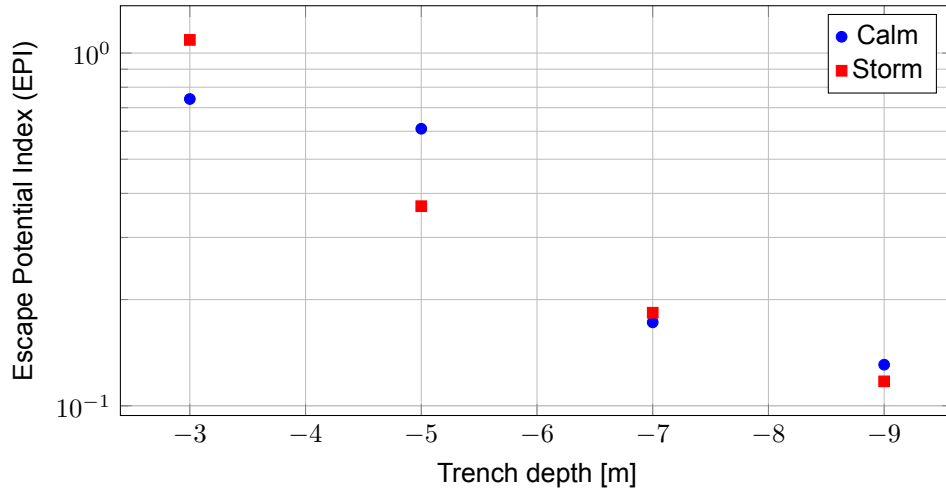


Figure 4.4: Distribution of Escape Potential Index (EPI) values by trench depth and sea state (reversed X-axis). Higher EPI indicates greater escape potential.

4.7.2. Execution Logic

Each simulation was evaluated for escape using two complementary criteria: (i) visual monitoring of soil concentration fields in ParaView and (ii) quantitative calculation of the outlet mass flux, integrated over time. A case was classified as “escape” when more than 10^{-5} of the sediment mass left the domain. Starting with a mass of 0.06 this gives minimum escape of 0.0166% to classify as escape. An adaptive edge-case approach was applied: initial runs focused on the most extreme cases (deepest and shallowest trenches with finest and coarsest sediments). Depending on whether these cases produced escape, intermediate ones were simulated next to pinpoint the escape threshold.

This adaptive strategy avoided redundant simulations, refined the empirical correlation between EPI and observed escape, and allowed progressive identification of critical transition regimes. More detail

are given in Appendix A.2.4.

5

Results

5.1. Qualitative Results: Overview of Preformed Simulations

The qualitative analysis examines the physical mechanisms governing sediment behaviour in the two sea states. Rather than quantifying the magnitude of sediment loss, this section focuses on identifying whether escape occurs, how chain motion and trench geometry interact to produce suspension, and which flow structures dominate under calm and storm forcing. These mechanistic observations form the basis for the quantitative threshold analysis presented later in Section 5.2.

5.1.1. Calm Sea State Results

Under calm conditions ($U_{in} = 0.05$ m/s; $v_{chain} = 0.1$ m/s), flow energy and shear stress were lower than in the storm regime. From the preliminary simulations it was found that the weaker background flow produced a stable recirculation cell inside the trench, and chain-induced motion remained mostly confined to the near-bed region. The shear velocity produced by the chain movement was significantly lower in this scenario. Overall, sediment escape was therefore limited to a few shallow, fine-grained cases.

Observed Escape Behaviour

For the finest sediment ($d_{50} = 0.0625$ mm), escape occurred in all trench depths. Even though the flow was weak, the small grain size and low settling velocity ($w_s = 0.003$ m/s) allowed the chain's upward stroke to lift suspended material into the near-surface layer across most depths (see Figure 5.1). This behaviour is consistent with the low Rouse number associated with this grain size, which predicts sustained suspension following the downward chain motion.

For the deepest trench, the upward motion alone was insufficient to lift the sediment out of the trench. However, the downward motion of the chain generated enough suspension to elevate the material high within the trench. This reduced the effective transport distance during the next upward stroke, essentially causing the deep trench to behave like a shallow one. Figure 5.2 illustrates this behaviour: sediment does not escape during the first upward motion but is gradually lifted along the trench flanks as the chain impacts the seabed and the material does not fully resettle before the next cycle. This makes for an relative short travelling distance for the soil and therefore the second upward motion does result in soil escape.

For $d_{50} = 0.25$ mm, escape was only observed in the shallowest trench ($z = -3$ m). The downward motion of the chain suspended a relatively large portion of the soil, similar to the behaviour seen for the finer grain size, and this suspension was the primary mechanism enabling escape. The next depth ($z = -5$ m) did not mobilize enough suspended soil during the downward motion and the subsequent upward motion lacked the strength to transport sediment over the required distance. The transition between Cases 5 and 6 marks the threshold between escape and no escape, corresponding to an EPI range of 0.25–0.30.

This depth dependent behaviour is primarily governed by the relative volume of the chain compared to

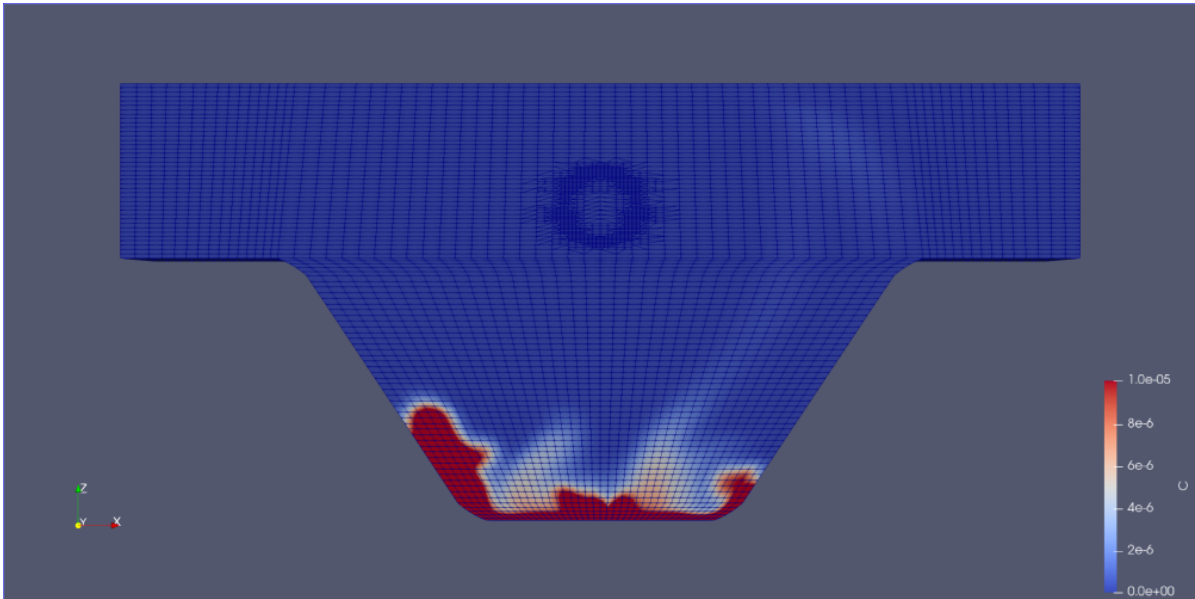


Figure 5.1: Fine-sand sequence under calm flow ($d_{50} = 0.0625$ mm, $z = -3$ m): sediment escapes during the first upward chain motion.

the trench. The shallow trench confines the chain more tightly, causing a larger proportion of the trench volume to be displaced during the downward stroke. This produces substantially more suspended material, which the subsequent upward stroke can then lift toward the outlet. In the deeper trench, the chain occupies a smaller fraction of the available volume, reducing the degree of mobilisation and preventing escape.

Sediment sizes $d_{50} = 0.375$ mm to $d_{50} = 1$ mm did not escape at any depth. In some cases particles were temporarily lifted onto the chain surface during the first upward motion but quickly slipped back due to insufficient carrying capacity. The flow field was dominated by gentle recirculation with no coherent upward jet formation resulting in no suspension, as predicted by the Rouse number.

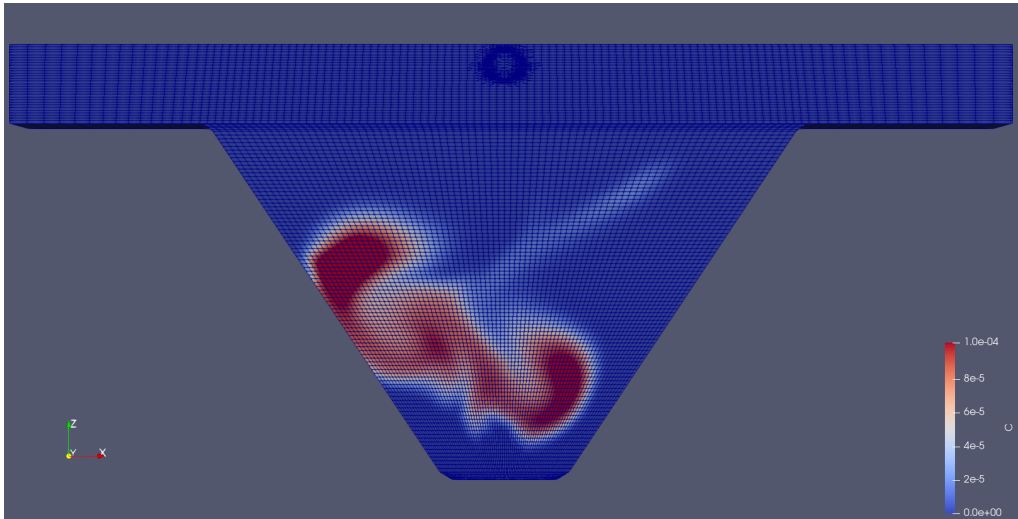
Characteristic Motion Patterns

Across the calm sea state simulations, two characteristic modes of flow–sediment interaction were observed. These modes reflect how the chain motion interacts with the suspended sediment column and explain the contrasting escape behaviours described in the previously.

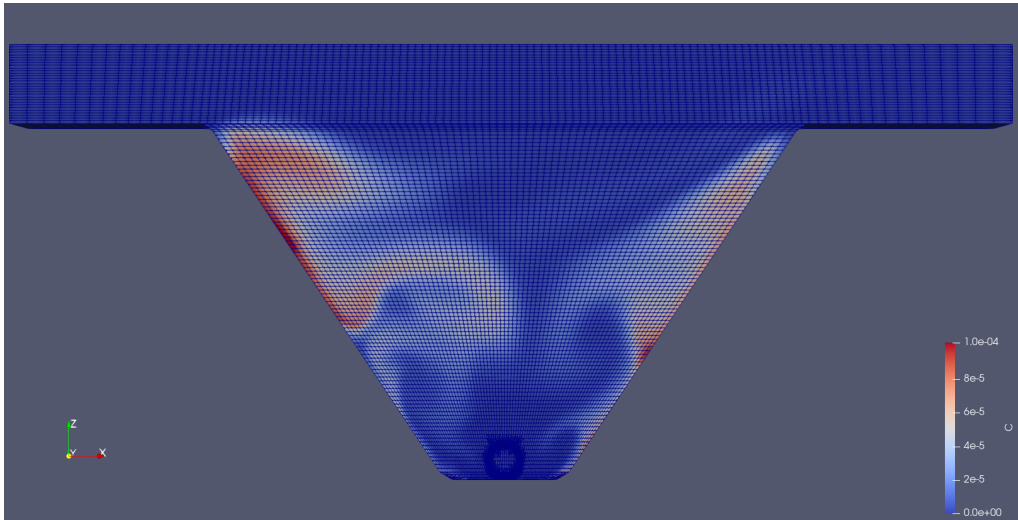
1. **Weak coupling:** in most cases, the relatively low chain velocity generates only mild, localised recirculation near the trench base. Fine sediments ($d_{50} = 0.0625$ mm) oscillate with each chain stroke and can immediately escape, while coarser grains ($d_{50} \geq 0.375$ mm) remain largely immobile and form a stable bed. Here, the chain motion influences the sediment, but the imparted momentum is insufficient to lift material towards the shoulder of the trench.
2. **Momentum transfer:** in the shallow fine sediment cases, particularly for $d_{50} = 0.0625$ mm and in the $z = -3$ m trench for $d_{50} = 0.25$ mm, the upward stroke of the chain imparts enough vertical momentum to the already suspended material to lift the sediment column to the outlet. At large depths, this mechanism becomes especially effective when the downward stroke has elevated the sediment high within the trench, shortening the required travel distance for escape.

EPI Threshold Evaluation

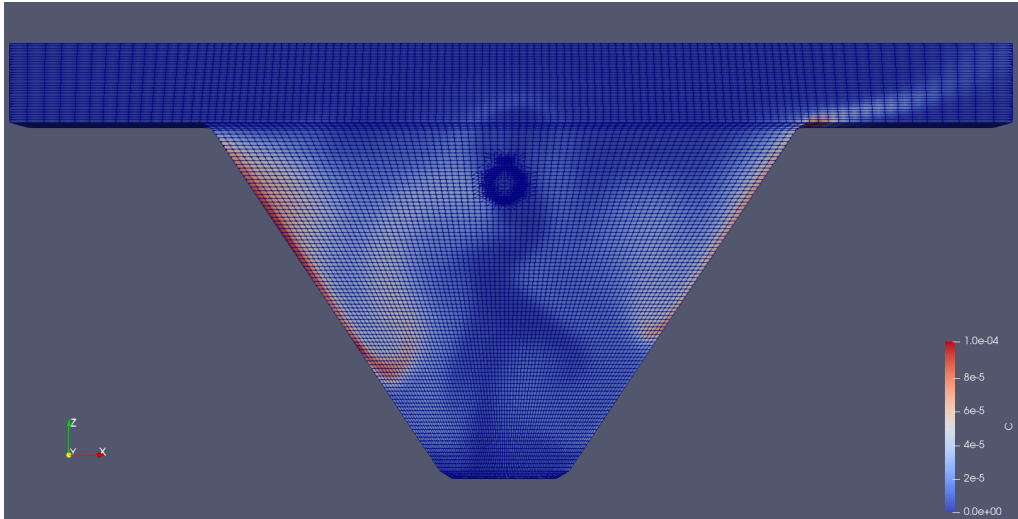
The EPI correctly predicted the onset of escape for the fine and very fine sands. The observed threshold range (EPI = 0.30–0.25) separates escape from full retention and is consistent with the behaviour identified in the simulations. Only a limited number of cases produced escape, yet none of the non-escaping cases exhibited EPI values within this range. This absence of overlap indicates that, for the present dataset, the identified threshold reliably distinguishes between escaping and non-escaping conditions.



(a) Soil does not escape during the first upward chain motion.



(b) Soil moves up due to downward motion of the chain and almost makes the soil escape the trench.



(c) Soil escapes the trench on the second upward motion.

Figure 5.2: Sequence of Case 4 soil movement: the soil escape happens due to downward motion.

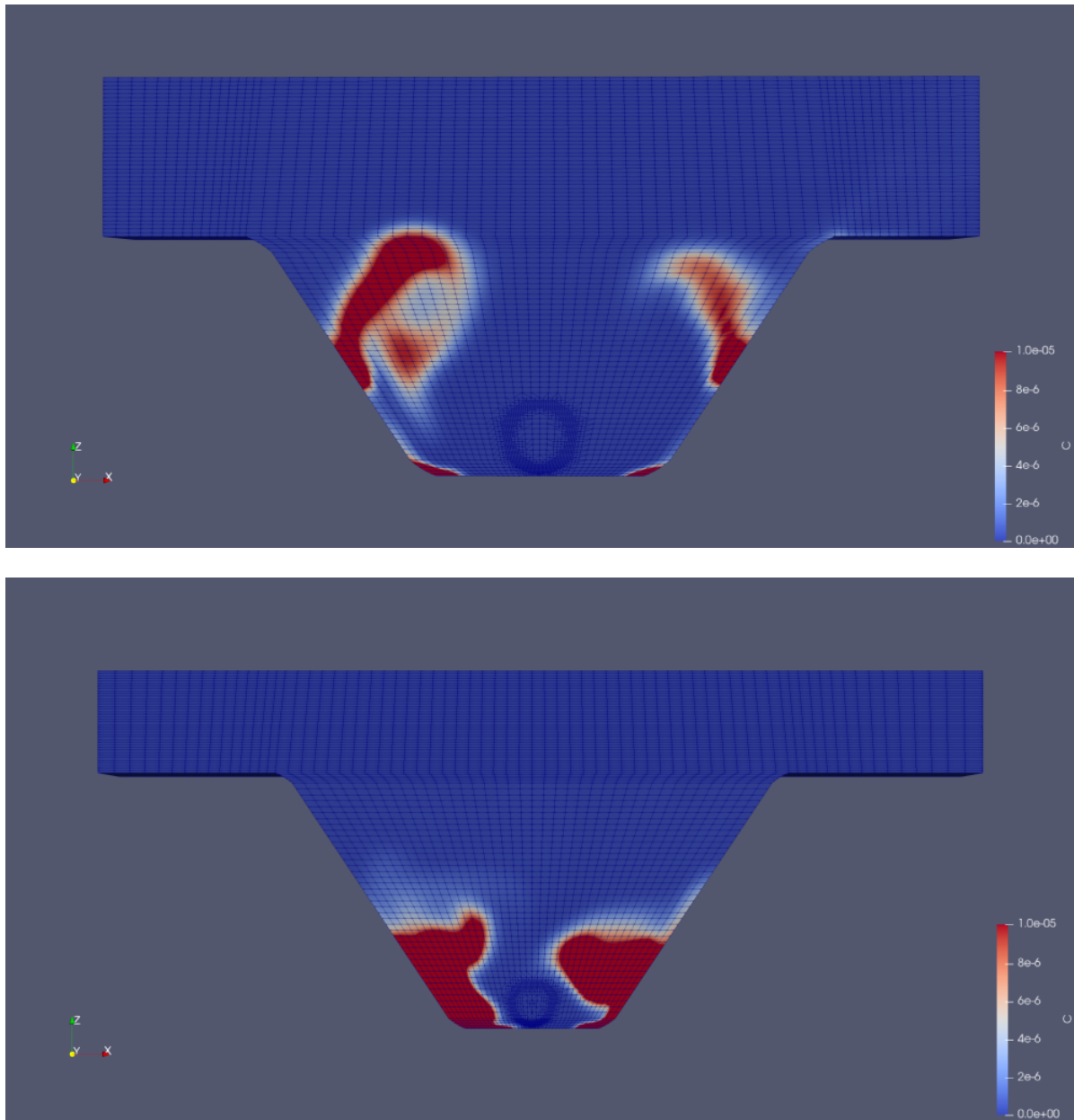


Figure 5.3: Comparison of Cases 5 (top) and 6 (bottom) after the downward chain motion. The only difference is trench depth (-3 m vs. -5 m), which strongly affects the volume and height of soil mobilised. The shallow trench experiences much greater suspension because the chain occupies a larger fraction of the trench volume.

Table 5.1: Observed escape behaviour under calm sea state conditions as a function of sediment size and trench depth.

Depth (m)	0.0625 mm	0.25 mm	0.375 mm	0.5 mm	1.0 mm
−3	Escape	Escape	None	None	None
−5	Escape	None	None	None	None
−7	Escape	None	None	None	None
−9	Escape	None	None	None	None

Summary

Sediment escape under calm conditions is rare and occurs only for the finest grain sizes and at shallow trench depths. Although the chain motion is capable of mobilising material, it does not generate sufficient or sustained upward transport once the particles exceed a critical grain size or the trench geometry limits suspension. As a result, the trench behaves predominantly as a depositional environment, with escape occurring only in cases where fine material remains suspended high within the trench between chain strokes. An overview of the observed behaviour is provided in Table 5.1, and additional case specific results are given in Appendix A.2.6.

5.1.2. Storm Sea State Results

Under storm conditions ($U_{in} = 0.36$ m/s; chain velocity $v_{chain} = 0.3$ m/s), strong vortex formation and a persistent upward jet developed by the chain motion are found in all simulations. This greatly increased sediment resuspension compared to the calm regime. Escape behaviour was governed jointly by grain size and trench depth, with the storm flow dominating the near-bed dynamics.

Observed Escape Behaviour

Figure 5.4 shows the typical flow pattern for the storm regime. A central upward jet forms above the chain and extends through the water column, while counter-rotating vortices near the trench corners enhance mixing and vertical entrainment. This pattern is consistent across all depths but becomes more confined as the trench deepens as the overall velocity inside the trench increases, see section 4.5.

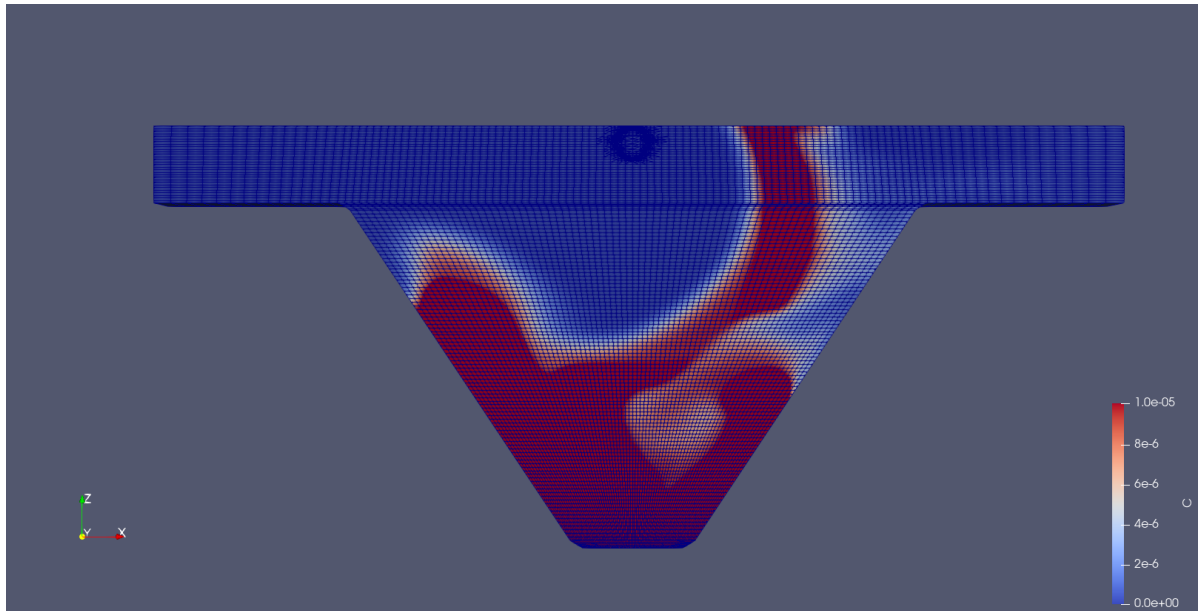


Figure 5.4: Representative storm case ($d_{50} = 0.0625$ mm, $z = -9$ m). Soil escapes vertically along the trench centreline. Red regions indicate concentrations above 10^{-5} . Current is from left to right

For the finest sediment ($d_{50} = 0.0625$ mm), soil escape occurred in all trenches, confirming full suspension under storm forcing ($P < 1$). Sediment was lifted vertically by the chain-induced jet and remained in suspension throughout the domain.

For $d_{50} = 0.25$ mm, escape was still observed across all depths, but the transport pathway shifted. Instead of uniform vertical rise, particles followed the recirculation vortex and exited primarily through the downstream outlet, as illustrated in Figure 5.5. Shallower trenches exhibited the most escape, while deeper configurations retained most of the suspended material near the sidewalls.

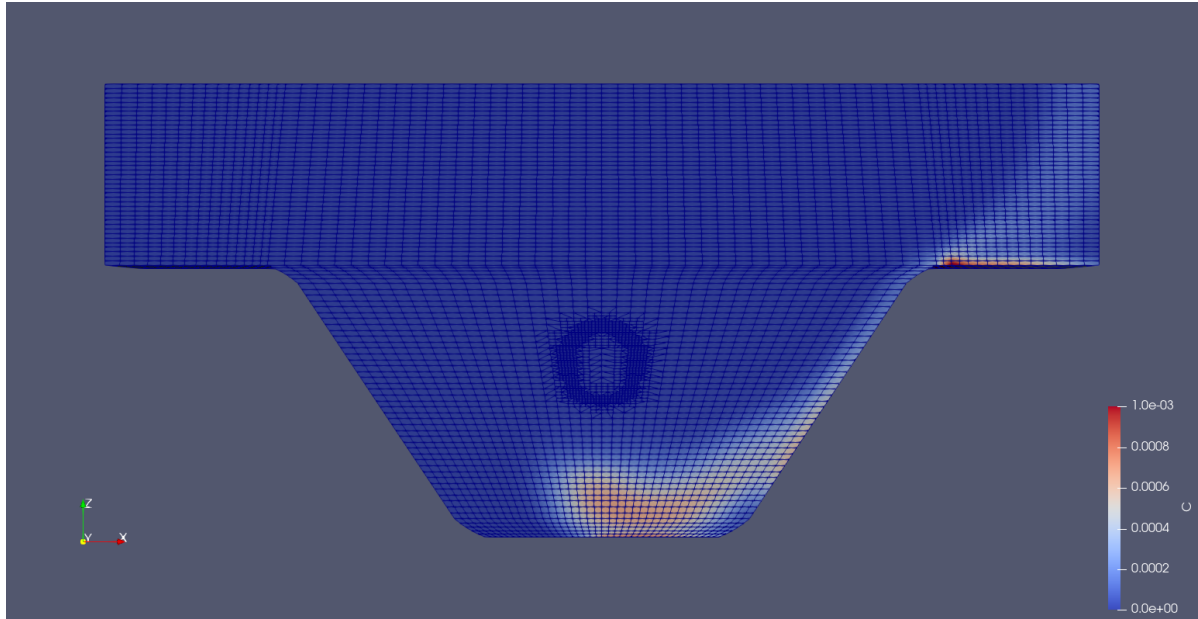


Figure 5.5: Outlet escape for a medium sand storm case ($d_{50} = 0.25$ mm, $z = -3$ m). Chain-induced motion couples with the background flow to eject sediment through the downstream outlet.

For $d_{50} = 0.375$ mm, escape was restricted to the two shallowest trenches ($z = -3$ and -5 m). Deeper cases still showed confined vortex circulation and local resuspension, but without escape.

At $d_{50} = 0.5$ mm, only the shallowest trench showed clear soil escape. The upward momentum produced by the chain and the flow still exceeded the local settling velocity, making it capable of transporting the soil. But deeper trenches had either lower flow velocity ($z = -5$) or the travelling distance of the soil by the chain was too large to result in soil escape.

For the coarsest sediment ($d_{50} = 1.0$ mm), a small but noticeable amount of soil escaped from the shallowest case ($z = -3$ m). The escape only happened at the first upward movement and all the other soil settled while no suspension was noticed during the rest of the simulation.

Characteristic Escape Mechanisms

Across all storm simulations, sediment was exported through two dominant mechanisms:

1. **Vertical escape** — small grained sediment is lifted directly upward by chain-induced jets interacting with the main recirculation vortex at sufficiently high velocities to transport sediment through the upper domain boundary. (Figure 5.4);
2. **Outlet escape** — larger sediment was lifted due to the combined strength of the flow and the chain, where lateral entrainment by the vortex core was stronger than the upward momentum and transported sediment toward the downstream outlet rather than allowing it to resettle or exit the domain through the top. (Figure 5.5).

A secondary process, similar to that observed in calm conditions, was also present: the downward chain motion produced upward wall jets along the trench flanks. These jets displaced sediment toward the rim but caused limited net escape. Here the threshold lies between a grain size of 0.25 and 0.375 mm.

EPI Threshold Evaluation

The EPI correctly ranked most escaping cases but some. All trenches shallower than 5 m exhibited escape regardless of EPI variation, while deeper trenches ($z \leq -7$ m) retained most sediment except

for fine grains ($d_{50} \leq 0.25$ mm). The single coarse sand escape case ($d_{50} = 1.0$ mm, $z = -3$ m) indicates that strong forcing and short confinement distances can locally exceed threshold predictions. There is overlap in EPI values from 0.0443–0.0641 for cases that show escape and those that do not, which indicates that EPI is not capable of giving a clear threshold on its own. How it can be used is explained in subsection 5.2.3.

Summary

Storm forcing substantially enhances sediment mobility by strengthening vortex circulation and chain–flow coupling. Fine sediments escape vertically in all trench depths, while medium and intermediate sands transition from vertical to outlet dominated transport depending on confinement. Coarse grains remain largely trapped except in the shallowest configurations, where the combined storm jet and reduced travel distance permit limited escape. Overall, the storm regime demonstrates that increasing flow energy broadens the range of grain sizes capable of escaping, but the influence of trench depth remains decisive in determining whether suspended sediment can ultimately leave the system.

Table 5.2 gives an overview for all storm cases.

Table 5.2: Observed escape behaviour for storm sea state cases as a function of sediment size and trench depth.

Depth (m)	0.0625 mm	0.25 mm	0.375 mm	0.5 mm	1.0 mm
–3	Escape	Escape	Escape	Escape	Escape
–5	Escape	Escape	Escape	None	None
–7	Escape	Escape	None	None	None
–9	Escape	Escape	None	None	None

More details for all storm cases are provided in appendix A.2.5.

5.1.3. Combined Interpretation of Sea States

To assess the combined effect of hydrodynamic forcing, grain size and trench geometry, the calm and storm simulations are compared in Table 5.3. The table summarises all 40 cases, grouped by sediment grain size and trench depth. This overview highlights how sediment mobility transitions with both energy level and confinement and highlights how sediment mobility shifts when moving from weak to energetic flow conditions.

Table 5.3: Comparison of observed soil escape across calm and storm sea states for all tested sediment sizes and trench depths.

Depth [m]	0.0625 mm		0.25 mm		0.375 mm		0.5 mm		1.0 mm	
	Calm	Storm	Calm	Storm	Calm	Storm	Calm	Storm	Calm	Storm
–3	Yes	Yes	Yes	Yes	None	Yes	None	Yes	None	Minor
–5	Yes	Yes	None	Yes	None	Yes	None	None	None	None
–7	Yes	Yes	None	Yes	None	None	None	None	None	None
–9	Yes	Yes	None	Yes	None	None	None	None	None	None

Cross-State Patterns

Three key trends emerge when comparing the calm and storm simulations. It is worth noting that the increase in background shear inside the trench does not scale proportionally with the increase in free stream velocity; the implications of this behaviour are discussed in Section 6.1.2.

1. **Depth-controlled stability.** Across both flow regimes, increasing trench depth consistently suppresses escape by reducing the relative influence of chain induced motion and increasing geometric confinement. Below $z = -7$ m, all sediment classes except the finest fraction remained

trapped. This behaviour is strongly linked to the decreasing chain-to-trench volume ratio with depth: as the available space increases, the downward chain motion displaces a smaller proportion of the trench volume, reducing its ability to generate suspended material.

2. **Grain-size dependence.** The transition between mobile and stable behaviour shifts with flow energy. In calm conditions the threshold lies between $d_{50} = 0.0625\text{--}0.25$ mm, whereas in storm conditions it increases to between $d_{50} = 0.25\text{--}0.375$ mm. Finer sands remain mobile across all depths, while coarser fractions ($d_{50} \geq 0.5$ mm) mobilise only when storm driven vortices substantially enhance the lifting potential.
3. **Non-linear sea-state response.** The transition from calm to storm conditions produces a much larger increase in escape occurrence than the change in inflow velocity alone would suggest. Storm forcing activates vertical jetting and strong lateral entrainment, enabling outlet or upward escape even for material that remains entirely stable in the calm regime. This illustrates that escape is controlled by threshold driven changes in vortex strength, not by a linear response to flow speed.

Interpretation

Taken together, the results show that seabed trench behaviour arises from a coupled balance between flow energy, sediment properties, and geometric confinement. Fine sands are highly mobile even in calm conditions, implying that natural backfilling of trenches composed of such material is unlikely to persist. Coarser sediments, by contrast, become mobile only during high energy storm events. This indicates that storms function as intermittent resetting mechanisms that remove accumulated fines, mobilise intermediate sediment classes, and episodically reshape the trench profile.

Taken together, the qualitative analysis establishes which combinations of trench depth, grain size, and flow regime lead to sediment escape. These results identify the mechanisms responsible for mobilising or retaining material but do not quantify the magnitude of transport. To determine how strongly each configuration contributes to net sediment loss, a quantitative evaluation of the escape ratios is presented next.

5.2. Quantitative Results: Metrics and Threshold Identification

Building on the qualitative classification of escape versus no escape, this section examines *how much* sediment is transported for each case. The escape ratios provide a direct measure of mobility and allow the depth–grain size thresholds to be expressed in terms of smooth quantitative trends rather than binary outcomes. This enables a more precise identification of stability boundaries in relation to both confinement and sediment properties.

In the following sections, depth–grain size thresholds are identified, followed by an evaluation of the Escape Potential Index (EPI), and finally a combined Rouse–EPI framework is developed to characterise the transition between mobility and stability across all cases.

5.2.1. Depth–grain size thresholds

For all sediment classes, escape ratios decrease sharply with increasing depth. Shallow trenches ($z = -3$ m) exhibit the highest mobility, while deeper trenches ($z \leq -7$ m) show zero escape for all but the finest two sediment sizes. This behaviour reflects the increasing carrying distance and the reduced effectiveness of chain-induced jetting in deeper geometries. The dip in escape ratio at $z = -5$ m, discussed further in chapter 6, marks a transition region where neither chain-soil distance is small enough to result in escape on its own nor increase in vortex strength that it fully compensates for the growing volume.

Figure 5.6 shows the depth–escape relationship for each grain size. Rather than repeating case-specific outcomes, the depth–escape curves clarify how each sediment class responds to increasing confinement:

- Silt to fine sand ($d_{50} = 0.0625\text{--}0.25$ mm). The escape ratio remains consistently above zero across all depths, indicating that even deep trenches do not fully confine these fractions. The dip at $z = -5$ m marks a local minimum in transport efficiency identified earlier as a decrease in ambient flow velocity (Appendix A, now expressed as a quantitative reduction in escape magnitude).

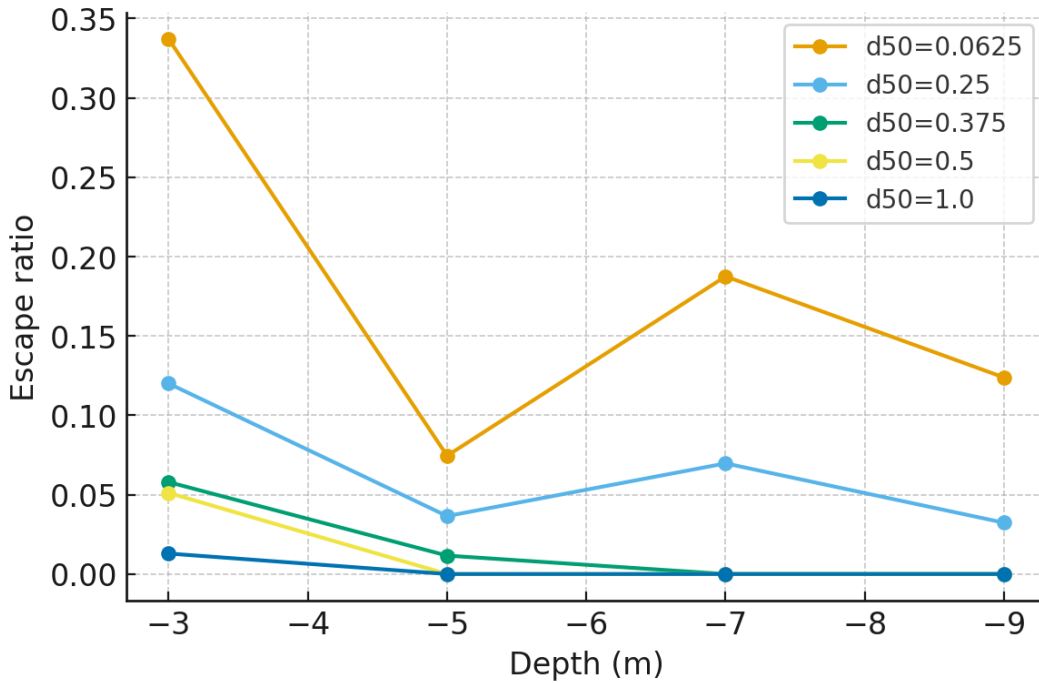


Figure 5.6: Escape rate shown for the storm cases. These lines define a stability boundary in (z, d_{50}) -space: trenches deeper than 5–7 m retain all but the very finest material.

- Intermediate sand ($d_{50} = 0.375$ mm). The curves show a steep decline from moderate escape at $z = -3$ m to zero escape at greater depths, producing a sharp cutoff in the depth–grain size plane. This identifies a quantitative stability boundary, complementing the mechanism-based interpretation from the qualitative results.
- Coarse sands ($d_{50} = 0.5$ – 1.0 mm). Escape ratios are near zero for all depths, with only a small non-zero value at $z = -3$ m. This confirms that even when escape occurs, the transported fraction is minimal, consistent with their high settling velocities.

Overall, the curves in Figure 5.6 show a clear stability boundary in (z, d_{50}) -space: trenches deeper than approximately 5–7 m retain all but the very finest material.

A case by case overview of the amount of soil escape is given in the appendix, Table A.4.

5.2.2. Validation of EPI trends

To evaluate whether the Escape Potential Index (EPI) can predict sediment escape, the measured escape ratios were compared to the corresponding EPI values. Because escape in the calm regime aligned cleanly with the EPI ordering, this analysis focuses on the storm cases where the transition behaviour is more complex.

Figure 5.7 shows the relationship between escape ratio and EPI for the storm cases, coloured by grain size and grouped by trench depth. Although higher EPI values generally correspond to larger escape ratios, the plot also reveals that escape does not occur at a single universal threshold. Several cases with relatively high EPI values, particularly for coarser grains at moderate depths, still show no escape, demonstrating that EPI alone is insufficient as a deterministic criterion.

The shaded background in Figure 5.7 makes this behaviour explicit by dividing EPI-space into three regions:

- a no-escape region (red) at low EPI values, where all cases remain fully confined;
- a transition zone (yellow), where escape depends strongly on grain size, trench depth, and sea state;

- an escape region (green) at high EPI values, where all cases exhibit measurable sediment loss.

This banded structure explains why EPI performs well as a *relative indicator* within a fixed hydrodynamic regime but fails to cleanly separate escaping from non-escaping cases across the entire parameter space. In calm conditions, escape initiates at approximately $EPI = 0.25\text{--}0.30$, whereas under storm forcing escape already appears at much lower values ($EPI = 0.064\text{--}0.085$). These distinct threshold bands illustrate the influence of background-flow energy on suspension behaviour and confirm that EPI alone cannot serve as a universal escape criterion.

Instead, EPI should be interpreted as a complement to the Rouse number: the Rouse number characterises the intrinsic suspension tendency of each grain size, while EPI captures how chain-induced uplift and trench confinement modify that environment. Their combined behaviour is analysed in the following subsection.

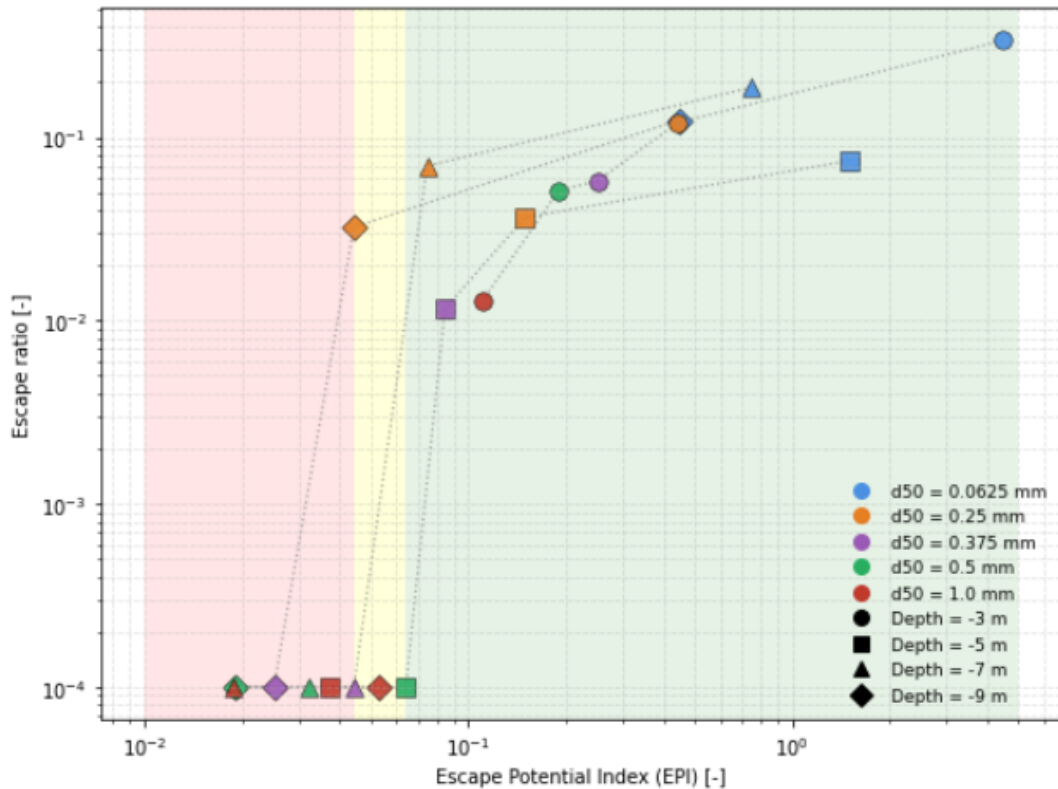


Figure 5.7: Escape ratio versus EPI for the storm cases, coloured by grain size and marked by trench depth. The plot shows that while higher EPI values correlate with larger escape ratios, escape does not occur consistently for a fixed EPI threshold.

5.2.3. Combined Rouse--EPI separation

Since EPI alone does not provide a universal threshold separating escape from non-escape cases, the next step is to examine how it interacts with the classical suspension proxy: the Rouse number. Plotting all cases in Rouse–EPI space (Figure 5.8) reveals that the two parameters complement one another rather than duplicating information. Although the Rouse number is contained within the definition of EPI, its role in the combined plot is different: the horizontal axis represents the background flow's intrinsic ability to suspend grains, while the vertical axis reflects how that suspension environment is modified by chain forcing and trench confinement. In this sense, EPI acts as a *vertical extension* of the Rouse axis, adding the influence of local uplift and geometry on top of the classical suspension behaviour.

The dashed blue line marks the conventional suspension limit at $P = 2.5$. Classical theory would predict negligible suspension to the right of this line, yet several cases in this region show clear escape. This confirms that chain-induced uplift can override the background flow limitation captured by the Rouse number alone.

When both metrics are plotted together, a remarkably consistent structure emerges: most escape cases fall above an increasing diagonal band, while most non-escape cases lie below it. The behaviour is well approximated by a standard logarithmic function:

$$\log_{10}(\text{EPI}) = a + b \text{Rouse},$$

with $a \approx 0.018$ and $b \approx 0.02$.

This diagonal separation captures a physically intuitive condition. It shows that escape requires the background flow to be energetic enough to permit partial suspension (low to moderate Rouse) and chain-induced uplift must be sufficiently strong compared to trench confinement (high EPI).

The combined Rouse–EPI space therefore provides a much clearer and more robust separation than either variable individually. Instead of a single scalar threshold, the result is a threshold that adapts to grain size, trench depth, and sea state. Specific cases that deviate from this trend are discussed in chapter 6.

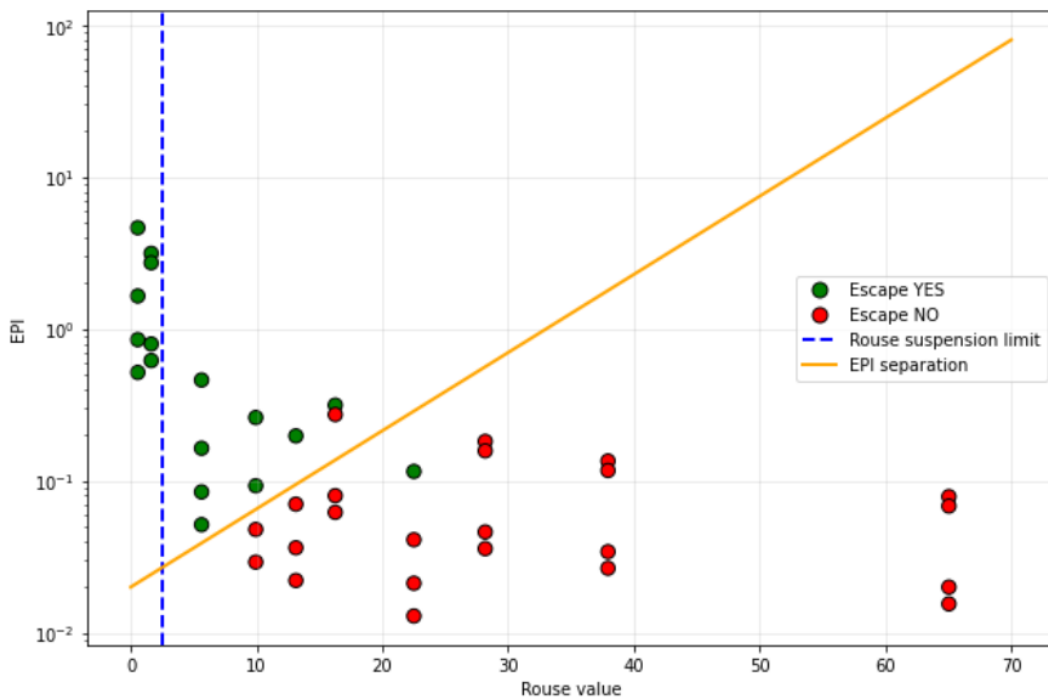


Figure 5.8: Combined Rouse–EPI distribution of all cases on a log scale for y-axis. Green symbols indicate escape and red symbols indicate no escape. The yellow line marks the empirical transition band that separates most escape cases from non-escape cases.

5.3. Application to North Sea Development Potential

The trench stability thresholds derived in this study make it possible to translate the simulation results into practical guidance for floating offshore wind development. By linking sediment grain size and trench depth to the likelihood of anchor exposure, which is directly correlated to the EPI, the results can be used to identify areas where mooring trenches will stabilise naturally without additional seabed protection.

Figure 5.9 shows the bathymetry of the North Sea. The deeper central basin is too deep for bottom fixed foundations, which underlines the growing relevance of floating offshore wind in this region. The sediment distribution in Figure 5.10 indicates that large parts of the deeper basin consist of medium to coarse sands. Based on the trench–stability limits identified earlier (Section 5.2), Figure 5.10 shows the area where the sediments are suitable to prevent trenches from extending beyond approximately 5–7 m. This means that anchors placed below this depth are unlikely to be exposed by long term chain

motion. As a result, these regions are suitable for floating offshore wind without requiring interventions such as rock or sand dumping.

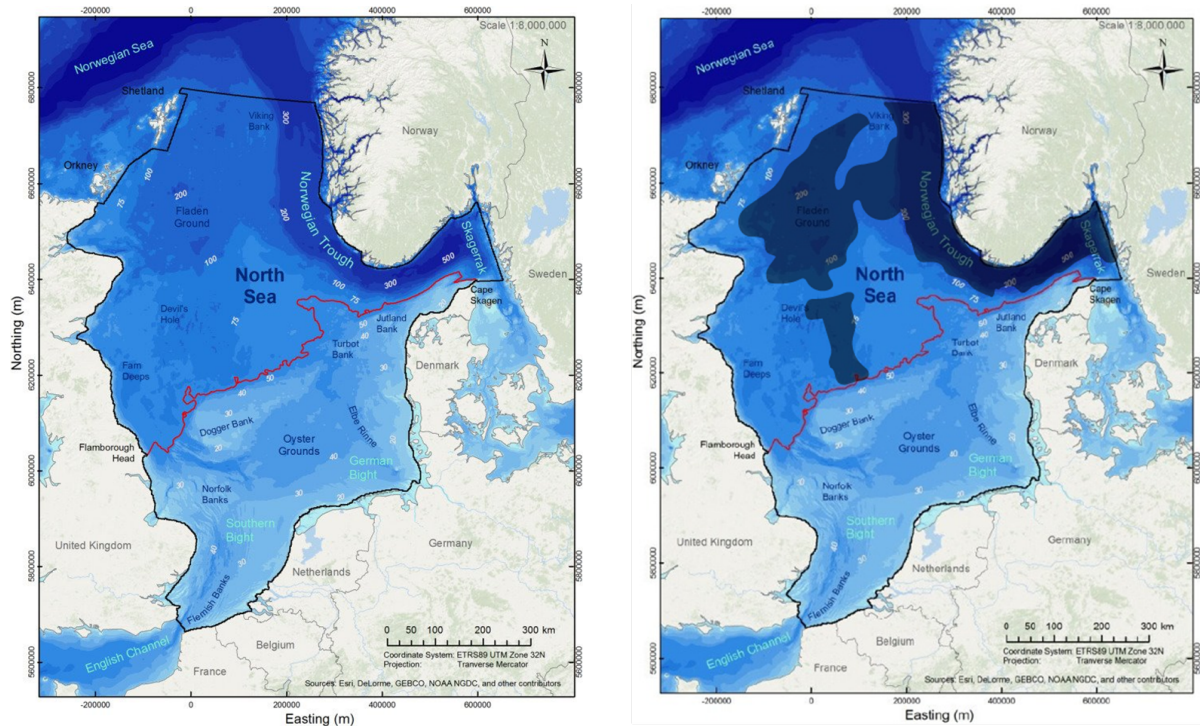


Figure 5.9: Comparison of bathymetry maps for the North Sea. The black contour indicates the deep water region where floating foundations become necessary. Taken and altered from [3]

Figure 5.11 presents the projected offshore wind build-out towards 2035, where the shallow coastal zones are already largely occupied by bottom fixed wind farms. Floating concepts therefore provide one of the few remaining options for further expansion.

By combining bathymetry, and sediment composition, it becomes clear that a substantial part of the deeper North Sea is geotechnically favourable for floating concepts. The new suitable zones represent a significant expansion potential compared to the currently used shallow areas.

Overall, the trench–stability threshold developed in this research provides a direct link between local seabed processes and large scale offshore wind planning. It allows developers and policymakers to identify zones where floating wind turbines can operate without additional seabed reinforcement, supporting more efficient use of the deeper North Sea.

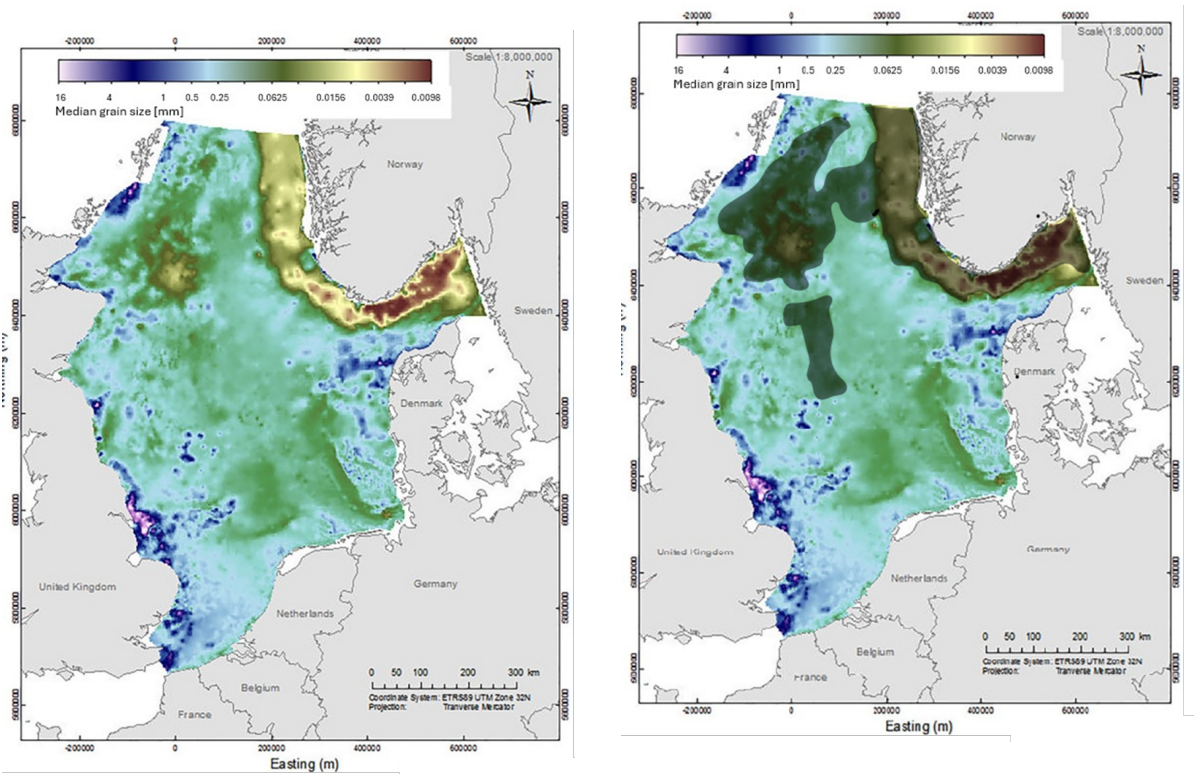


Figure 5.10: Median grain size (d_{50}) distribution. Coarser regions align with naturally stable trenches. Darkened area is not suitable for floating offshore wind due to anchor mooring trenches. Taken and altered from [3]

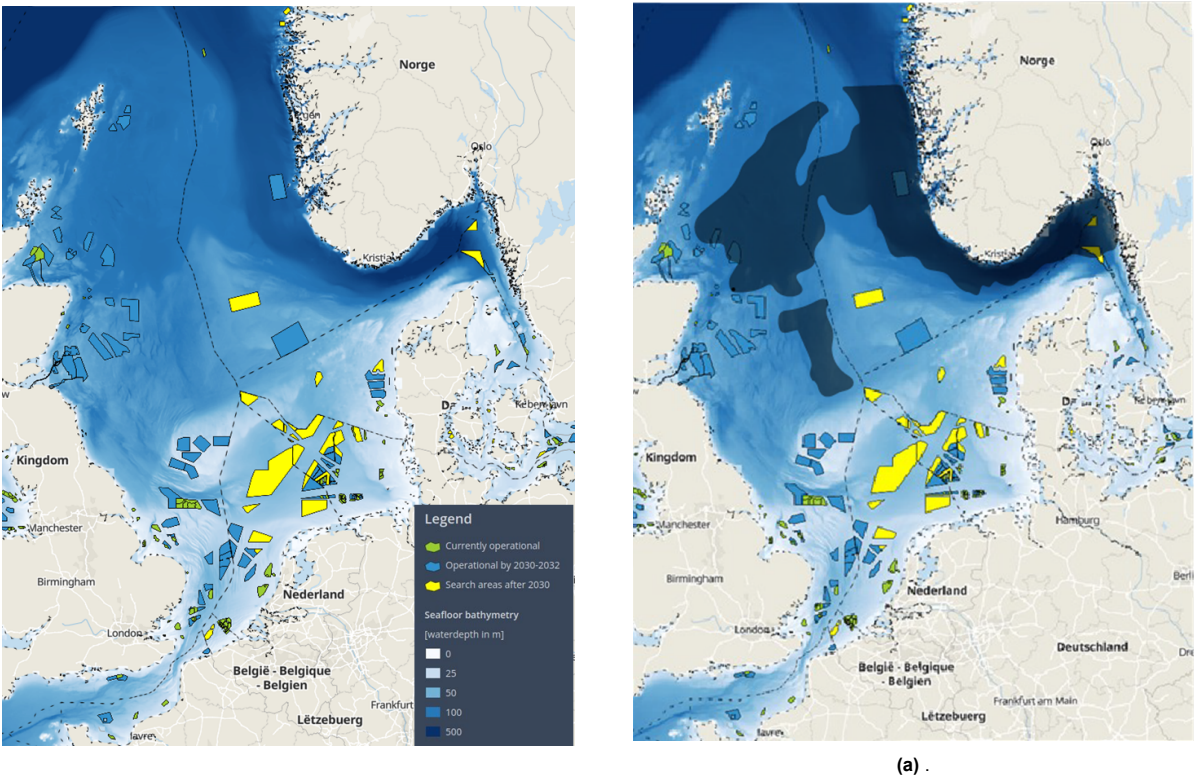


Figure 5.11: Comparison of projected Offshore wind projects planned up to 2035. Black contour marks areas suitable for floating wind parks without intervention. Taken and altered from [3]

6

Discussion

6.1. Simulation Evaluation

The simulations provide a coherent picture of how trench geometry, sediment properties, and hydrodynamic forcing jointly determine sediment escape from mooring chain trenches. Rather than focusing on individual cases, this discussion interprets the broader physical patterns, evaluates the predictive metrics used, and reflects on the implications and limitations of the modelling approach.

6.1.1. Interpretation of Trench Behaviour

The results demonstrate that trench depth is the dominant control on sediment escape outside of the sea state, but they also reveal a more fundamental geometric mechanism. The effectiveness of chain-induced uplift depends strongly on the ratio between chain volume and trench volume. When this ratio is high, as in shallow trenches, the downward chain stroke displaces a sizeable portion of the sediment column and injects it directly into the recirculation zone. This amplifies suspension even under weak background flow. In deeper trenches the same chain motion interacts with only a small fraction of the available volume, producing limited uplift and allowing most sediment to resettle.

This geometric scaling provides a unifying explanation for the observed depth thresholds across both sea states and suggests that the confinement ratio may serve as a predictive parameter for trench stability in oscillatory mooring line environments and might be interesting to research a decrease in anchor diameter as to decrease this phenomenon.

Sediment size further modulates this depth dependent behaviour. Fine sands remain mobile across all geometries because their low settling velocities allow even weak chain-induced uplift to sustain suspension. In contrast, intermediate and coarse sands escape only when chain forcing and background flow combine to generate sufficient vertical momentum. This selective mobility is consistent with observations from cyclically loaded trenches, where finer material is removed first while coarser fractions accumulate. As infill restores part of the trench depth, subsequent oscillatory loading can again mobilise fines and gradually erode the trench back toward its pre-infill geometry. The present results therefore reinforce the view that sediment sorting in mooring-line trenches is governed by a combined balance of grain-scale settling dynamics and geometry controlled flow confinement.

A related effect appears at the intermediate depth of $z = -5$ m in the storm cases. Here the upward jet is consistently weaker than at the shallower or deeper configurations, producing reduced vertical support for the grains. Consequently, sediment is lifted from the trench but lacks the momentum required to reach the outlet or the top boundary, leading instead to deposition along the slope and just outside of the trench, between the shoulder and the outlet. This behaviour is consistent with earlier studies reporting preferential accumulation just outside trench rims under oscillatory or turbulent forcing and therefore increasing the height of the trench wall. The reduced escape ratios at this depth thus reflect a local minimum in jet effectiveness rather than a general failure of storm driven suspension.

6.1.2. Evaluation of Predictive Metrics

Interaction Between Background Flow, Chain-Induced Turbulence, and Trench Confinement

The relationship between inflow velocity and the shear experienced inside the trench is strongly modified by the trench geometry and cannot be interpreted using classical open boundary layer scaling. In theory, bed shear increases approximately with the square of the free stream velocity, but the confined trench disrupts this relationship. Much of the background flow is diverted around or above the trench, so only a fraction of the incoming momentum reaches the bed. As a result, increasing the ambient velocity from 0.05 to 0.36 m/s produces only a near linear increase in the computed bed shear. This behaviour highlights that the background flow inside the trench is governed primarily by geometric intrusion rather than by the free stream velocity itself, and is therefore more accurately reflected by the Rouse number, which captures the suspension capacity of the ambient shear rather than the total flow speed.

In contrast, the shear generated in the immediate vicinity of the moving chain exhibits a strongly non-linear response. The downward motion of the chain injects momentum directly into the lower water column, producing localised turbulence and uplift that far exceed what the background flow alone would generate. This amplification explains why the EPI values, which incorporate chain-induced vertical velocity and confinement effects, show a much steeper response to increased forcing. Chain motion therefore acts as a secondary turbulence source capable of triggering sediment resuspension even when the Rouse number indicates that the background flow is insufficient for suspension. Together, these behaviours show that sediment mobility in mooring trenches is controlled by an interplay between background flow suspension capacity (Rouse) and chain-induced uplift (EPI), with trench geometry controlling how much of either mechanism can be expressed within the cavity.

Rouse Number

The Rouse number provided a physically intuitive predictor of suspension behaviour. Even though no erodible seabed was included, the suspension regimes observed in the simulations matched classical thresholds. This indicates that the resolved shear velocities and vertical transport processes were captured with adequate accuracy to reproduce first order suspension dynamics. However, it is noted that this study only represents the transport of soil and not the erosion. The assumption to neglect the erosion is based on the findings of Lu [20], who found that chain forcing on sand will suspend the soil into the water, see also subsection 2.3.2.

Escape Potential Index

The EPI correctly ranked cases by their relative mobility but did not yield a universal threshold separating escape from no escape. Instead, the results reveal a transition band in EPI-space:

- calm flow: escape initiates for $EPI \approx 0.25\text{--}0.30$,
- storm flow: escape appears already at $EPI \approx 0.0443\text{--}0.0641$.

This shift demonstrates that the effective threshold depends strongly on the hydrodynamic energy of the system. Escape requires both suspension and sufficient vertical transport to overcome geometric confinement. EPI captures the uplifting potential but is sensitive to the flow regime, while confinement is governed primarily by trench depth. The combined Rouse–EPI analysis therefore suggests that EPI should be interpreted as a complementary metric to the Rouse number rather than a standalone escape criterion. Together, the two parameters describe the balance between background suspension capacity and chain-induced uplift.

Two cases deviate from the main separation trend in the Rouse–EPI space (see Figure 6.1). One storm case shows escape even though it lies below the separation band. This behaviour reflects its distinct geometry: the injected sediment travels only a short distance before encountering the upward moving chain, enabling escape through a mechanism that differs from the deeper trenches.

Conversely, one calm case at $z = -5$ m with $d_{50} = 0.25$ mm lies above the separation band but shows no escape. This indicates that favourable EPI conditions are not always sufficient. Several mechanisms may explain this outcome. First, subtle variations in vortex structure and recirculation can trap resuspended particles before they reach the free stream. Second, the EPI does not incorporate geometric nuances such as small differences in injection position, local curvature of the trench shoulder,

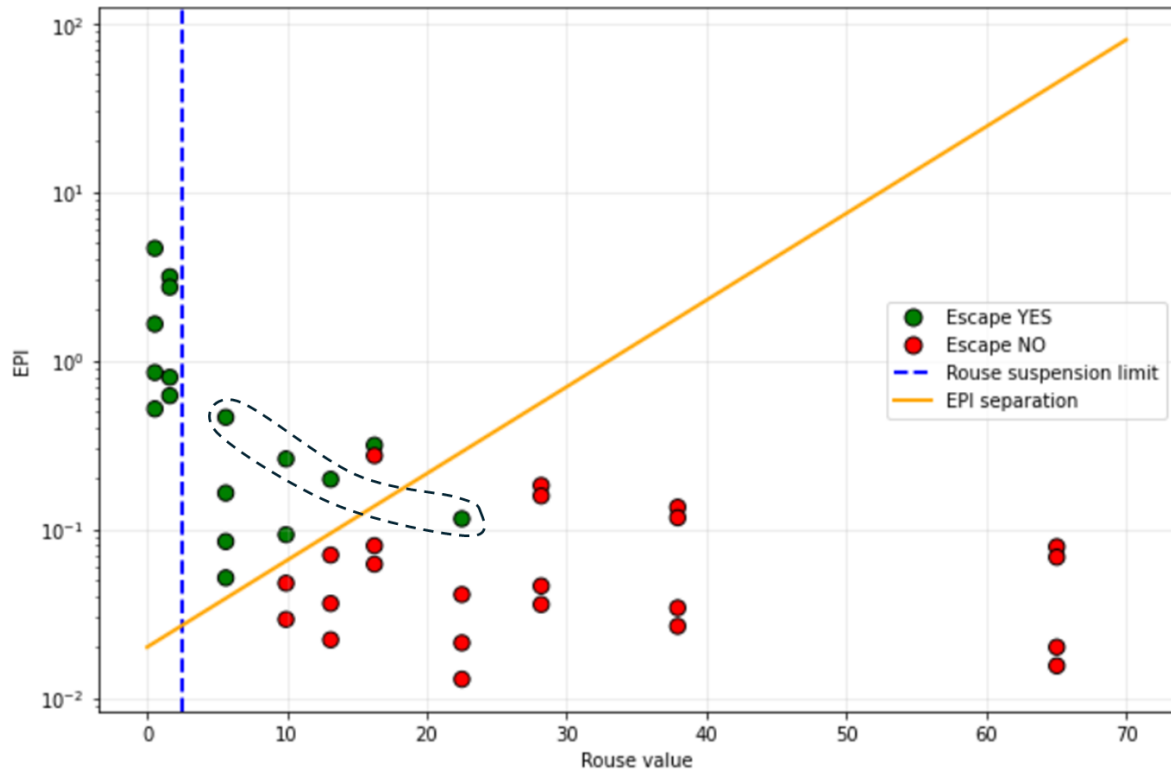


Figure 6.1: EPI separation line with the dotted line showing all the depths of $z = -3\text{m}$. Here the escape is partly due to the relative low travelling distance between the injected soil and the starting position of the chain resulting in a different escape mechanism than other depths.

or variations in chain penetration depth. Third, the apparent outlier may reflect that the separation is not a single line but rather a finite transition region within which escape is sensitive to small perturbations.

It is also possible that the shallowest storm case represents the true outlier, which would imply a steeper or more curved separation band. In either interpretation, the existence of near threshold cases demonstrates that EPI–Rouse space contains a transition zone rather than a strict boundary. Further work is required to refine the separation shape and identify whether additional geometric parameters would improve universality.

6.2. Influence of Model Assumptions and Limitations

Modelling the coupled interaction between hydrodynamics, sediment transport, and moving mooring chains is physically and numerically complex. Capturing all relevant processes simultaneously; bed deformation, consolidation, multi-grain mixtures, chain–soil contact mechanics, turbulence generation, and realistic chain kinematics would require a fully coupled morphodynamic framework that goes well beyond current immersed boundary capabilities in OpenFOAM. Because of these constraints, several simplifying assumptions were necessary to make the problem computationally tractable and to isolate the core mechanisms governing suspension and escape.

The most significant simplification is the absence of a deformable seabed. Without frictional sliding, consolidation processes, or erosion–deposition feedback, the injected sediment interacts with the trench purely through hydrodynamic forces. This likely overestimates upward momentum and underestimates the stabilising influence of bed roughness, particularly for the coarser grain sizes.

A second simplification concerns the trench geometry. The simulations use steep, clay-like trench walls in combination with sandy sediment classes. Although natural sandy trenches typically develop slopes near 30° , the steeper geometry reflects the mixed stratigraphy frequently encountered in the North Sea. Recent geological analyses indicate that dense sand bodies are often overlain by weaker fine-grained layers due to long term subsurface rearrangement. Such inverted or layered structures can support

steep, cohesive sidewalls even when mobile sand is present in the upper layer [1]. This provides a plausible physical basis for the idealised trench geometry adopted in this study.

A further limitation arises from the treatment of cohesive sediments. Although the grain-size classes in the model span silt to coarse sand, cohesive beds can fracture into centimetre scale clasts when struck by a moving chain. These fragments behave temporarily like larger pseudo grains before slowly disaggregating. Existing literature on cohesive erosion demonstrates that lump detachment and mass erosion can occur under sufficiently high stresses [31], but most work focuses on steady or oscillatory boundary layer flows. The response of cohesive beds to impulsive loading, such as mooring chain impact, remains poorly constrained. Thus, while the behaviour modelled here is plausible for non-cohesive sediments, the applicability to cohesive seabeds requires further study.

Another limitation is the use of an incompressible flow solver. In reality, the chain motion generates rapid local accelerations and pressure fluctuations that may introduce weak compressibility effects, particularly near the chain surface where velocities change direction abruptly. Compressibility can influence transient pressure peaks and thus the detailed structure of the upward jet and recirculation zones.

The incompressible assumption therefore smooths the pressure response and may slightly under predict the peak uplift forces acting on the sediment. However, the sediment transport mechanisms observed here, jet driven suspension, confinement controlled recirculation, and depth dependent escape thresholds, are dominated by momentum exchange rather than density variations. Consequently, incompressible modelling captures the primary dynamics relevant for trench scale sediment mobility, even though a fully compressible formulation would be required to resolve fine scale pressure transients associated with chain impact. This would also directly make the use of larger amount of soil inside the domain possible, while also being able to simulate a seabed. What the differences are between the solver used and a compressible solver, such as `driftFluxFoam`, is given in section C.7

The use of a solid cylinder is another limitation. A mooring chain is made out of shackles and will therefore behave differently moving through water. It will be better modelled as two smaller cylinders instead of one large cylinder, this represents the cross sectional view of a chain. This adaptation will most likely lead to more local turbulence but a lower magnitude of the overall turbulence in the mesh, as less water is disturbed by the chain movement. With respect to interaction with the soil, two smaller cylinders will produce less upward jets but simultaneously produce more local turbulence. It is therefore unsure what the impact on the transport capacity of the chain will be.

Finally, the simulations also employ steady inflow conditions to represent calm and storm sea states. Real seabed environments involve tidal oscillations, wave orbital velocities, and intermittent storm forcing, none of which are included here. The thresholds identified in this work should therefore be interpreted as simplified design envelopes rather than complete representations of the natural environment.

6.3. Comparison with Previous Studies

The key trends observed in this study align with findings by Gao, Bhattacharjee, and others, who report rapid trench initiation driven by chain-induced uplift in sandy beds, followed by stabilisation as geometric confinement increases. Their work identified depth thresholds beyond which continued erosion becomes limited. The present results show a comparable behaviour: each grain size exhibits a characteristic depth at which escape ceases, consistent with the notion that confinement eventually outweighs the uplift generated by the chain. This mechanism may help explain why trenches within the same region do not always develop to identical depths, even under similar soil conditions. Variations in current direction, chain velocity, or mooring line tension could shift the effective threshold and lead to different equilibrium profiles.

The current study extends previous work in two key ways. First, it quantifies how escape behaviour depends jointly on trench depth, grain size, and the strength of chain forcing, revealing a combined parameter space that earlier qualitative studies did not fully resolve. Second, it demonstrates that confinement provides a strong stabilising mechanism even under energetic flow conditions as the geometry alters the flow. This supports the observations of Lu [20], who noted that soil can be suspended by chain motion; in the present simulations, such suspension is primarily driven by the downward stroke

of the chain rather than the upward one. Similarly, Gao [12] reported that trench formation in sand is triggered only once a critical flow velocity is exceeded. The present results show that transitioning from calm to storm sea states can produce this critical condition for specific grain sizes, leading to escape during storms even when no escape occurs under calm conditions.

6.4. Implications for Offshore Mooring and Site Selection

The depth–grain size thresholds identified here have direct relevance for floating offshore wind deployment. The strong confinement effect shows that trench growth is largely self limiting: once depths of five to seven metres are reached, most North Sea sediment types no longer escape, even under energetic storm forcing. Medium and coarse sands therefore offer natural resistance against further chain driven deepening, while fine sands may remain mobile initially but become increasingly constrained as the trench develops.

For site selection, this implies that regions characterised by coarser sediments or naturally deeper trench formation pose a lower risk of progressive erosion reaching the anchor or altering mooring geometry. Combining the thresholds with regional sediment maps can help identify locations where long term trench evolution is unlikely to demand intervention. Nevertheless, these sediment based criteria must be considered alongside broader constraints such as vessel corridors, ecological zones, and grid layout when assessing suitability for floating wind installations.

7

Conclusion

7.1. Research Questions

This thesis set out to determine the conditions under which sediment escape from a seabed trench ceases. The main research question and five sub questions are answered below.

Main Research Question

Under what conditions does sediment escape from a seabed trench cease, and how do trench geometry, sediment properties, and current velocity together establish this stabilization threshold?

Sediment escape halts when the trench becomes sufficiently deep and the sediment sufficiently coarse that neither chain-induced turbulence nor the ambient flow can lift particles toward the outlet. Depth exerts the strongest control: once trenches exceed roughly seven metres, escape becomes rare for all but the finest material. Coarser grains stabilise at shallower levels because their settling velocity counteracts upward motion. Calm inflow promotes stabilisation, while storm inflow can mobilise intermediate grains at shallow depths, revealing a non-linear relation between escape potential and near bed current strength. Stabilisation therefore results from the combined influence of trench depth, sediment size, flow velocity and chain forcing.

The newly introduced Escape Potential Index (EPI) provides a practical framework for interpreting these conditions. Classical Rouse predictions suggest minimal suspension for most simulated cases, yet the results show escape across much of the parameter space. The EPI resolves this discrepancy by integrating settling behaviour with trench geometry, local velocity fields, and chain-induced uplift. In combination with the Rouse number, the EPI reveals a threshold band separating escaping from stable cases. This Rouse–EPI space offers the first unified indication of a stabilisation boundary for trench evolution.

Research Question 1

How does trench geometry influence internal vortex formation and sediment lifting potential?

Shallow trenches experience strong interaction between chain motion and the ambient flow. Because the chain occupies a larger fraction of the trench volume, its downward stroke displaces sediment over a short distance and injects grains directly into the upward moving vortex, producing high escape rates. With increasing depth, the same chain energy is distributed over a larger confined volume, and suspended grains must travel farther before reaching the trench shoulders. These effects weaken the lifting potential and suppress escape as depth increases. A transition region occurs at five metres, where vortex strength is locally weakest due to reduced disturbance of the bottom current and insufficient cavity size for a fully developed vortex.

Research Question 2:

How sensitive is sediment escape to variations in current velocity near the seabed?

Sediment escape shows a clear but non-linear sensitivity to ambient current velocity. Increasing the inflow from 0.05 to 0.36, m/s raises background shear inside the trench, but the increase remains modest and nearly linear due to geometric shielding.

Despite this small rise in shear, escape behaviour changes substantially. Calm currents cannot maintain grains in suspension, whereas storm currents can transport lifted material toward the outlet, enabling escape for intermediate and coarse sands at shallow depths.

Thus, escape sensitivity arises from increased transport capacity rather than a large increase in near bed shear. The chain's role in initiating suspension is significant and is addressed separately in Research Question 4.

Research Question 3:

How do different soil properties affect resuspension thresholds?

Because the simulations consider non-cohesive sandy sediments, the relevant soil property controlling resuspension is grain size and its associated settling velocity. Fine grains have low settling velocities and therefore remain suspended for longer after being lifted by the chain. This makes their resuspension threshold low and largely insensitive to trench depth, allowing them to escape under both calm and storm conditions.

Intermediate sands (0.25–0.375 mm) settle more quickly, so their mobility depends on whether chain-induced uplift and background flow combine to overcome their settling rate. They remain stable at depth in calm conditions but become mobile in shallow storms, where vertical momentum is sufficient to sustain suspension.

Coarse sands have high settling velocities and therefore require both strong forcing and limited confinement to be resuspended. In most configurations these grains settle too quickly to reach the outlet, producing consistently high thresholds.

Within the scope of this study, the transition between mobile and stable behaviour occurs between median grain sizes of 0.25 and 0.375 mm, which marks the point where settling velocity becomes larger than the uplift produced by the chain.

Research Question 4:

How does turbulence enhancement caused by a mooring chain affect the onset of sediment resuspension?

The moving chain generates local turbulence and shear that far exceed the background flow, creating conditions under which sediment can be lifted even when classical Rouse predictions indicate no suspension. This additional forcing injects momentum directly into the lower part of the water column, especially during the downward stroke of the chain, and acts as a trigger that initiates resuspension under otherwise stable conditions.

The effect becomes clear when comparing calm and storm states. Increasing the inflow velocity from 0.05 to 0.36 m/s represents an 8.5 multiple in current speed, yet the computed shear stress increases from $\tau_{\text{calm}} = 0.0062 \text{ Pa}$ to $\tau_{\text{storm}} = 0.45 \text{ Pa}$, a multiple of approximately 72.

This non-linear increase reflects the quadratic dependence of chain generated shear on velocity and shows how relatively modest changes in chain speed can dramatically amplify local turbulence within the trench. In contrast, the background flow produces only a near-linear increase in shear, meaning that the chain motion contributes far more to the suspension and escape potential than the ambient current alone.

As a result, chain-induced turbulence provides the critical resuspension mechanism that overcomes settling forces and initiates motion across all grain sizes. The onset of escape is therefore governed not by the background flow itself, but by the strong, non-linear turbulence generated by the chain. This

amplification explains why sediment that remains entirely stable under calm conditions becomes mobile once the combined chain forcing and background flow exceed the resuspension threshold.

Research Question 5:

What are the critical stabilization thresholds for trench geometries under steady seabed flow, with and without chain dynamics?

The results reveal three clear stabilisation regimes. Shallow trenches subjected to storm flow exhibit near-universal escape across most grain sizes. At intermediate depths, fine material remains mobile while intermediate and coarse sands are retained under calm conditions but show partial escape during storms. Deep trenches of seven metres and beyond act as fully confining systems, retaining all sediment except the very finest class.

Chain dynamics shift these thresholds substantially. In the absence of chain motion, escape occurs only when the sediment has negligible settling velocity and is therefore dominated by buoyancy and background flow. When chain forcing is added, even the coarsest tested grain size ($d_{50} = 1 \text{ mm}$) is able to escape from a 3 m deep trench, demonstrating that chain-induced turbulence can overcome stabilisation that would otherwise persist.

The combined stabilisation boundary for cases with chain dynamics is captured by the Rouse–EPI relationship shown in Figure 5.8, which provides a consistent threshold separating mobile from stable behaviour.

7.2. Future Work and Recommendations

The present study provides a first order characterisation of sediment escape and stabilisation in mooring line trenches. To develop a more complete and operationally relevant framework, several directions for future work and practical recommendations can be identified. These are grouped into four themes: model development, sediment physics, environmental forcing, and engineering application.

7.2.1. Model Development

Several modelling assumptions currently limit the predictive capability of the framework, and future work should therefore focus on refining the numerical model. A key improvement would be the inclusion of a deformable bed layer so that sliding, armouring, consolidation, and erosion–deposition feedback can be captured, enabling long term trench evolution under cyclic loading to be simulated. Extending the model into full three-dimensional space would allow transverse vortices and asymmetric chain–flow interactions to be resolved, processes that strongly influence suspension pathways. The chain representation itself should also be enhanced: articulated stud links or realistic cross-sectional shapes would reduce uncertainty in the local turbulence generation close to the chain. Likewise, more realistic chain kinematics, including irregular motion, lateral displacement, variable tension, or multi link dynamics, would better reflect the non-periodic response of real mooring lines. Another important extension is the move toward three-dimensional longitudinal trench modelling, which would allow trench evolution to be studied along the entire chain footprint rather than only in cross-section. To explore stabilisation thresholds beyond those considered here, future work will also require improved mesh quality and solver stability for deeper trenches. Finally, upgrading solver capability remains crucial: successfully coupling the immersed boundary method with a modern multiphase solver would allow sediment suspension and bed deformation to be modelled simultaneously. The attempted coupling in this study was limited by backward compatibility constraints, and revisiting this effort within a newer OpenFOAM architecture is recommended.

7.2.2. Sediment Behaviour

Offshore seabeds often contain mixed or cohesive layers, whereas the present simulations consider only non-cohesive sand. Future work should therefore examine cohesive sediment mechanics, including lump detachment, mass erosion, and flocculation behaviour. The influence of graded or mixed sediment beds must also be considered to represent realistic grain size distributions and stratification. Additionally, pore pressure and consolidation effects could be incorporated to account for seabed strength evolution and compressibility under repeated chain loading. Finally, depth dependent armouring ef-

fects should be explored to understand how deep trenches influence natural armouring and selective erosion patterns.

7.2.3. Environmental Forcing

The simulations in this study rely on steady current conditions, even though real seabed environments experience highly unsteady, multi-directional forcing. Future research should incorporate wave–current interaction to account for oscillatory near-bed velocities and wave-driven turbulence. The representation of chain dynamics should also be expanded to include multi-cycle loading, variable tension, and directional changes over time. Oblique and spatially variable inflow conditions are needed to capture realistic metocean forcing along the chain footprint. A wider spectrum of inflow velocities, including transitional states between calm and storm conditions, extreme events, and slowly varying background currents, should be examined. Introducing time dependent or directionally varying inflow would further improve the realism of offshore environmental representation.

7.2.4. Engineering Application and Recommendations

The depth–grain-size thresholds derived in this work have direct implications for offshore planning, inspection, and maintenance. To support operational decision making, stabilisation thresholds should be integrated with regional sediment maps to identify areas where natural trench stabilisation is likely or unlikely under North Sea conditions. These thresholds should also be incorporated into site selection procedures to avoid regions dominated by fine sands that remain mobile even in deep trenches. Mitigation strategies such as controlled infill, targeted placement of coarser material, or modified trench geometries could be evaluated to reduce long term sediment mobility. Chain-induced turbulence must be considered explicitly in design by accounting for chain velocity, diameter, and contact frequency when assessing trench development risks. Irregular chain dynamics, including lateral sweep and variable tension, should also be considered, as these may increase sediment mobilisation. Finally, depth sensitivity guidance based on the findings of this study should be incorporated into planning tools to improve stabilisation predictions for floating wind projects.

7.2.5. Implementation Outlook

Many of the above extensions can be achieved by upgrading to a modern OpenFOAM solver and establishing a robust coupling with the immersed boundary method, which has to be ported to that OpenFOAM version. Such developments would enable fully coupled, three-dimensional morphodynamic simulations capable of capturing the detailed processes that shape mooring line trenches under realistic environmental forcing, but doing so requires extensive expertise in C++ and computational fluid dynamics.

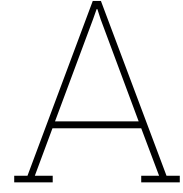
References

- [1] Margherita Bassi. *Huge Parts of the North Sea Seabed Are Upside Down, New Study Reveals*. Accessed: 2025-11-13. Aug. 2025. URL: <https://gizmodo.com/huge-parts-of-the-north-sea-seabed-are-upside-down-new-study-reveals-2000647544>.
- [2] Subir Bhattacharjee et al. "Serpentina FPSO Mooring Integrity Issues and System Replacement: Unique Fast Track Approach". In: (May 2014).
- [3] Frank-Detlef Bockelmann et al. "Mapping mud content and median grain-size of North Sea sediments – A geostatistical approach". In: *Marine Geology* 397 (2018), pp. 60–71. ISSN: 0025-3227. DOI: <https://doi.org/10.1016/j.margeo.2017.11.003>. URL: <https://www.sciencedirect.com/science/article/pii/S0025322717301172>.
- [4] B. Cerfontaine et al. "Anchor geotechnics for floating offshore wind: Current technologies and future innovations". In: *Ocean Engineering* 279 (2023), p. 114327. DOI: [10.1016/j.oceaneng.2023.114327](https://doi.org/10.1016/j.oceaneng.2023.114327). URL: <https://doi.org/10.1016/j.oceaneng.2023.114327>.
- [5] Benjamin Cerfontaine, S.M. Gourvenec, and D.J. White. "Specificities of floating offshore wind turbines for risk and safety evaluation of anchoring systems". In: *Geotechnical Engineering Challenges to Meet Current and Emerging Needs of Society*. CRC Press, Sept. 2024. DOI: [10.1201/9781003431749-10](https://doi.org/10.1201/9781003431749-10). URL: <https://doi.org/10.1201/9781003431749-10>.
- [6] Jean-Louis Colliat et al. "Formation and Development of Seabed Trenching from Subsea Inspection Data of Deepwater Gulf of Guinea Moorings". In: *Offshore Technology Conference*. Houston, Texas, USA: Offshore Technology Conference, Apr. 2018. ISBN: 978-1-61399-571-6. DOI: [10.4043/29034-MS](https://doi-org.tudelft.idm.oclc.org/10.4043/29034-MS). URL: <https://doi-org.tudelft.idm.oclc.org/10.4043/29034-MS>.
- [7] Copernicus Marine Service. *NORTHWESTSHELF_ANALYSIS_FORECAST_PHY_004_013*. <https://data.marine.copernicus.eu/viewer/expert>. Accessed: May 2025. 2025.
- [8] Hess Corporation. *Ivanhoe and Rob Roy Fields Decommissioning Programmes Close-Out Report*. Tech. rep. ABD-DOC-RPT-01000. Hess Corporation, Dec. 2015.
- [9] Xiaowei Feng, Susan Gourvenec, and David J. White. "Load capacity of caisson anchors exposed to seabed trenching". In: *Ocean Engineering* 171 (2019), pp. 181–192. URL: <https://www.elsevier.com/locate/oceaneng>.
- [10] Gael Veroa Fernandez et al. "Trenching of Mooring Lines Using a Discrete Element Method Approach". In: Oct. 2024. DOI: [10.1201/9781003588559-47](https://doi.org/10.1201/9781003588559-47). URL: <https://www.researchgate.net/publication/384921738>.
- [11] S. F. Frankenmolen, D. J. White, and C. O'Loughlin. "Chain-Soil Interaction in Carbonate Sand". In: *Offshore Technology Conference (OTC)*. Presented at the Offshore Technology Conference, Houston, Texas, May 2016. Houston, Texas, USA: OnePetro, May 2016. ISBN: 978-1-61399-437-5. DOI: [10.4043/27102-MS](https://doi-org.tudelft.idm.oclc.org/10.4043/27102-MS). URL: <https://doi-org.tudelft.idm.oclc.org/10.4043/27102-MS>.
- [12] Yangyang Gao et al. "Experimental study on the sandy seabed trench development of the catenary mooring chain at touchdown zone". In: *Ocean Engineering* 264 (2022), p. 112325. DOI: [10.1016/j.oceaneng.2022.112470](https://doi.org/10.1016/j.oceaneng.2022.112470). URL: <https://www.sciencedirect.com/science/article/pii/S002980182201753X>.
- [13] Acteon Group. *Scaling Up for Floating Wind: How Mooring Systems Evolve with Turbine Size*. Accessed October 2025. 2024. URL: <https://acteon.com/insights/blog/scaling-up-for-floating-wind>.
- [14] Shi He and Aijun Wang. "Time and Frequency Domain Dynamic Analysis of Offshore Mooring". In: *Journal of Marine Science and Engineering* 9.7 (2021). ISSN: 2077-1312. DOI: [10.3390/jmse9070781](https://doi.org/10.3390/jmse9070781). URL: <https://www.mdpi.com/2077-1312/9/7/781>.

- [15] Jianwu Huang et al. "Analysis of mooring performance and layout parameters of multi-segment mooring system for a 15 MW floating wind turbine". In: *Frontiers in Energy Research* Volume 12 - 2024 (2024). ISSN: 2296-598X. DOI: 10.3389/fenrg.2024.1502684. URL: <https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2024.1502684>.
- [16] Hossein Janbazi and Hodjat Shiri. "Incorporation of the riser-seabed-seawater interaction effects into the trench formation and fatigue response of steel catenary risers in the touchdown zone". In: *Ocean Engineering* 289 (Dec. 2023), p. 116288. DOI: 10.1016/j.oceaneng.2023.116288.
- [17] Noor Laham et al. "A surrogate model to efficiently predict changing strength and stiffness of soft soils through whole-life episodic cyclic loading". In: *Computers and Geotechnics* (2025). URL: <https://www.elsevier.com/locate/compgeo>.
- [18] Chern Fong Lee, Sindre Fjermedal, and Muk Chen Ong. "Design and comparative analysis of mooring systems for a combined wind and wave energy system at intermediate water depth". In: *Journal of Ocean Engineering and Science* (2025). ISSN: 2468-0133. DOI: <https://doi.org/10.1016/j.joes.2024.11.002>. URL: <https://www.sciencedirect.com/science/article/pii/S2468013325000105>.
- [19] Feng Zi Li et al. "Experimental Investigation on Scour under a Vibrating Catenary Riser". In: *Journal of Engineering Mechanics* 139.12 (2013), pp. 1721–1730. DOI: 10.1061/(ASCE)EM.1943-7889.0000546.
- [20] Wenyue Lu et al. "Experimental investigation of a taut mooring line accounting for the chain–sand interaction at model scale". In: *Journal of Marine Science and Technology* 27.1 (June 2021), pp. 1–10. DOI: 10.1007/s00773-021-00833-x.
- [21] Guangyu Luo et al. "Model tests on chain-soil interaction of anchor pile for taut mooring system through transparent sand". In: *Ocean Engineering* 309 (2024), p. 118419. URL: <https://www.sciencedirect.com/science/article/pii/S002980182400018X>.
- [22] Leonid Pekker. "A Calculator for Sediment Transport in Microchannels Based on the Rouse Number". In: (Dec. 2017).
- [23] S. J. Rui et al. "Anchor chain profiles in sand based on centrifuge model tests". In: *IOP Conference Series: Earth and Environmental Science* 1337 (2024), p. 012063.
- [24] S. J. Rui et al. "Review of mooring line and anchor-seabed interaction for floating wind turbines". In: *Proceedings of the 5th International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2025)*. Corresponding author: shengjie.rui@ngi.no. Nantes, France: Norwegian Geotechnical Institute, June 2025. ISBN: 978-8-5878-758-0.
- [25] Shengjie Rui et al. "A Framework for Mooring and Anchor Design in Sand Considering Seabed Trenches Based on Floater Hydrodynamics". In: *Sustainability* 15.12 (2023), p. 9403. DOI: 10.3390/su15129403.
- [26] Shengjie Rui et al. "Assessment of seabed trench formation based on marine sediment properties and chain-bar penetration tests". In: *Engineering Geology* 342 (Nov. 2024), p. 107746. DOI: 10.1016/j.enggeo.2024.107746.
- [27] Shengjie Rui et al. "Axial interaction between anchor chain and sand. Part II: Cyclic loading test". In: *Applied Ocean Research* 114 (Sept. 2021), p. 102815. DOI: 10.1016/j.apor.2021.102815.
- [28] Shengjie Rui et al. "Numerical investigations on load transfer of mooring line considering chain-seabed dynamic interaction". In: *Marine Georesources and Geotechnology* (Nov. 2020). DOI: 10.1080/1064119X.2020.1846646. URL: <https://www.researchgate.net/publication/346996445>.
- [29] Shengjie Rui et al. "Numerical prediction of potential 3-dimensional seabed trench profiles considering complex motions of mooring line". In: *Applied Ocean Research* 139 (2023), p. 103704. DOI: 10.1016/j.apor.2023.103704.
- [30] Shengjie Rui et al. "Review on Seabed Trenches Induced by Mooring Lines and Analyses of Anchor Bearing Capacity". In: *Journal of Marine Science and Application* 22 (2023), pp. 296–310. DOI: 10.1007/s11804-023-00333-x. URL: <https://doi.org/10.1007/s11804-023-00333-x>.

- [31] Lawrence P Sanford and Jerome P.-Y Maa. "A unified erosion formulation for fine sediments". In: *Marine Geology* 179.1 (2001), pp. 9–23. ISSN: 0025-3227. DOI: [https://doi.org/10.1016/S0025-3227\(01\)00201-8](https://doi.org/10.1016/S0025-3227(01)00201-8). URL: <https://www.sciencedirect.com/science/article/pii/S0025322701002018>.
- [32] K. Sassi et al. "Insights into the Mechanisms of Anchor Chain Trench Formation". In: *Offshore Site Investigation Geotechnics 8th International Conference Proceedings*. Accessed via Delft University of Technology institutional login. Society for Underwater Technology, 2017, pp. 963–970. DOI: 10.3723/OSIG17.963. URL: <https://doi-org.tudelft.idm.oclc.org/10.3723/OSIG17.963>.
- [33] "Shared mooring systems for offshore floating wind farms: A review". In: *Energy Reviews* 3.1 (2024), p. 100063. ISSN: 2772-9702. DOI: <https://doi.org/10.1016/j.enrev.2023.100063>. URL: <https://www.sciencedirect.com/science/article/pii/S2772970223000500>.
- [34] K. Shen, Z. Guo, and L. Wang. "Prediction of the whole mooring chain reaction to cyclic motion of a fairlead". In: *Bulletin of Engineering Geology and the Environment* 78 (2019), pp. 2197–2213. DOI: 10.1007/s10064-018-1300-z. URL: <https://doi.org/10.1007/s10064-018-1300-z>.
- [35] R. Soulsby, R. Whitehouse, and US Army Corps of Engineers. *Critical Thresholds for Transport and Erosion (v6.3) – Soulsby and Whitehouse*. <https://www.hec.usace.army.mil/confluence/rasdocs/d2sd/ras2dsedtr/6.6/model-description/critical-thresholds-for-transport-and-erosion#id-.CriticalThresholdsforTransportandErosionv6.3-SoulsbyandWhitehouse>. HEC-RAS 2D Sediment Transport Manual, U.S. Army Corps of Engineers. (Visited on 10/08/2025).
- [36] Chao Sun et al. "Numerical Investigations into Development of Seabed Trenching in Semitaught Moorings". In: *Journal of Geotechnical and Geoenvironmental Engineering* 146.10 (2020). Published: October 1, 2020; Received: November 20, 2019; Accepted: May 13, 2020. ISSN: 1090-0241. DOI: 10.1061/(ASCE)GT.1943-5606.0002347. URL: downloaded.
- [37] Lizhong Wang et al. "Seabed trenching near the mooring anchor: History cases and numerical studies". In: *Ocean Engineering* 218 (Dec. 2020), p. 108233. DOI: 10.1016/j.oceaneng.2020.108233.
- [38] Li-zhong Wang, Kai Li, and Feng Yuan. "Lateral cyclic interaction between catenary riser and soft seabed". In: *Applied Ocean Research* 63 (2017), pp. 11–23. DOI: 10.1016/j.apor.2017.01.001.
- [39] Lingzhi Xiong, Jianmin Yang, and Wenhua Zhao. "Dynamics of a taut mooring line accounting for the embedded anchor chains". In: *Ocean Engineering* 121 (2016), pp. 403–413. DOI: 10.1016/j.oceaneng.2016.05.022.
- [40] Lingzhi Xiong et al. "Anchor loads in taut moorings: The impact of inverse catenary shakedown". In: *Applied Ocean Research* 67 (Sept. 2017), pp. 225–235. DOI: 10.1016/j.apor.2017.06.010.
- [41] Hang Xu et al. "Investigations on the mooring safety considering the coupling effect of the mooring line snap tension and anchor out-of-plane loading". In: *Applied Ocean Research* 141 (2023), p. 103753. ISSN: 0141-1187. DOI: <https://doi.org/10.1016/j.apor.2023.103753>. URL: <https://www.sciencedirect.com/science/article/pii/S0141118723002948>.
- [42] Jianxing Yu et al. "Nonlinear dynamic response of touchdown zone for steel catenary riser under multiple internal solitary waves". In: *Ocean Engineering* 297 (2024), p. 117141. DOI: 10.1016/j.oceaneng.2024.117141.
- [43] Yang Yu et al. "Experimental Study of the Dynamic Performance of Steel Catenary Riser within the Touchdown Zone". In: *Journal of Marine Science and Engineering* 11.2 (2023), p. 315. DOI: 10.3390/jmse11020315.
- [44] Yang Yu et al. "Three-dimensional trenches induced by lateral riser-soil interaction and their influence on the behavior of SCR". In: *Ocean Engineering* 276 (May 2023), p. 114233. DOI: 10.1016/j.oceaneng.2023.114233.
- [45] Min-Hao Zhang, Zhen-Yu Yin, and Yong Fu. "Pull-out capacity and failure mechanism of suction anchors in clay considering trench configuration and local scour effects". In: *Engineering Geology* 347 (2025), p. 107942. ISSN: 0013-7952. DOI: <https://doi.org/10.1016/j.enggeo.2025.107942>. URL: <https://www.sciencedirect.com/science/article/pii/S0013795225000389>.

- [46] Z. Zhang et al. "Seabed trenching near the mooring anchor: History cases and numerical studies". In: *Ocean Engineering* 218 (2020), p. 108233. DOI: 10.1016/j.oceaneng.2020.108233. URL: <https://www-sciencedirect-com.tudelft.idm.oclc.org/science/article/pii/S0029801820311550>.



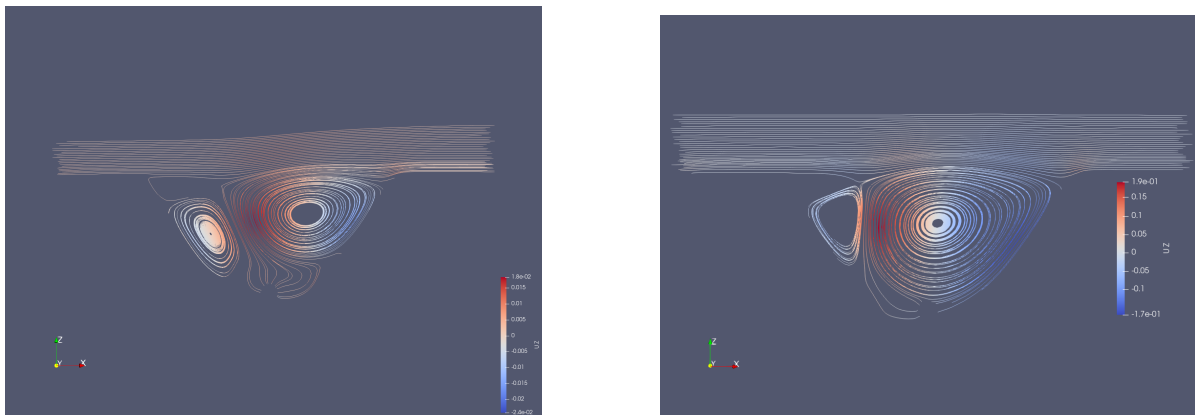
Full Simulation Results

This appendix presents the full set of simulation results supporting the analysis in Chapter 5. It includes steady-state flow behaviour, chain-induced flow responses, sediment transport mechanisms, escape evaluations, adaptive simulation strategies, and case-by-case outcomes for both sea states.

A.1. Flow-Field Results

A.1.1. Steady-State Flow Fields

Eight steady state flow fields were analysed: four depths under two sea states. Table 4.5 shows the simulation time required to reach steady flow. Longer times result from higher inflow velocities and deeper trench geometries, which require more time for flow stabilization. Simulations start with a zero-flow mesh, gradually ramping up to the target velocity.



(a) Stream tracer plot at $z = -5$ m.

(b) Vertical velocity contour plot at $z = -5$ m.

Figure A.1: Flow field visualizations at $z = -5$ m: (a) Calm sea state $t = 200$ and (b) storm sea state $t = 1200$.

Storm Sea State Figure A.2 illustrates storm flow behaviour across increasing trench depths. Vortex-dominated, energetic flows form across all cases, with distinct upward (red) and downward (blue) zones. As depth increases, vortex structure strengthens, and vertical mixing intensifies.

At $z = -3$ m, shallow geometry causes a weak recirculation bubble dominated by a low-energy vortex. The flow separates but does not reattach, forming a broad stagnation zone. The chain slightly amplifies this effect but remains secondary.

At $z = -5$ m, a closed, clockwise vortex forms as the separated shear layer gains space to reattach. This transition eliminates the stagnation zone and enables coherent recirculation.

At $z = -7$ m, the vortex expands vertically, increasing upward velocities and energy transfer. The chain lies below the main flow and has minimal influence.

At $z = -9$ m, a strong, symmetric vortex dominates the trench. Upward flow along the left wall and smooth flow deflection above indicate persistent recirculation and high resuspension potential.

Stream tracer plots show that deeper trenches lead to stronger and more organised flow structures. The flow evolves from a stagnant bubble to a coherent vortex cavity as depth increases, enhancing the potential for sediment resuspension under storm forcing.

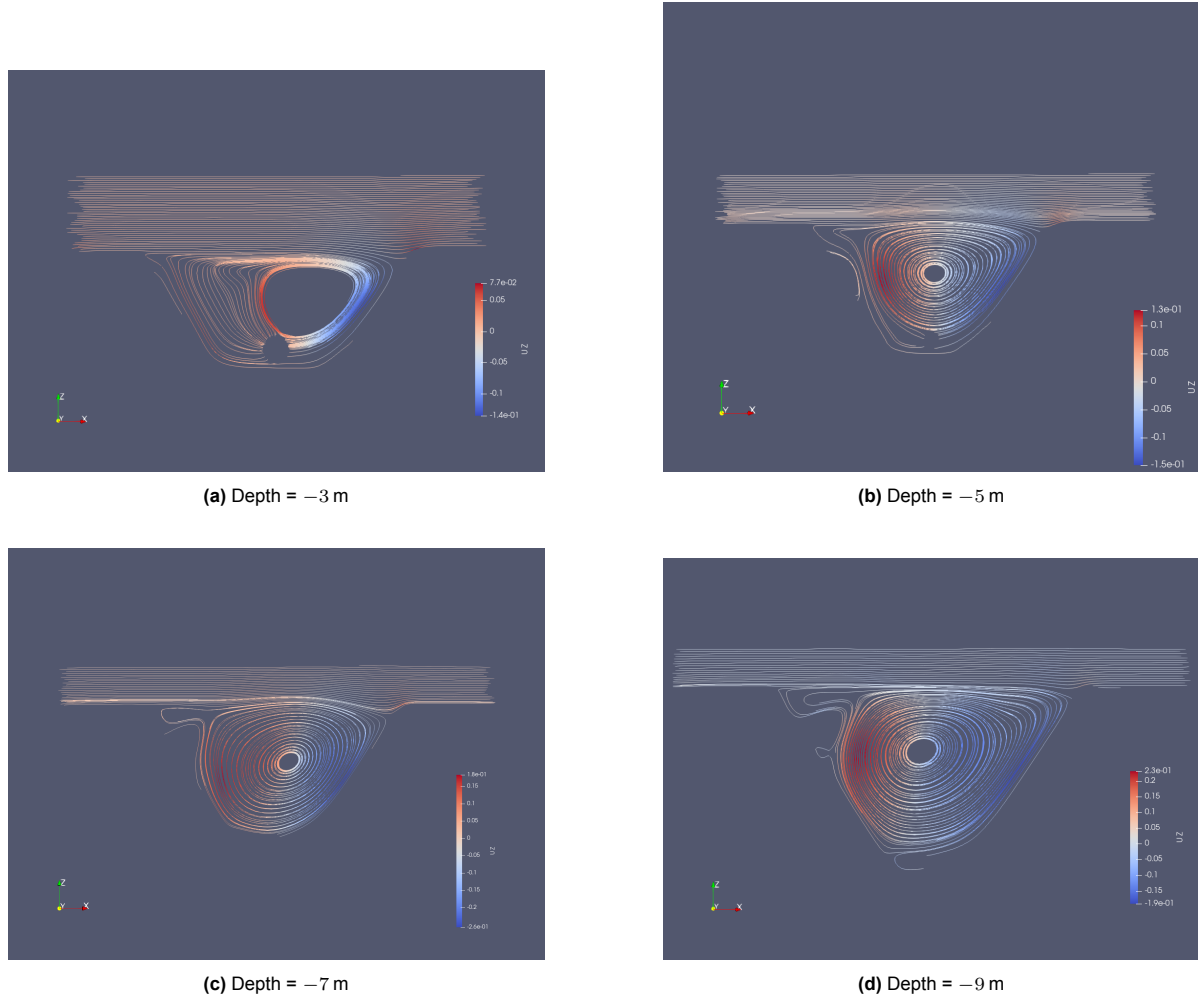


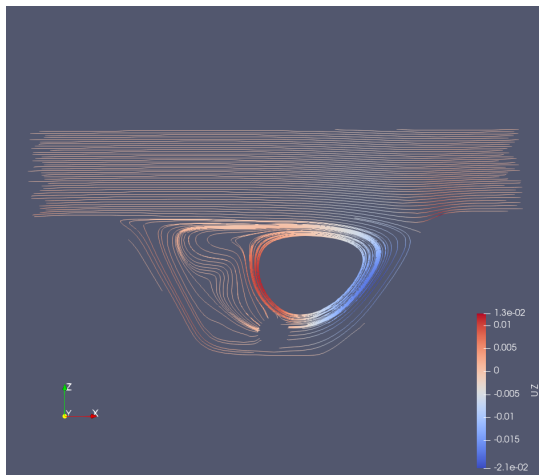
Figure A.2: Stream tracer plots showing vertical flow velocity (colour) and flow direction (streamlines) at increasing trench depths for the storm seastate.

The same analysis was conducted under calm sea state conditions ($U = 0.05$ m/s). Figure A.3 shows the resulting flow fields at trench depths of -3 m, -5 m, -7 m, and -9 m.

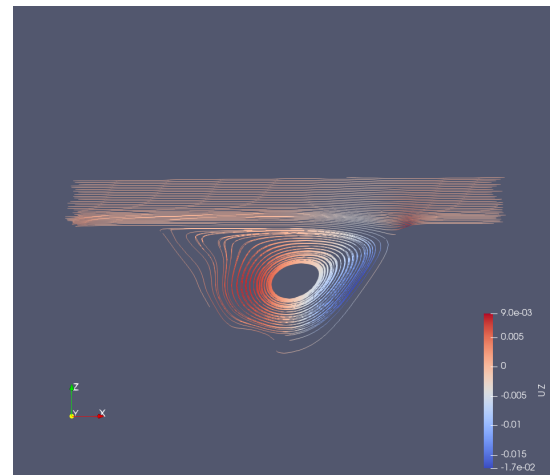
At -3 m and -5 m, strong recirculation zones form around the chain, visible as voids at the trench floor. Compact vortices with alternating upward and downward flows interact with the overhead current. These patterns are strongest on the downstream (left) side, suggesting chain-induced disturbance at shallow depths.

At -7 m and -9 m, the flow becomes more stable and organised. A single large vortex dominates, deflecting the overhead flow and reducing vertical gradients. The chain lies below this region, indicating limited interaction and lower energy.

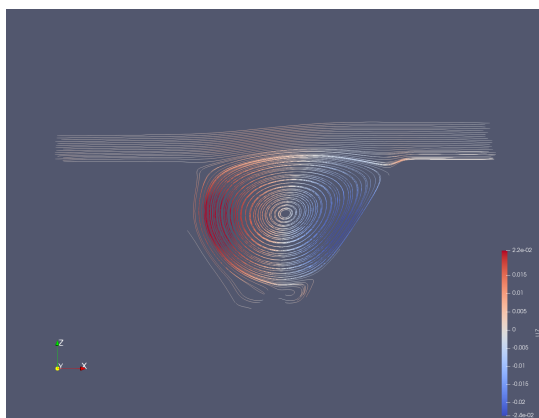
In general, increasing trench depth leads to more stable, larger-scale vortex structures. While the chain disturbs the flow at shallow depths, it has little effect at greater depths.



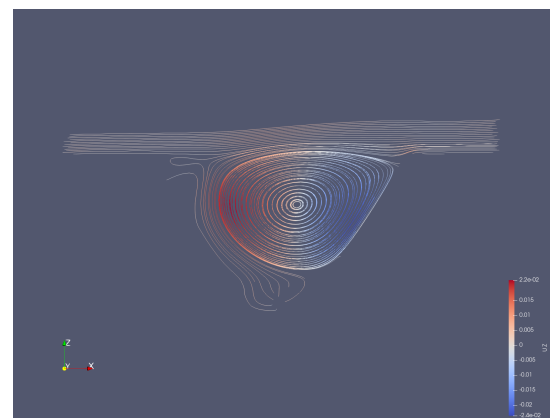
(a) Depth = -3 m



(b) Depth = -5 m



(c) Depth = -7 m



(d) Depth = -9 m

Figure A.3: Stream tracer plots under calm conditions, showing vertical velocity and flow direction at increasing trench depths.

Comparison of Storm and Calm Sea States Comparing storm and calm cases reveals how flow energy influences vortex development.

At -3 m, both cases produce a broad recirculation zone, but storm conditions generate stronger, more open vortices with enhanced fluid exchange. Calm flows are weaker and more confined, indicating greater sediment stability.

At -5 m, both regimes transition from shallow separation to confined circulation. In calm conditions, twin vortices form near the chain. Storm flow creates a dominant, clockwise vortex with stronger vertical motion and sediment entrainment potential.

At -7 m and -9 m, both flows form large recirculating vortices. The storm case shows more vertical extension and stronger upward jets, while calm flows remain slower and broader. In both, the chain lies below the vortex and does not affect the main flow.

Overall, storm conditions increase vortex strength, near-bed shear, and sediment mobility. Calm flows favour deposition and stability. Trench depth controls whether the trench behaves as a dynamic or stable environment.

A.1.2. Chain-Induced Flow Fields

Figure A.4 shows the evolution of vertical velocity and streamlines for one and a half oscillation cycles of the chain under storm conditions. Red regions represent upward flow and blue regions represent downward motion.

At $t = 0$ s, the flow is steady and symmetric. When the chain begins its upward motion ($t = 20$ – 30 s), two counter-rotating vortices form, and a vertical jet develops above the chain. Flow asymmetry emerges due to the outlet boundary on the right-hand side. By $t = 30$ s, the main vortex weakens and the jet begins to expand upward. More pronounced vortex shedding would likely occur with a realistic chain geometry, as observed by Rui et al. [26].

As the chain descends ($t = 40$ – 70 s), the upward jet collapses, and a downward inflow forms as fluid re-enters the trench. Secondary vortices appear along the chain and near the trench corners. Upward wall jets also develop, caused by fluid displacement from the narrowing space beneath the chain. By $t = 90$ – 110 s, the flow reorganizes into a dominant clockwise vortex, though minor asymmetries persist. Most probable due to the outflow being at the right hand side of the trench.

The wall shear stress undergoes a large change in value during the simulation. While the chain is moving the value decreases and increases for the section of the wall that is the closest to the chain. This make the value have a range of 0 to 0.45 Pascal. The wall shear stress induced by the current flow was approximately 0.17 Pascal, making the addition of the chain velocity an increase in wall shear stress at local points.

Overall, each upward stroke injects momentum into the trench, forming vortex pairs that connect the trench interior with the surrounding flow. This process enhances local turbulence, increases wall shear and creates a "trail" underneath the chain and an overall upward flow. Even without external currents, chain motion alone is sufficient to intermittently resuspend sediment from the trench floor.

Chain-Induced Flow under Calm Conditions Figure A.5 presents the time evolution of streamlines for the calm sea state. At $t = 0$ s, the fluid remains still, with no pre-existing vortex structure. When the chain starts its upward motion, upward jets form both above and below the chain. Around $t = 50$ s, a clockwise vortex appears on the right side and a smaller counter-clockwise vortex forms on the left.

At the top of the stroke, the upward jet initially generated beneath the chain continues upward along the right-hand side. The vortices weaken as the flow stabilizes, and it is expected that any resuspended sediment would be transported away by even weak background currents.

When the chain reverses direction ($t = 100$ – 150 s), downward motion occurs above and below the chain, as shown by the blue velocity regions. The upward jet from the first stroke remains active, indicating persistent vertical flow near the trench's upper boundary. As the chain descends further, the narrowing space near the bottom increases local velocity, enhancing the potential for soil resuspension.

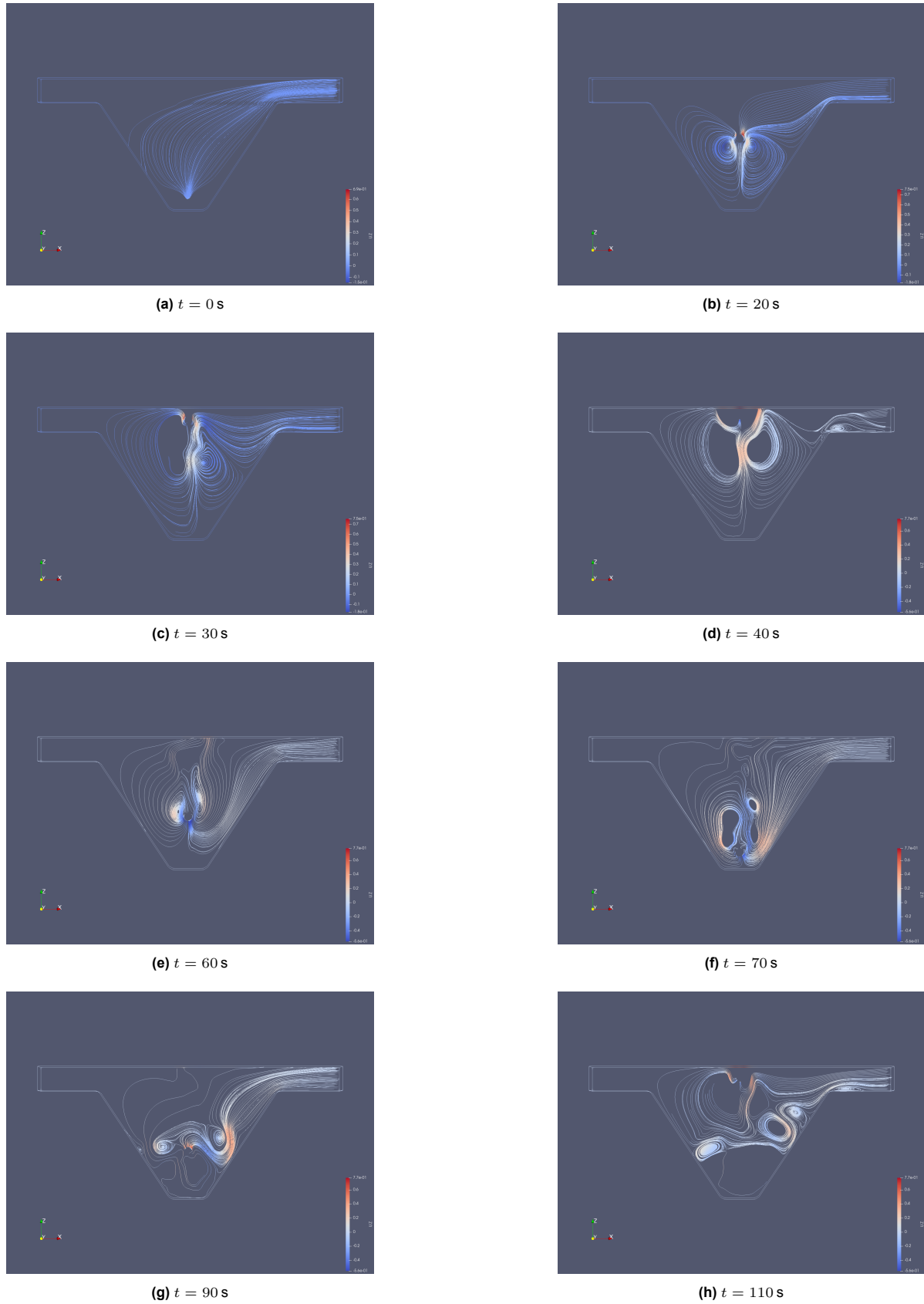


Figure A.4: Time evolution of stream tracer plots under storm conditions at various time steps.

Between $t = 100\text{--}150$ s, the vortex strengthens, and fluid begins to recirculate within the trench. By $t = 200$ s, vortex stretching and smaller secondary structures emerge near the bottom corners.

At $t = 270$ s, during the second upward motion, the vortex pattern observed at $t = 50$ s does not reappear, indicating a non-periodic flow response between cycles. This suggests that the chain-induced trench flow is path-dependent and not strictly symmetric between upward and downward strokes.

The wall shear stress undergoes a small change in value during the simulation. While the chain is moving the value decreases and increases for the section of the wall that is the closest to the chain, just like in the storm scenario, but here the value has a range of 0 to 0.0067 Pascal. The wall shear stress induced by the current flow was approximately 0.02 Pascal, making the addition of the chain velocity an lesser increase in wall shear stress at local points than for the storm scenario.

These maximum wall shear stresses, so for both scenarios, are independent of the trench depth.

Overall, several points are identified where sediment may be lifted, either directly by vertical jets generated by the chain or indirectly through sustained vortex activity within the trench. Even under calm conditions, the chain induces sufficient flow to disturb settled soil and promote short term resuspension.

A.2. Sediment Transport Results

A.2.1. Flow-Only Sediment Transport

Predicted Particle Behaviour Based on Flow Structure

Based on the theoretical mobility threshold (see Table 4.6), particle trajectories were predicted prior to full transport simulations. Release positions varied lateral location (left, centre, right), with fine sediment introduced at $z = -1$ m, representing potential resuspension under near-bed shear.

Storm Sea State In storm conditions, the flow fields suggest high transport potential. At $z = -3$ m, weak recirculation and low shear promote local settling, though shallow geometry might allow limited escape. At $z = -5$ m, asymmetry in the flow increases entrainment potential on the right side. Deeper trenches ($z = -7$ m and -9 m) host strong, symmetric vortices that generate sustained upward motion capable of suspending fine sediment ($d_{50} = 0.0625$ mm), as the vertical velocity exceeds the settling velocity ($w_s = 0.003$ m/s). However, most particles are expected to remain trapped in the circulation, as the vortex residence time exceeds the duration of upward transport paths.

Calm Sea State In calm flow, shear stress and vertical motion are insufficient for sustained transport. At $z = -3$ and -5 m, minor flow separation near the chain causes weak shear zones, but the energy remains below the critical threshold for motion. Deeper trenches ($z = -7$ and -9 m) show stable, low-energy vortices with minimal vertical gradients. These structures favour deposition rather than resuspension.

Comparison Storm flows exceed the critical shear velocity for fine sand ($u_* = 0.013$ m/s) and correspond to Rouse numbers $P < 1.2$, indicating full suspension regimes. Calm flows ($u_* = 0.0045$ m/s) remain below all thresholds, confirming deposition-dominated conditions. The predicted non-linear response suggests that small increases in flow energy can shift the trench from stable to erosive behaviour.

Settling Velocity Threshold and Particle Escape

To verify these predictions, two sets of flow-only simulations were performed, so without chain motion. These tests isolate the background flow transport capacity and serve as baseline cases for later comparison. The first uses a zero-settling tracer to evaluate whether the flow can transport material in the absence of gravitational resistance, creating a situation where only the buoyancy forces are in play. The second adds a small but realistic settling velocity, based on the d_{50} value, to determine whether such resistance prevents escape under otherwise identical conditions.

Baseline Tracer Case The tracer simulation with zero settling velocity serves as a baseline test to evaluate the intrinsic transport capacity of the flow field. Fine sediment ($d_{50} = 0.0625$ mm) was released

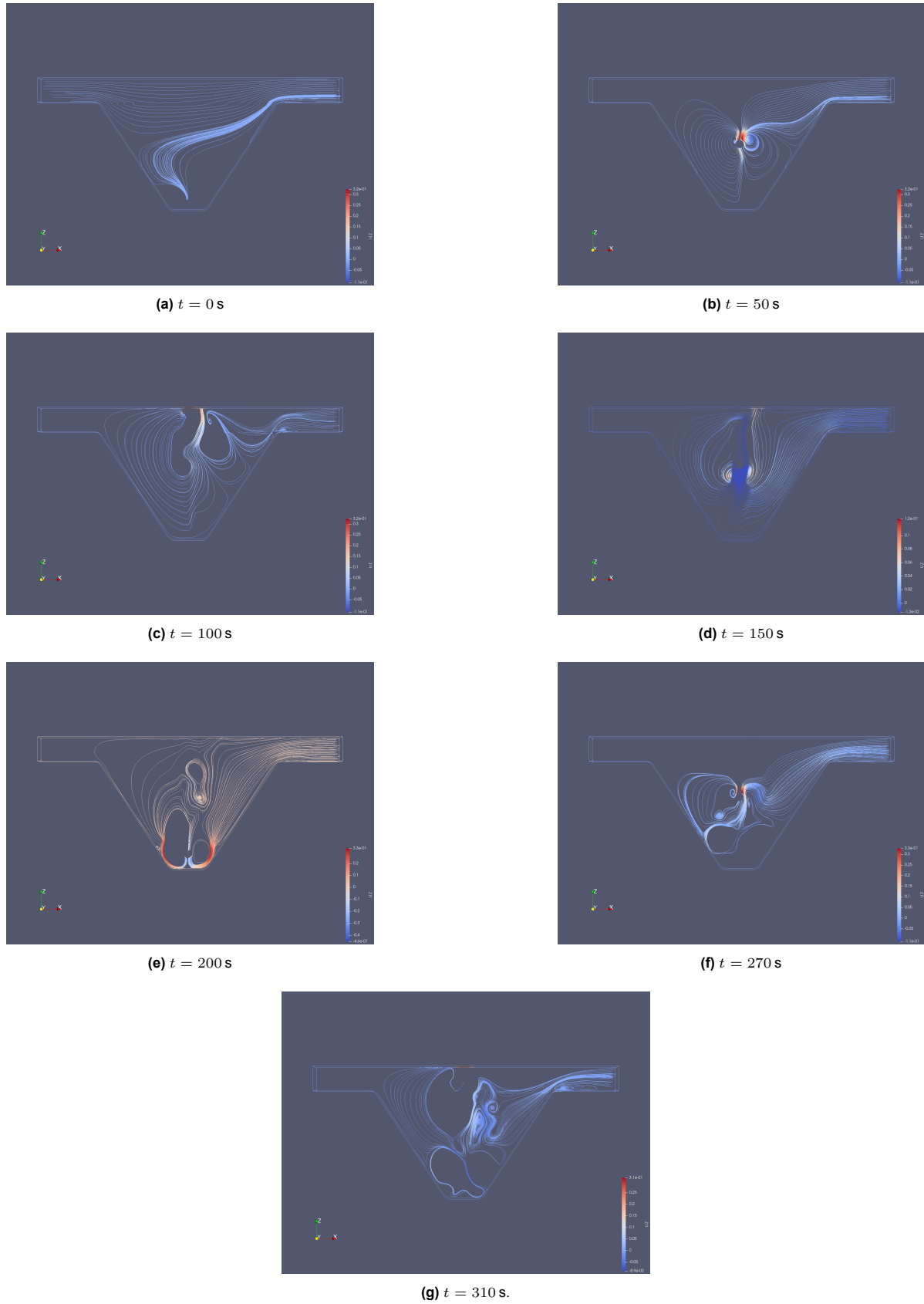


Figure A.5: Time evolution of stream tracer plots under calm conditions from $t = 0$ to $t = 310$ s.

at $z = -1$ m, both at the centreline and near the trench sidewalls. The tracer behaves as a passive scalar, slightly denser than the surrounding water, and thus purely follows the velocity field.

Under calm conditions, the tracer disrupted the steady-state vortex, which did not recover over time. Most material accumulated along the left trench wall and to the left of the chain, indicating a significant horizontal flow component. Although vertical motion was weak, some tracer escaped the trench (Figure A.6a), as portions of the flow still exited the domain. The escaping concentration in the overlying flow remained small ($c \approx 10^{-5}$), with most of it concentrated toward the bottom left corner. This pattern was caused by the initial flow structure, where the right-side injection experienced strong downward flow, while the left-side injection was lifted slightly and transported outward. The central injection moved downward moderately.

These dynamics suggest that the left side of the trench, where the flow is weakest as its in the shadow of the chain, acts as a preferential accumulation zone. This observation is consistent with the Rouse number prediction of partial suspension for fine sediment in calm flow ($P = 1.63$), which means only a small part of the soil is suspended. Although the Rouse number is formally defined for non-zero settling velocities, the zero-settling tracer represents the limiting case where $P \rightarrow 0$, corresponding to ideal suspension. In this scenario, suspension was maintained and some escape occurred, as expected in the absence of settling.

In the storm case, the flow re-established its vortex structure approximately 75 seconds after tracer injection. During the first recirculation cycle, a fraction of the tracer escaped the trench by following streamlines that exited the domain. Because the tracer lacked settling velocity, this escape directly reflects the flow's capacity to transport material. Subsequent circulation maintained a weak suspended concentration near the right-hand wall (Figure A.6).

The lateral movement of the tracer was also significantly different compared to the calm case. In storm conditions, the vortex circulation remained intact after injection: tracer moved from left to right near the surface and from right to left near the trench bottom, forming a full clockwise rotation. In contrast, under calm conditions, horizontal transport occurred mainly near the bottom, with little circulation aloft. These differences highlight the stronger coherence and transport potential of the storm-induced flow field.

Fine Sediment Case The second case included a small but realistic settling velocity to test whether soil escape remains possible under gravitational effects. Fine sediment ($d_{50} = 0.0625$ mm, $w_s = 0.003$ m/s) was released under identical flow conditions, again without chain motion.

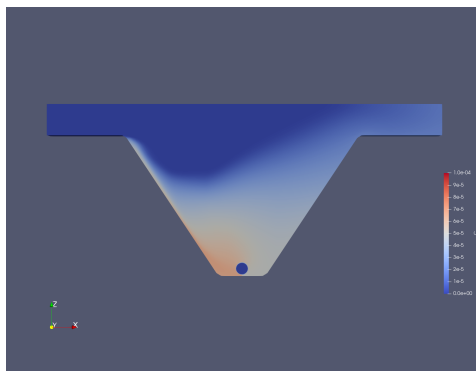
In the storm scenario, maximum upward velocities reached 0.23 m/s, nearly two orders of magnitude higher than the settling rate. Despite this, the soil remained trapped within the main vortex and did not escape the trench. The particles stayed suspended within the recirculating flow, consistent with the Rouse number of $P = 0.56$, which predicts full suspension but not continuous export.

Under calm conditions, the maximum upward velocity (0.022 m/s) was only slightly above the settling velocity, resulting in rapid deposition and minimal motion. This agrees with $P = 1.63$, corresponding to partial suspension and deposition-dominated behaviour. Repeated simulations with coarser sediment confirmed that, once settling is introduced, no escape occurs under any condition. The flow retains suspended material in the vortex, while deposition dominates over time.

Horizontal sediment injection position

Based on preliminary flow-field analysis, the horizontal position at which sediment is introduced can strongly influence its initial momentum and therefore its likelihood of entering upward or downward flow regions. To evaluate this effect, a sensitivity test was performed in which sediment was injected at three different horizontal locations: near the left wall, at the trench centre, and near the right wall.

These tests showed that sediment introduced on the right-hand side consistently entered a strong downward jet, suppressing upward transport and leading to negligible escape. This behaviour reflects the asymmetric vortex structure inside the trench, where the right-hand side is dominated by recirculation directed toward the trench floor. Sediment placed near the left wall, by contrast, was exposed to the upward branch of the primary vortex and therefore provided a more representative measure of true escape potential under hydrodynamic forcing. The centre was exposed to less of the initial jets. For



(a) Dye concentration — calm conditions

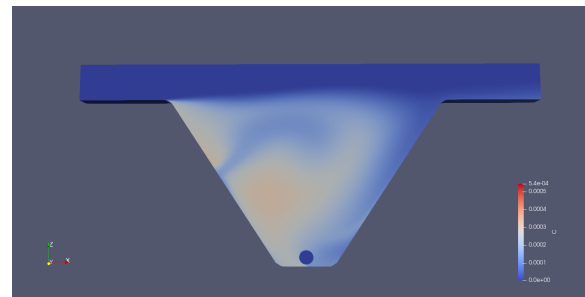
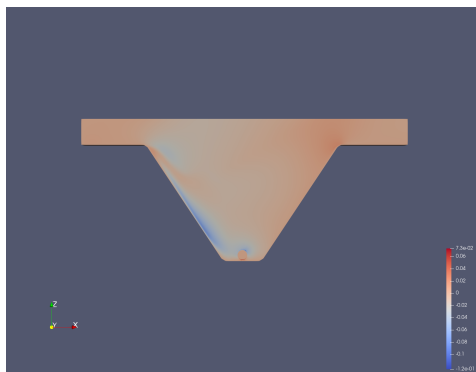
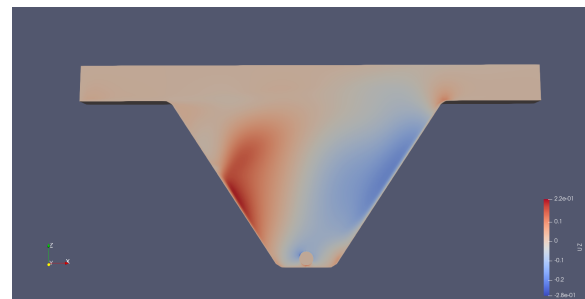
(b) Dye concentration — storm conditions ($z = -9$ m).(c) Vertical flow — calm conditions ($z = -9$ m).(d) Vertical flow — storm conditions ($z = -9$ m).

Figure A.6: Final simulation results at $z = -9$ m under calm and storm conditions. Top row: only buoyancy soil concentration. Bottom row: vertical flow field, red is upwards and blue is downwards flow.

this reason, the centre injection point was selected for the full simulation campaign. This location offers three key advantages:

1. It avoids structurally biased no-escape outcomes. Injecting sediment directly into a persistent downward jet would predetermine the result and prevent meaningful evaluation of how escape thresholds depend on depth, grain size, and sea state.
2. It ensures consistency and comparability across all cases. By introducing sediment at a location that is equally influenced by both upward and downward flow components, the results reflect the intrinsic trench dynamics rather than artefacts of the injection location.
3. It aligns with the physical assumption that suspended sediment follows the local fluid motion. Since the model treats sediment as a dilute scalar field with minimal slip relative to the fluid, a centrally located injection point provides a neutral starting condition whose behaviour is governed primarily by the developing flow field rather than by initial placement bias.

Summary and Interpretation

The two baseline simulations reveal a clear threshold in the transport response. Without settling velocity, the flow itself can export material from the trench, as shown by tracer escape along outgoing streamlines in storm conditions. When even a small settling velocity is included, no escape occurs: fine sediment remains suspended but confined within the vortex. These results confirm that the Rouse number predictions hold under simulated conditions and that background flow alone cannot produce net soil loss for realistic sediment. Instead, the trench acts as a temporary suspension zone during storm events and as a depositional basin under calm conditions.

A.2.2. Simulation Prioritisation Based on Rouse Number and EPI

Following the validation of flow behaviour and sediment transport thresholds, full trench simulations were designed to identify the conditions under which soil escapes the trench domain. The goal of this simulation campaign is to find transition points between no escape, partial escape, and full suspension, using a systematic and computationally efficient strategy.

Based on previous findings, it was observed that soil released on the right side of the trench generally does not escape, as the local downward flow is too strong. In contrast, particles released at the centre or left side of the trench have a higher chance of escape due to upward or weaker downward flow, especially under storm conditions. Under calm flow conditions, no escape was observed without chain motion.

Since each simulation requires six threads, only two cases can be run in parallel. To reduce total simulation time, storm cases were prioritised first, as they are more likely to exhibit escape and thus provide early information for threshold estimation. Simulations were scheduled adaptively: initial edge cases are evaluated first, and based on their outcomes, subsequent cases are selected to refine the escape threshold.

A.2.3. Escape Evaluation Method

The EPI provides a non-linear estimate of escape likelihood but is not a strict predictive tool. Cases lower in the ranking may still produce escape, depending on subtle flow and sediment interactions. Therefore, the EPI is used primarily to guide the simulation order, not to predict outcomes deterministically.

Each simulation is evaluated for escape in two ways:

1. **Visual check in ParaView:** During the simulation, particle fields are monitored to detect visible soil escape through the outlet.
2. **Numerical outlet flux:** The solver calculates how much soil exits through the outlet by integrating the product of local concentration and flux. A case is classified as "escape" if more than 1×10^{-5} of the initial soil mass exits the domain.

A.2.4. Edge-Case Strategy and Execution Order

To efficiently explore the simulation space, an edge-case strategy was applied based on the assumption that sediment escape correlates with the Escape Potential Index (EPI). The simulations are grouped into 32 distinct cases, each defined by a unique combination of flow velocity, sediment diameter (d_{50}), trench depth, and chain velocity (see Table A.1). These are divided into categories of four, where the only varying parameter is trench depth.

The top and bottom category, an *edge* cases is identified, case 20 and 29. Figure A.7 shows the step logic for choosing the next case.

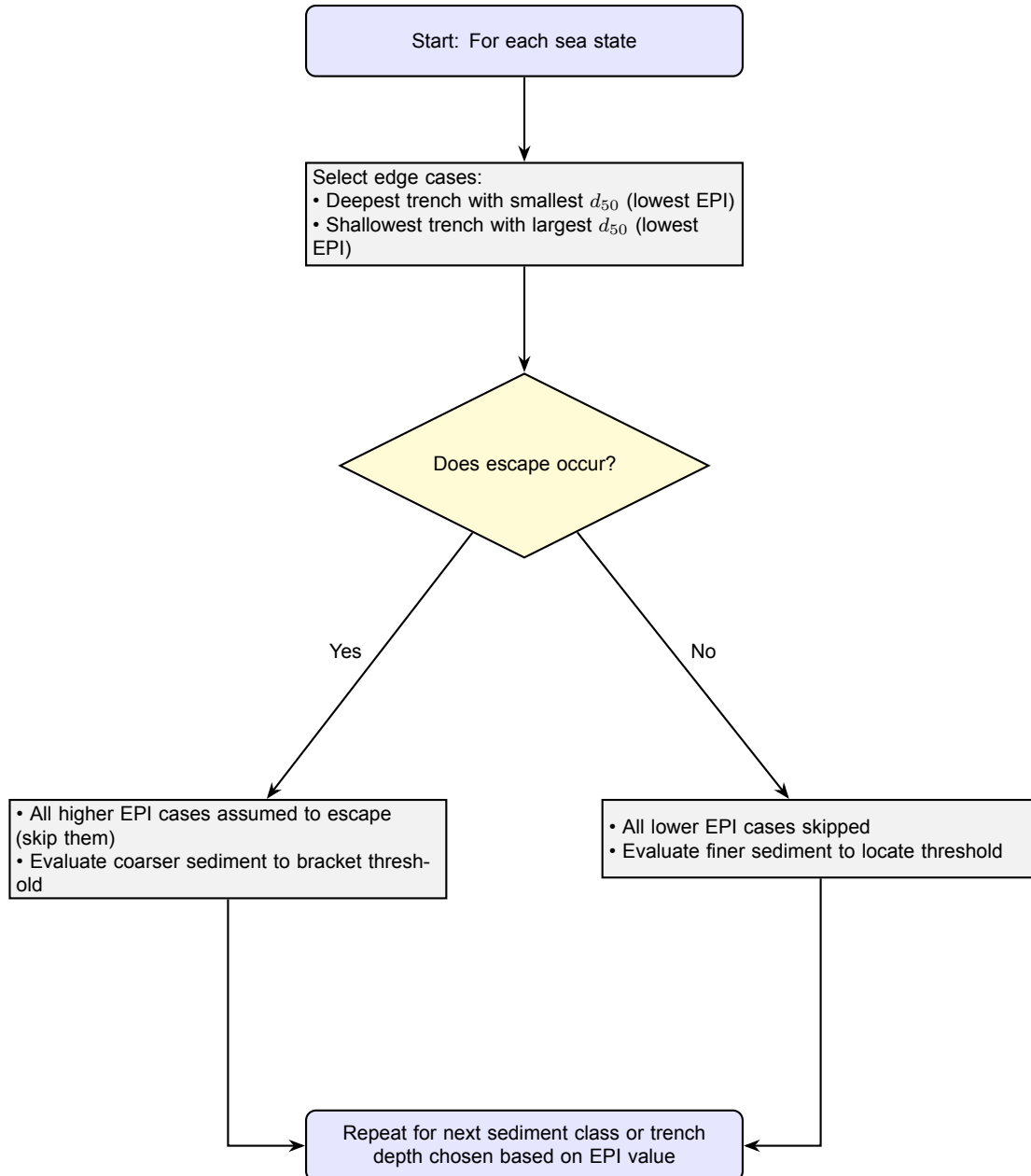


Figure A.7: Edge-case logic used to evaluate sediment escape thresholds in the simulation campaign.

This strategy avoids unnecessary simulations by eliminating interior cases once edge-case outcomes are known. The case selection sequence is adaptive: each new simulation is selected based on the outcomes of previous runs, gradually narrowing down the threshold between escape and no-escape behaviour.

Table A.1: Hydrodynamic and sediment parameters with Escape Potential Index (EPI) and priority ranking.

Case	Flow Speed [m/s]	d_{50} [mm]	Depth [m]	Max Upward Flow	Chain Velocity [m/s]	Rouse Number	EPI	EPI Order
1	0.05	0.0625	-3	0.013	0.1	1.63	3.0211	2
2	0.05	0.0625	-5	0.009	0.1	1.63	2.4879	4
3	0.05	0.0625	-7	0.022	0.1	1.63	0.7029	6
4	0.05	0.0625	-9	0.022	0.1	1.63	0.5332	8
5	0.05	0.25	-3	0.013	0.1	16.26	0.3029	12
6	0.05	0.25	-5	0.009	0.1	16.26	0.2494	13
7	0.05	0.25	-7	0.022	0.1	16.26	0.0705	33
8	0.05	0.25	-9	0.022	0.1	16.26	0.0534	36
9	0.05	0.375	-3	0.013	0.1	28.18	0.1747	9
10	0.05	0.375	-5	0.009	0.1	28.18	0.1439	15
11	0.05	0.375	-7	0.022	0.1	28.18	0.0407	20
12	0.05	0.375	-9	0.022	0.1	28.18	0.0308	26
13	0.05	0.5	-3	0.013	0.1	37.94	0.1298	17
14	0.05	0.5	-5	0.009	0.1	37.94	0.1069	23
15	0.05	0.5	-7	0.022	0.1	37.94	0.0302	25
16	0.05	0.5	-9	0.022	0.1	37.94	0.0229	28
17	0.05	1.0	-3	0.013	0.1	65.04	0.0757	37
18	0.05	1.0	-5	0.009	0.1	65.04	0.0624	32
19	0.05	1.0	-7	0.022	0.1	65.04	0.0176	29
20	0.05	1.0	-9	0.022	0.1	65.04	0.0134	39
21	0.36	0.0625	-3	0.077	0.3	0.56	4.4539	1
22	0.36	0.0625	-5	0.13	0.3	0.56	1.5040	3
23	0.36	0.0625	-7	0.18	0.3	0.56	0.7502	5
24	0.36	0.0625	-9	0.23	0.3	0.56	0.4453	7
25	0.36	0.25	-3	0.077	0.3	5.63	0.4430	14
26	0.36	0.25	-5	0.13	0.3	5.63	0.1496	16
27	0.36	0.25	-7	0.18	0.3	5.63	0.0746	21
28	0.36	0.25	-9	0.23	0.3	5.63	0.0443	34
29	0.36	0.375	-3	0.077	0.3	9.94	0.2509	11
30	0.36	0.375	-5	0.13	0.3	9.94	0.0847	22
31	0.36	0.375	-7	0.18	0.3	9.94	0.0423	38
32	0.36	0.375	-9	0.23	0.3	9.94	0.0251	27
33	0.36	0.5	-3	0.077	0.3	13.13	0.1900	10
34	0.36	0.5	-5	0.13	0.3	13.13	0.0641	18
35	0.36	0.5	-7	0.18	0.3	13.13	0.0320	24
36	0.36	0.5	-9	0.23	0.3	13.13	0.0190	30
37	0.36	1.0	-3	0.077	0.3	22.51	0.1108	19
38	0.36	1.0	-5	0.13	0.3	22.51	0.0374	35
39	0.36	1.0	-7	0.18	0.3	22.51	0.0187	31
40	0.36	1.0	-9	0.23	0.3	22.51	0.0111	40

Furthermore, this method enables progressive refinement of the EPI model. If observed outcomes deviate from EPI predictions, adjustments can be made to improve the escape potential formula for future applications or other offshore environments.

A.2.5. Storm Sea State Case Results

The first simulation is Case 24, which has the highest EPI values in the lowest category of the storm cases and was therefore prioritised. The solver calculated an escape value of 4.13×10^{-6} , which is below the defined threshold of 1×10^{-5} . However, visual inspection during the simulation revealed that a significant amount of soil exited the domain, not through the outlet, but through the top of the mesh.

This upward leakage is tracked by the solver via a dedicated measurement originally intended for chain-induced leakage. Since the chain is stationary when the escape occurs and does not interact with the upper mesh region, this value now effectively captures the vertical transport of soil driven solely by flow. The measured escape through the top is approximately 2.38×10^{-4} , which is significantly greater than the outlet-based flux and clearly indicates soil loss. As shown in Figure A.8, red regions represent concentrations above 1×10^{-5} , and soil is visible all the way up to the mesh top. The total escape rate, considering both outlet and top-boundary losses, is approximately 0.1238.

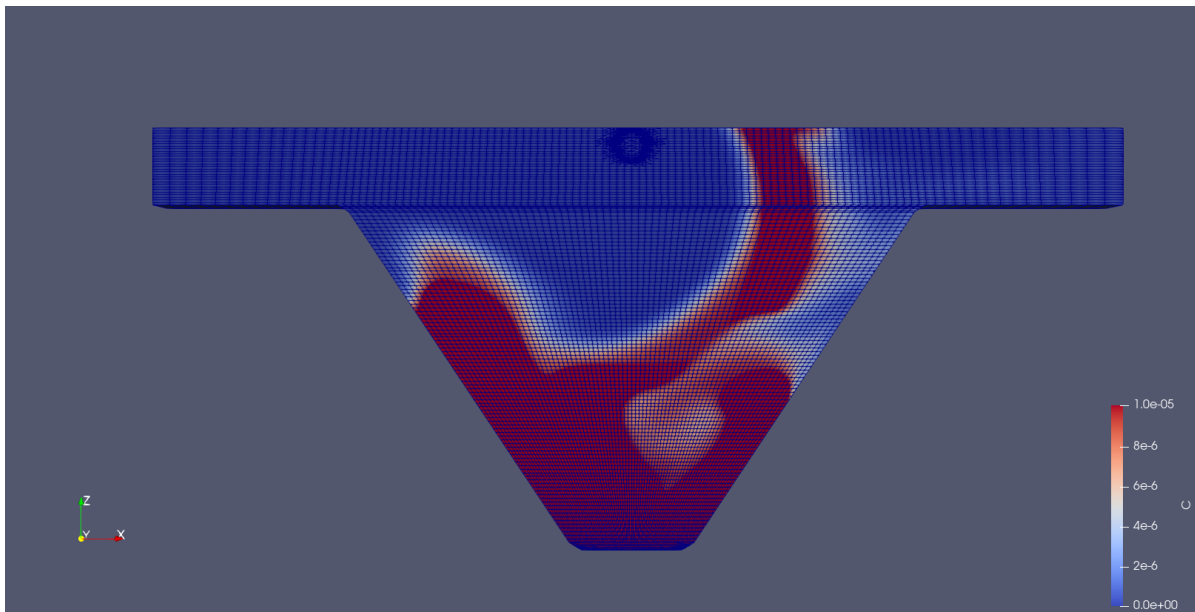


Figure A.8: Final time step for Case 24. Soil is visibly concentrated near the top boundary, indicating significant vertical escape.

To validate the threshold from the opposite end of the EPI spectrum, Case 37 was selected next. The solver-based escape was 2.87×10^{-5} , above the threshold. Visual confirmation of escape through the outlet is shown in Figure A.9, with no top-boundary losses observed. This confirmed Case 37 as a positive escape case.

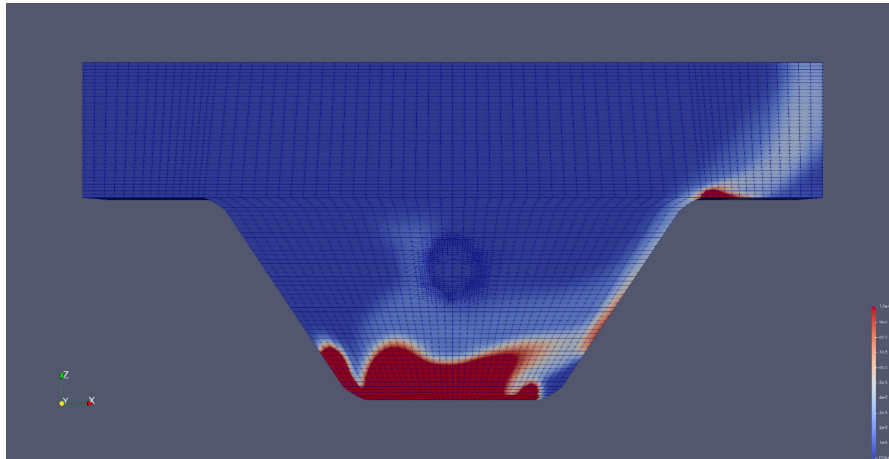


Figure A.10: Case 33, soil escapes the trench via outlet flow.

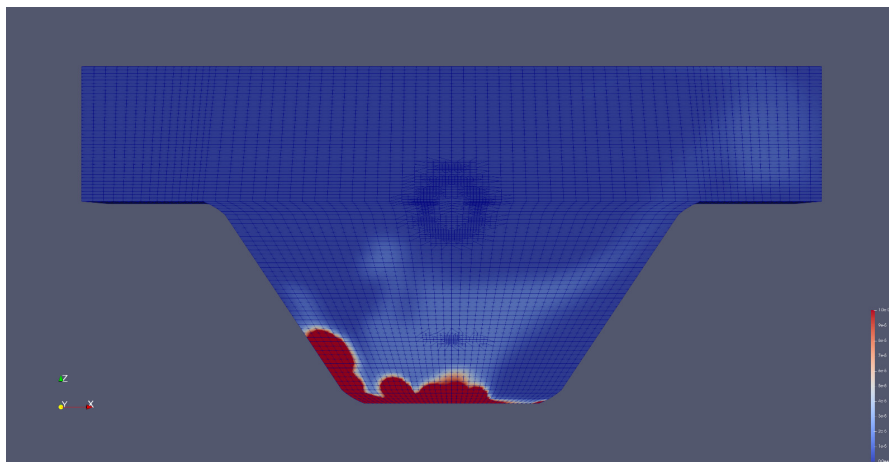


Figure A.9: Case 37, time step 48. Soil visibly exits through the outlet.

To further refine the threshold, Case 38 was simulated. It produced an escape value of only 2.09×10^{-6} , and the visual check confirmed that no significant soil escaped. This allows Case 38 to be classified as a non-escape case. Based on the EPI ranking, Case 34 was chosen next, as its EPI lies between Case 37 and Case 38. Case 34 also showed minimal escape (4.06×10^{-6}), and the simulation confirmed confinement of the soil within the trench.

Case 33 was then run to assess the effect of shallower depth within the same sediment class. It showed an escape rate of 8.37×10^{-5} , which clearly exceeds the threshold. Visual evidence of outlet-based escape is provided in Figure A.10. The simulation confirms that at shallower depths, the upward flow generated by the chain's motion is sufficient to carry fine sediment out of the trench. Next is case 34, which showed no escape as the threshold was not.

As now the threshold EPI is between 0.19 and 0.0641, case 33 and 34 respectfully, case 30 is chosen next. Soil escape occurred beginning with the first upward chain motion. The induced flow trail picked up soil and transported it through the top of the mesh. Additional escape occurred during the downward motion. Most of the escaped soil settled in a low-velocity region just outside the trench. As a result, the escape rate was modest, with a concentration leaving through the top measured at 7.595×10^{-5} . Including the outlet transport, the total escape value was 7.67×10^{-5} , corresponding to an escape ratio of 0.0166. When estimating and including soil located near the trench edge, the escape ratio increases to ≈ 0.1354 . The chain shows difficulty in lifting soil compared to the 0.25 mm case, indicating a new threshold condition.

At a depth of $z = -7$, which represents case 31, the escape rate is lower since no significant escape occurs during downward motion. As the trench volume increases, the relative influence of the chain's motion decreases, reducing the induced upward force. The chain still manages to transport some suspended soil out of the trench during the second upward motion, aided by the flow field that prevents immediate settling. The escape ratio for this case is 0.0070.

At the deepest depth ($z = -9$), case 32, the chain's ability to displace soil remains, which is expected as the velocity conditions remain unchanged. However, while the chain can still lift soil, most of it resettles on the trench bottom. The suspended soil does not reach the trench top and is not carried outside.

Next, Case 28 was selected. This case lies just above Case 32, which showed no soil escape, in the EPI ranking. Case 28 recorded an escape rate of 3.36×10^{-5} , exceeding the threshold. The eye test confirmed soil escape, as seen in Figure A.11.

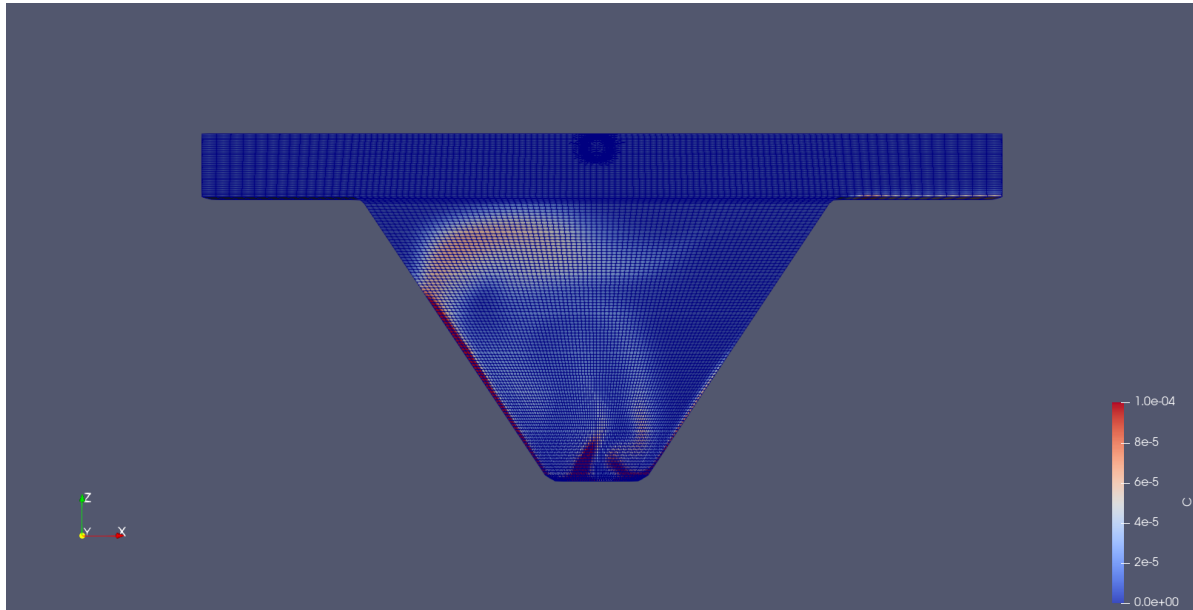


Figure A.11: Case 28, final time step. Soil accumulates just outside the trench.

A noteworthy mechanism in this case involves the downward chain stroke generating upward wall jets that lift soil over the trench edge. While much of this material is then pushed downward again by the main flow, some accumulates in low-velocity zones near the rounded trench lip, suggesting potential long-term morphological change. Not all material reaches the outlet, but the upward displacement is sufficient to classify this case as one exhibiting escape.

Summary Based on the results, the threshold for sediment escape under storm conditions is not accurately measured by the EPI. Escape occurred in all cases with the shallowest depth, indicating that shallow depth alone may be sufficient to enable soil loss, regardless of small variations in EPI.

Furthermore, these findings indicate that the current EPI formulation, while effective as a first-order heuristic, requires adjustment. For example, Case 34 had a higher EPI than Case 31, despite showing no escape. An overview is given in Table A.2.

Table A.2: Escape Cases for in the storm seastate

Case	Flow Speed [m/s]	d_{50} [mm]	Depth [m]	Max Upward Flow	Chain Velocity [m/s]	Rouse Number	EPI	Soil Escape
21	0.36	0.0625	-3	0.077	0.3	0.56	4.4539	Yes
22	0.36	0.0625	-5	0.13	0.3	0.56	1.5040	Yes
23	0.36	0.0625	-7	0.18	0.3	0.56	0.7502	Yes
24	0.36	0.0625	-9	0.23	0.3	0.56	0.4453	Yes
25	0.36	0.25	-3	0.077	0.3	5.63	0.0787	Yes
26	0.36	0.25	-5	0.13	0.3	5.63	0.1496	Yes
27	0.36	0.25	-7	0.18	0.3	5.63	0.0746	Yes
28	0.36	0.25	-9	0.23	0.3	5.63	0.0443	Yes
29	0.36	0.375	-3	0.077	0.3	9.94	0.2509	Yes
30	0.36	0.375	-5	0.13	0.3	9.94	0.0847	Yes
31	0.36	0.375	-7	0.18	0.3	9.94	0.0423	Yes
32	0.36	0.375	-9	0.23	0.3	9.94	0.0251	No
33	0.36	0.5	-3	0.077	0.3	13.13	0.1900	Yes
34	0.36	0.5	-5	0.13	0.3	13.13	0.0641	No
35	0.36	0.5	-7	0.18	0.3	13.13	0.0320	No
36	0.36	0.5	-9	0.23	0.3	13.13	0.0190	No
37	0.36	1.0	-3	0.077	0.3	22.51	0.1108	Yes
38	0.36	1.0	-5	0.13	0.3	22.51	0.0374	No
39	0.36	1.0	-7	0.18	0.3	22.51	0.0187	No
40	0.36	1.0	-9	0.23	0.3	22.51	0.0526	No

A.2.6. Normal Sea State Case Results

As with the storm scenario, two edge cases are selected to initiate the simulation sequence: Case 4 and Case 17. Based on insights from the storm cases and to minimise computational cost, Case 17 is evaluated first. Case 4 is also simulated, but similar to the storm approach, escape is anticipated. However, the EPI difference between Case 4 and its neighbouring case is too large to make a reliable inference without verification.

As shown in Figure A.12, no particle escape is observed for Case 17. Unlike the storm scenario, most of the soil remains on the trench bottom, with no visible suspension. This can be attributed to the weak flow field. While storm conditions were capable of suspending the sediment (Figure A.9), the normal sea state does not generate enough flow strength, as predicted by the associated Rouse numbers (see Table 4.6).

Following the outcome of Case 17, Case 14 is not expected to show escape either, and the next logical case to examine is Case 13. In this case, some soil is carried on top of the chain during the upward motion (Figure A.13). However, the chain velocity is insufficient to transport the sediment out of the trench. Due to the low velocity field, the soil slips off the chain before reaching trench-top level.

Case 9 further confirms the absence of escape. The flow field is nearly negligible, and the chain motion induces no significant soil transport. Based on this result, Case 6 is tested next. Although its EPI is roughly 30% higher, it still shows no escape. Again, the combination of weak flow and insufficient chain momentum prevents resuspension or trench exit.

Escape is first observed in Case 5. A small amount of soil escapes during the initial upward chain swing, when the sediment is still relatively high in the trench. Some particles also leave through the top of the mesh. The total escaped concentration corresponds to an escape ratio of 0.007—the lowest among all cases with observed escape. Similar to the storm scenario, the shallowest trench still allows for escape. This is primarily due to the limited vertical distance between the soil release point (at $z = -1$) and the chain's initial movement zone (starting at $z = -3$). This 1.5–2 meter gap makes it easier for the chain to push sediment upward without requiring significant carrying capacity.

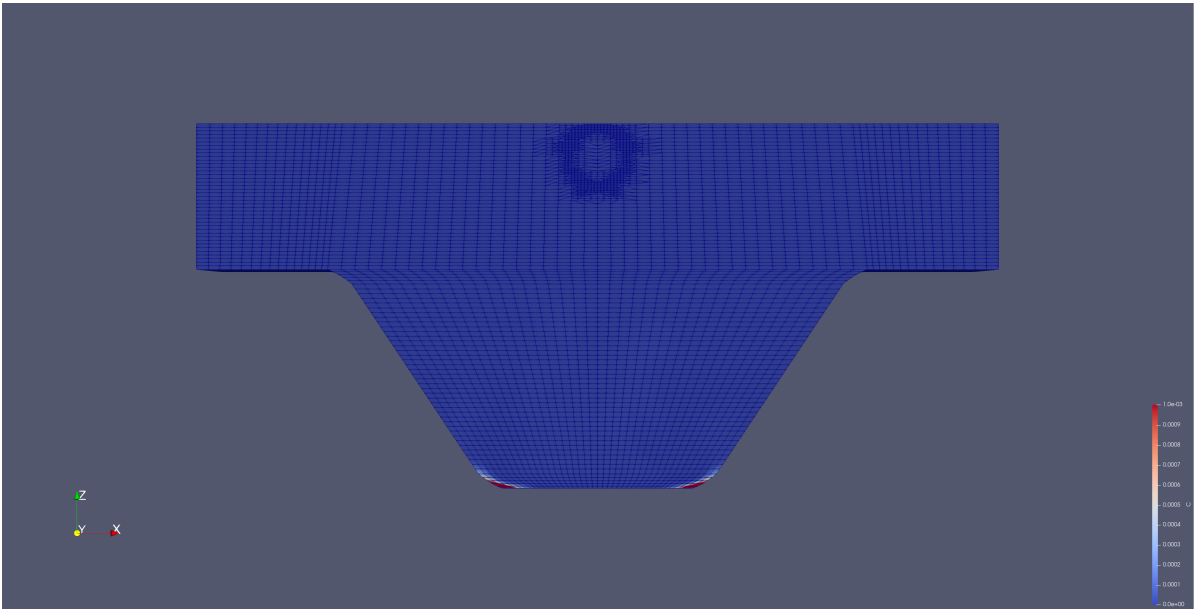


Figure A.12: Case 17, soil remains on the trench bottom without suspension.

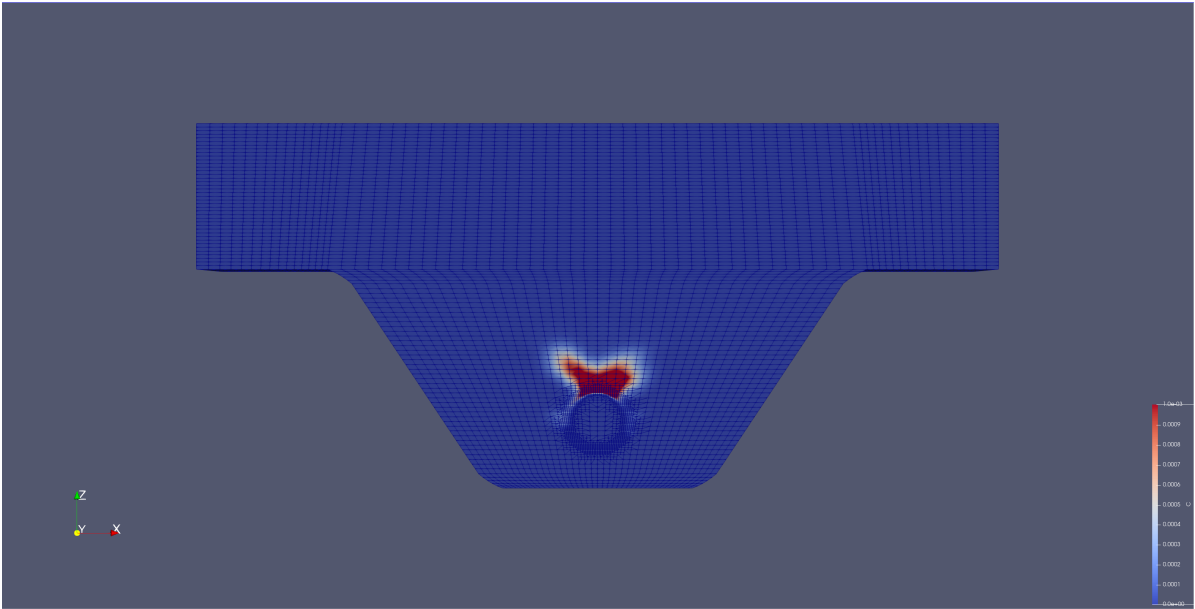


Figure A.13: Case 13, soil temporarily on top of the chain during the first upward motion.

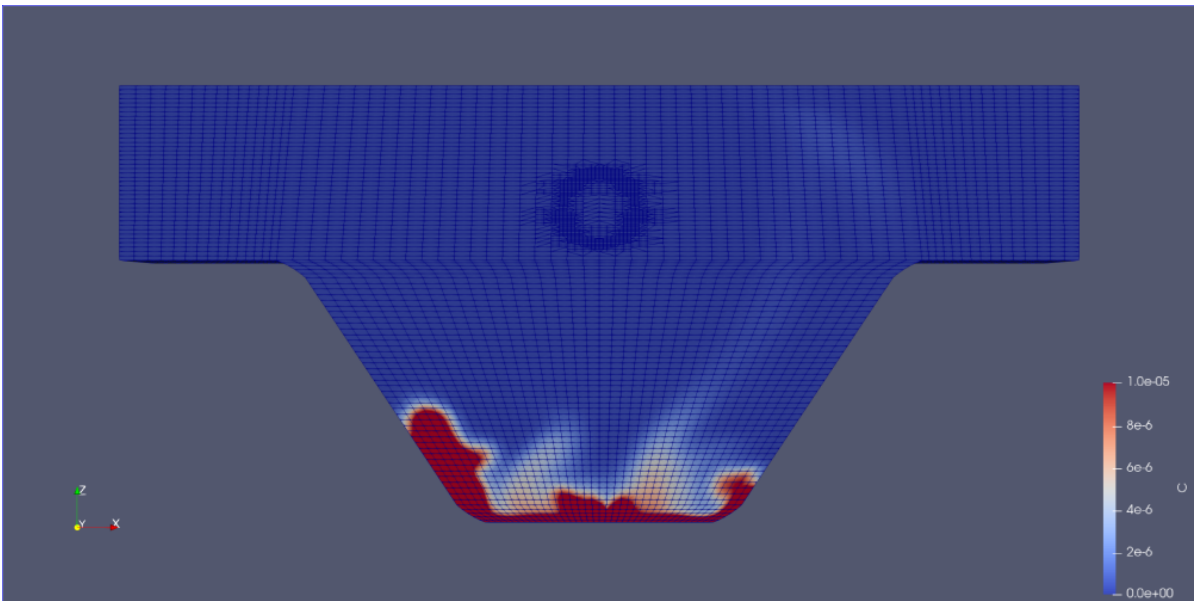


Figure A.14: Case 5, soil escapes during the first upward chain motion.

Edge Case 4 shows substantial escape. In Figure A.15, the soil’s behaviour is shown across three chain movements; upward, downward, and upward again. Even in this favourable configuration with the smallest particle size, the chain is not strong enough to cause escape during the first upward motion alone. Most soil displacement originates from the chain’s downward movement, mirroring behaviour observed under storm conditions.

As the chain rises again, soil begins to leave the trench on both flanks. Depending on local flow direction, some sediment is either pushed back or fully ejected (Figure A.15b). By the final upward motion (Figure A.15c), particles are observed both on top of the chain and along the trench edge. While the right-side soil is lifted by the chain’s downward-induced flow, the soil atop the chain is actively carried out.

Most notably, the soil does not return to the bottom throughout the simulation. This behaviour suggests that for even finer sediments—such as silts or clays—trench clearing by chain motion could be even more effective. Over a timespan of 30 years, repeated chain movements may therefore result in significant long-term sediment removal.

The following table represents the cases and shows which have soil escape and which don’t. Only a yes or no is mentioned as no backup for numerical values apart found in this research can be validated. An EPI between 0.3029 and 0.2494 is the threshold for soil escape in the normal sea state condition. No adjustments on the EPI are necessary. In Table A.3 an overview of all the normal sea state cases is given.

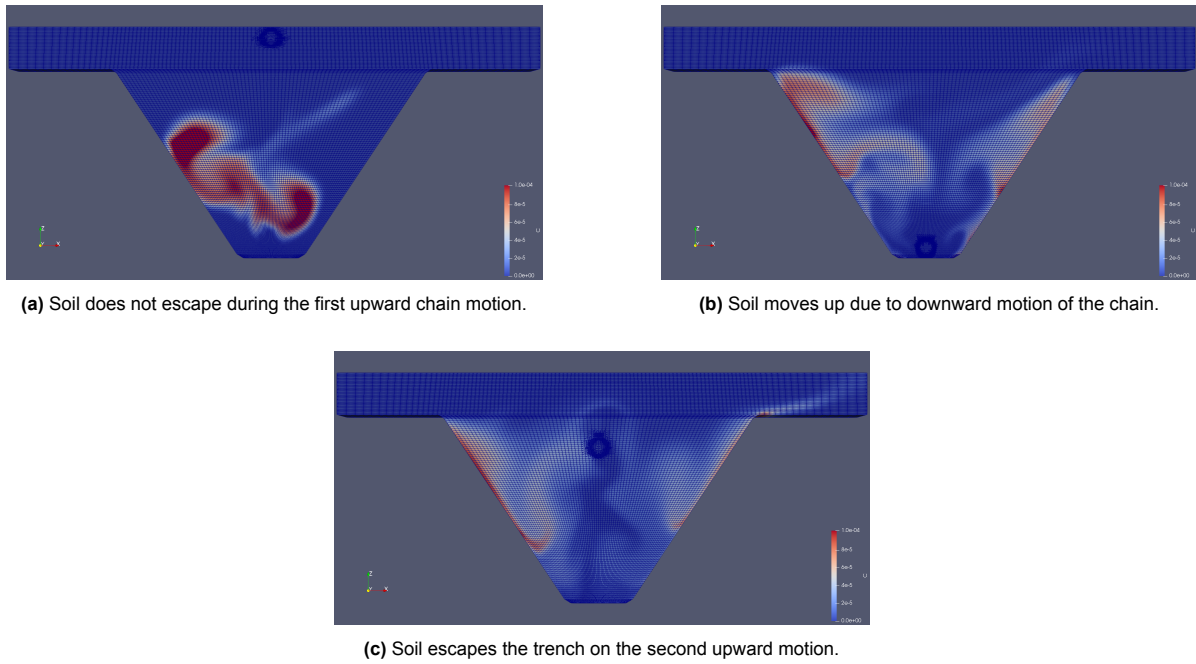


Figure A.15: Sequence of Case 4 soil movement: (a) initial upward motion, (b) downward chain motion, and (c) second upward motion causing soil escape.

Table A.3: Escape Potential Index (EPI) for all simulation cases with priority ranking.

Case	Flow Speed [m/s]	d_{50} [mm]	Depth [m]	Max Upward Flow	Chain Velocity [m/s]	Rouse Number	EPI	Soil Escape
1	0.05	0.0625	-3	0.013	0.1	1.63	3.0211	Yes
2	0.05	0.0625	-5	0.009	0.1	1.63	2.4879	Yes
3	0.05	0.0625	-7	0.022	0.1	1.63	0.7029	Yes
4	0.05	0.0625	-9	0.022	0.1	1.63	0.5332	Yes
5	0.05	0.25	-3	0.013	0.1	16.26	0.3029	Yes
6	0.05	0.25	-5	0.009	0.1	16.26	0.2494	No
7	0.05	0.25	-7	0.022	0.1	16.26	0.0705	No
8	0.05	0.25	-9	0.022	0.1	16.26	0.0534	No
9	0.05	0.375	-3	0.013	0.1	28.18	0.1747	No
10	0.05	0.375	-5	0.009	0.1	28.18	0.1439	No
11	0.05	0.375	-7	0.022	0.1	28.18	0.0407	No
12	0.05	0.375	-9	0.022	0.1	28.18	0.0308	No
13	0.05	0.5	-3	0.013	0.1	37.94	0.1298	No
14	0.05	0.5	-5	0.009	0.1	37.94	0.1069	No
15	0.05	0.5	-7	0.022	0.1	37.94	0.0302	No
16	0.05	0.5	-9	0.022	0.1	37.94	0.0229	No
17	0.05	1.0	-3	0.013	0.1	65.04	0.0757	No
18	0.05	1.0	-5	0.009	0.1	65.04	0.0624	No
19	0.05	1.0	-7	0.022	0.1	65.04	0.0176	No
20	0.05	1.0	-9	0.022	0.1	65.04	0.0134	No

Summary In the normal sea state, edge case simulations began with Case 17 and Case 4 to explore the lower and upper bounds of sediment mobility. Case 17 showed no escape, confirming that weak ambient flow prevents suspension, unlike in storm scenarios. Stepwise testing of intermediate cases (Cases 13, 9, and 6) confirmed this trend, with no significant sediment transport observed due to limited

Table A.4: Escape ratios for selected storm sea state cases. Cases not listed showed negligible or zero escape.

Case	Escape Ratio	Sea State	
1	0.3170	Calm Sea State	
2	0.0542		
3	0.0295		
4	0.0174		
5	0.0070		
<i>Cases 6–20 omitted: no significant escape</i>			
21	0.3370	Storm Sea State	
22	0.0745		
23	0.1875		
24	0.1238		
25	0.1200		
26	0.0365		
27	0.0697		
28	0.0323		
29	0.0579		
30	0.0116		
<i>Case 31 & 32 omitted: no significant escape</i>			
33	0.0511		
<i>Cases 34–36 omitted: no significant escape</i>			
37	0.0129		
<i>Cases 38–40 omitted: no significant escape</i>			

chain-induced momentum.

Escape first occurred in Case 5, even though minimally, primarily during the chain's initial upward movement. The limited trench depth in this case facilitated escape despite low velocities. In contrast, Case 4, an edge case with the lowest particle size, exhibited notable sediment loss, especially during and after the chain's downward motion. The soil did not resettle, suggesting that finer material may be even more susceptible to long-term removal under repeated chain operation. This also shows insignificant overall influence of the chain on soil transport.

A.2.7. Cases Observation and quantification

For a grain size of $d_{50} = 0.0625$ mm, the predicted behaviour based on the Rouse number was confirmed: soil escape occurred under both sea states. This validates the Rouse-based expectations for fine-grained sediment. However, for coarser sediments where suspension was not anticipated according to the Rouse number, soil escape was still observed in certain cases. These deviations are explained by the interaction between chain-induced turbulence and the ambient flow field, which jointly contributed to local increases in shear velocity sufficient to resuspend sediment.

The storm scenario led to more frequent escape events compared to the normal sea state. This is due to the stronger background flow in combination with the chain motion, which enhanced the overall turbulence and sediment mobility within the trench. For the finest tested grain size, $d_{50} = 0.0625$ mm, no combination of depth or current condition was capable of retaining the soil within the trench. Additionally, in the storm scenario, no sediment of any grain size remained in trenches at a depth of $z = -3$ m, indicating that such shallow trenches will inevitably be cleared during storm events.

These two outcomes, total loss of 0.0625 mm grains and universal clearing of 3-meter-deep trenches under storm conditions, support the findings of Gao and Lu, who showed that sand trenches tend to stabilise after deepening, and Rui et al., who demonstrated that clay is easily washed away after seabed disturbance.

In general, escape ratios were found to decrease with increasing trench depth, see Table A.4. This trend is due to a combination of factors. First, deeper trenches impose a longer carrying distance on sediment, increasing the chance of loss before it reaches the trench top. Second, as trench volume

increases, the ratio between the displaced water volume and the trench size decreases. This reduces the relative influence of the chain's movement, lowering the upward forces acting on the sediment.

The threshold behaviour across depths and grain sizes is clearly visible. Trenches consistently deepen to at least 3 meters under all tested conditions. At a depth of 5 meters, sediment with $d_{50} \geq 0.35$ mm is retained, while finer sediments are transported out. For $d_{50} = 0.25$ mm, the trench remains at 3 meters under calm conditions, but storms can extend this to a theoretical depth of 9 meters.

The type of soil outflow also varies by grain size: when the chain is able to push or trail the sediment for extended periods, this typically signals further trench deepening. Conversely, if the soil does not settle after the downward motion of the chain, this suggests either direct escape or delayed removal due to subsequent suspension.

A particularly interesting finding is that a trench depth of 5 meters exhibits a unique transitional behaviour. While it is often sufficient to retain coarser sediment, it also shows the lowest escape ratios among the depths where escape occurs. This is likely due to the combination of a weak flow field at this depth and a reduced chain-induced vertical force. As a result, sediment begins its upward motion from a lower position in the trench and must be carried over a longer path. In many cases, this leads to settling on the trench slope before reaching the outlet.

Altogether, these results confirm that for depths shallower than 5 meters, the chain alone may be sufficient to lift sediment out of the trench. However, at greater depths, assistance from the ambient flow field becomes increasingly necessary to achieve particle escape.

B

IbBousSoilFoam

This appendix summarises how the custom solver `IbBousSoilFoam` was constructed by combining four components:

1. The immersed boundary (IB) framework of `foam-extend 5.0`,
2. A Boussinesq-type formulation from the baseline `buoyantBoussinesqPimpleFoam` family,
3. A scalar transport equation adapted from thermal/contaminant transport and modified for suspended sediment.
4. Merging the transport equations and extra momentum terms from `settlingFoam` into solver

The result is a single-fluid, incompressible, buoyancy-coupled solver capable of representing dilute sediment suspension and a vertically oscillating mooring chain without mesh deformation.

The sections below detail the implementation logic that complements the main text of this thesis.

B.1. Overview of Modifications

The original `buoyantBoussinesqPisoFoam` handles:

1. Incompressible RANS flow,
2. Boussinesq buoyancy based on temperature,
3. A temperature transport equation,
4. PIMPLE pressure–velocity coupling.

`IbBousSoilFoam` replaces and extends this structure by:

1. removing the temperature equation and adding a sediment transport equation,
2. replacing thermal buoyancy with sediment–induced buoyancy,
3. adding drift–flux settling through a dedicated slip–velocity model,
4. integrating a moving immersed boundary (IB) with dynamic refinement,
5. adapting `UEqn` and `pEqn` to IB and sediment-dependent density,
6. adding IB-aware flux correction and Courant number control.

These modifications convert a thermal buoyancy solver into a hydrodynamic–sediment solver with moving geometry.

B.2. Replacement of Temperature by Sediment Concentration

B.2.1. Original thermal formulation

The base solver transported temperature via

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \nabla \cdot (\mathbf{U} T) = \nabla \cdot (\kappa_{\text{eff}} \nabla T), \quad (\text{B.1})$$

and used the Boussinesq relation

$$\rho_{\text{eff}} = 1 - \beta (T - T_{\text{ref}}). \quad (\text{B.2})$$

B.2.2. Modified sediment formulation

Temperature is removed completely and replaced by a sediment concentration field C . The governing equation implemented in CEqn.H is

$$\frac{\partial C}{\partial t} + \nabla \cdot (C \mathbf{U}) + \nabla \cdot (C \mathbf{w}_s) = \nabla \cdot (\mathbf{D}_{\text{eff}} \nabla C), \quad (\text{B.3})$$

where w_s is the settling (slip) velocity and D_{eff} is the turbulent diffusivity. The mixture density is now

$$\rho(C) = 1 - \beta(C - C_{\text{ref}}), \quad (\text{B.4})$$

with

$$\beta = \frac{\rho_s - \rho_f}{\rho_f}. \quad (\text{B.5})$$

which directly replaces the original thermal expression.

All energy-model components have been removed.

B.3. Summary of Solver Modifications

Feature	buoyantBoussinesqPisoFoam	lbBousSoilFoam
Transported scalar	Temperature T	Sediment concentration C
Buoyancy model	Thermal expansion: $\rho_{\text{eff}} = 1 - \beta(T - T_{\text{ref}})$	Sediment-driven density variation: $\rho_{\text{eff}} = 1 - \beta C$
Settling / drift flux	Not included	Soulsby settling velocity, slip flux ϕ_{slip}
Immersed boundary	None	Diffused-interface IB (γ , $s\Gamma$ masks)
Mesh motion	None	Dynamic refinement near IB
Momentum equation	Thermal Boussinesq forcing	Sediment buoyancy + IB reconstruction
Pressure equation	p_{rgh} with thermal coupling	p corrected for sediment gradients and IB
Additional fields	T, k, ε	$C, V_{dj}, \gamma, s\Gamma, \phi_{\text{slip}}, \rho_k$

B.4. Buoyancy and Sediment Coupling

As mentioned above, suspended sediment modifies the mixture density, which in turn alters the pressure–gravity balance. Following the Boussinesq hypothesis, density variations are small and appear only in the buoyancy term. The mixture density is updated after each sediment-transport solve as

The buoyancy force enters the momentum equation through a pressure–gravity reconstruction term:

```

1 surfaceScalarField ghf("gh", g & mesh.Cf());
2
3 solve
4 (
5     ddtUEqn
6     + relax(HUEqn, UUr)
7     ==
8     - fvc::grad(p)
9     + fvc::reconstruct( (-ghf * fvc::snGrad(rhok)) * mesh.magSf() )
10 );

```

This ensures consistent sediment–flow coupling: velocity affects sediment through advection, and suspended sediment affects velocity through buoyancy only.

B.5. Settling Velocity and Slip-Flux Model

The solver replaces thermal “drift” terms with a Soulsby-style settling velocity to model gravitational settling of suspended grains. The magnitude of the downward slip velocity is supplied via the dictionary entry `V0`, where $V0$ represents the settling velocity w_s :

```

1 dimensionedVector V0(VdjModelCoeffs.lookup("V0"));
2 dimensionedScalar alphaMin(VdjModelCoeffs.lookup("alphaMin"));

```

The settling velocity field is evaluated each time step as:

$$V_{dj} = \begin{cases} 0, & C < \alpha_{\min}, \\ V_0, & C \geq \alpha_{\min}, \end{cases} \quad (\text{B.6})$$

implemented as:

```

1 Vdj = V0 * max(sign(C - alphaMin), scalar(0));

```

The corresponding slip flux through faces is:

```

1 phiSlip = rho * (mesh.Sf() & fvc::interpolate(Vdj));

```

Sediment Transport Equation

The full transport equation solved for concentration C is:

```

1 fvScalarMatrix CEqn
2 (
3     rho * fvm::ddt(C)
4     + fvm::div(rhoPhi, C)           // advection
5     + fvm::div(phiSlip, C)          // settling flux
6     - fvm::laplacian(Deff, C)       // diffusion
7 );
8
9 CEqn.relax();
10 CEqn.solve();
11
12 rhok = (1.0 - beta*(C - Cref)); // density update

```

The effective turbulent diffusivity is computed as

```

1 dimensionedScalar Sc_t("Sc_t", dimless, 1);
2
3 volScalarField Deff =
4 rho*( turbulence->nu()/Sc_t
5     + turbulence->nut()/Sc_t );

```

B.6. Immersed Boundary Implementation

The solver uses the diffused-interface immersed boundary method from foam-extend. Two mask fields are generated:

- $\gamma(\mathbf{x}, t)$: cell mask (suppresses velocity inside the chain),
- $s\Gamma(\mathbf{x}, t)$: face mask (suppresses flux through IB-cut faces).

Both are reconstructed every PIMPLE iteration using:

```
1
2 #include "updateIbPatchFields.H"
3 #include "updateIbMasks.H"
```

Velocity Enforcement

The IB method reconstructs the instantaneous velocity in IB-affected cells using a weighted blend:

$$\mathbf{U}(\mathbf{x}) = \gamma \mathbf{U}_f + (1 - \gamma) \mathbf{U}_s,$$

where $\mathbf{U}_f$ is the fluid velocity and $\mathbf{U}_s$ is the local solid-body velocity. This ensures a no-slip boundary condition without moving the mesh.

Flux Correction and Continuity

Fluxes are temporarily converted to the absolute frame, corrected for IB motion, and then returned to the relative frame:

```
1 fvc::makeAbsolute(phi, U);
2
3 // enforce continuity with IB constraints
4 phi = fvc::interpolate(U) & mesh.Sf();
5 adjustPhi(phi, U, pcorr);
6
7 pcorrEqn.solve();
8 phi -= pcorrEqn.flux();
9
10 fvc::makeRelative(phi, U);
```

IB Courant Number

A dedicated Courant number is computed to maintain stability near the chain:

$$Co_{IB} \max \left(\frac{s\Gamma, |\phi|}{|\mathbf{S}|} \Delta t \right), \quad (\text{B.7})$$

where only fluid faces contribute because $s\Gamma = 0$ inside the chain.

B.7. Solver Flowchart

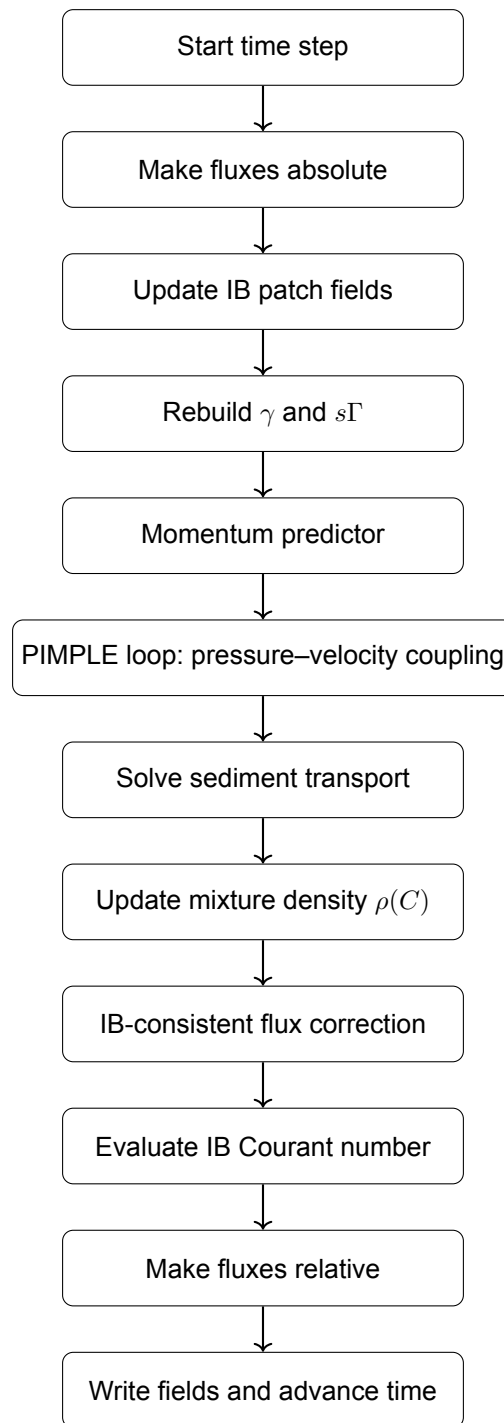
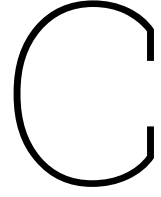


Figure B.1: Operational flowchart of the custom solver IbBousSoilFoam.



Numerical Implementation

This appendix provides the detailed numerical implementation of the solver framework used in this study. It complements the description in Chapter 4 by specifying the mesh domains, the discretisation schemes, solver settings, pressure–velocity coupling, buoyancy formulation, immersed boundary treatment, and the numerical verification tests that support the reliability of the results.

C.1. Mesh Geometry Across Trench Depths

All four computational domains used in this study ($z = -3, -5, -7, -9$ m) share an identical topological structure. Each mesh consists of a fixed trench core, depth-dependent outer seabed extensions, rounded trench corners, and the same block and boundary layout. Only the *horizontal extent* of the upper trench and the outer domain changes with trench depth; the trench bottom itself remains geometrically identical across cases. This ensures that differences in flow and sediment behaviour arise from depth alone rather than geometric inconsistencies.

(1) Fixed trench core (vertices A--D)

For every depth, the inner trench is defined by the same four vertices:

$$A = (4, 3, z), \quad B = (7, 3, z), \quad C = (7, 0, z), \quad D = (4, 0, z).$$

These points form a trench footprint that is 3 m wide in the x -direction and 3 m tall in the y -direction. Because A–D are unchanged across all meshes, the trench cross-section, the chain's relative position, and the refinement band around the immersed boundary remain consistent across simulations.

(2) Depth-dependent widening via outer seabed points (E--H)

The distinguishing geometric feature between meshes is the outward shift of the seabed vertices E–H. As trench depth increases, the horizontal domain widens to avoid artificial confinement and to provide adequate distance between the trench and the inlet/outlet boundaries.

For example, at $z = -5$ m:

$$E = (0.667, 3, 0), \quad F = (10.333, 3, 0), \quad G = (10.333, 0, 0), \quad H = (0.667, 0, 0).$$

and for $z = -7$ m:

$$E = (-0.667, 1, 0), \quad F = (11.667, 1, 0), \quad G = (11.667, 0, 0), \quad H = (-0.667, 0, 0),$$

At shallower depths (e.g. $z = -3$), E–H lie closer to the eachother in order to preserve the 63° . At deeper depths (e.g. $z = -9$) they shift outward significantly.

A quantitative comparison of this widening is provided in Table C.1.

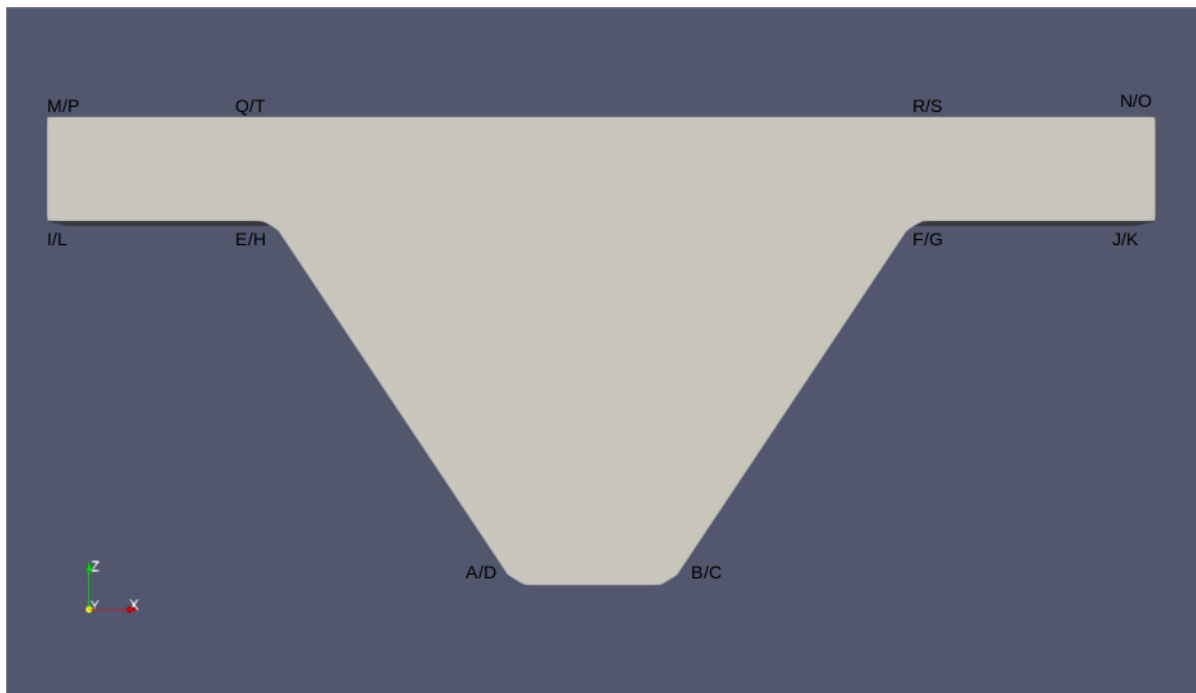


Figure C.1: Annotated vertex map showing the trench vertices (A–D), the widening seabed vertices (E–H) and the vertices that make up the inlet the outlet and the top of the mesh (I–P). The second letter denotes the same point but at $y = 0$ instead of $y = 1$. These points define the mesh geometry consistently across all four trench depths.

(3) Rounded trench geometry

All trenches include smooth circular arc edges connecting the trench centre to the side walls. These rounded corners improve numerical stability by reducing singular stagnation points and preventing abrupt velocity gradients.

For the $z = -5$ m case, for instance:

```
arc 24 25 (4.0 1 -2.9)
arc 22 23 (7.0 1 -2.9)
arc 26 27 (4.0 0 -2.9)
arc 20 21 (7.0 0 -2.9)
arc 28 29 (-0.667 1 -0.1)
arc 34 35 (11.667 1 -0.1)
arc 30 31 (-0.667 0 -0.1)
arc 33 32 (11.667 0 -0.1)
```

arc 24 25 (4.0 1 -2.9) means that two points are made along point A between which an arced line is made. This is done for all 8 points along the trench and is a

The same arc structure is applied for all 8 points along the trench and for all depths.

(4) Block structure

Every mesh is composed of the same six hexahedral blocks:

1. trench centre block,
2. left trench wall,
3. left seabed block,
4. flat region between trench walls,
5. right trench wall,
6. right seabed block.

There are so much blocks due to the arcing of the corners. They result in two more blocks as the upper and lower part of the arcs have to be connected as well. Because block connectivity is unchanged, grading, resolution distribution, and solver configuration remain identical across depths.

(5) Boundary conditions

Each mesh contains the same patch structure:

- inlet and outlet,
- top (free-stream),
- bottom (solid seabed),
- trenchSideWalls (rigid boundaries),
- sideWallFront and sideWallBack (empty), enabling 2D extrusion.

This ensures that no difference in boundary treatment occurs between the simulations.

Summary

Across all depths, the inner trench geometry (A–D) remains fixed while outer seabed points (E–H) shift outward to expand the horizontal computational domain. Rounded trench edges, block topology, and boundary conditions remain unchanged. As a result, the domain width increases from approximately 7 m at $z = -3$ to 15 m at $z = -9$ m, allowing deeper trenches to be simulated without unwanted boundary influence.

Depth (m)	A–D Coordinates	E–H X-positions (m)	Domain Width (m)
–3	Fixed: (4–7, 0–3, z)	$x_E = 2.0$, $x_F = 9.0$	7.0
–5	Fixed	$x_E = 0.67$, $x_F = 10.33$	9.66
–7	Fixed	$x_E = -0.67$, $x_F = 11.67$	12.34
–9	Fixed	$x_E = -2.0$, $x_F = 13.0$	15.00

Table C.1: Geometric widening of the computational domain with trench depth. Vertices A–D remain fixed for all meshes, while widening is achieved only through the outward motion of vertices E–H.

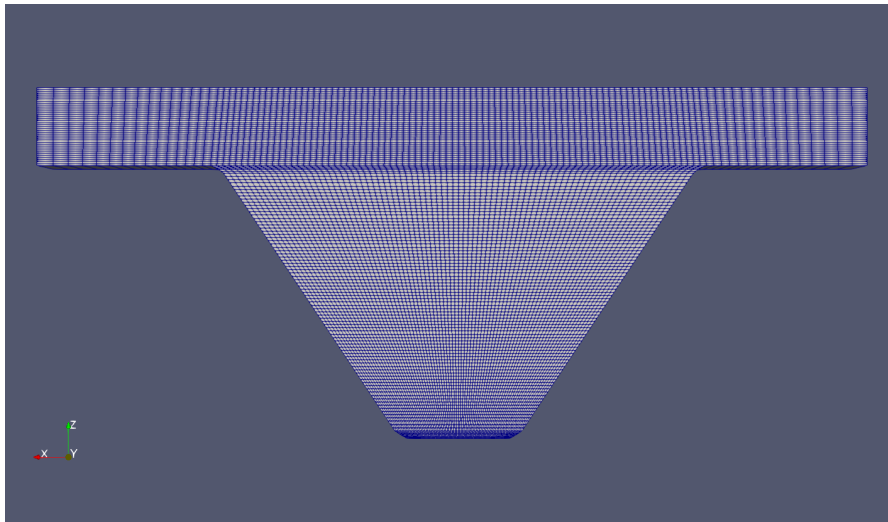


Figure C.2: Mesh for the $z = -7$ m trench geometry shown without the immersed chain. The fixed trench footprint and depth-dependent domain widening are apparent.

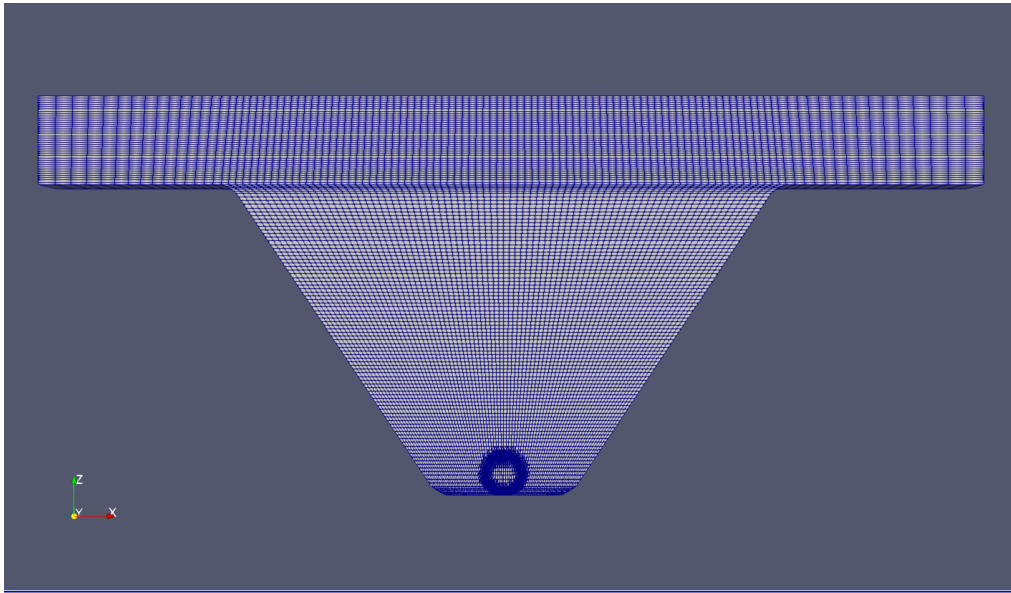


Figure C.3: Same mesh as Fig. C.2, now including the immersed chain. The chain is handled by the immersed boundary method and refined dynamically during simulation.

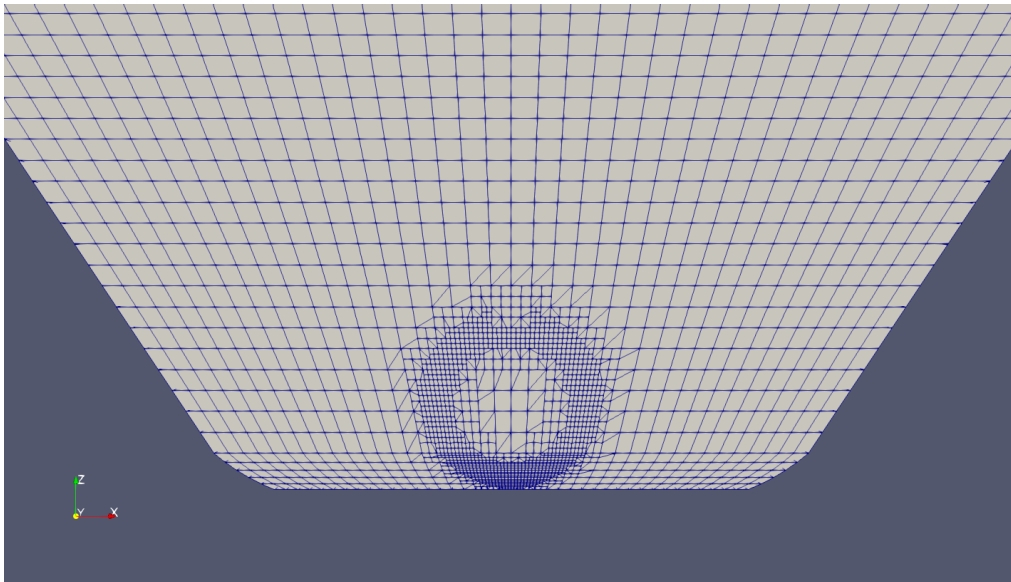


Figure C.4: Local refinement near the mooring chain. Cells within the IB-defined refinement band are refined by up to two levels, improving near-body resolution. It clearly shows that refinement is dependant on the original resolution.

C.2. Discretisation Schemes

All simulations are performed with the finite volume method (FVM) on a collocated mesh, as implemented in OpenFOAM. The general transport equation for a variable ϕ is discretised according to Equation (4.3), using second order schemes for diffusion and bounded schemes for convection.

A representative `fvSchemes` configuration is listed below.

```

1 ddtSchemes
2 {
3     default          Euler;
4 }
5
6 gradSchemes
```

```

7 {
8     default cellLimited Gauss linear 1;
9 }
10
11 divSchemes
12 {
13     default none;
14     div(phi,U) Gauss GammaVDC 0.5;
15     div(phi,k) Gauss upwind;
16     div(phi,epsilon) Gauss upwind;
17     div(phi,omega) Gauss upwind;
18     div(phi,C) Gauss upwind;
19     div(((interpolate(U)&S)+meshPhi),C) Gauss upwind;
20     div((sGamma*(interpolate((U-V_ib))&S)),C) Gauss upwind;
21     div((rho*(S&interpolate(Vdj))),C) Gauss limitedLinear 1;
22     div((rho*phi),C) Gauss limitedLinear 1;
23     div((nuEff*dev(T(grad(U)))) Gauss linear;
24     div((nuEff*dev2(T(grad(U)))) Gauss linear;
25 }
26
27
28 laplacianSchemes
29 {
30     default Gauss linear limited 0.5;
31 }
32
33
34 interpolationSchemes
35 {
36     default linear;
37 }
38
39 snGradSchemes
40 {
41     default limited 0.5;
42 }

```

Listing C.1: Representative `fvSchemes` used for the simulations.

The key points, consistent with the description in Section 4.2, are:

- Diffusive terms are approximated with second order central differencing (`Gauss linear`).
- Convective terms for the velocity and sediment fields use bounded upwind type schemes to balance accuracy and stability.
- Temporal discretisation uses the `backward` scheme, which is implicit and first order accurate in time, as stated in Section 4.2.

If different schemes were applied to specific fields or in particular test runs, these variants can be documented here as a short table or additional code listing.

C.3. Linear Solvers and PIMPLE Configuration

The pressure–velocity–sediment coupling is handled through the PIMPLE algorithm, which combines features of SIMPLE and PISO. The main solver settings are specified in `fvSolution`. A representative configuration is shown below.

```

1 solvers
2 {
3     // Pressure correctors (p, pFinal and any pcorr)
4     "p|pFinal|pcorr"
5     {

```

```

6      solver          PCG;
7      preconditioner  DIC;
8      minIter         1;
9      maxIter         1000;
10     tolerance       1e-8;
11     relTol          0.0;
12 }
13
14 // Mixture continuity (density)
15 rho
16 { \\ is calculated so no PDE
17 }
18
19 // Momentum, turbulence and -meshmotion flux fields
20 "U|UFinal|omega|nut|phi"
21 {
22     solver          BiCGStab;
23     preconditioner  ILU0;
24     minIter         1;
25     maxIter         1000;
26     tolerance       1e-8;
27     relTol          0.0;
28 }
29 "k|epsilon"
30 {
31     solver          BiCGStab;
32     preconditioner  ILUC0;
33     minIter         1;
34     maxIter         1000;
35     tolerance       1e-8;
36     relTol          0.0;
37 }
38 // -Driftflux fraction field
39 "C.*"
40 {
41     nAlphaCorr       2;
42     nAlphaSubCycles  1;
43     MULESCorr        yes;
44     nLimiterIter     3;
45     alphaApplyPrevCorr yes;
46
47     solver           smoothSolver;
48     smoother         symGaussSeidel;
49     tolerance        1e-6;
50     relTol           0.0;
51     minIter          1;
52 }
53
54 "C.*Diffusion"
55 {
56     solver          PCG;
57     preconditioner  DIC;
58     tolerance       1e-6;
59     relTol          0.0;
60     minIter         1;
61 }
62 }
63
64 // -----
65 // PIMPLE controls (for transient with dynamic mesh & IBM)
66 // -----

```

```

67 PIMPLE
68 {
69     momentumPredictor      yes;
70     nOuterCorrectors        4;
71     nCorrectors              2;
72     nNonOrthogonalCorrectors 1;
73
74     // IBM / -dynamicmesh necessities
75     checkMeshCourantNo      no;
76     correctPhi               yes;
77
78     // Pressure reference (if needed)
79     pRefPoint                (0 0 0.05);
80     pRefValue                0;
81 }
82
83 // -----
84 // -Potentialflow settings
85 // -----
86 potentialFlow
87 {
88     nNonOrthogonalCorrectors 1;
89     writePhi                  yes;
90     writePhiMass              yes;
91     pRefCell 0;
92     pRefValue 0;
93 }
94
95 // -----
96 // Relaxation factors
97 // -----
98 relaxationFactors
99 {
100     fields
101     {
102         p          1;
103         pcorr       1;
104     }
105
106     equations
107     {
108         U          1;
109         UFinal      1;
110         k           0.8;
111         epsilon     0.8;
112     }
113 }

```

Listing C.2: Representative `fvSolution` for the trench simulations.

These settings reflect the methodological description in Chapter 4:

- **Pressure fields** (p , p_{Final} , p_{corr}) are solved using a conjugate–gradient method (PCG) with a diagonal incomplete Cholesky (DIC) preconditioner, which is suitable for symmetric Poisson-type systems and consistent with the pressure-correction loop used in PIMPLE.
- **Velocity, turbulence, and flux fields** (U , U_{Final} , ω , k , ϵ , ϕ) are solved using Krylov subspace algorithms (BiCGStab) combined with ILU-based preconditioners (ILU0 or ILUC0). These settings provide robustness under immersed-boundary forcing and dynamic-flux corrections.
- **PIMPLE settings** use four outer correctors and two velocity–pressure correctors with a single non-orthogonal correction. This configuration matches the mesh quality (moderate non-orthogonality)

and ensures stable coupling between the momentum, pressure, sediment transport, and immersed-boundary updates.

- **Residual tolerances** for all primary fields are between 10^{-6} and 10^{-8} , in line with the convergence criteria applied in the simulations (see Section 4.4). These tolerances ensure numerical stability and accuracy for the transient RANS–IBM formulation.

C.4. Time Step and Courant Number Control

As described in Section 4.4, all simulations were performed with a **constant time step**, chosen such that the Courant number remained safely below the stability limit for transient RANS simulations with immersed boundaries. A maximum Courant number of

$$Co_{\max} < 0.4$$

was enforced throughout the research. This value provides a balance between numerical stability and computational efficiency and is consistent with the temporal stability analysis discussed in Section 4.2. Because the mesh is fixed and the immersed boundary does not deform the grid, a constant time step proved sufficient, and adaptive time-stepping was not required.

A representative `controlDict` for a storm–state simulation is shown below. The time step is fixed at $\Delta t = 0.01$ s, which maintains a Courant number below the target threshold for all flow configurations considered.

```

1 application      IbBousSoilFoam;
2
3 startFrom        latestTime;
4 startTime        0;
5
6 stopAt           endTime;
7 endTime          275;
8
9 deltaT           0.01;
10 adjustTimeStep   no;
11 maxCo            0.4;
12
13 writeControl      timeStep;
14 writeInterval     50;
15
16 purgeWrite        0;
17 writeFormat        ascii;
18 writePrecision     6;
19 writeCompression  off;
20
21 timeFormat         general;
22 timePrecision      6;
23
24 runtimeModifiable true;
25
26 libs
27 (
28     "libimmersedBoundary.so"
29     "libimmersedBoundaryDynamicMesh.so"
30     "libincompressibleImmersedBoundaryTurbulence.so"
31 );
32
33 functions
34 (
35     minMaxP
36     {
37         type minMaxField;
38         functionObjectLibs ("libfieldFunctionObjects.so");

```

```

39     name p;
40 }
41 minMaxU
42 {
43     type minMaxField;
44     functionObjectLibs ("libfieldFunctionObjects.so");
45     name U;
46 }
47 minMaxNut
48 {
49     type minMaxField;
50     functionObjectLibs ("libfieldFunctionObjects.so");
51     name nut;
52 }
53 minMaxK
54 {
55     type minMaxField;
56     functionObjectLibs ("libfieldFunctionObjects.so");
57     name k;
58 }
59 minMaxEpsilon
60 {
61     type minMaxField;
62     functionObjectLibs ("libfieldFunctionObjects.so");
63     name epsilon;
64 }
65 );

```

Listing C.3: Representative controlDict used in the simulations.

The monitoring functions (minMaxField) were included to track numerical stability during long transient runs, especially in cases with strong upward jets or steep concentration gradients.

C.5. Post-Processing Scripts

Python script for reconstructing of the mesh

To speed up the simulation time the mesh is divided into 6 parts, each calculated by 1 processor. Normally, after the calculations, this would get reconstructed into 1 mesh via the command *reconstructPar*. As the IB moves through the mesh the number of cells is not equals every time step and therefore also not equal for each processor. This makes it impossible to reconstruct the mesh via this command. In order to still be able to view it as one mesh, a python file was written to recreate the reconstructPar command. This file is shown here.

```

1 from paraview.simple import *
2 import os
3 import glob
4
5 # Step 1: Create missing .foam files in each processor folder
6 processor_dirs = sorted(glob.glob("processor*"))
7
8 if not processor_dirs:
9     exit(1)
10
11 for d in processor_dirs:
12     foam_file = os.path.join(d, f"{d}.foam")
13     if not os.path.exists(foam_file):
14         open(foam_file, 'a').close()
15         print(f"Created_{foam_file}")
16     else:
17         print(f"Found_{foam_file}")
18

```

```

19 # Step 2: Find all .foam files
20 foam_files = sorted(glob.glob("processor*/processor*.foam"))
21
22 if not foam_files:
23     print("No .foam files found after creation.")
24     exit(1)
25
26 print(f"Found {len(foam_files)} .foam files to load:")
27 for f in foam_files:
28     print(f"_{f}")
29
30 # Step 3: Load all .foam files into ParaView as separate readers
31 view = GetActiveViewOrCreate('RenderView')
32
33 for f in foam_files:
34     full_path = os.path.abspath(f)
35     print(f>Loading {full_path}")
36     reader = OpenFOAMReader(FileName=full_path)
37     reader.MeshRegions = ['internalMesh']
38     Show(reader, view)
39
40 Render()
41 print("\nDone")

```

Listing C.4: Python script used to generate per-processor .foam files and load them into ParaView

This command as to be run inside paraView and loads in all the processors one by one. Inside paraView these 6 processors are grouped as one and so it can be altered and viewed as one mesh.

C.6. Numerical Verification

The verification tests described conceptually in Section 4.6 are detailed here. They consist of grid refinement, time step refinement, and sensitivity to turbulence model choice.

C.6.1. Grid Refinement Study

A grid refinement study was conducted to assess the sensitivity of the numerical solution to spatial resolution within the trench region. Three meshes with progressively finer cell sizes were tested, all values are taken at time step = 100:

Mesh level	Cells	Maximum pressure in the mesh [Pa]	C through outlet [-]
Coarse	2400	0.32	0.000123698
Medium	4800	0.38	0.000145788
Fine	16000	0.41	0.000146410

The relative differences between the medium and fine meshes remained below 2% for both the velocity field and the concentration flux through the outlet, consistent with the findings reported in Section 4.6. Based on this convergence behaviour, the medium mesh was selected for all production simulations as the most efficient trade-off between computational cost and accuracy.

It is important to note that, in this solver, spatial resolution is not solely determined by the base mesh produced with `blockMesh`. The immersed boundary (IB) method applies dynamic local refinement around the oscillating chain, increasing the local cell count by up to 20,000 additional cells whenever the chain moves through the domain. Given that the medium base mesh contains only 4800 cells, the IB-refined region dominates the effective spatial resolution during the simulations.

Consequently, the global grid convergence behaviour is strongly influenced by this IB-driven refinement. Refining the base mesh further provides only marginal benefit, because the smallest and most dynamically relevant flow structures (chain-induced vortices and shear layers) are already fully resolved within the high-resolution IB refinement band.

To maintain spatial accuracy outside the IB region, the base mesh was deliberately refined near the trench walls and seabed, where no automatic refinement takes place. The central domain relies primarily on the IB procedure, while the wall regions are resolved by graded refinement in `blockMesh`.

This dual approach ensures consistent resolution of both near-wall shear and chain-induced turbulence, even before IB refinement is applied.

Overall, the mesh refinement study shows that the dominant source of spatial resolution is the IB refinement, which is why the medium mesh provides convergence comparable to the fine mesh. The base grid influences only the non-IB regions, whereas the IB mechanism ensures high fidelity around the moving chain.

C.6.2. Time Step Refinement Study

A similar procedure was followed for the time step. At least two time steps were compared, for example:

Δt [s]	minimum pressure [Pa]	Mean C at outlet [-]
2.0×10^{-2}	-0.36	0.000096225
1.0×10^{-2}	-0.50	0.000194319
2.5×10^{-3}	-0.52	0.000127549

Differences in the key diagnostic quantities remained negligible, in agreement with the temporal stability statement in Section 4.6.

C.6.3. Turbulence Model Sensitivity

Finally, the $k\epsilon$ closure was compared with an alternative RANS model, $k\omega$. Section 4.6 mentions deviations smaller than 4% in near bed velocity.

A concise comparison table can be added here, for example:

Turbulence model	Max velocity [m/s]	Max pressure [Pa]
k- ϵ model	0.4	0.037
k- ω SST model	0.37	0.037

The small differences confirm that the main trends and the inferred escape thresholds are robust with respect to the selected RANS closure.

Together, the details in this appendix substantiate the numerical framework used in the main text and provide sufficient information for reproducibility or further extension of the solver.

C.7. Comparison to DriftFlux-Type Two-Phase Solvers

To place the capabilities of `IbBousSoilFoam` in context, Table C.2 summarises the main differences between this solver and a classical drift-flux formulation (e.g. `driftFluxFoam`). The comparison highlights which physical terms are included, which are simplified, and how this affects the present trench-escape simulations.

Implication for this work: `IbBousSoilFoam` correctly represents suspended-load dynamics and chain-induced uplift, making it suitable for identifying escape thresholds and qualitative transport mechanisms. However, dense-sediment physics (hindered settling, granular stresses, bedload) and long-term trench morphodynamics are outside its modelling scope. These limitations are inherent to `foam-extend-5.0`, the version in which the IB method is implemented. In this environment, the only available soil-transport solver is `settlingFoam`, which still relies on hard-coded turbulence and transport models. For the IB to interact consistently with a sediment model, these components would need to be fully rewritten and coupled so that boundary conditions update correctly during the simulation.

A further complication is that the IB method may not operate reliably within compressible solvers. Preliminary tests indicate that flux divergences inside the mesh become unmanageable when applied to compressible formulations, suggesting that substantial redevelopment would be required before an IB-based, fully coupled multiphase sediment model could be made operational.

Model Component	Drift-Flux Solvers	IbBousSoilFoam
Momentum equations	Mixture momentum with drift corrections; inertia depends on sediment fraction	Single-fluid momentum; sediment enters only through buoyancy
Phase interaction	Explicit drift velocity based on drag laws; includes hindered settling and phase coupling	Constant settling velocity; no drag or hindered-settling effects
Mass conservation	Separate mass/volume-fraction equations; mixture density affects continuity	Single scalar transport equation for C ; mixture remains incompressible
Sediment stresses	May include granular pressure or rheology for dense beds	Not included; sediment treated as a dilute passive scalar
Turbulent dispersion	Particle-turbulence interaction models; variable turbulent Schmidt number	Simple eddy diffusivity proportional to ν_t
Bed evolution	Can be coupled with Exner or morphodynamic models	No bed change; rigid trench walls

Table C.2: Condensed comparison between drift-flux two-phase solvers and the IbBousSoilFoam model used in this study.