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Propeller-Induced Seabed Scour: A Review of Hydrodynamic Mechanisms, CFD Modeling, and Coastal Engineering Implications

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Abstract

Seabed scour caused by propellers is an increasingly widespread issue with respect to offshore developments as a result of the continually rising sizes of vessels. This literature review aggregates current research literature from 2020 through 2025 with respect to hydrodynamic principles of propeller jets, seabed scouring, computational fluid dynamic models of scouring, and related coastal engineering principles. Major research findings buttress the importance of jetting confinement factors, sediments, and transient conditions of vessel operation. Although research progress in computational fluid dynamic models of seabed scouring from Reynolds averaged Navier Stokes models to more complex models has been beneficial, major research gaps must be filled in models of seabed scouring on cohesive sediments, more representative models of maneuvering conditions, and valid comparisons with real-world data. Major research areas that need to be emphasized in the not too distant research future must encompass research on dynamic principles of seabed sediments, real-world hydrodynamic principles of vessels, data gathering for real-world applications, and engineering models of enhancing seabed scouring resilience.

Keywords

Propeller-Induced Scour, Seabed Erosion, Coastal Infrastructure, Hydrodynamic Mechanisms, CFD Modeling, Sediment Transport

1. Introduction

Seabed erosion caused by propeller jets, collectively known as propeller-induced scour, is a rising risk to the stability of maritime structures globally [1]. This rising number of larger, more powerful trading vessels combined with the proliferation of offshore renewable energy installations has transformed what was hitherto a trivial maintenance issue into a serious geotechnical risk [2] [3]. This type of scour is fundamentally different from that caused by ambient currents; it is characterized by the presence of a strongly turbulent, rotational, or even wall-confined jet that exposes the seabed to regionally extreme bed shear stresses [4] [5]. Despite many decades of cross-disciplinary research into the hydrodynamics of high-speed jets of water, relevant seabed sediment processes, and numerical simulations, there remains an evident chasm between the laboratory-based academic research efforts, often with idealized assumptions, and real-world ports or offshore applications [6] [7]. This paper draws together some of the current literature related to four essentially intertwined areas of study: basic hydrodynamic principles of propeller jet behavior, the mechanics of scouring, current numerical models of scouring, and the subsequent engineering implications. This review aims to consolidate current understanding through an analysis of recent experimental, numerical, and field observation studies, thereby establishing a framework for identifying key research needs to better align theoretical understanding with effective engineering practice.

Literature Search Methodology

A literature search was carried out for peer-reviewed publications between the years 2020 and 2025. Databases such as Scopus, Web of Science, and Google Scholar were searched using keywords such as "propeller-induced scour", "CFD scour modeling", "jet erosion", or "coastal infrastructure scour". While searching for publications, the titles and abstracts were filtered to select publications that were relevant to either the hydrodynamics of propeller jets or the scouring of sediments or related studies of numerical models for engineering purposes. A total of 37 publications were selected for this literature review.

2. Propeller Jets Hydrodynamics

The hydrodynamic processes involved for propeller-induced scouring are complicated and relate to the interaction of a high-speed swirling jet of water with the bed of sediments, often in a constrained geometry of ports or waterways. This document synthesizes the literature into the current state of understanding with respect to the major hydrodynamic issues that emerge in the literature.

A cross-section of the hydrodynamics of a jet induced by a propeller, with two panels that work in tandem with each other, is shown in **Figure 1**. While the left panel describes the spatial process of jet development with the Zone of Flow Establishment (ZFE) and the Zone of Established Flow (ZEF), the right panel describes the velocity decay process of the jet for three important boundary conditions: for a jet in the open, attached to a boundary, or in shallow water. **Figure 1** distills the important conclusion that any boundary or seabed confinement does indeed work to slow down velocity decay by promoting higher velocity levels with a subsequent influence on bed scour.

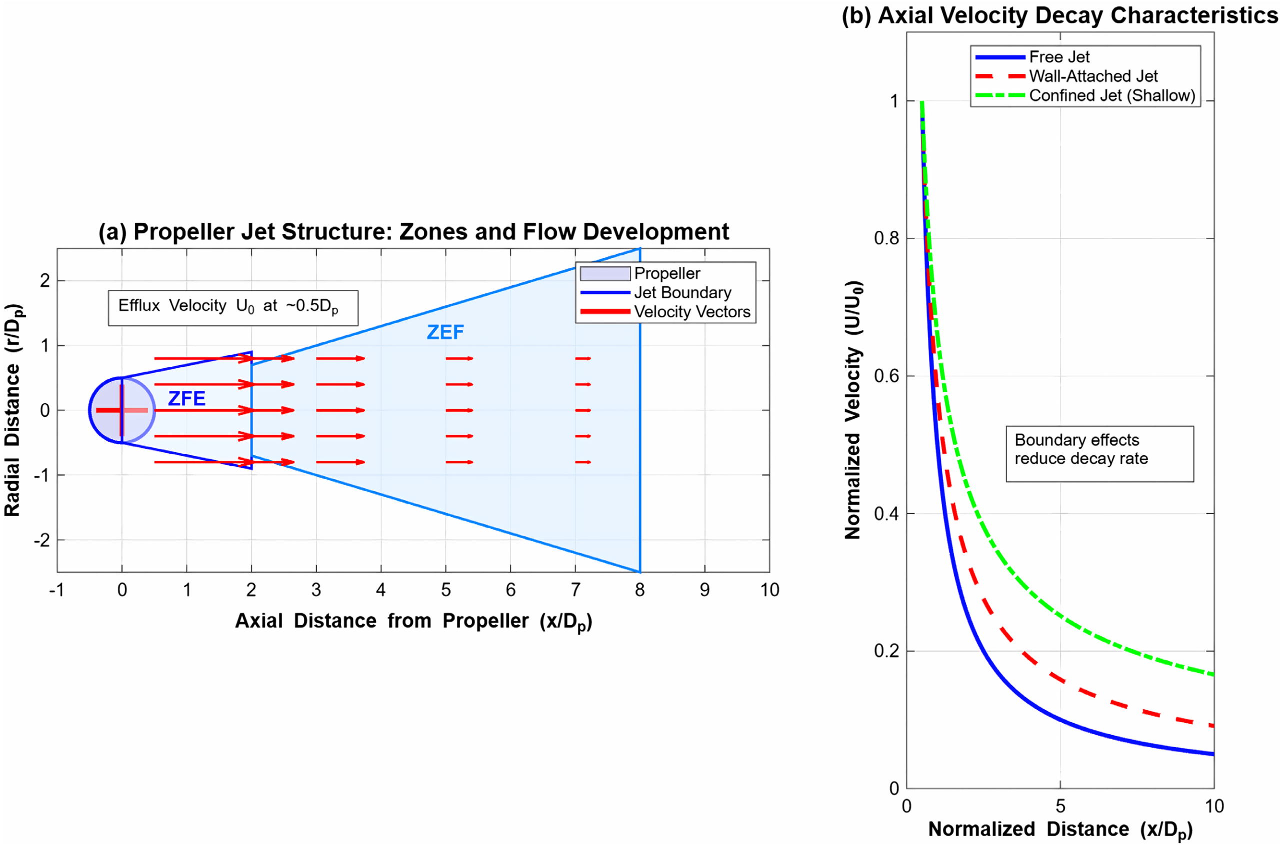


Figure 1. Propeller jet hydrodynamics: (a) schematic of jet development showing the Zone of Flow Establishment (ZFE) and Zone of Established Flow (ZEF) with velocity vectors; (b) normalized axial velocity decay for free, wall-attached, and confined jets.

2.1. Velocity Decay and Jet Structure

The erosive force of the propeller depends on the characteristics of the turbulent jet it generates. One of the experimental correlations for such jets is that the maximum velocity of efflux (U_0) is always found at about 0.5 times the diameters of the propeller downstream of the plane of the propeller [8]. The velocity distribution in such a jet decreases axially with a rate of decay that is one of the major factors responsible for the bed shear stress. It is found that the velocity distribution is affected by the hub of the propeller, resulting in a bi-velocity peak, and that the swirling velocity does not affect it significantly [8] [9].

This is important information for simplifying models representing real-world complex phenomena but could potentially neglect some complex interactions, such as that of maneuvering, where some influences of swirl velocity could appear in sediment entrainment.

One of the key considerations is the presence of boundaries. As a jet approaches the seabed or the quay wall, it is drawn to the boundary by the Coandă effect, with the attendant reduction in lateral dispersion and enhanced boundary flow speeds [9] [10]. Huang *et al.* [11] showed that in recessed areas with small clearance heights ($Z_b/D_p < 1$), the boundary jet-attachment process can extend the area of high seabed shear stress. A major limitation of current hydrodynamic models is their focus on steady-state or "bollard-pull" conditions. Almost all of the foundational works, including the more popular literature reviews, investigate fixed propeller configurations, disregarding the dynamic influences of a moving body, in which the coupling between the jet phenomenon and a time-varying inflow field could appreciably influence jet growth as well as bed impingement [8] [11].

2.2. Confined vs. Unconfined Jet

The presence of a solid boundary significantly alters the scouring effect. When an unconfined jet hits a flat seabed, a scour hole is formed with geometry dependent mostly on the energy of the jet as well as the bed material properties [12]. A jet striking a vertical quay wall, on the other hand, becomes confined, resulting in the development of complex three-dimensional vortex systems (such as wall or horseshoe vortices) that enhance erosion [5] [13]. This amplification of scour depth by the presence of a wall was measured to be 50% - 70% by Cihan *et al.* [5], whereas the merging of scour holes with unique geometry was observed by Cui *et al.* [12] for twin-propellers striking a wall.

It is observed that the rotation of the propellers (whether it is external or internal in twin systems) affects the point of maximum scour depth in the cross-direction by causing differences in the merging of twin jets [6] [13]. Nonetheless, the current study offers a simplification by identifying "confined" or "unconfined" conditions. But in real-world harbor operations, the jet could quickly change between the two conditions or remain partially confined by sloping banks or rubble mounds, which is not captured adequately in existing literature.

2.3. Scaling Laws and Similarity Considerations

Scaling from the results of models to prototype predictions is an engineering tradition, accomplished by means of densimetric Froude similitude [6] [10]. This allows the ratio of inertio- to gravitational forces on sediment particles to be scaled consistently and has been shown to work for the prediction of scour depth at equilibrium. More recent theoretical efforts, however, aimed at finding more basic models of scaling. Scaling models for equilibrium scour of sediments by a turbulent wall jet were developed by Dey & Ali [13] or Lu *et al.* [14] by means of dimensional analysis and turbulence models. These models propose a "wall jet scour number", which expresses jet velocity, scale, grain size, and critical shear velocity. This idea offers a very attractive theoretical basis, which goes clearly beyond empirical models [14] [15].

A critical assessment of such work indicates that there is a certain contrast between theoretical models and their ability to work in practice. Although these new scaling models work very well with regard to the historical data sets employed, it is important to note that such validation is practically limited to classical wall jet tests and, by no means, to rotating propeller jets with their characteristic rotation and turbulence. Moreover, as it is observed by Wei *et al.* [9], some issues with regard to the turbulence intensity or transport modes (bedload or suspension) remain to be resolved for Froude models, avoiding possible anomalies in calculating rates of scour development.

On a positive note, it is certain that the engineering community would appreciate some efforts to validate new theoretical models of propeller scour on a large scale.

3. Seabed Scour Mechanisms Induced by Propeller Jets

Propeller jet interactions with the seabed represent an important engineering consideration for the stability of coastal/offshore constructions, navigation, and seabed mobility. This literature review distills the current literature to better understand the involved phenomena, models, and current state of knowledge with respect to propeller-induced scouring. It is organized around key topics extracted from the body of literature, progressing from basic interactions of flows with the seabed to more complex considerations. The key findings from this reviewed literature are summarized in **Table 1**.

3.1. Temporal Development of Scour Holes

There is a widely documented three-stage pattern of propeller scour development: initial rapid growth, a phase of reduced rates of the process, and finally, an equilibrium phase [10] [16]. Initially, the rates of scour development are very vigorous; it is documented that more than 60% of the total scour depth can develop in the first tenth of the total development time [10] [17]. These vigorous rates of development pose critical challenges to the monitoring of infrastructure development stages before an obvious equilibrium is reached.

Equilibrium timescales are extremely uncertain. In laboratory flume experiments, for example, equilibrium can be reached in a matter of hours [17], whereas in the real situation, intermittent scouring timescales could be of the order of years [1] [18]. This difference is one of the significant drawbacks of laboratory experiments, since here the propellers work continuously, whereas the real situation involves aggregate periods of high thrust in brief instances of berthing or maneuvering. Additionally, it is also found that in the real situation, lower levels of equilibrium are usually observed, as opposed to laboratory experiments [1] [2]. This is likely due to the presence of natural variability in sediments, armoring, or periodic replenishments through natural transport of sediments into the area—a situation that is not taken into account in laboratory experiments. An interesting laboratory observation of "jet flipping" in wall jet experiments, where the jet switching between bed-attachment and surface-attachment modes results in periodic scouring and fill, implies that the situation of equilibrium is not fixed in many real-world flow situations [19].

Although helpful as a theoretical construct, there is considerable variability in real-world timescales for development with flow intensity (F_0), type of sediments, and boundary conditions. Real-world timescales for scour at the field scale could potentially be longer on account of scale effects and seabed properties [9] [11]. "Equilibrium" in real-world applications is more likely a state of dynamic equilibrium, where scour is effectively negligible over engineering timescales (**Figure 2**).

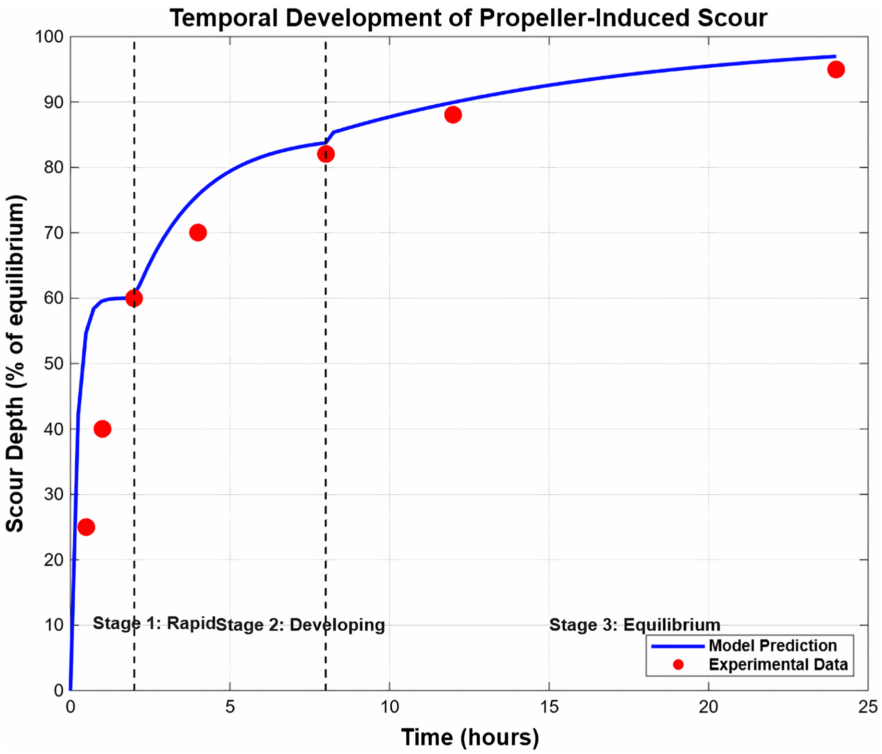


Figure 2. Temporal development of propeller-induced scour depth, showing the characteristic three-stage evolution: rapid initial scour (Stage 1: 0 - 2 hours), slower development (Stage 2: 2 - 8 hours), and approach to quasi-equilibrium (Stage 3: 8+ hours). Model curve corresponds to logarithmic growth for clear-water scour. Experimental data points indicate variability of laboratory results [9] [11] [20].

3.2. Key Governing Parameters

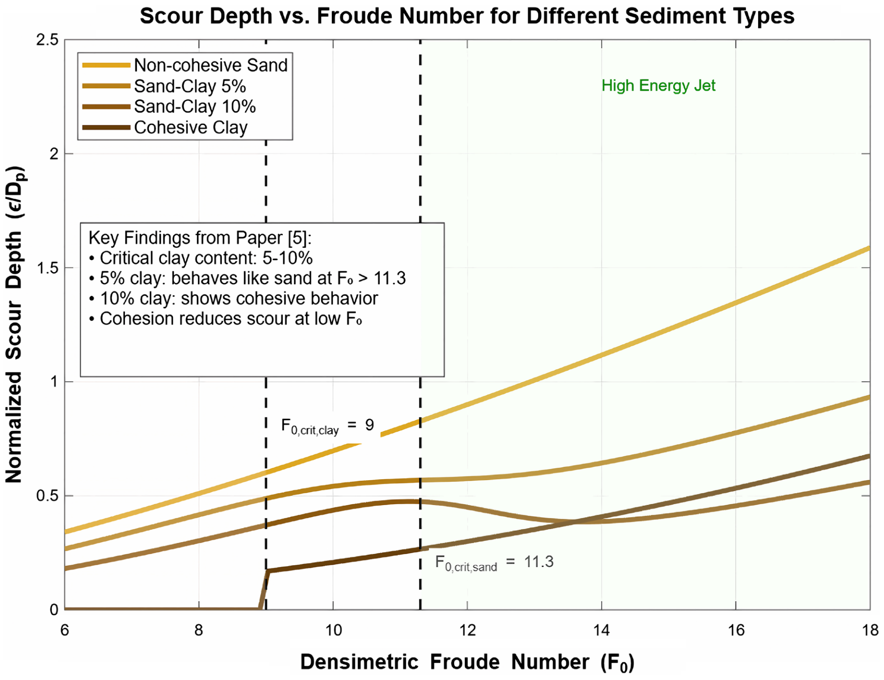
Systematic experiments have revealed the major factors that contribute to the extent of scour. Bed shear stress, calculated from jet velocity just above the bed, is the principal erosive agent. It is most sensitive to the clearance height of the propeller (Z_b), with various experiments clearly indicating an inverse relationship, where shorter clearance height caused maximum scour depth with a resulting change in the hole geometry [5] [10] [20]. The densimetric Froude number (F_0, defined as the ratio of jet velocity to the submerged settling velocity of sediment particles, reflecting the relative importance of inertial to gravitational forces) is found to significantly indicate the scour depth, being a major input for various prediction relations for scour depth [5] [6] [20].

However, the relationship between these variables is complicated and nonlinear. For example, the role of the wall clearance (X_w) with respect to scour depth is important only up to a certain point (approximately $8D_p$) beyond which it ceases to be effective [20]. Again, the impingement angle of the jet determines the geometry of the scour, with higher impingement angles resulting in narrower scarps [16]. The engineering issue here is that these variables are interrelated. A change in the draft of the vessel (which affects Z_b) with respect to cargo operations will mean that there is a corresponding change in the impingement angle as well. Currently, most of the engineering equations are of the form that each of these variables is independent, which could be a reason for the considerable scatter of data that is observed.

3.3. Influence of Sediment Type

This depends largely on the type of sediments on the seabed. While for uniform sands that are non-cohesive, scour depth is inversely related to grain sizes, as more shear force is needed for larger grains to break away [15] [21]. More research work is limited to this type of sand, understandably for obvious reasons, establishing a robust but limited body of knowledge.

Figure 3 shows the effect of the presence of clays on scour depth. Çihan *et al.* [5] gave a great contribution to the understanding of the effect of sand-clay mixtures by determining that a 5% - 10% mixture of clays significantly decreases the scour depth for low- to moderate-energy jets. Notably, for high-energy jets ($F_0 >$ 11), the scour depth for clays was almost the same as that for non-cohesive sands, despite the electrochemical bonds between particles, revealing that there is a threshold energy beyond which hydrodynamic forces become dominant over electrochemical bonds. This result is of great importance for ports with muddy sediments but is limited to a study employing kaolin clays. A huge research gap is left for other clay materials.


Scour Depth vs. Froude Number for Different Sediment Types

Key Findings from Paper [5]:
- Critical clay content: 5-10%
- 5% clay: behaves like sand at $F_0 > 11.3$
- 10% clay: shows cohesive behavior
- Cohesion reduces scour at low F_0

Figure 3. Normalized scour depth (ε/D_p) as a function of densimetric Froude number for different sediment types. Non-cohesive sand has the maximum scouring ability. The critical value of 5% - 10% of clay mentioned by Cihan *et al.* [5] is transitional: 5% clays classify as sands for F_0 values larger than 11.3 since there is less scouring for lower F_0 values, indicating that it is a cohesive material. A threshold F_0 value of about 9 is observed for a purely cohesive material like clay for which there is little erosion below it [16].

Table 1. Summary of key findings from reviewed literature on seabed scour mechanisms induced by propeller jets.

Paper (Author, Year)	Scour Type Studied	Jet-Seabed Interaction Parameters	Sediment/Seabed Properties	Scour Development Behavior	Key Findings	Limitations
Cihan *et al.* (2025) [5]	Local equilibrium scour near vertical quay wall (confined scour).	Wall clearance (X_w/D_p), propeller offset height (y_0/D_p), densimetric Froude number (F_0), clay content (p).	Sand-clay mixtures (d_{50} = 0.24 mm sand; kaolin clay d_{50} = 0.0042 mm); clay content 0%, 5%, 10%.	Scour depth increases with F_0 and decreases with X_w; cohesion reduces scour at low F_0.	Critical clay content for cohesion effect ~5% - 10%; wall effect negligible for $F_0 > \sim 11.3$.	Limited to fine sand & kaolin clay; no field validation.
Curulli *et al.* (2022) [6]	Local equilibrium scour near vertical quay wall (confined scour).	Wall clearance, bed clearance, rotational speed, densimetric Froude number (F_0 = 23 - 32).	Uniform sand: d_{50} = 0.25 mm, d_{90} = 0.375 mm.	Two scour holes form: near wall (deflected jet) and far from wall (direct jet impact).	Formulas to estimate eroded volume from scour dimensions; backward rotation does not affect near-wall scour morphology.	Limited to two bed/wall clearances; no cohesive sediments.
Wei *et al.* (2020) [9]	Unconfined (free jet) scour; Confined scour at vertical and sloped quays.	Densimetric Froude number (F_o), clearance ratio (Z_b/D_p), toe/wall clearance, rudder angle.	Non-cohesive sand (d_{50}). Clear-water scour conditions.	Temporal development follows log-time relationship.	Maximum scour depth depends mainly on Fo and Z_b/D_p. Confined scour involves interplay of jet flow and junction vortex.	Empirical scour equations are dimensionally inconsistent; scale effects not fully addressed.
Huang *et al.* (2025) [11]	3D local scour in restricted water (equilibrium).	Clearance height (Z_b), Propeller efflux velocity (V_p), Densimetric Froude number (F_{ro}), Impingement angle.	Non-cohesive sediment (wood flour). D_{50} = 0.58 mm.	Three-stage evolution: rapid initial (>60%), slower development, equilibrium.	Proposed logarithmic equation for max scour depth over time. Scour depth & length ↑ as Z_b ↓.	Sediment is wood flour; settling similarity not considered; model scale 1:36.
Cui *et al.* (2020) [12]	Quay-wall scour (local, equilibrium 3D scour by twin propellers).	Clearance from bed, Propeller-to-wall distance, Rotation direction, Efflux velocity, F_0.	Uniform sand. d_{50} = 0.2 mm.	Three-stage evolution: axial formation, obstructed expansion, equilibrium.	Maximum scour depth increases up to 70% due to wall at close distance ($3D_p$).	Static propeller position (berthed ship); not applicable to maneuvering.

Continued

Macías-Lezcano *et al.* (2024) [22]	Confined scour at vertical quay wall (equilibrium).	Wall clearance (X_w), bed clearance (Z_b), impingement angle, propeller speed (n_p), sediment size (d_{50}).	Coarse/medium sand, fine gravel; uniform gradation.	Time evolution tracked; equilibrium defined by erosion rate.	Linear relationship: $\varepsilon_{max} \propto X_w$ for $X_w <$ Xmu; scour depth increases with n_p, decreases with Z_b and d_{50}.	Limited to $X_w \leq 8D_p$, $Z_b \leq 2.5D_p$; scale effects may apply.
Llull *et al.* (2021) [23]	Confined local scour near vertical quay wall; time-dependent.	Wall clearance (X_w), bed clearance (C_h), efflux velocity (U_0), sediment size, time (t).	Uniform sand: d50 = 375 μm; non-cohesive.	Two scour holes form (HBH & FWH); may merge; evolution tracked up to 60 min.	X_w is dominant parameter; scour depth $\propto U0^2/X_w$; threshold F_0, wall ≈ 0.25 triggers scour.	Sediment size fixed; scaling effects not fully quantified.
Craig *et al.* (2023) [16]	Local scour/ resuspension (instantaneous erosion, not equilibrium hole).	Bed shear stress (via empirical formula), clearance (H_p), cohesive sediment.	Two classes: 60% fines (clay/silt), 40% fine sand; $\tau_c = 0.318$ N/m^2.	Threshold, development, and deposition stages after propeller stop.	Erosion rate follows linear relationship with excess shear stress for cohesive sediments. hp-based model better than RPM-based.	Focus on resuspension, not long-term scour hole; homogeneous bed assumption.

In addition, natural seabeds are often graded or layered. This is observed by Duan *et al.* [4], who point out that "armoring layers" can form on these types of seabeds, with the finer material being stripped away, leaving a layer of coarse material that shields the seabed from erosion. This self-limiting effect is probably one of the major contributing factors for the difference between laboratory-predicted scour depths and real-world observations, and is never accounted for in current models of scour. Perhaps the biggest flaw in the current state of scour research is that it is almost entirely limited to uniform, non-cohesive sand.

4. CFD Modeling of Propeller-Induced Scour

4.1. Methods of CFD: From RANS to High-Fidelity Approaches

Computational Fluid Dynamics (CFD) is the architectural foundation of current scour models. Reynolds Averaged Navier-Stokes (RANS) equations, solved with turbulence models k-epsilon or k-ω, remain the most widely used models of turbulence that strike the best ratio between solution accuracy and computational efficiency for engineering purposes [1]-[3] [24]. For example, turbulence models of RANS type were successfully used for resolution of the horseshoe vortex system and the universal scour development around fixed structures, such as monopiles [2]. On the other hand, applying time-averaging to solve RANS relations could be inappropriate for resolution of important energy-containing fabric of turbulence, characteristic of strongly unsteady flows, such as those induced by rotating propellers [25]. In such cases, more accurate LES/DES approaches could be utilized for simulations [2] [4] aimed at more profound research. Though these models provide significantly better predictability of mixing in turbulence and vortex phenomena, their great computational cost limited their application until now for such complex tasks as engineering-scale scour simulations [25] [26].

Consequently, a pragmatic selection strategy emerges: RANS models are well-suited for large-scale engineering screening, preliminary design, or situations where computational efficiency is paramount. In contrast, LES or DES methods are restricted to forensic studies, basic research on turbulent physics, or situations where modeling the complex transient behavior of a propeller jet plays a crucial role in the problem under investigation.

4.2. Propeller Modeling Approaches

One of the key challenges in the numerical modeling of scour caused by a propeller is representing the propeller in the CFD model correctly. This varies from a considerable simplification to a detailed representation. One of the ways of simplification is using the actuator disk or momentum source term, where essentially the effect of the propeller is simulated by adding momentum to the computational domains without necessarily requiring a detailed representation of the geometry [16] [27]. This is a considerable simplification that helps reduce the computational complexity of the simulation, allowing for larger domains to be modeled with a considerable emphasis on far-field dispersion of the sediment cloud. Nonetheless, it is ineffective for modeling the complex turbulence, tip vortices, and boundary regional rotational flows that are important for bed scouring around the bed [27]. A more detailed representation is gained using the Sliding Mesh or Overset Mesh models, that attempt to represent the geometry of the propeller explicitly with rotation incorporated. This is much more detailed for representing the complex, swirling jets correctly [20] [24] [28]. A significant research gap here is that in almost all of the existing literature related to the use of CFD models for scouring, propellers' geometry for such scouring processes is either entirely disregarded or fixed structures such as piles or pipelines are modeled [1] [4] [7] [10]. This is a significant research gap that suggests that despite evidence of preceding research in the area of numerical models for scouring in general, applications of such models for the peculiar hydrodynamic conditions created by a propeller are still remarkably underdeveloped [9].

From the table produced using numerical methodology (**Table 2**), it is observed that the research field is in a state of transition, where a trade-off between methodologies is evident. Most of the research is either using actuator disk models with reduced complexity to estimate large-scale sediment transport plumes but with no consideration for bed scour mechanics or using advanced sliding meshes to estimate the rotation of the propeller with models that only account for suspended loads. This state of affairs draws attention to a critical gap in research: there is no integrated approach that is able to couple complex propeller hydrodynamic models with a sophisticated bed scour mechanics framework that can estimate bed-load transport rates and the developed scour hole geometry, implying that despite significant research efforts in various aspects of the issue, a capable CFD-based prediction tool for studying propeller-induced scour seems to remain a promise for the future.

Table 2. Summary of numerical modeling approaches for propeller-induced scour.

(Author, Year)	CFD Method & Turbulence Model	Propeller Modeling Approach	Sediment/Morpho dynamics Model	Validation Data	Key Numerical Findings	Model Limitations/Gaps
Craig *et al.* (2023) [16]	EFDC+ (3D RANS; Smagorinsky & Mellor-Yamada closures)	Actuator Disk/Momentum Source. Efflux velocity converted to momentum flux; empirical jet profiles on subgrid.	Suspended load only. SEDZLJ-based erosion formula for cohesive sediment; fully coupled transport of two size classes.	Field ADV/PIV velocity data and TSS concentration samples from a tugboat operatio.	Accurately reproduced horizontal/vertical plume extent. Nash-Sutcliffe Efficiency for erosion depth: 0.85 - 0.98.	Propeller model is empirical; bed load neglected; ship hull wake not modeled; performance grid-dependent.
Shouman & Helal [20]	RANS (Standard k-ε & Transition-sensitive K-Kl-ω)	Multiple Reference Frame (MRF). Fluid zone around propeller rotates as a rigid body (steady-state approximation).	Not Applicable. Study focused solely on propeller hydrodynamics, not sediment transport.	Experimental open-water test data (KT, KQ, η) and PIV/LDV wake measurements.	Provided a methodology for turbulence model selection based on blade geometry. K-Kl-ω reduced error at high advance ratios.	MRF is a steady-state approximation; no sediment/ scour modeling; no cavitation or multiphase effects.
Kaidi *et al.* (2021) [24]	URANS with SST k-ω; VOF for free surface; Finite Volume (Fluent)	Full Geometry Resolution (hull, twin propellers, rudders). Moving wall for seabed; no actuator disk simplification.	Suspended load via UDF. Convection-diffusion equation for SSC; empirical reference concentration (van Rijn). No bed morphology update.	Experimental trench data (velocity & SSC profiles) and propeller jet velocity compared to empirical formulas.	Good agreement with experimental SSC & velocity; V0 matched established formulas; quantified confinement effects.	No morphodynamic bed evolution; steady RANS may under-predict unsteadiness; model depends on empirical concentration calibration.
Liu Liang *et al.* (2024) [28]	Unsteady RANS with VOF; k-ε turbulence model; Two-Layer All y+ wall treatment.	Sliding Mesh for transient propeller simulation (compared with less accurate MRF).	Depth-averaged cohesive sediment (MIKE21 MT module). Two-way coupling via bed shear stress.	Monitoring station sediment concentration data and KRISO tank test data.	Thrust/torque errors < 2.62%; sediment model error < 5%; propeller wake reduced siltation by up to 0.11 m/month.	No waves; depth-averaged sediment model limits vertical process capture; limited to cohesive sediment.

Continued

Srše *et al.* (2023) [27]	MIKE 3 FM (3D RANS with k-ε closure)	Actuator Disk/Source Model. Propeller as a moving momentum source (nozzle) with semi-empirical integral jet equations.	Suspended sediment only (MIKE 3 MT). Empirical erosion based on critical shear stress; passive transport with two way coupling.	Satellite imagery of surface plumes and in-situ water samples from a similar manoeuvre.	Reproduced spatial pattern of resuspension plumes and identified high-risk erosion/ deposition zones.	Simplified propeller model; no bed-load or morphological update; validation data limited in resolution.

4.3. Sediment and Morphodynamic Modeling

Hydrodynamics models coupled with sediment transport models are critical for scour simulations. When it comes to bed-load transport models, models developed by Engelund & Fredsøe, Van Rijn, or Meyer-Peter & Müller are universally coupled with CFD numerical solvers through equations such as the Exner equation for bed change representation [1] [3] [29] [30]. These models are fairly robust for sandy sediments but require calibration for application to sediments with grade or for cohesive sediments [2] [4]. When it comes to suspended load transport models, their representation is achieved through a convection-diffusion term with source terms representing entrainment or deposition with calibrated models [7] [22] [29]. Quite often, researchers who emphasize bed-load transport models ignore suspended transport models, thereby potentially causing a loss of total scour depth or downstream deposits [30]. More complex models include bi-directional models that provide bed geometry information back to the flow solution. While physically more accurate, such models increase computational complexities [4] [29].

The finest scale description is that given by the coupled Discrete Element Method (DEM)/CFD model, representing the sediment as discrete elements that interact with the fluid phase as well as with each other [10] [19] [31]. This is very good for capturing the physics of granular media but is ludicrously expensive in computation, allowing it to be practically used only for small-scale, small-time simulations with simplifications of the grain geometry to mere spheres [31] [32]. This means that there is a natural ordering here: Large-scale simulations with transport relations in RANS models for the phenomena, small-scale investigations with Coupled DEM/CFD for the processes.

5. Coastal Engineering Implications and Mitigation

5.1. Infrastructure at Risk & Assessment Techniques

Propeller scour directly impacts various forms of infrastructure. Quayside walls can become vulnerable to toe erosion by confined jets, potentially undermining structural integrity [5] [13] [20]. Foundations in the comparatively harsh offshore environment, such as jackets supporting offshore wind turbine platforms, encounter complex scour conditions that are very different from those of monopiles, with both local pile scour and global scour beneath the platform [7] [33] [34]. Submarine pipelines can become prone to free spanning as a result of local erosion, making fatigue a possibility [26].

As for testing, empirical equations like the ones suggested in the PIANC guidelines (2015) are used by engineers. Nevertheless, it is observed in various research studies that such equations, developed using data from monopile structures, can be unreliable for other cross-sections [2] [8] [20]. Improved equations with important parameters such as wall clearance were suggested by Macías-Lezcano *et al.* [22] among other researchers. A major flaw is that these equations are developed using laboratory data for uniform sands. Their application in real environments with cohesive or graded sediments, complex loading, or complicated cross-sections is still dubious.

5.2. Mitigation Strategies: Structural and Operational

Successful risk management requires a diversified approach. Structural methods of risk reduction include riprap armor work, concrete mattresses, and aprons. Chen *et al.* [18] used their research to quantify the effectiveness of riprap with respect to jacket foundations, concluding that it could lower scour depth by approximately 80% in clear-water scour, although its effectiveness decreases with live bed scour. One important lesson from such research is that protection must be designed for sufficient depth and area to prevent edge scour. A primary limitation of structural solutions is their substantial upfront capital and installation cost, alongside ongoing maintenance requirements in a dynamic marine environment.

Additionally, operational measures are often the earliest forms of defense. These measures include minimizing propeller revolutions per minute during critical maneuvers, using tug support to minimize the thrust of the principal propeller in proximity to infrastructure, and improving docking maneuvers [25] [27] [35]. Castells-Sanabra *et al.* [21] showed that other methods of conducting maneuvers could potentially lower scour by up to 80%. Simulation of ship maneuvers with hydrodynamic models has been used to visualize real-time scour risk [27]. However, the effectiveness of operational measures can be constrained by practical requirements for port efficiency, safety protocols, and the need for coordination between vessel crews and port authorities, which may limit their consistent application.

In many cases, the most robust and economical solution is an integrated one that takes into account bed protection strategies such as targeting the quay toe, as well as other operational measures. An important research area that is still missing in the literature is the cost-benefit analysis of various portfolios of measures in terms of their lifetime cost, which would be of great use for the engineer/designer.

5.3. Toward Risk-Based Design and Monitoring

These inherent uncertainties are pushing the need for probabilistic risk models. A study by Kim *et al.* [36] introduced a procedure for determining the ultimate limit state reliability of the foundation with respect to the risk of scour, taking into consideration the uncertain parameters of environmental loads and scour prediction. This helps in more rational design, as it is based on reliability, unlike the use of arbitrary safety factors.

The key to the future of scour prediction is the coupling of monitoring systems with prediction models. This is where "digital twins", or real-time models of physical systems updated with real-time data from sensors, promise to be an important new approach [37]. In practice, such a system would function by continuously integrating field measurements—for instance, bathymetric data from multi-beam sonar—into a calibrated predictive scour model, enabling the real-time updating of risk assessments for critical infrastructure. Real-time bathymetric monitoring is one method of tracking scour development. While their application is intriguing, it is important to note that monitoring-prediction systems are still in their infancy with regard to their application in engineered systems.

6. Conclusion and Future Research Directions

Seabed scour caused by propellers is a multidisciplinary area of complexity that falls at the crossroads of hydrodynamics, sediment mechanics, computational modeling, and geotechnical engineering. This literature review has managed to synthesize the current state of research that shows that the fundamentals of principles such as jet attenuation, confinement, and the three stages of scouring development have been well established in an ideal laboratory setting. This would indicate that it is not yet a straightforward situation as it applies to real-world applications that involve real sediments found at sea.

Numerical models have evolved significantly, with methodologies spanning from effective RANS models to informative but expensive DEM simulations. However, there remains a gap between what researchers achieve with current state-of-the-art models and what needs to be developed for the purposes of engineering design applications. Current trends in coastal engineering work toward more proactive approaches that combine monitoring, management, and selective shielding based on what is emerging as a risk-based paradigm.

There is a need for collective efforts to fill the mentioned gaps. It is imperative to prioritize research efforts in understanding cohesive sediment erosion, typifying hydrodynamic forces, and gaining key data through field validations. It is important that more interactions between researchers seeking answers in fundamental questions and practitioners trying to solve real-world engineering challenges be encouraged for the development of models, design principles, or management practices that would make it possible to better face the increasingly complex threat of scour caused by a propeller in such a context of increasingly heavy maritime traffic.

Future Research Directions

A synoptic analysis of the literature reviewed highlights the various gaps that need to be addressed for growth in the area.

1) Cohesive and Heterogeneous Sediment Dynamics: There is an urgent need to shift current research emphasis from the dominance of uniform sand to more investigations of scouring in layers of cohesive sediments (clay-silt mixtures), which are more abundant in harbor areas. This would need the development of new experimental techniques that account for the effective strength of sediments, besides developing erosion formulas that include geotechnical properties like the undrained strength of sediments into their models [4] [5].

2) Transient & Realistic Hydrodynamic Conditions: Research should progress from current fixed bollard pull hydrodynamic conditions. Experimental & computational research should be prioritized related to real ship maneuvers like acceleration, braking, turning, and using bow/stern thrusters. It is important for risk analysis of scours formed by such dynamic high forces for safe functioning of ports with heavy traffic [10] [20] [35].

3) Bridging the Scale Gap with Field Validation: One of the biggest challenges is the limited availability of good-quality, broad-spectrum data for field validations. There is a need for collaboration in gathering coordinated data during the execution of port activities, such as accurate thrust or propeller data of the vessels, detailed bathymetry observations before/after the incident, or near-bed hydrodynamic observations. All these observations are critical for validating models at various scales [1] [8].

4) Multipurpose Numerical Tools for Engineers: High-quality simulations using CFD-DEM or LES can yield valuable information, whereas for various engineering applications, it is important to develop accurate and reliable models. Currently, more attention is desired for improving standardized numerical models that couple various models such as RANS with morphodynamics. A proposal by Yazdanfar *et al.* [19] for upscaling is useful for this purpose, including its application for scouring caused by a propeller.

5) Integration with Structural Life Cycle and Risk Analysis: Research should focus on integrating scouring models with structural life cycle risk analysis to better evaluate the real effects of scouring on structural foundation strength, natural frequency, and fatigue life [30] [36]. Additionally, the development of risk analysis models that incorporate hydrodynamic scour analysis, structural risk analysis, and economic optimization techniques would enable more effective and optimized structural risk management.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] van Rijn, L.C., Geleynse, N., Perk, L. and Schoonhoven, D. (2025) Scour near Offshore Monopiles, Jacket-Type and Caisson-Type Structures. *Journal of Marine Science and Engineering*, **13**, Article 266. https://doi.org/10.3390/jmse13020266

[2] Qu, L., An, H., Draper, S., Watson, P., Zhao, M., Harris, J., *et al.* (2024) A Review of Scour Impacting Monopiles for Offshore Wind. *Ocean Engineering*, **301**, Article ID: 117385. https://doi.org/10.1016/j.oceaneng.2024.117385

[3] Zhao, M. (2022) A Review on Recent Development of Numerical Modelling of Local Scour around Hydraulic and Marine Structures. *Journal of Marine Science and Engineering*, **10**, Article 1139. https://doi.org/10.3390/jmse10081139

[4] Duan, B., Wang, D., Qin, C. and Duan, L. (2025) Local Scour around Marine Structures: A Comprehensive Review of Influencing Factors, Prediction Methods, and Future Directions. *Buildings*, **15**, Article 2125. https://doi.org/10.3390/buildings15122125

[5] Cihan, K., Yüksel Ozan, A., Yıldız, O. and Doğu, A. (2025) Scour Caused by Propeller Jet Flow on Clay/sand Mixture Seabed near Vertical Quay Wall. *Journal of Marine Science and Engineering*, **13**, Article 2051. https://doi.org/10.3390/jmse13112051

[6] Curulli, G., Llull, T., Penna, N., Mujal-Colilles, A., Gironella, X., Sánchez-Arcilla, A., *et al.* (2022) Relationship between Eroded Volume and Main Scour Hole Dimensions near Quay Walls Caused by Internal Counter-Rotating Twin-propellers. *Ocean Engineering*, **259**, Article ID: 111744. https://doi.org/10.1016/j.oceaneng.2022.111744

[7] Ahmad, N., Kamath, A. and Bihs, H. (2020) 3D Numerical Modelling of Scour around a Jacket Structure with Dynamic Free Surface Capturing. *Ocean Engineering*, **200**, Article ID: 107104. https://doi.org/10.1016/j.oceaneng.2020.107104

[8] Si, J., Lim, S. and Wang, X. (2020) Experimental Study on the Cyclical Jet-Flipping in the Wall Jet Scour Hole. *Journal of Hydraulic Research*, **59**, 757-765. https://doi.org/10.1080/00221686.2020.1818317

[9] Wei, M., Chiew, Y. and Cheng, N. (2020) Recent Advances in Understanding Propeller Jet Flow and Its Impact on Scour. *Physics of Fluids*, **32**, Article ID: 101303. https://doi.org/10.1063/5.0023266

[10] Zheng, Z., Hu, Z., Xie, X. and Huang, W. (2024) Local Scour around the Monopile: A Microscopic Perspective Using Cfd-dem. *Ocean Engineering*, **299**, Article ID: 117318. https://doi.org/10.1016/j.oceaneng.2024.117318

[11] Huang, W., Li, S., Lu, Y., Zhou, C., Mu, D. and Liu, X. (2025) Influence of Propeller Clearance on the Jet Scour Process in Restricted Water. *International Journal of Sediment Research*, **40**, 729-741. https://doi.org/10.1016/j.ijsrc.2025.06.001

[12] Cui, Y., Lam, W.H., Ong, Z.C., Ling, L., Siow, C.L., Robinson, D., *et al.* (2020) Experimental Scours by Impinging Twin-Propeller Jets at Quay Wall. *Journal of Marine Science and Engineering*, **8**, Article 872. https://doi.org/10.3390/jmse8110872

[13] Dey, S. and Ali, S.Z. (2025) Scaling Laws of Turbulent Wall-Jet Scour: Planar and Circular Wall Jets. *Physics of Fluids*, **37**, Article ID: 021401. https://doi.org/10.1063/5.0260064

[14] Lu, Y., Cheng, N., Wei, M. and Luo, A. (2023) Scaling Laws for Two- and Three-Dimensional Wall Jet Scour Based on the Phenomenological Theory of Turbulence. *Journal of Hydraulic Research*, **61**, 422-430. https://doi.org/10.1080/00221686.2023.2222276

[15] Benseghier, Z., Cuéllar, P., Luu, L., Delenne, J., Bonelli, S. and Philippe, P. (2020) Relevance of Free Jet Model for Soil Erosion by Impinging Jets. *Journal of Hydraulic*

Engineering, **146**, Article ID: 04019047.
https://doi.org/10.1061/(asce)hy.1943-7900.0001652

[16] Craig, P.M., Jung, J.Y., Mausolff, Z., Bastidas, L.A., Mathis, T. and Wang, P. (2023) Modeling Sediment Resuspension and Transport Processes Induced by Propeller Wash from Ship Traffic. *Journal of Hydraulic Engineering*, **149**, Article ID: 04023009. https://doi.org/10.1061/jhend8.hyeng-13229

[17] Kartal, V. and Emiroglu, M.E. (2022) Experimental Study of Scour Morphology from Plunging Water Jets. *Water Supply*, **22**, 5410-5433. https://doi.org/10.2166/ws.2022.143

[18] Chen, H., Zhang, J., Guo, Y., Ji, Y., Guan, D. and Luo, M. (2025) Experimental Investigation of Riprap Protection for a Jacket Foundation under Varying Hydrodynamic Actions. *Applied Ocean Research*, **165**, Article ID: 104850. https://doi.org/10.1016/j.apor.2025.104850

[19] Yazdanfar, Z., Lester, D., Robert, D. and Setunge, S. (2021) A Novel CFD-DEM Upscaling Method for Prediction of Scour under Live-Bed Conditions. *Ocean Engineering*, **220**, Article ID: 108442. https://doi.org/10.1016/j.oceaneng.2020.108442

[20] Shouman, M.R. and Helal, M.M. (2021) Influence of Marine Propeller Geometry on Turbulence Models Selection for CFD Simulations. *Marine Technology Society Journal*, **55**, 150-164.

[21] Castells-Sanabra, M., Mujal-Colilles, A., LLull, T., Moncunill, J., Martínez de Osés, F.X. and Gironella, X. (2020) Alternative Manoeuvres to Reduce Ship Scour. *Journal of Navigation*, **74**, 125-142. https://doi.org/10.1017/s0373463320000399

[22] Macías-Lezcano, J., Llull, T. and Aberle, J. (2024) Scouring Induced by a Confined Propeller Jet Nearby a Vertical Quay Structure: Scale Model Tests. *Eighth International Symposium on Marine Propulsors smp*'24, Berlin, 17-20 March 2024, 229-236.

[23] Llull, T., Mujal-Colilles, A. and Gironella, X. (2021) Twin Propeller Time-Dependent Scouring Processes. Physical Experiments. *Ocean Engineering*, **236**, Article ID: 109461. https://doi.org/10.1016/j.oceaneng.2021.109461

[24] Kaidi, S., Smaoui, H. and Sergent, P. (2021) Numerical Investigation of the Inland Transport Impact on the Bed Erosion and Transport of Suspended Sediment: Propulsive System and Confinement Effect. *Journal of Marine Science and Engineering*, **9**, Article 746. https://doi.org/10.3390/jmse9070746

[25] Lee, C., Lee, H. and Seok, W. (2025) A Comparative Study of RANS and PANS Turbulence Models for Flow Characterization around the Joubert BB2 Submarine. *Journal of Marine Science and Engineering*, **13**, Article 1088. https://doi.org/10.3390/jmse13061088

[26] Liu, J., Lu, J. and Liang, Z. (2024) Computational Simulation of Monopile Scour under Tidal Flow Considering Suspended Energy Dissipation. *Water*, **16**, Article 1940. https://doi.org/10.3390/w16141940

[27] Srše, J., Perkovič, M. and Grm, A. (2023) Sediment Resuspension Distribution Modelling Using a Ship Handling Simulation along with the MIKE 3 Application. *Journal of Marine Science and Engineering*, **11**, Article 1619. https://doi.org/10.3390/jmse11081619

[28] Liang, L., Hao, Z., Chaonan, Z., Jinbiao, C., Baoji, Z., Xiangen, B., *et al.* (2024) Study on the Effect of Marine Propeller Wake on Sediment Siltation in a Shallow Water Channel. *Brodogradnja*, **75**, 1-22. https://doi.org/10.21278/brod75308

[29] Samma, H., Khosrojerdi, A., Rostam-Abadi, M., Mehraein, M. and Cataño-Lopera, Y. (2020) Numerical Simulation of Scour and Flow Field over Movable Bed Induced

by a Submerged Wall Jet. *Journal of Hydroinformatics*, **22**, 385-401. https://doi.org/10.2166/hydro.2020.091

[30] Bordbar, A., Knir, J., Kelefouras, V., Hickling, S.J.S., Short, H. and Lee, Y.C. (2025) Flow Dynamics and Local Scour around Seabed-Mounted Artificial Reefs: A Case Study from Torbay, UK. *Journal of Marine Science and Engineering*, **13**, Article 1425. https://doi.org/10.3390/jmse13081425

[31] Wang, Y., Wang, Y., Zhang, J., Hu, J., Duan, Z. and Zhang, Q. (2025) Prediction of Scouring Hole Morphology Induced by Underwater Jets Using CFD-DEM Simulation. *Water*, **17**, Article 2163. https://doi.org/10.3390/w17142163

[32] Song, S. and Park, S. (2022) Unresolved CFD and DEM Coupled Simulations on Scour around a Subsea Pipeline. *Journal of Marine Science and Engineering*, **10**, Article 556. https://doi.org/10.3390/jmse10050556

[33] Li, X., Zhang, B. and Wang, C. (2025) Scour Characteristics and Bearing Capacity Response of MGB Hybrid Foundations in Offshore Wind Applications. *Journal of Marine Science and Engineering*, **13**, Article 1726. https://doi.org/10.3390/jmse13091726

[34] Li, B., Wang, Y., Qi, W., Wang, S. and Gao, F. (2022) Lateral Bearing Capacity of a Hybrid Monopile: Combined Effects of Wing Configuration and Local Scour. *Journal of Marine Science and Engineering*, **10**, Article 1799. https://doi.org/10.3390/jmse10121799

[35] Shi, L., Cheng, Y., Zheng, Y., Xia, B. and Huang, X. (2024) Experimental Study on Local Scour at the Monopile Foundation of an Offshore Wind Turbine under the Combined Action of Wave-Current-Vibration. *Journal of Marine Science and Engineering*, **12**, Article 963. https://doi.org/10.3390/jmse12060963

[36] Kim, Y., Ngo, D., Lee, J. and Kim, D. (2022) Ultimate Limit State Scour Risk Assessment of a Pentapod Suction Bucket Support Structure for Offshore Wind Turbine. *Energies*, **15**, Article 2056. https://doi.org/10.3390/en15062056

[37] Hoballah Jalloul, M., Satari, R., Welzel, M., Schendel, A., Kerpen, N.B., Wynants, M., *et al.* (2025) Wave-Current Induced Scour around Complex Offshore Structures: Towards a Refined Analysis of Local Scour at Jacket Piles. *Ocean Engineering*, **338**, Article ID: 121983. https://doi.org/10.1016/j.oceaneng.2025.121983