

Article

Numerical Investigation of Coupled Vortex-Induced Vibration and Scour of Subsea Pipelines under Ocean Currents

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Abstract

Sediment transport beneath subsea pipelines is essentially a highly complex multiphase flow problem, involving strong coupling between hydrodynamics, structural response, and sediment transfer. Accurately capturing this process is of significant scientific and engineering importance for predicting seabed evolution and ensuring the structural safety and stability of subsea pipelines. In this study, the coupled vortex-induced vibration (VIV) and scour behaviour of subsea pipelines under steady current conditions is investigated using a computational fluid dynamics (CFD)-based numerical approach. The solver is developed within SedFoam by incorporating dynamic mesh motion to account for pipeline vibration. The pipeline is modelled as a single-degree-of-freedom system with a vertically mounted spring and a concentrated mass. The numerical results reveal a strong interaction between pipeline VIV and the evolving seabed morphology. Repeated pipeline motion toward the seabed significantly modifies the local scour profile and promotes the formation of a sand dune beneath the pipeline. The presence of the sand dune alters the near-bed flow field and suppresses vortex shedding beneath the pipeline. As the scour process develops and the fluid–structure–seabed interaction intensifies, the VIV response of the pipeline is progressively reduced. The present study highlights the important coupling mechanisms between pipeline vibration and seabed scour and provides insights into the dynamic evolution of pipeline–seabed interaction.

Keywords: vortex-induced vibration; pipeline scour; seabed morphology; computational fluid dynamics



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1. Introduction

Submarine pipelines in proximity to the seabed experience intricate interactions between hydrodynamic forces, structural responses, and sediment dynamics [1,2]. Under the combined effects of waves and ocean currents, seabed sediments undergo a series of transport processes, including incipient motion, suspension, advection, and deposition [3]. This process is influenced not only by the overall hydrodynamic conditions but also by the local flow around the pipeline, unsteady pressure fluctuations induced by vortex shedding, and interparticle interactions within the sediment [4,5]. These coupled effects make sediment transport beneath pipelines a highly complex and dynamic phenomenon [6]. Therefore, sediment transport beneath pipelines is essentially a highly complex multiphase flow problem, involving the coupled mechanisms of fluid mechanics, sediment

dynamics, and ocean engineering, and exhibiting significant nonlinearity and multi-scale characteristics [7]. Accurately revealing and simulating this process is of great scientific and engineering importance for understanding scour beneath pipelines and ensuring their structural safety and stability.

Early studies on submarine pipeline scour were mainly conducted using experimental methods. Mao [7] experimentally investigated the scour process beneath a stationary pipeline under steady current conditions. The results showed that scour primarily occurs in the jet region below the cylinder and the wake region downstream, developing rapidly at the early stage and gradually stabilizing at the later stage. Sumer et al. [8] systematically carried out experiments on scour beneath stationary pipelines under steady currents and compared the results with vibrating pipeline cases. They also provided an overview of the complex fluid–structure–seabed interactions of scour in coastal and marine environments [6]. After the onset of fully developed vortex shedding, the scour depth under vibrating pipelines develops faster than that under fixed pipelines. Based on this understanding, Sumer and Fredsøe [1,9] and Sumer et al. [4] investigated scour beneath pipelines under wave and current conditions. They found that the main mechanism initiating scour is the increased pressure difference between the front and rear parts of the pipeline, which induces seepage flow within the sediment. This seepage reduces the submerged weight of sediment particles, making them more easily entrained. Sui et al. [10,11] conducted experimental studies on the span shoulder migration rate of submarine pipelines on a flat seabed under combined wave–current effects, covering pure current, pure wave, and combined wave–current conditions. Their studies systematically analyzed the effects of dimensionless parameters such as the Shields number and the Keulegan–Carpenter number on the migration rate and proposed a prediction model applicable to combined wave–current conditions. These experimental studies have revealed the formation mechanisms, evolution processes, and equilibrium characteristics of pipeline scour, providing a solid foundation for subsequent theoretical analysis and numerical modelling. However, most experimental studies have used rigid stationary pipelines, making it difficult to account for structural vibrations and the influence of VIV on the scour process.

Numerical studies of submarine pipeline scour generally refer to simulating the flow field and sediment transport around the pipeline using computational fluid dynamics (CFD). Current numerical methods for simulating the dynamic scour process can be mainly divided into two categories: single-phase flow models coupled with morphodynamic models; and multiphase flow models that simultaneously solve fluid flow and sediment transport. Liang et al. [12] developed a numerical framework coupling flow and a suspended-load model to simulate the formation and evolution of scour holes beneath pipelines under steady currents. Their model solved the advection–diffusion transport and settling of suspended sediment concentrations, and successfully reproduced the temporal development of scour depths that were in good agreement with experiments. However, because the suspended-load model is based on a quasi-static assumption of sediment motion, it requires the seabed surface to remain separated from the structure throughout the scour process. As a result, it is more suitable for modelling scour beneath stationary objects and is less able to capture the intense sediment mobilization and possible self-burial that can occur when the pipeline moves. In addition to quasi-static morphodynamic models, more recent approaches have emerged that simultaneously solve fluid flow and sediment transport using multiphase flow coupling. A representative example is the SedFoam solver developed by Chauchat et al. [13] and Cheng et al. [14]. SedFoam is a two-phase Euler–Euler method, treating sediment particles as a continuous solid phase interacting with the fluid phase, and simultaneously solving the fluid momentum equations and the transport of sediment volume fraction. This allows a more realistic representation of transient sediment dynamics

such as incipient motion, suspension, advection, and deposition. Yin et al. [15] adopted the SedFoam solver to conduct a numerical study of scour around subsea pipelines near the seabed. They provided sufficient numerical validations including the seabed profiles and the scour depth by comparing the experimental and numerical results [7,16]. Huang et al. [17] also provided the corresponding numerical validation of the SedFoam for the scour under wave conditions by comparing with the experimental results of Sumer and Fredsøe [18]. These validations indicate that the SedFoam solver can provide accurate predictions of scour under various marine environmental conditions. Huang et al. [19] and Fraga et al. [20] further adopted the SedFoam solver to conduct a numerical study of the scour beneath a subsea piggyback pipeline and analyzed the influence of the piggyback location on the overall scour of the pipelines under wave conditions and steady currents. They found that the flow patterns, the shape and the depth of scour holes are significantly influenced by the additional small pipeline. All the above studies focus on scour beneath stationary pipelines. However, vortex shedding in the wake of pipelines generates unsteady hydrodynamic forces that can induce structural vibrations, thereby influencing the development and evolution of scour holes. The coupling between VIV and the scour process of the pipeline remains insufficiently understood and is still under active investigation. Accurately capturing this interaction requires modelling pipeline motion, which involves the integration of dynamic mesh techniques and six-degree-of-freedom (6-DOF) motion solvers. Such capabilities are not yet fully developed within the SedFoam framework and represent an important direction for future research.

This study incorporates pipeline motion to investigate the coupled VIV and scour of pipelines in ocean currents. The SedFoam solver is further developed on the OpenFOAM platform by integrating dynamic mesh techniques and the 6-DOF model. The proposed model will be applied to examine the interaction between VIV and scour of the pipeline under strong ocean current conditions, where scour effects are pronounced. The structure of this study is organized as follows: Section 2 introduces the numerical methodology, including the governing equations, turbulence model, dynamic mesh technique, and the 6-DOF model. Section 3 describes the physical model, the CFD domain and boundary conditions (BCs), pipeline structural modelling and case setup. Section 4 presents and analyses the simulation results of the coupled VIV and scour process of the pipeline. Section 5 provides the conclusion of this study.

2. Numerical Method

The numerical method employed in this study is based on the SedFoam solver developed by Chauchat et al. [13] and Cheng et al. [14]. This solver is capable of simulating the scour process beneath stationary pipelines. However, modelling pipelines subjected to VIV requires dynamic mesh techniques to capture pipeline motion. This allows for the simulation of both the scour evolution beneath moving pipelines and the coupled interaction between VIV and scour.

2.1. Governing Equations

SedFoam is a three-dimensional (3D) two-phase flow solver developed for sediment transport problems. It is built upon the existing two-phase Eulerian solver, twoPhaseEulerFoam, in the open-source CFD platform OpenFOAM (Version 2.4). In this approach, the sediment phase is treated as a continuum medium, and a constitutive model is introduced to describe the sediment stress. The mass conservation equations for the sediment and water phases are expressed as follows:

$$\frac{\partial \varphi}{\partial t} + \frac{\partial \varphi u_i^s}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial \phi}{\partial t} + \frac{\partial \phi u_i^f}{\partial x_i} = 0 \quad (2)$$

where $i = 1, 2$ denote the streamwise and vertical directions, respectively. The sediment and water fractions are denoted as φ and ϕ , respectively. They range from 0 to 1 and their sum is equal to one $\varphi + \phi = 1$. u_i^s and u_i^f represent the flow velocities of the sediment and water, respectively. The momentum conservation equations are presented as:

$$\frac{\partial \rho^s \varphi u_i^s}{\partial t} + \frac{\partial \rho^s \varphi u_i^s u_j^s}{\partial x_i} = -\varphi \frac{\partial p}{\partial x_i} - \frac{\partial p^s}{\partial x_i} + \frac{\partial \tau_{ij}^s}{\partial x_i} + \varphi \rho^s g + \varphi \phi K (u_i^f - u_i^s) - \phi \frac{1}{S_c} K v_t^f \frac{\partial \varphi}{\partial x_i} \quad (3)$$

$$\frac{\partial \rho^f \phi u_i^f}{\partial t} + \frac{\partial \rho^f \phi u_i^f u_j^f}{\partial x_i} = -\phi \frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}^f}{\partial x_i} + \phi \rho^f g - \varphi \phi K (u_i^f - u_i^s) + \phi \frac{1}{S_c} K v_t^f \frac{\partial \varphi}{\partial x_i} \quad (4)$$

where ρ^s and ρ^f are the densities of sediment and water, respectively, p is the pressure, p^s is the normal stress of the sediment. τ_{ij}^s and τ_{ij}^f are the shear stresses of the sediment and water, respectively. τ_{ij}^f has the form:

$$\tau_{ij}^f = \rho^f \phi \left[2\nu_{Eff}^f S_{ij}^f - \frac{2}{3} k \delta_{ij} \right] \quad (5)$$

$$\nu_{Eff}^f = \nu_t^f + \nu_{mix} \quad (6)$$

$$S_{ij}^f = \frac{1}{2} \left(\frac{\partial u_i^f}{\partial x_j} + \frac{\partial u_j^f}{\partial x_i} \right) - \frac{1}{3} \left(\frac{\partial u_k^f}{\partial x_k} \right) \delta_{ij} \quad (7)$$

where ν_{Eff}^f is the effective viscosity, k is the turbulence kinetic energy, and δ_{ij} is the Kronecker delta. S_{ij}^f is the deviatoric term of the strain rate tensor for the fluid phase. The last two terms in Equations (3) and (4) are the momentum coupling between the sediment and water, and K is a drag parameter. The interphase momentum exchange follows the standard SedFoam formulation. The drag coefficient is calculated using the Schiller–Naumann correlation [15], whereas the momentum exchange coefficient is closed using the formulation of Ding and Gidaspow [16]. In this model, the model of Ergun [17] for $\phi \leq 0.8$ and the model of Wen and Yu [18] $\phi > 0.8$ are combined.

$$K = \begin{cases} \frac{0.75 C_d \rho^f \|u^s - u^f\| \phi^{-h_{exp}}}{d}, & \phi > 0.8 \\ \frac{150(1-\phi)\rho^f \nu^f}{\phi d^2} + \frac{1.75 \rho^f \|u^s - u^f\|}{d}, & \phi \leq 0.8 \end{cases} \quad (8)$$

$$C_d = \begin{cases} \frac{24}{Re_p} \left(1 + 0.15 Re_p^{0.687} \right), & Re_p \leq 1000 \\ 0.44, & Re_p > 1000 \end{cases} \quad (9)$$

$$Re_p = \frac{d \phi}{\nu^f} \|u^s - u^f\| \quad (10)$$

where $h_{exp} = 2.65$ is a hindrance exponent, C_d is the particulate Reynolds number and ν^f is the kinematic viscosity of water. The particle normal stress includes two contributions: shear-induced and collisional components:

$$p^s = p^{sf} + p^{sc} \quad (11)$$

The permanent contact component p^{sf} is calculated as:

$$p^{sf} = \begin{cases} 0, & \varphi < \varphi_{\min}^{\text{Fric}} \\ Fr \frac{(\varphi - \varphi_{\min}^{\text{Fric}})^{\eta_0}}{(\varphi_{\max} - \varphi)^{\eta_1}}, & \varphi > \varphi_{\min}^{\text{Fric}} \end{cases} \quad (12)$$

where $Fr = 0.05$, $\eta_0 = 3$ and $\eta_1 = 5$. $\varphi_{\max} = 0.635$ is the maximum sediment concentration and $\varphi_{\min}^{\text{Fric}} = 0.57$ represents a random loose packing sediment concentration. The sediment normal stress induced by particle collisions is expressed in two different forms. The first one is the viscosity-dominated case, which is given by the following equations:

$$p^{sc} = \left(\frac{B_\phi \varphi}{\varphi_{\max} - \varphi} \right)^2 \rho^s d^2 \|S_{ij}^s\| \quad (13)$$

$$S_{ij}^s = \frac{1}{2} \left(\frac{\partial u_i^s}{\partial x_j} + \frac{\partial u_j^s}{\partial x_i} \right) - \frac{1}{3} \left(\frac{\partial u_k^s}{\partial x_k} \right) \delta_{ij} \quad (14)$$

where B_ϕ is a parameter in the constitutive model that represents the shear-induced dilation behaviour of the sediment phase. The second one is inertia-dominated, and its expression is given as follows:

$$p^{sc} = \left(\frac{B_\phi \varphi}{\varphi_{\max} - \varphi} \right)^2 \nu^s \|S_{ij}^s\|^2 \quad (15)$$

The frictional shear stress is given as:

$$\tau_{ij}^s = \sqrt{2} \sin \theta_f p^{sc} \frac{S_{ij}^s}{\sqrt{S_{ij}^s S_{ij}^s}} \quad (16)$$

where $\theta_f = 32^\circ$.

2.2. Turbulence Model

SedFoam is capable of simulating both laminar and turbulent flow regimes. The turbulence model is applied to the flow of water, while the turbulence effect of the sediment flow is neglected. For turbulence modelling in sediment transport problems, SedFoam provides three optional models: a simplified mixing-length model (only applicable in one-dimensional cases), the k- ϵ model, and the k- ω model. To better capture the VIV behaviour, the present study adopts the k- ω turbulence model. The governing equations for the turbulent kinetic energy (k) and the specific dissipation rate (ω) are given as follows:

$$\frac{\partial k}{\partial t} + u_j^f \frac{\partial k}{\partial x_j} = \frac{R_{ij}^f}{\rho^f} \frac{\partial u_i^f}{\partial x_j} - \beta^* k \omega + \frac{\partial}{\partial x_j} \left[\left(\nu^f + \sigma_k \nu_t^f \right) \frac{\partial k}{\partial x_j} \right] - \frac{2K(1-\alpha)\varphi k}{\rho^f} - \frac{\nu^f}{S_c \phi} \frac{\partial \varphi}{\partial x_j} (s-1)g \quad (17)$$

$$\frac{\partial \omega}{\partial t} + u_j^f \frac{\partial \omega}{\partial x_j} = C_{1\omega} \frac{\omega}{k} \frac{R_{ij}^f}{\rho^f} \frac{\partial u_i^f}{\partial x_j} + \frac{\partial}{\partial x_j} \left[\left(\nu^f + \sigma_k \nu_t^f \right) \frac{\partial \omega}{\partial x_j} \right] - C_{2\omega} \omega^2 - C_{3\omega} \frac{2K(1-\alpha)\varphi \omega}{\rho^f} - C_{4\epsilon} \frac{\omega}{k} \frac{\nu^f}{S_c \phi} \frac{\partial \varphi}{\partial x_j} (s-1)g + \frac{\sigma_d}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \quad (18)$$

where R_{ij}^f is the Reynolds stress tensor and ν_t^f is the turbulent viscosity:

$$\nu_t^f = \frac{k}{\max \left[\omega, C_{\lim} \frac{S_{ij}^f}{\sqrt{\beta}} \right]} \quad (19)$$

$$\sigma_d = \begin{cases} 0, & \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} < 0 \\ \frac{1}{8}, & \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \geq 0 \end{cases} \quad (20)$$

In Equation (20), $\frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}$ is the cross-diffusion term. The model constants in this two-phase $k - \omega$ 2006 model are: $\sigma_k = 0.6$, $\sigma_\omega = 0.5$, $C_{1\omega} = 0.52$, $C_{2\omega} = 0.0708$, $C_{3\omega} = 0.35$, $C_{4\omega} = 1$ and $C_{lim} = 0.875$.

2.3. Dynamic Mesh and 6-DOF Model

The VIV simulations of pipelines require the use of dynamic mesh techniques. In this study, the dynamic mesh method provided by the OpenFOAM solver `sixDoFRigidBodyMotion` is employed. This method divides the computational domain into three zones—a rigid motion zone that moves together with the moving boundary, a deforming mesh zone, and a stationary mesh zone—based on two user-specified parameters, `innerDistance` and `outerDistance`, measured from the moving boundary, as shown in Figure 1. The motion of the moving boundary is calculated using a 6-DOF model, and its translational and rotational motions are governed by the following equations:

$$m \frac{dV}{dt} = \sum F \quad (21)$$

$$I \frac{d\omega}{dt} = \sum M \quad (22)$$

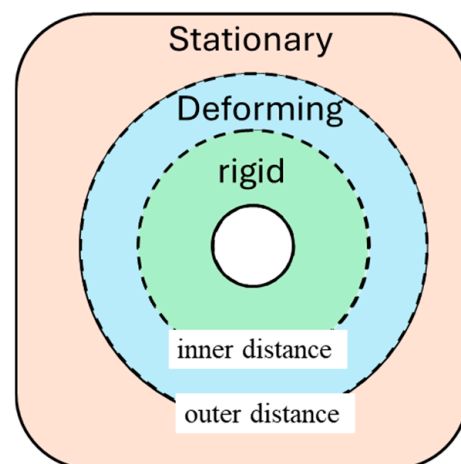


Figure 1. Description of the deforming mesh strategy.

Here, m is the mass of the body, I is the moment of inertia of the body, F is the external force acting on the body, and M is the external moment acting on the body with respect to a fixed reference point rather than the centre of mass. The moment of inertia I will vary as the body moves.

3. Physical Model and Case Setup

3.1. Physical Model

The structural specifications of the pipeline's sections are shown in Table 1 and Figure 2. The structural parameters of the pipeline structures are selected based on the engineering design, which is representative of typical offshore oil and gas pipelines. The first layer is made of steel to ensure the pipeline's integrity under harsh marine environments. The steel layer is covered by a three-layer polyethylene (3LPE) to protect the steel layer from corrosion due to the seawater. The third layer is made of concrete to increase the weight

of the pipeline and protect it from dropped objects. The outer diameter of the pipeline is 0.5 m. Two different pipelines are adopted, as shown in Tables 2 and 3. The first one is not covered with a heavy concrete layer, while the other one is covered with a 40 mm heavy concrete layer. Comparisons of their scour behaviours and VIV performances are conducted. The scour process and the structural response of the scaled pipeline under the current conditions are investigated. The scale model is applied to the CFD model and the structural model as described in Sections 3.2 and 3.3.

Table 1. Specifications of the pipelines' structure.

	Description	Unit	Pipeline 1	Pipeline 2
Fluid in Pipeline	Diameter	m	0.454	0.374
	Density	kg/m ³	50	800
Steel layer	Outer diameter	m	0.494	0.414
	Thickness	mm	20	20
	Density	kg/m ³	7850	7850
	Young's Module	GPa	210	210
3LPE cover	Outer diameter	m	0.5	0.42
	Thickness	mm	3	3
	Density	kg/m ³	940	940
Concrete layer	Outer diameter	m	0.5	0.5
	Thickness	mm	0	40
	Density	kg/m ³	2400	2400

Table 2. Structural specifications of Pipeline 1's section.

Description	Symbol	Unit	Full Scale	Scale Model
Diameter	D	m	0.5	0.05
Mass per unit	ρA	kg/m	246	2.46
Bending stiffness	EI	Nm ²	1.76×10^8	1.76×10^3
Gravity per unit in water	G	N/m	442	4.42
Free span	L	m	40	4
Natural frequency in air	f_0	Hz	1.88	5.95
Natural frequency in water ($C_a = 1$)	$f_{0,true}$	Hz	1.40	4.41
Sectional stiffness	k_0	N/m ²	34,405	3441
Equivalent position	Δy	mm	47.5	4.75

Table 3. Structural specifications of Pipeline 2's section.

Description	Symbol	Unit	Full Scale	Scale Model
Diameter	D	m	0.5	0.05
Mass per unit	ρA	kg/m	425	4.25
Bending stiffness	EI	Nm ²	1.011×10^8	1.011×10^3
Gravity per unit in water	G	N/m	2191	21.91
Free span	L	m	40	4
Natural frequency in air	f_0	Hz	1.086	3.435
Natural frequency in water ($C_a = 1$)	$f_{0,true}$	Hz	0.895	2.83
Sectional stiffness	k_0	N/m ²	19,775	1977.5
Equivalent position	Δy	mm	111	11.1

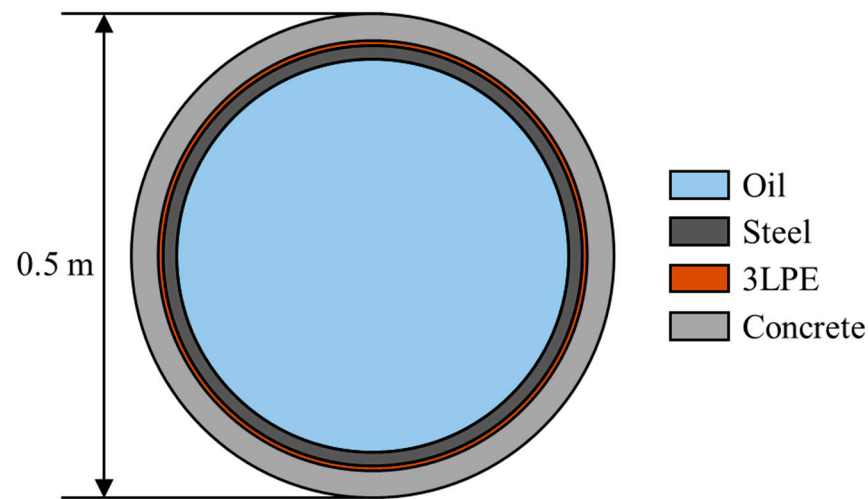


Figure 2. Description of the pipeline's structure.

3.2. CFD Domain and BCs

The CFD domain and the boundary conditions (BCs) for the scour beneath a pipeline are shown in Figure 3, and the specifications of the scour of this pipeline are shown in Table 4. The origin of the coordinate system is located at the centre of the cylinder, and the seabed interface is located just below the cylinder. The inlet boundary is set on the left side above the seabed at 15D from the cylinder centre. The lower part of the left boundary below the seabed interface is set as a wall boundary to prevent excessive entrainment of sediment by the incoming flow, which could otherwise change the prescribed inlet velocity profile. The bottom boundary is located 3.5D below the seabed interface and is specified as a wall boundary. The top boundary is located 4.6D above the seabed interface and is specified as a symmetry boundary. The right boundary is placed 20D downstream from the cylinder centre and is set as an outlet boundary.

Table 4. Specifications of the scour of a pipeline.

Description	Symbol	Unit	Value
Kinematic viscosity of water	ν^f	m ² /s	10 ^{−6}
Gravitational acceleration	g	m/s ²	9.81
Density of water	ρ^f	kg/m ³	1000
Density of sediment	ρ^s	kg/m ³	2650
Initial concentration of sediment	ϕ_0	-	0.6128
Diameter of the pipeline	D	m	0.05
Averaged diameter of sediment	d_{50}	mm	0.036
Roughness of the seabed	k_s	mm	0.009
Gap between the pipeline and the seabed	e	m	0
Shear velocity	u_*	m/s	0.04318
Shield number	θ	-	0.32

The sediment properties were selected to represent the typical ranges encountered in offshore engineering applications. The initial sediment concentration was varied from 0.54 to 0.80, while the median sediment diameter ranged from 0.01 to 0.40 mm. The seabed roughness was specified as 2.5 times the average diameter of the sediment, following a commonly adopted empirical relationship. The gap between the pipeline and the seabed

was chosen as 0 for the present study. The velocity profile at the inlet BC follows the logarithmic law, as shown in Equation (23):

$$u_x(y) = \frac{u_*}{\kappa} \log\left(\frac{y + D/2}{k_s/30}\right) \quad (23)$$

where u_* is the shear velocity, $\kappa = 0.41$ is the von Kármán constant, and k_s is the seabed roughness. The shear velocity is set to 0.04318 m/s to ensure that the resulting scour hole is sufficiently large to accommodate the pipeline's VIV behaviour. This results in a shield number of 0.32.

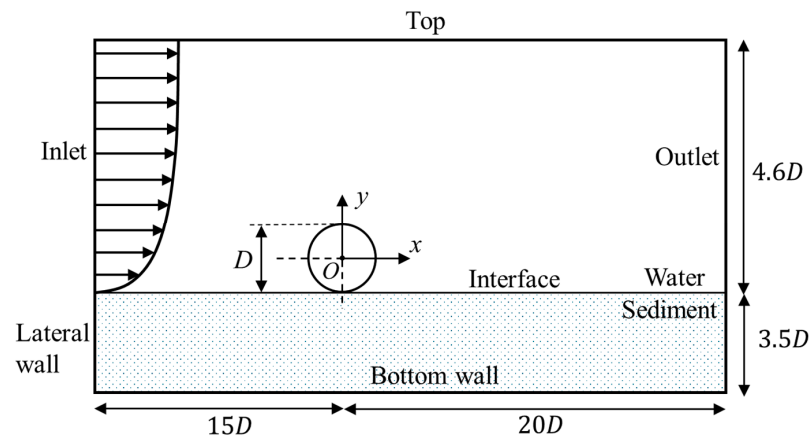


Figure 3. Description of the scour of pipelines.

The grids for the scour simulations are shown in Figure 4. Two types of grids are used for different cases. The grid with a thin layer attached to the cylinder is used for the stationary case, where the cylinder is fixed. The minimum cell height is 0.02 mm. The mesh size around the thin layer is 0.75 mm. The grid without the attached layer is used for the VIV cases. The mesh size around the cylinder is also 0.75 mm. The total cell numbers are 192,629 and 188,809, respectively. The regions near the seabed interface, behind and beneath the pipeline, are refined using the snappyHexMesh technique to accurately capture the wakes and the sediment transport.

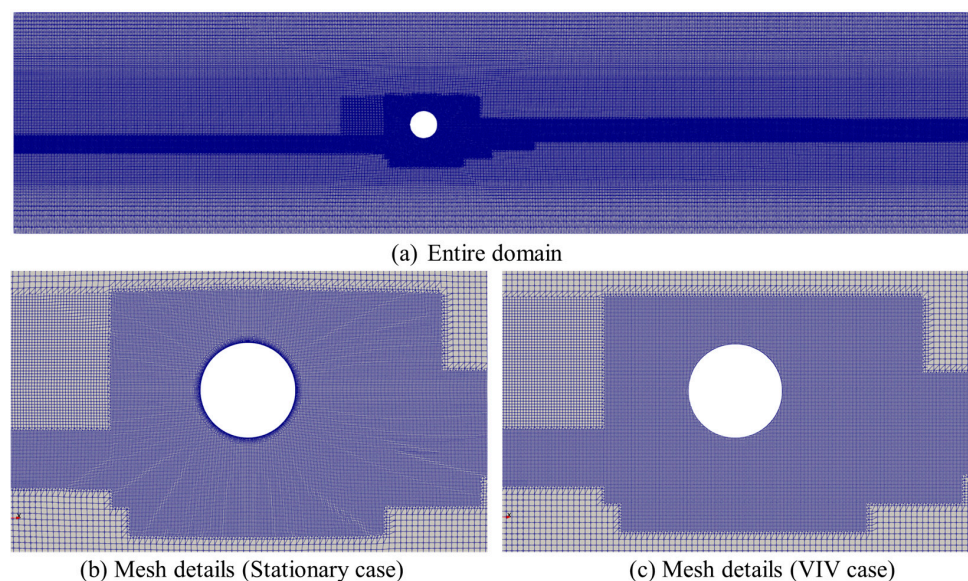


Figure 4. Grids of the 2D scour of a pipeline: (a) Entire domain; (b) Mesh details around the pipeline (Stationary case); (c) Mesh details around the pipeline (VIV cases).

3.3. 3D Structural Model

The submarine pipeline is assumed to be a slender body with uniform cross-sectional properties. Initially, the pipeline lies uniformly on a flat seabed interface. The pipeline is subjected to ocean currents and waves acting perpendicular to its axis. The scour initiates from a certain point near the middle of the pipeline and then propagates symmetrically toward both sides at the same migration speed. The 3D scour process is illustrated in Figure 5. The pipeline is not treated as a perfectly rigid body. As the scour progresses and a free-spanning section develops, this section may experience VIV. In this study, the scour process beneath the vibrating and deforming pipeline is still assumed to be two-dimensional (2D), while its structural characteristics are represented using a 3D structural model. A fixed free span of 4 m (scale model) is applied to the present VIV cases (see Tables 2 and 3).

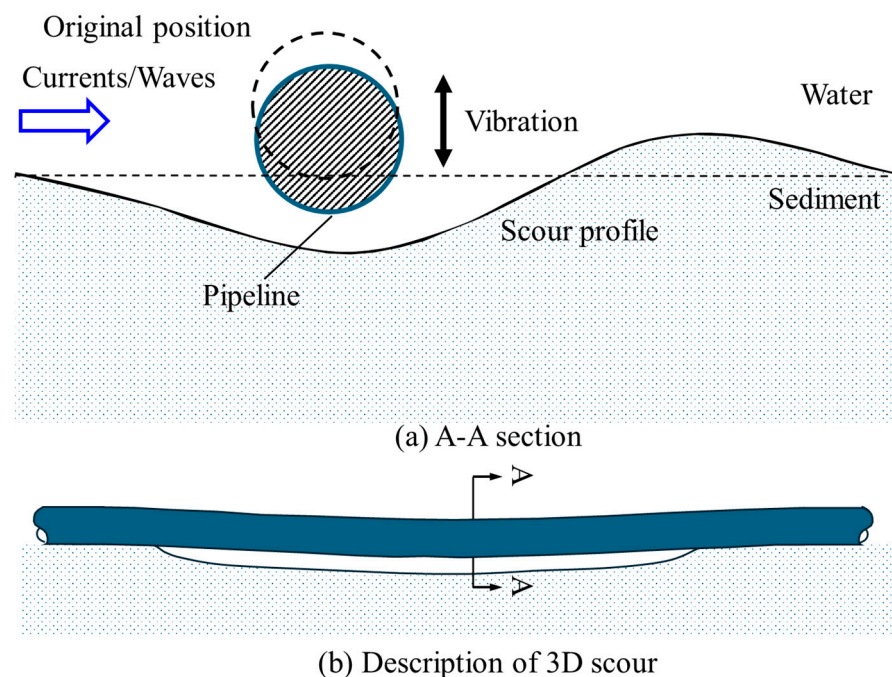


Figure 5. Description of 3D scour of a pipeline.

The Euler–Bernoulli beam theory is adopted to describe the structural characteristics of the 3D pipeline. The natural frequency of the structural vibration of the 3D pipeline with two fixed ends can be calculated using Equation (24).

$$f_0 = \frac{4.73^2}{2\pi L^2} \sqrt{\frac{EI}{\rho A}} \quad (24)$$

where L is the length of the free-spanning segment of the pipeline, EI is the bending stiffness of the cross-section of the submarine pipeline. ρA is the mass per unit length of the cross-section. The corresponding stiffness of the two-dimensional cross-section is given in Equation (25).

$$k_0 = m_0(2\pi f_0)^2 \quad (25)$$

where m_0 is the mass of the cross-section. It should be noted that this mass does not include the added mass. The structural damping is not included in the present study.

3.4. Case Setup

There are two types of simulations conducted in the present study, which are shown in Table 5. The first one is the simulation of a 2D stationary pipeline. A total time of 40 s is simulated to ensure that the scour becomes steady and the scour hole becomes sufficiently large. After that, the pipeline is relieved to allow for the VIV behaviours of the pipelines. The stationary case is controlled by a Courant number of 0.15, while the VIV cases are controlled using a maximum time step of 0.01 ms. The Courant numbers of the VIV cases are much smaller than 0.15.

Table 5. Simulation types of the scour of a pipeline.

Type of Simulation	Sectional Mass	Sectional Stiffness	Simulation Time	Courant Number	Time Step
Stationary Case	-	-	40 s	0.25	-
VIV Case 1	2.46 kg/m	3440.5 N/m ²	1.6 s	-	0.01 ms
VIV Case 2	4.25 kg/m	1977.5 N/m ²	1.5 s	-	0.01 ms

4. Results and Discussion

4.1. Verification and Validation of the Present Numerical Model

The Sedfoam solver was validated for stationary cases under current or wave conditions by Yin et al. [19], Huang et al. [20,21] and Fraga et al. [22] by comparing the experimental results of Mao [7] and Sumer and Fredsøe [23]. The present study is a continuation of the numerical work of Yin et al. [19], Huang et al. [20] and Fraga et al. [22] to investigate the coupled effects of pipeline VIV and scour.

The validation case from the experimental data of Mao [7] was also selected to validate the present numerical model. The specifications of the validation case from Mao [7]'s experiments are shown in Table 6. The Shields number in this case is 0.33, which is slightly higher than that in Table 4. A convergence study with three different grids was conducted, where the mesh details of the three grids are shown in Table 7. Variations in the mesh along the x and y directions were applied. The mesh sizes around the cylinder were 3.5 mm, 3 mm and 2.5 mm, respectively. Figure 6 shows the comparisons of the scour profiles at 11s obtained using the three computational grids. Overall, the predicted scour profiles are in good agreement. The results obtained with Mesh 2 and Mesh 3 show closer agreement than those with Mesh 1 and Mesh 2, indicating that the solution has become nearly grid-independent with Mesh 2. Therefore, Mesh 2 was selected for the subsequent simulations, as it provides a good balance between computational accuracy and efficiency.

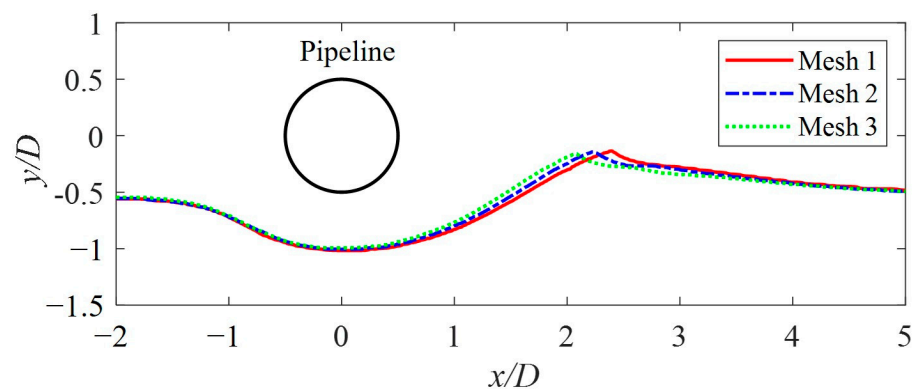


Figure 6. Comparisons of the scour profiles at 11 s obtained using the three computational grids.

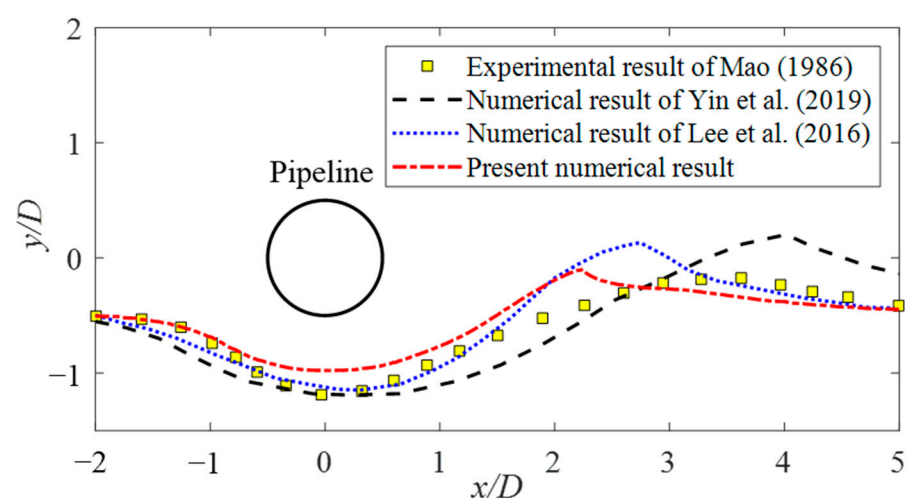
Table 6. Specifications of the validation case from Mao [7]’s experiments.

Description	Symbol	Unit	Value
Kinematic viscosity of water	ν^f	m^2/s	10^{-6}
Gravitational acceleration	g	m/s^2	9.81
Density of water	ρ^f	kg/m^3	1000
Density of sediment	ρ^s	kg/m^3	2600
Initial concentration of sediment	ϕ_0	-	0.6
Diameter of the pipeline	D	m	0.05
Averaged diameter of sediment	d_{50}	mm	0.036
Roughness of the seabed	k_s	mm	0.009
Gap between the pipeline and the seabed	e	m	0
Shear velocity	u_*	m/s	0.04318
Shield number	θ	-	0.33

Table 7. Mesh details of three grids.

Case No	Total Mesh No	Mesh No Along x	Mesh No Along y	Mesh Size Around Cylinder
Mesh 1	143,268	500	87	3.5 mm
Mesh 2	188,924	585	100	3 mm
Mesh 3	274,258	700	120	2.5 mm

Figure 7 shows the comparison of the scour profile at 11 s between the experimental result of Mao [7], the numerical result of Yin et al. [19] using the $k - \varepsilon$ model, the numerical result of Lee et al. [24] and the present numerical result using the $k - \omega$ model during the 2D scour beneath a stationary pipeline. The present numerical model is in overall agreement with the experimental data. However, the present numerical model does not predict scour depth well compared with the other two methods. The reason can be attributed to the selected turbulence model. A comparison of the scour depth predicted using the $k - \varepsilon$ model and the $k - \omega$ model was performed by Fraga et al. [23], which indicated that the $k - \omega$ model underestimates the scour depth compared to the $k - \varepsilon$ model. Although using the $k - \omega$ model underestimates the scour depth, the predictions for the rear part of the scour hole and the downstream scour profile are better than those using the $k - \varepsilon$ model. In general, the $k - \omega$ model was selected for further scour simulations.

**Figure 7.** Comparison of the scour profile between the experimental result of Mao [7], the numerical result of Yin et al. [19] using $k - \varepsilon$ model, the numerical result of Lee et al. [24] and the present numerical result using $k - \omega$ model during 2D scour beneath a stationary pipeline.

4.2. Scour of Stationary Pipelines

Figure 8 shows the scour profiles of the stationary pipeline from 1 s to 5 s. The onset of scour beneath the pipeline is clearly illustrated. First, the gap between the pipeline and the seabed is opened by the incoming flow. Then, the scour rapidly develops as a high-velocity gradient in the gap is formed. After the onset of scour, the scour hole beneath the pipeline is formed gradually. Figure 9 shows the seabed profiles during the 2D scour process beneath a stationary pipeline from 10 s to 40 s. Under a high shear velocity and a large Shields number, the sediment on the seabed is rapidly mobilized. As time progresses, the scour depth gradually increases, and the sediment dune behind the pipeline grows and gradually moves downstream.

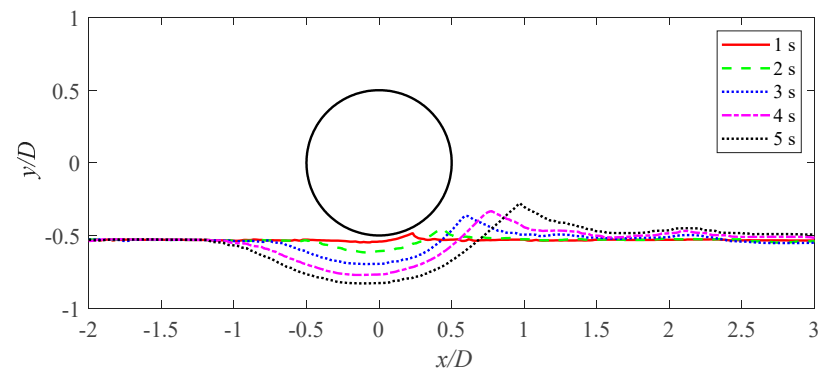


Figure 8. Scour profiles of the stationary pipeline at 1 s to 5 s.

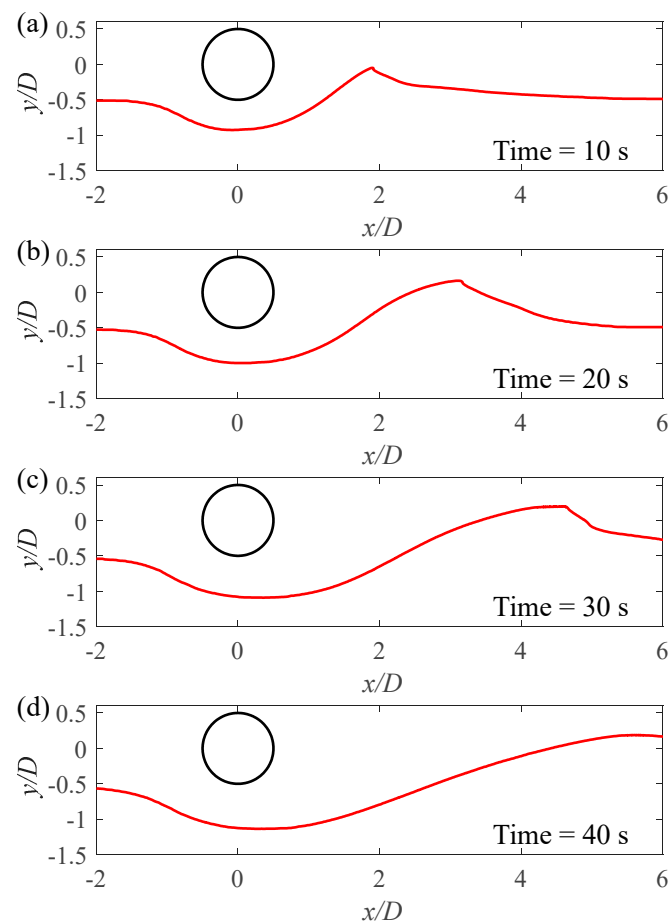


Figure 9. Seabed profiles during the 2D scour beneath a stationary pipeline: (a) 10 s (b) 20 s (c) 30 s (d) 40 s.

Figure 10 presents the velocity and vorticity contours during the scour beneath a stationary pipeline under a steady current. The high-velocity jet beneath the pipeline persistently erodes the bed, creating a scour hole that gradually extends downstream. In the early stage of 10–20 s, the bed remains relatively flat, with a locally intensified flow concentrated under the pipeline, and scour mainly occurs at the front edge and bottom region. In the later stage of 30–40 s, the scour hole becomes deeper. Vortex shedding becomes significant in the wake region. The vortices increase the local velocity and bed shear stress, which further deepens and extends the scour hole downstream. This also results in noticeable seabed undulations.

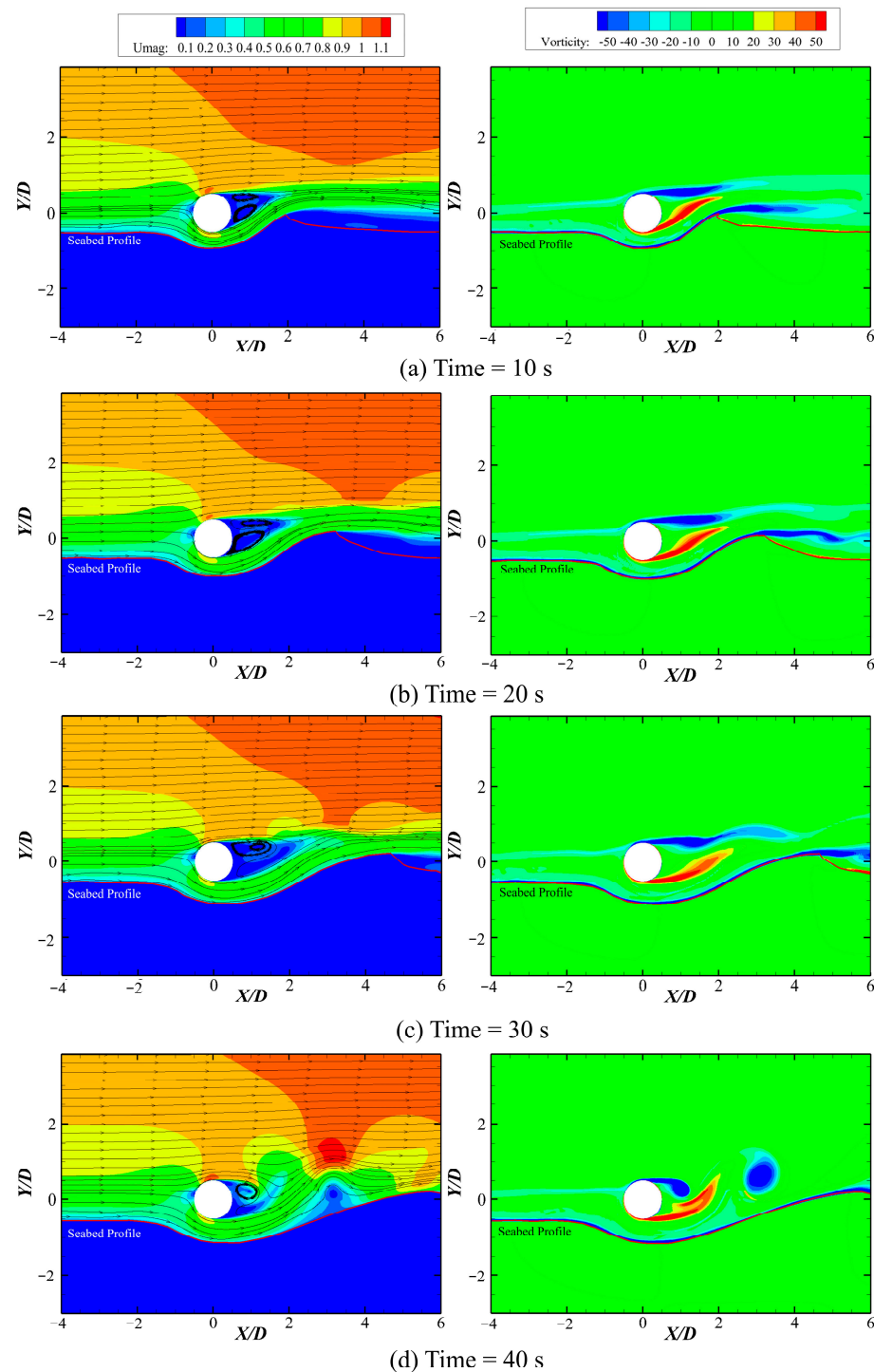


Figure 10. Velocity and Vorticity contours during the 2D scour beneath a stationary pipeline.

Figure 11 shows the drag and lift coefficients of the 2D stationary pipeline during the scour process. It can be observed that vortex shedding induces significant fluctuations in both the drag and lift forces. The vertical lift fluctuations are likely to excite structural vibrations of the pipeline, potentially developing into VIV. Such near-bed VIV could further change the seabed profile, which will be discussed in Section 4.2. The vortex shedding frequency is approximately 3.4884 Hz.

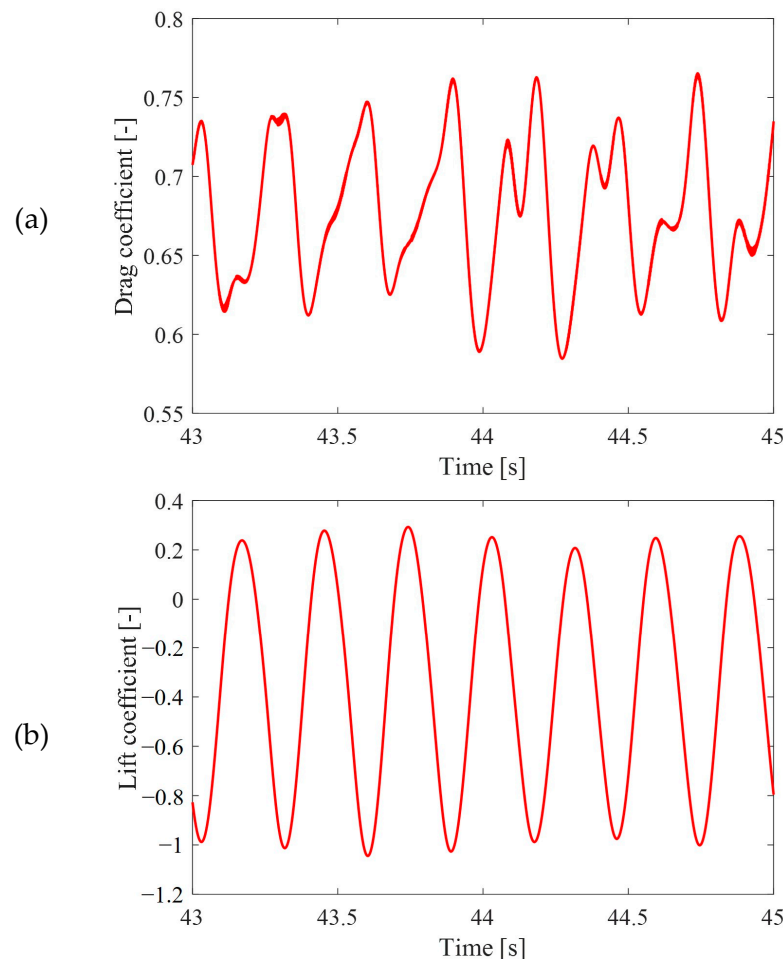


Figure 11. Drag and lift coefficients of the stationary pipeline during the 2D scour process. (a) Drag coefficient; (b) Lift coefficient.

4.3. Scour of Moving Pipelines

4.3.1. Scour of Pipeline 1

Figure 12 shows the vertical displacement and velocity of Pipeline 1 during the scour process from 40 s to 41.6 s, where V_c is the incoming velocity at the level of the pipeline centre calculated using Equation (23). The simulation time of this moving case is only 1.6 s, much shorter compared with the stationary case in Section 4.1. However, there are around 6 periods of the VIV process observed in this case. The average VIV period is found to be approximately 0.21 s, closely matching the period derived from the natural frequency in water in Table 2. The vibration amplitudes of displacement and velocity increase gradually with time. One of the reasons is that the response is still in the initial transient stage, and the pipeline has not yet reached a fully developed steady-state vibration. The degradation of the seabed due to pipeline vibration motion may be responsible for the amplification of the amplitudes.

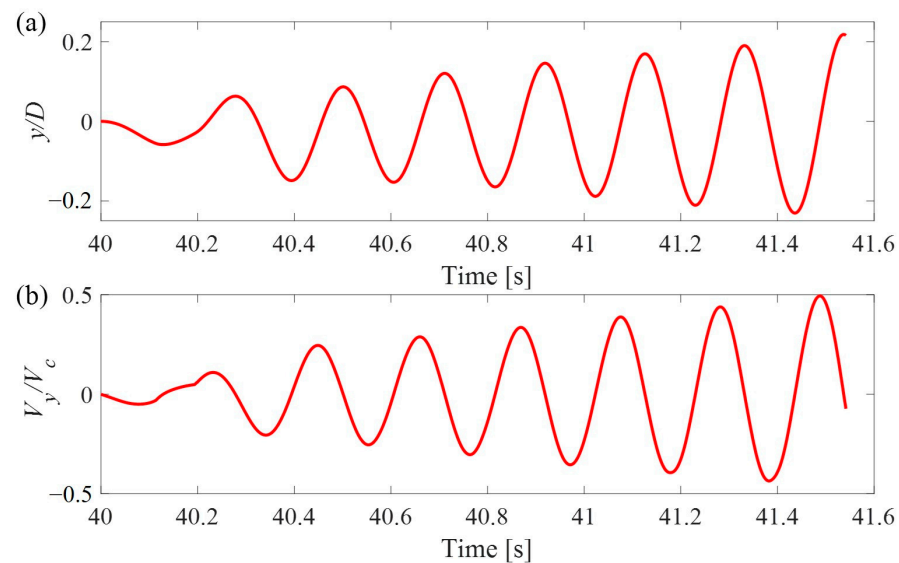


Figure 12. (a) Vertical displacement and (b) velocity of Pipeline 1.

Figure 13 shows the seabed profiles at the instants when Pipeline 1 reaches its minimum clearance from the seabed. The pipeline in the figure is shown at its initial position. Every time the pipeline approaches the seabed, the sediment right behind the pipeline is rapidly entrained by the accelerated flow in the gap as the gap becomes small. A significant sand dune is formed and grows as the pipeline repeatedly moves toward the seabed during the VIV process. Figure 14 shows the velocity and vorticity contours of Pipeline 1's scour at one of these instants, 41.24 s. A highly concentrated vorticity region is observed in the gap between the pipeline and the sand dune. This is attributed to the substantial velocity difference between the low-speed flow near the pipeline surface and the accelerated flow adjacent to the sand dune, which produces a strong shear layer in the region in between. This intense vorticity region also plays a dominant role in the development of the sand dune. Figure 15 shows the velocity and vorticity contours of Pipeline 1's scour at 41.34 s, corresponding to an instant when the pipeline reaches its maximum distance from the seabed. At this moment, vortex shedding happens at the upper part of the pipeline. A comparison of the vortex structures in Figures 14b and 15b indicates that the vortex shedding above the pipeline develops more freely, while that beneath the pipeline does not. The vortex directly hits the sand dune and then vanishes in the shear layer near the seabed, which is the main directly for the asymmetry of the vortex shedding above and beneath the pipeline.

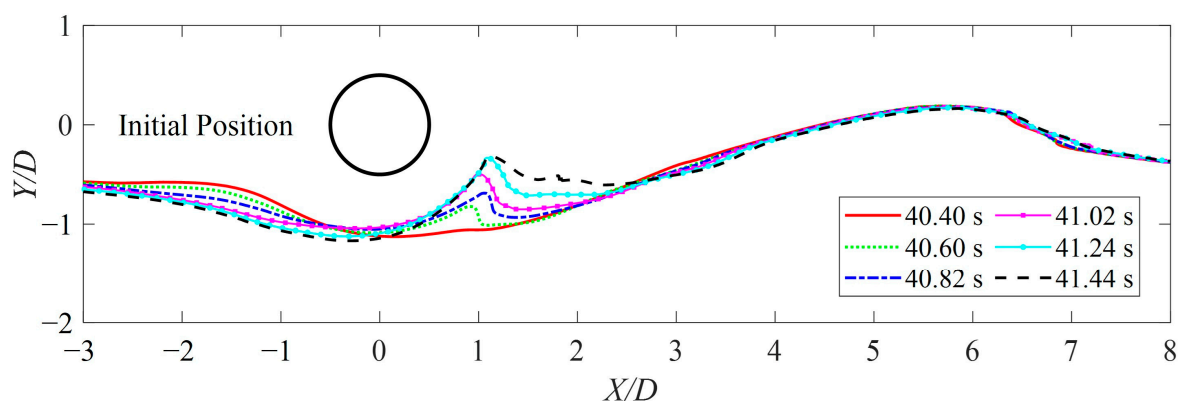


Figure 13. Seabed profiles at the instant when Pipeline 1 reaches its minimum clearance from the seabed.

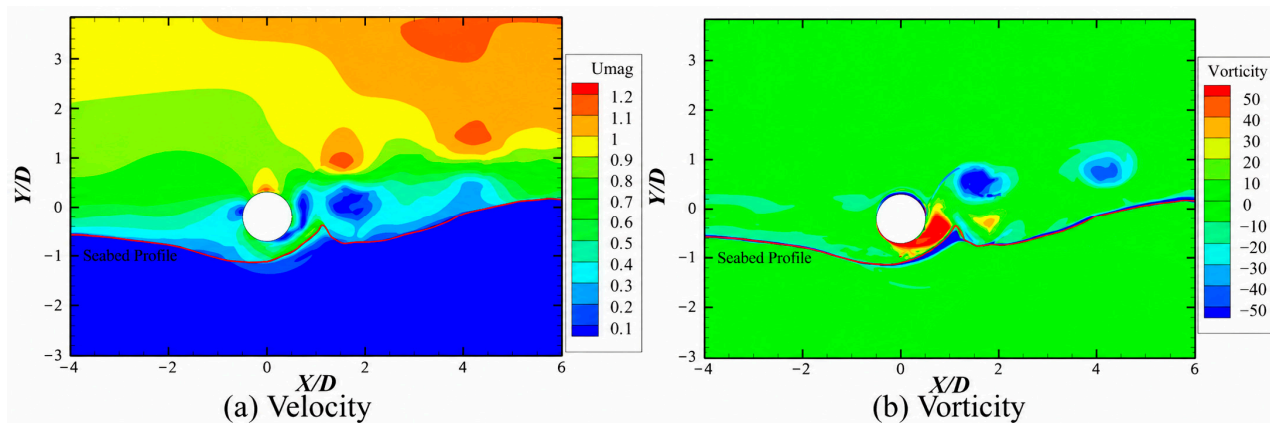


Figure 14. (a) Velocity and (b) vorticity contours of Pipeline 1's scour at 41.24 s.

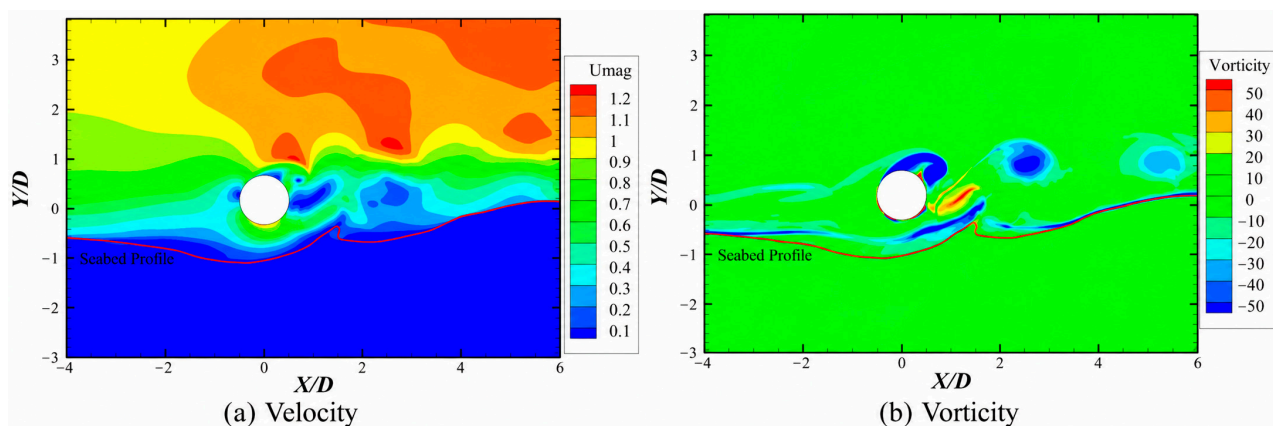


Figure 15. (a) Velocity and (b) vorticity contours of Pipeline 1's scour at 41.34 s.

4.3.2. Scour of Pipeline 2

Figure 16 shows the vertical displacement and velocity of Pipeline 2 during the scour from 40 s to 41.78 s. The vibrations of the pipeline become stable after the first two periods. The VIV period is observed to be 0.2944 s, while the steady amplitude of the vertical displacement is recorded as 0.346D. The VIV period is found to be shorter than that obtained from the natural period of the pipeline in water (0.353 s), as shown in Table 3. The amplitude is much greater than that of Pipeline 1, as a softer pipeline section is adopted. This higher amplitude will induce more interaction between the pipeline's VIV and the scour beneath it, as can be seen in Figure 17, where the seabed profiles are shown at the instants when Pipeline 2 reaches its minimum clearance from the seabed. The sand dune behind the pipeline is more significant compared with that of Pipeline 1. This suggests that intense VIV of the pipeline can lead to rapid evolution of the seabed profile beneath the pipeline.

Figure 18 shows the velocity and vorticity contours of Pipeline 2's scour at 41 s, which is one of the instants at which Pipeline 2 reaches its minimum clearance from the seabed. As the sand dune grows higher than the top of the pipeline, the flow beneath the pipeline is fully blocked. Within the gap between the pipeline and the sand dune, the flow velocity decreases substantially, and the vorticity is greatly suppressed. Figure 19 shows the velocity and vorticity contours of Pipeline 2's scour at 41.16 s, where the pipeline reaches its highest position. As the pipeline–seabed gap increases rapidly after the pipeline moves upward, the flow velocity beneath the pipeline rises again. This high-velocity flow progressively erodes and flattens the sand dune. At this instant, regular vortex shedding is also observed above the pipeline.

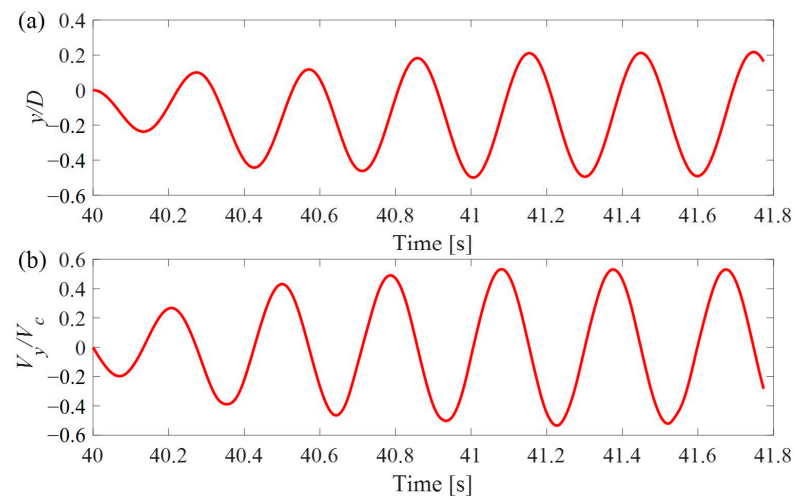


Figure 16. (a) Vertical displacement and (b) velocity of Pipeline 2.

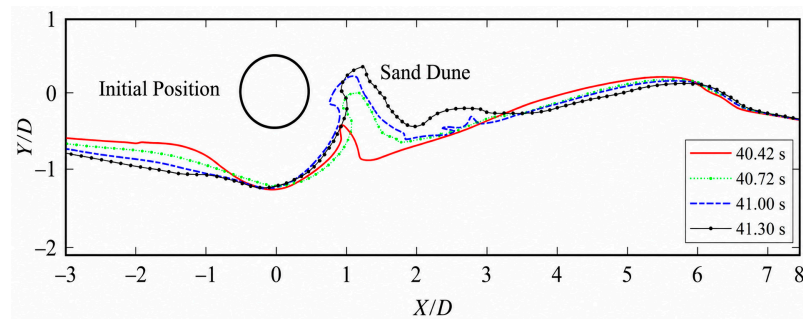


Figure 17. Seabed profiles at the instant when Pipeline 2 reaches its minimum clearance from the seabed.

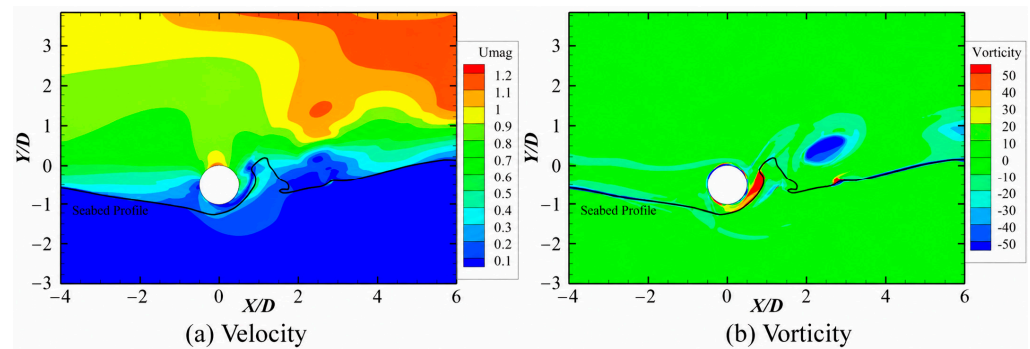


Figure 18. Velocity and vorticity contours of Pipeline 2's scour at 41 s.

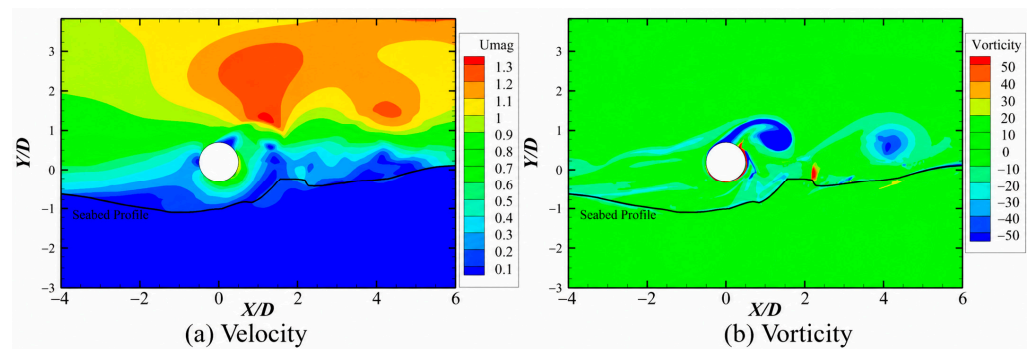


Figure 19. Velocity and vorticity contours of Pipeline 2's scour at 41.16 s.

4.3.3. Remark

The above cases in Sections 4.3.1 and 4.3.2 clearly reveal the interaction between pipeline's VIV and its scour process. It is interesting to compare the VIV amplitude response of the pipeline during the scour process with that observed in the absence of seabed scour. Figure 20 shows the amplitude ratio of the pipeline's VIV under various true reduced velocities V_r , where the amplitude ratio $A_0^* = A_0/D$, $V_r = U_\infty / (Df'_{0,true})$, A_0 is the amplitude of the pipeline's VIV, U_∞ is the incoming velocity and $f'_{0,true}$ is 0.21 s and 0.2944 s as observed from the numerical results in Sections 4.3.1 and 4.3.2. Pipeline 1 has a mass ratio of 1.253. The experimental results with a mass ratio of 1.2 from Govardhan and Williamson [25] are selected for comparison. Pipeline 2 has a mass ratio of 2.165. The numerical results with a mass ratio of 2.4 from Anwar et al. [26] are selected for comparison. The specific range of the amplitude ratio with the true reduced velocity is given because of the changing amplitude in the time domain simulations and the varying incoming velocity as the pipeline is in the boundary layer of the incoming flow. For the first case, the amplitude ratio is slightly higher than the experimental results. For the second case, the amplitude ratio is significantly lower than that of Anwar et al. [26]. It remains unclear why the amplitude ratio becomes larger in the first case. However, when the interaction between the pipeline VIV and the scour process becomes significant, the VIV response of the pipeline is substantially suppressed, as observed in the second case.

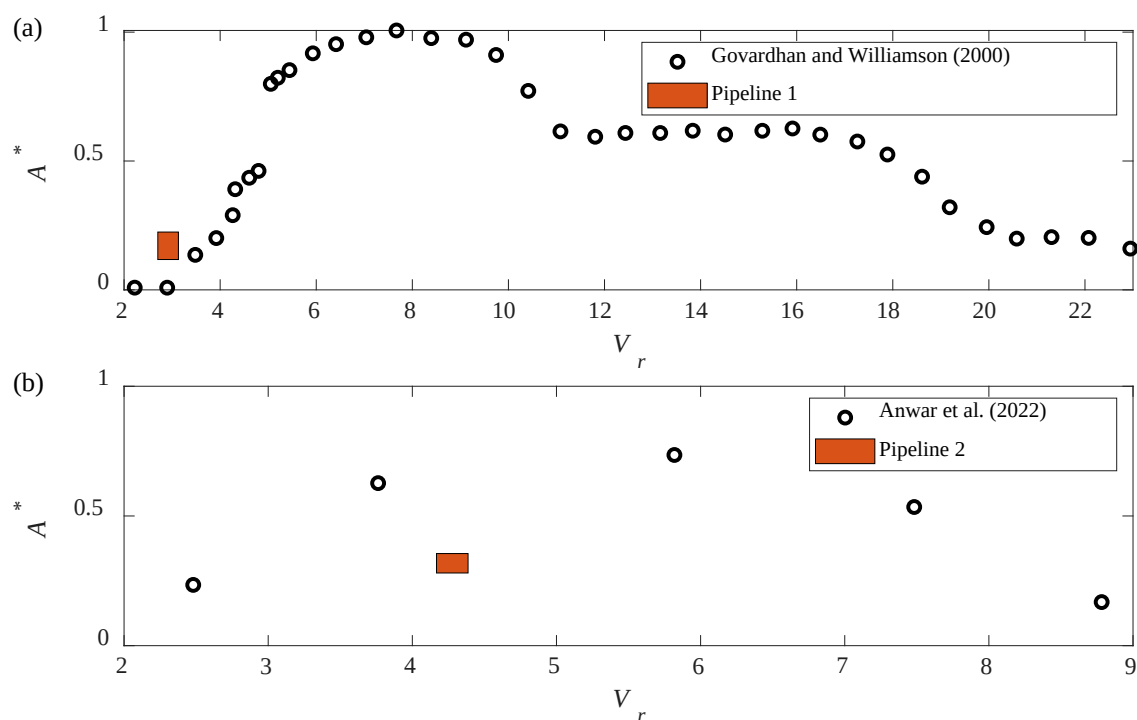


Figure 20. Amplitude ratio of the pipeline's VIV under various true reduced velocity: (a) Mass ratio = 1.2; (b) Mass ratio = 2.4. The results of Govardhan and Williamson (2000) [25] and Anwar et al. (2022) [26] are given for comparisons.

5. Conclusions

This study investigated the coupled VIV and scour of a free-span pipeline under steady current conditions using a CFD-based fluid–structure interaction approach. A dynamic mesh technique was incorporated into SedFoam to simulate the simultaneous evolution of pipeline vibration and seabed morphology, while the pipeline was modelled as a single-degree-of-freedom system with a vertical spring and a concentrated mass.

The numerical results demonstrate that pipeline VIV and local scour are strongly coupled processes. Repeated downward motion of the vibrating pipeline continuously modifies the seabed profile beneath the pipeline, leading to the formation of a sand dune within the scour hole. This morphological evolution suppresses near-bed vortex shedding, weakens the hydrodynamic excitation acting on the pipeline, and consequently reduces the VIV amplitude. These results indicate that the evolving seabed provides an important self-regulating mechanism that alters both the flow field and the structural response, highlighting the necessity of accounting for seabed evolution in VIV analyses.

The proposed coupled CFD framework provides an effective tool for investigating the interaction between pipeline dynamics and seabed scour. The findings improve the fundamental understanding of VIV–scour coupling and provide a more realistic basis for predicting the long-term stability, fatigue performance, and integrity of free-span submarine pipelines in offshore engineering applications. It should be noted that the present study considers only the motion of the centre section of the pipeline free span. A comprehensive evaluation of the three-dimensional structural responses requires a more sophisticated fluid–structure interaction model that accounts for the entire pipeline. Future work will extend the present model to investigate more realistic coupled scenarios, including different initial gaps between the pipeline and the seabed, varying incoming shear velocities, and different free-span lengths.

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Abbreviations

The following abbreviations are used in this manuscript:

BC	Boundary conditions
CFD	Computational fluid dynamics
VIV	Vortex-induced vibration
2D	Two-dimensional
3D	Three-dimensional
6-DOF	Six-degree-of-freedom

References

1. Sumer, B.M.; Fredsøe, J. *The Mechanics of Scour in the Marine Environment*; World Scientific: Singapore, 2002.
2. Whitehouse, R. *Scour at Marine Structures: A Manual for Practical Applications*; Thomas Telford: London, UK, 1998.
3. Soulsby, R. *Dynamics of Marine Sands: A Manual for Practical Applications*; Thomas Telford: London, UK, 1997.
4. Sumer, B.M.; Truelsen, C.; Sichmann, T.; Fredsøe, J. Onset of scour below pipelines and self-burial. *Coast. Eng.* **2001**, *42*, 313–335. [[CrossRef](#)]

5. Fredsøe, J. Pipeline–seabed interaction. *J. Waterw. Port. Coast. Ocean. Eng.* **2016**, *142*, 03116002. [[CrossRef](#)]
6. Sumer, B.M. Flow-structure-seabed interactions in coastal and marine environments. *J. Hydraul. Res.* **2014**, *52*, 1–13. [[CrossRef](#)]
7. Mao, Y. *The Interaction Between a Pipeline and an Erodible Bed*; Series Paper No. 39; Institute of Hydrodynamics and Hydraulic Engineering, Technical University of Denmark: Lyngby, Denmark, 1986.
8. Sumer, B.M.; Mao, Y.; Fredsøe, J. Interaction between vibrating pipe and erodible bed. *J. Waterw. Port. Coast. Ocean. Eng.* **1988**, *114*, 81–92. [[CrossRef](#)]
9. Sumer, B.M.; Fredsøe, J. Onset of scour below a pipeline exposed to waves. In *Proceedings of the International Offshore and Polar Engineering Conference, Edinburgh, UK, 11–16 August 1991*; ISOPE: Golden, CO, USA, 1991.
10. Sui, T.; Yang, Q.; Yang, M.; Zhang, C.; Zheng, J.; Fuhrman, D.R. Clear-water span shoulder migration beneath pipelines in wave-plus-current conditions on a flat sea bed. *Ocean. Eng.* **2025**, *327*, 120922. [[CrossRef](#)]
11. Sui, T.; Yang, Y.; Yang, Z.; Zhang, C.; Zheng, J. Experimental study on the irregular wave-induced pore pressure of a sloping beach with cross-shore profile evolution. *Ocean. Eng.* **2025**, *324*, 120680. [[CrossRef](#)]
12. Liang, D.; Cheng, L.; Li, F. Numerical modeling of flow and scour below a pipeline in currents: Part II. *Scour Simulation. Coast. Eng.* **2005**, *52*, 43–62. [[CrossRef](#)]
13. Chauchat, J.; Cheng, Z.; Nagel, T.; Bonamy, C.; Hsu, T.-J. SedFoam-2.0: A 3-D two-phase flow numerical model for sediment transport. *Geosci. Model Dev.* **2017**, *10*, 4367–4392. [[CrossRef](#)]
14. Cheng, Z.; Hsu, T.-J.; Calantoni, J. SedFoam: A multi-dimensional Eulerian two-phase model for sediment transport and its application to momentary bed failure. *Coast. Eng.* **2017**, *119*, 32–50. [[CrossRef](#)]
15. Schiller, L.; Naumann, A. Über die grundlegenden berechnungen bei der schwerkrafthaftaufbereitung. *VDI Ztg.* **1933**, *77*, 318–320.
16. Ding, J.; Gidaspow, D. A bubbling fluidization model using kinetic theory of granular flow. *AIChE J.* **1990**, *36*, 523–538. [[CrossRef](#)]
17. Ergun, S. Fluid flow through packed columns. *Chem. Eng. Prog.* **1952**, *48*, 89–94.
18. Wen, C.; Yu, Y. Mechanics of fluidization. *Chem. Eng. Prog. Symp. Ser.* **1966**, *62*, 100.
19. Yin, G.; Cheng, Z.; Liu, S.; Ong, M.C. Numerical investigation of scour around subsea pipelines near the seabed. In *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering, Glasgow, UK, 9–14 June 2019*; ASME: New York, NY, USA, 2019; p. V001T01A005.
20. Huang, J.; Yin, G.; Ong, M.C.; Myrhaug, D.; Jia, X. Numerical investigation of scour beneath pipelines subjected to an oscillatory flow condition. *J. Mar. Sci. Eng.* **2021**, *9*, 1102. [[CrossRef](#)]
21. Huang, J.; Yin, G.; Ong, M.C.; Jia, X. Numerical investigation of scour beneath a subsea piggyback pipeline. In *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering, Virtual, Online, 3–7 August 2020*; ASME: New York, NY, USA, 2020; p. V06AT06A003.
22. Fraga, V.S.; Yin, G.; Ong, M.C.; Myrhaug, D. CFD investigation on scour beneath different configurations of piggyback pipelines under steady current flow. *Coast. Eng.* **2022**, *172*, 104060. [[CrossRef](#)]
23. Sumer, B.M.; Fredsøe, J. Scour below pipelines in waves. *J. Waterw. Port. Coast. Ocean. Eng.* **1990**, *116*, 307–323. [[CrossRef](#)]
24. Lee, C.H.; Low, Y.M.; Chiew, Y.M. Multidimensional rheology-based two-phase model for sediment transport and applications to sheet flow and pipeline scour. *Phys. Fluids* **2016**, *28*, 053305. [[CrossRef](#)]
25. Govardhan, R.; Williamson, C. Modes of vortex formation and frequency response of a freely vibrating cylinder. *J. Fluid Mech.* **2000**, *420*, 85–130. [[CrossRef](#)]
26. Anwar, M.U.; Lashin, M.; Khan, N.B.; Munir, A.; Jameel, M.; Muhammad, R.; Guedri, K.; Galal, A.M. Effect of variation in the mass ratio on vortex-induced vibration of a circular cylinder in crossflow direction at Reynold number= 104: A numerical study using RANS model. *J. Mar. Sci. Eng.* **2022**, *10*, 1126. [[CrossRef](#)]

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