

# Numerical Investigation of Hydrodynamic Characteristics During Water Exit of a Cylindrical Structure Subjected to Wave–Current Coupled Effects

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Received: 08 April 2025 / Accepted: 12 May 2025  
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## Abstract

The synergistic interaction of underwater ocean currents and surface wave dynamics governs the hydrodynamic behavior of structures in practical marine environments. However, research on their kinematic characteristics under composite hydrodynamic loading across varying sea state conditions is lacking. To elucidate the effects of wave–current coupling on the motion characteristics of structures, this study simulates the motion processes of a cylindrical structure in diverse sea state conditions. Changes in the structure’s attitude, velocity, and trajectory height are considered. Through the analysis of the pressure and velocity fields during the movement of the cylindrical structure, the hydrodynamic characteristics of the structure’s surface emergence are further systematically investigated. The results demonstrate the minimal fluid–structure interaction influence on cylindrical structure dynamics during the underwater phase. Notably, the horizontal motion characteristics exhibit intensified variations with the increases in wave levels, which reveals a strong coupling between near-surface dynamics and wave. Further investigation of the cylindrical structure’s motion characteristics during water exit at various wave phases under identical sea state conditions reveals the emergence of the cylindrical structure at the wave crest, and its lateral displacement is considerably larger than when it emerges at the wave trough. In addition, the emergence of the cylindrical structure at corresponding opposite phases reverses the cylindrical structure’s deflection direction. Under the combined effect of wave–current coupling, the cylindrical structure’s lateral displacement in the negative direction of the x-axis increases with current velocity enhancement during the underwater movement phase, and it is accompanied by a corresponding reduction in the deflection angle between the cylindrical structure body and free surface. Furthermore, the hydrodynamic effect of varying sea states during water exit induces a pronounced lateral motion in the postemergence trajectory and concurrently causes a substantial reduction in vertical altitude. Investigation of the cylindrical structure’s dynamic behavior under the combined influence of multiple complex launch conditions can provide a scientific reference to ensure the safety of underwater cylindrical structure launches.

**Keywords** Structure water exit; Wave level; Wave phase; Wave–current coupling

## 1 Introduction

The trans-medium motion of a structure involves a series of complex processes, including underwater motion, water-to-air trans-phase, and airborne motion (Breton et al., 2020;

Dayton et al., 2020). During the water-exit phase, the density and viscosity of water are more than 800 and 60 times those of air, respectively. This condition greatly affects the stability of a structure’s motion trajectory and the accuracy of its landing point (Zhao et al., 2015; Zhang and Tarn, 2003). Therefore, the water-exit process of structures has attracted notable attention from scholars, which led to extensive research on theoretical models, experimental methods, and numerical simulations (Zheng et al., 2024; Del Buono et al., 2021; Sui et al., 2024). Von. Karman (1929) proposed a computational model for the effect of objects on a free liquid surface. Greenhow (1988) conducted numerical simulations on the water-exit problem. The numerical method he used allowed the water exit of an object and its continued movement to a location distant from the free surface after the water exit phase. Nguyen et al. (2021) studied the effect of impact velocity on the motion characteristics of an oblique cylinder. The density of the cylinder had a crucial influence on its dynamic characteristics. The circular cylinder caused deformation of the free surface

## Article Highlights

- A 2D coupled fluid-structure interaction model is developed for structure water-exit dynamics.
- Wave-induced attitude perturbations are quantified under wave level 3–5 conditions.
- Critical velocity thresholds for motion stability are identified via parametric analysis.

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during the water-exit process, which revealed the dynamic changes in the multiphase fluid interface and validated the reliability of the two-dimensional (2D) simulation (Zhang et al., 2022a). Yun et al. (2025) studied the relationship between the jump height of a vehicle during water exit and its release depth. The vertical release followed a linear pattern, while the horizontal release exhibited irregular changes due to the influence of the wake vortex. The computational fluid dynamics (CFD) method is used to study the flow characteristics during the water-exit process of high-speed cylinders, revealing the influence of the cylinder's initial velocity on pressure distribution and drag characteristics and provides important guidance for the improvement of motion stability in future studies (Zhang et al., 2022b; Sun et al., 2022).

Further development of research technology prompted several research on the motion of different structures. Hu et al. (2017) proposed a theoretical method for an unmanned submersible that can submerge into the water and fly in the air. A numerical approach was used to validate the motion model during the water-exit process. Through experimental and computational approaches, comparative studies demonstrated the geometric dependence of kinematic stability, where conical nose profiles exhibited greater resistance to more interference than conventional cylindrical configurations (Lu et al., 2022). Parametric analyses quantified trajectory sensitivity to initial angles and Froude number variations and identified critical thresholds for stable transition across the air–water interface (Zhuang et al., 2023). Boundary condition analyses confirmed that the minimum velocity requirement for reliable water exit exceeds 10.8 m/s under wave-interference conditions, with hydrodynamic cavitation patterns displaying morphology-dependent features in the shoulder region during vertical launches (Liu et al., 2023). The study of water exit and flight characteristics of folding wings introduced a new method for the prediction of water-to-air trans-phase, which provided a foundation for rapid design and motion control (Zhou et al., 2024; Sun et al., 2024). Innovative gas-phase lubrication systems were developed to minimize hydrodynamic drag through non-contact propulsion in underwater channels (Weiland et al., 2010). Based on experiments and machine learning, a study on the trans-phase hydrodynamic characteristics of multi-rotor hybrid air–water vehicles proposed a prediction method for the drag experienced during the water entry and exit process using data (Wei et al., 2022). By establishing a coupled water-exit motion model, a study investigated the effect of the initial angle on motion deflection and trans-phase stability (Wang et al., 2022; Tan et al., 2019). Although multiphysics modeling efforts overcame single-medium motion constraints through longitudinal dynamic formulations, which enabled repeated air–water transitions below critical Froude numbers (Ma et al., 2020), many scholars have studied the unique cavitation phenomena during the

water entry and exit process, which revealed the characteristics of cavitation growth, detachment, and collapse. These findings provide important insights into the design of submersible vehicles and structures (Li et al., 2023; Nguyen et al., 2022; Chen et al., 2020). The research on the influence of shoulder vent cavities on the hydrodynamic characteristics of water-exiting objects revealed that they can reduce drag, increase motion speed, and improve the stability of a structure during water exit (Qu et al., 2024).

With advancements in CFD, numerical simulation methodologies employing Fluent software have adopted continuity equations and Navier–Stokes (N–S) formulations to model incompressible fluid–structure interactions. Dynamic mesh refinement techniques enabled high-fidelity wave generation modeling and achieved a spatial resolution below 0.1 $\lambda$  for wave–current coupling simulations (Kim et al., 2016; Martínez-Ferrer et al., 2018). A numerical method of wave generation using physical paddle motion was used as a basis to establish a high-precision and stable wave simulation model (Liu et al., 2018). Comparative simulations using 2D/3D numerical wave tanks demonstrated that under wind-wave–current coupling conditions, wave-phase velocity increased by 12%–18% relative to that of pure wave scenarios, which correlated with wavelength stretching and 23% wave height attenuation (Wei, 2012). A study on the trans-phase motion of structures in a wave environment analyzed the hydrodynamic characteristics during the water-exit process, and it provided technical support for the design of transport machines (Li et al., 2024). By employing large eddy simulation with the volume of fluid (VOF) multiphase approach and Kunz cavitation model, this study elucidates the dynamic mechanisms of supercavitation evolution in axisymmetric vehicles under variable-speed motion. These findings establish foundational metrics for the development of transient cavitation dynamic-informed control strategies for variable-speed underwater systems (Xu et al., 2024). Close-spaced underwater projectiles exhibit severe cavity fragmentation from wake interference but retain their motion stability, which can be used to establish pivotal guidelines for clustered launch systems via coupled simulations and experiments (Gao et al., 2025). A validated Eulerian multiphase finite-element method revealed asymmetric cavity dynamics in high-speed water entry: free surface uplift inhibits expansion, and closure jets and deep-closure necking accelerate contraction through pressure redistribution (Liu et al., 2024). By integrating a sensor array with deep-learning algorithms and optimizing sensor layout techniques, Zhang et al. (2024) attain real-time precise prediction of shear stress on marine structures without prior knowledge of internal solitary wave parameters. Du et al. (2024) combine convolutional neural networks with soap film tunnel-based flow-field visualization technology to achieve the intelligent recognition of wake types generated by rotating triangular structures.

Theoretical methods and CFD have consistently been the main research approaches for the investigation of water-to-air trans-phase processes, particularly for cavitation phenomena and emergence characteristics of underwater structures. Previous studies have mostly focused on the motion posture, flow field evolution, and changes in posture during the emergence of structures in underwater environments. The effect of currents is mainly concentrated in the underwater phase, and that of waves is most prominent near the water surface. The structure's attitude, flight speed, and trajectory height change. However, some gaps have been observed in the studies on cylindrical structures' motion characteristics under the combined influence of various sea state environments. Current research inadequately addresses the multiscale hydrodynamic interactions governing marine structure posture evolution during water emergence under different wave level conditions, particularly the dynamic fluid–structure interactions during critical phase transitions. Although many scholars have studied the trans-medium motion of structures, most of the research focuses on cavitation phenomena and the effect of waves on structure trajectory. How complex ocean current disturbances affect structure underwater motion can still be extensively explored. This study uses the CFD software Fluent combined with dynamic grid technology to perform numerical simulations on the hydrodynamic characteristics of a cylindrical structure under various wave levels, emergence phases, and wave–current coupling effects. It also provides a detailed analysis of the structure emergence process and offers scientific references for the safety of underwater structure movement.

This work employs numerical simulation methods to investigate the coupled effects of wave level, water-exit phase, and wave–current interactions on the motion characteristics of structures during water-exit processes. The research framework is organized as follows: Chapter 1 identifies critical gaps in the multiphysics modeling of marine structure water–exit dynamics, with an emphasis on unresolved phase-dependent wave–current interactions that necessitate systematic investigation. Chapters 2–3 establish a 6-degree-of-freedom  $k$ - $\omega$  SST (Shear-Stress Transport)-wave–current computational framework, which was rigorously validated for multiregime phase transition fidelity. Chapter 4 introduces the design scheme of this research, including the model dimensions and parameter settings during simulation. Chapter 5 systematically investigates synergistic parameters (wave levels/wave-phase/wave–current coupling) on structure kinematic signatures, with quantitative trajectory comparisons conducted with multiphysics flow-field visualizations for analysis. Chapter 6 synthesizes cylindrical structure dynamic regime characterization through computational models, which establishes quantifiable design principles for marine cylindrical structure operations under coupled wave–current conditions.

## 2 Numerical method

### 2.1 Water-exit calculation theory

The emergence of a cylindrical structure spans the gas and liquid phases. To handle the relationship between these media, this study employs the VOF method to capture the free surface motion. The continuity equation, N–S equations, motion equations, and the SST  $k$ - $\omega$  turbulence model are used to solve the emergence process. The basic equations for numerical simulation are expressed as follows.

Continuity Equation:

$$\nabla \cdot \mathbf{u} = 0 \quad (1)$$

where  $\mathbf{u}$  denotes the fluid velocity.

N–S Equation:

$$\frac{D\mathbf{u}}{Dt} = \mathbf{f} - \frac{1}{\rho} \frac{\partial p}{\partial \mathbf{x}} + \frac{\mu}{\rho} \frac{\partial}{\partial \mathbf{x}} \left( \frac{\partial \mathbf{u}}{\partial \mathbf{y}} \right) \quad (2)$$

where  $p$  refers to the pressure,  $(x, y)$  denotes the spatial coordinate,  $\frac{D\mathbf{u}}{Dt}$  indicates the acceleration of fluid particles, and  $\mathbf{f}$  corresponds to the body force (or external force). The term  $\frac{1}{\rho} \frac{\partial p}{\partial \mathbf{x}}$  represents the pressure gradient force, and  $\frac{\mu}{\rho} \frac{\partial}{\partial \mathbf{x}} \left( \frac{\partial \mathbf{u}}{\partial \mathbf{y}} \right)$  is the viscous force term, where  $\mu$  stands for the dynamic viscosity coefficient of the fluid.

SST  $k$ - $\omega$  Turbulence Model Transport Equations:

$$\begin{aligned} \frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k \mathbf{u})}{\partial \mathbf{x}} &= \frac{\partial}{\partial \mathbf{y}} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial \mathbf{y}} \right] + G_k - \rho \varepsilon \quad (3) \\ \frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon \mathbf{u})}{\partial \mathbf{x}} &= \frac{\partial}{\partial \mathbf{y}} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial \mathbf{y}} \right] + \\ &\quad \rho C_1 E \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} \quad (4) \end{aligned}$$

where  $\sigma_k = 1.0$ ,  $\sigma_\varepsilon = 1.2$ ,  $C_2 = 1.9$ ,  $C_1 = \max[0.43, \eta/(\eta + 5)]$ ,  $\eta = (2E_{ij} \cdot E_{ij})^{1/2} \frac{k}{\varepsilon}$ ,  $E_{ij} = \frac{1}{2} \left( \frac{\partial \mathbf{u}}{\partial \mathbf{x}} + \frac{\partial \mathbf{u}}{\partial \mathbf{y}} \right)$ .

For an accurate description of the motion process of the object, the following motion equations are used to solve for the cylindrical structure's movement:

Translation Motion Equations:

$$m \frac{du}{dt} = F_t \cos(\theta) - F_{Dx} + F_{Ax} \quad (5)$$

$$m \frac{dv}{dt} = F_t \sin(\theta) - F_{Dy} + F_{Ay} + F_b - mg \quad (6)$$

Rotational Motion Equation:

$$I \frac{dv}{dt} = M \quad (7)$$

where  $m$  and  $I$  represent the mass and moment of inertia, respectively.  $u$  and  $\omega$  denote the linear and angular velocities, respectively.  $F_t$  refers to the thrust provided to the cylindrical structure during its motion, and  $F_{Dx}$  and  $F_{Dy}$  indicate the drag forces acting on the cylindrical structure in the horizontal and vertical directions, respectively.  $F_{Ax}$  and  $F_{Ay}$  mean the air resistance forces acting on the cylindrical structure in the horizontal and vertical directions, respectively.  $F_b$  refers to the buoyant force acting on the cylindrical structure's center of mass, and  $\theta$  and  $M$  are the cylindrical structure's pitch angle and moment, respectively.

In the VOF model, the fluid in each computational grid is defined by the volume fraction of each phase.

$$\begin{cases} \alpha_1 = 1 & \text{indicates that the phase is water} \\ \alpha_2 = 0 & \text{indicates that the phase is air} \\ 0 < \alpha < 1 & \text{indicates the region is the interface} \\ & \text{between water and air} \end{cases}$$

The fluid density and dynamic viscosity are directly mixed based on the phase volume fractions. The mixed density and dynamic viscosity are computed as follows:

$$\rho = \alpha \rho_w + (1 - \alpha) \rho_a \quad (8)$$

$$\mu = \alpha \mu_w + (1 - \alpha) \mu_a \quad (9)$$

where  $\rho_w$  and  $\rho_a$  denote the liquid and air densities, respectively, in  $\text{kg/m}^3$ .  $\mu_w$  and  $\mu_a$  are the dynamic viscosities of the liquid and air, respectively, in  $\text{Pa}\cdot\text{s}$ .

Dynamic mesh technology is employed during calculations, with a spring-based smoothing model and a local grid reconstruction model used to prevent excessively distorted grids during the computation, which can otherwise affect the accuracy of results.

## 2.2 Wave-generation calculation theory

The basic idea of boundary wave generation is to define fluid motion at the fluid velocity inlet boundary. Fluent is customized through its user-defined function (UDF) capability, which allows for secondary development. Through the use of the velocity field function, which corresponds to the second-order Stokes wave, the wave height equation, and macros provided by Fluent, a C language program is created. This program generates UDF files for the fluid velocity and volume fraction at the wave-generating bound-

ary, which are then linked to Fluent for calculation to ultimately achieve boundary wave generation.

To simulate the second-order Stokes wave, we define the fluid velocity at the inlet boundary based on the velocity field corresponding to the second-order Stokes wave. The coordinate value of the velocity inlet boundary is set as  $x = 0$ , and the function form of the velocity field of the second-order Stokes wave at  $x = 0$  constitutes the wave-generation function in the water phase:

$$\begin{aligned} u(y, t) &= \frac{\pi H}{T} \frac{\cosh k(y+d)}{\sinh kd} \cos(-\omega t) + \\ &\quad 0.75 \frac{\pi H}{T} \frac{\cosh 2k(y+d)}{\sinh^4 kd} \cos 2(-\omega t) \\ v(y, t) &= \frac{\pi H}{T} \frac{\sinh k(y+d)}{\sinh kd} \sin(-\omega t) + \\ &\quad 0.75 \frac{\pi H}{T} \frac{\sinh 2k(y+d)}{\sinh^4 kd} \sin 2(-\omega t) \end{aligned} \quad (10)$$

where  $T$ ,  $L$ ,  $H$  and  $D$  represent the wave period, wavelength, wave height, and water depth, respectively.  $k$  is the wave number, given by  $k = 2\pi/L$ ,  $\omega$  is the angular frequency of the wave, given by  $\omega = 2\pi/T$ .

As the velocity inlet includes the air and water phases, the free surface at the interface between the air and water phases changes continuously over time and position during wave-motion simulation. Based on the VOF method for free surface tracking, the wave surface equation at the interface between the two phases at the velocity inlet is defined:

$$\eta(t) = \frac{H}{2} \cos(-\omega t) + \frac{\pi H^2}{8L} \frac{\cosh kd}{\sinh^3 kd} \cosh 2(-\omega t) (\cosh 2kd + 2) \quad (11)$$

## 3 Validation

### 3.1 Structural water-exit validation

To validate the accuracy of the selected model in simulating the water-exit process of a structure, this section employs the horizontal cylinder water-exit experiment conducted by Greenhow (1988) under constant force for comparative verification. At the initial moment of the experiment, a horizontal cylinder with a diameter  $D = 0.11$  m is stationary at the bottom of the water tank. After commencing the experiment, the cylinder undergoes water-exit motion under the influence of a constant upward thrust. Figure 1(a) shows the 2D numerical water tank (with a size of  $0.6 \text{ m} \times 0.6 \text{ m}$  and with a water depth of  $0.3 \text{ m}$ ) established for the numerical simulation based on the experimental setup. The boundary of the horizontal cylinder is set

as a no-slip wall, and the upper boundary of the tank is set as a pressure outlet, with the left and right boundaries also set as no-slip walls. The numerical simulation results exhibit a strong agreement with experimental measurements (Figure 1(b)). The displacement–time curve of the cylinder motion obtained through numerical simulations demonstrates a close alignment with experimental data over time. This quantitative validation confirms the accuracy of the numerical model developed in this work for the simulation of the water-exit dynamics of cylindrical structures.

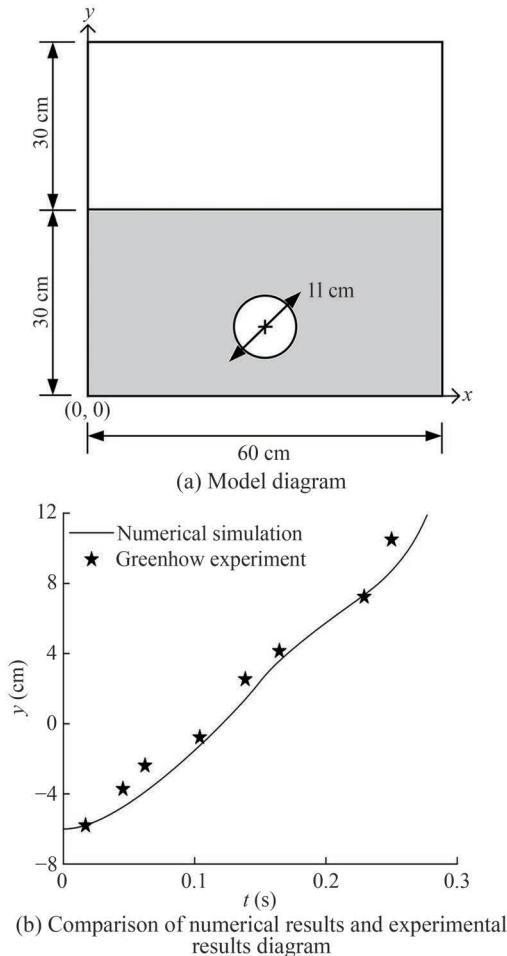


**Figure 1** Comparison of structural water-exit verification results

Figure 2 illustrates the free surface variations obtained from numerical simulations at various time instants corresponding to the experiments. During the initial stage of the cylinder's motion, the cylinder gradually moves upward, which causes the water above it to bulge and form a layer of water covering its upper surface as the cylinder continues to ascend, as shown in Figures 2(a)–(c). As the cylinder continues its ascent, the water above the cylinder flows downward around the cylinder, which creates a depression in the free surface on both of its sides. Some of the fluid remains trapped on the cylinder surface and continues to

adhere to the surface after the cylinder exits the water (Figures 2(d)–(f)). The numerical methodology adopted in this study demonstrates robust capability in capturing intricate free surface evolution during cylindrical water-exit processes.

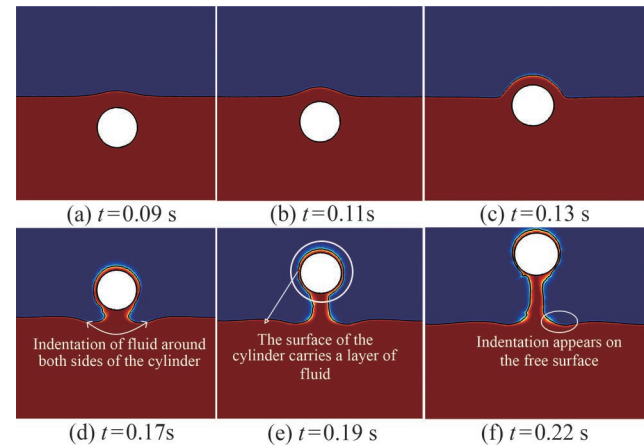


**Figure 2** Structural water exit motion process

### 3.2 Numerical simulation and validation of waves

A 2D numerical water tank geometric model incorporating critical design parameters for cylindrical structure motion analysis is established. The 2D computational domain is set to  $80 \text{ m} \times 70 \text{ m}$  (length  $\times$  width), with a static water depth of  $D = 30 \text{ m}$  (Figure 3). The domain is stratified into air and water phases, with the following boundary conditions: The left boundary serves as a velocity inlet for wave generation, the right and top boundaries act as pressure outlets with hydrostatic pressure correction, and the bottom boundary is a no-slip wall. The VOF model is implemented with an open-channel flow formulation to capture the gas–liquid interface dynamics. Table 1 summarizes the physical properties of the two phases. The velocity–inlet wave generation method is employed, where the water body at the inlet boundary undergoes periodic variations based on the wave-making function at the initial moment.

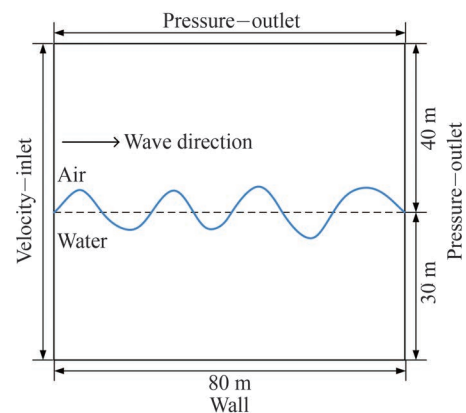


**Figure 3** Numerical water tank geometric model

Over time, the water body at the boundary continuously propagates forward and ultimately achieves wave motion and propagation throughout the entire computational domain.

**Table 1** Physical property parameters for flow-field calculation

| Water density<br>(kg/m <sup>3</sup> ) | Water dynamic<br>viscosity (kg/m·s) | Air density<br>(kg/m <sup>3</sup> ) | Air dynamic<br>viscosity (kg/m·s) |
|---------------------------------------|-------------------------------------|-------------------------------------|-----------------------------------|
| 998.2                                 | 0.001003                            | 1.225                               | $1.7894 \times 10^{-5}$           |

Wave-height meters are placed at  $x = 10$  m,  $x = 25$  m, and  $x = 55$  m to monitor wave-height variations. The results of numerical simulation are compared with theoretical values (Figure 4). Given the expansion of the computational domain, a certain attenuation exists between the simulated and theoretical values at the monitoring points where the waves arrive. However, the difference is small, and numerical waveforms are generally consistent with their theoretical counterparts at various positions along the tank. This finding indicates that the wave generation method used in the simulation can produce a stable wave field.

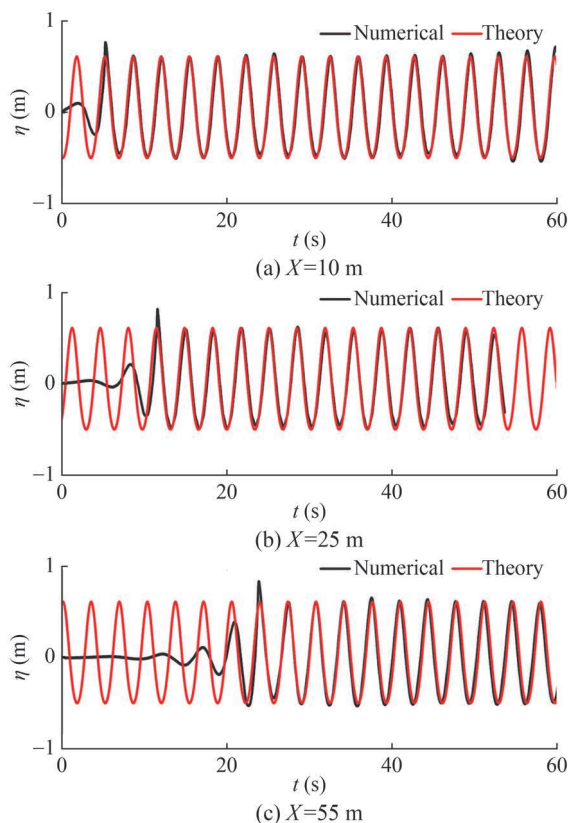


**Figure 4** Comparison of numerical and theoretical waveforms

## 4 Working condition design

### 4.1 Design of numerical simulation conditions

As shown in Figure 5(a), the dimensions of the computational domain are  $80 \text{ m} \times 70 \text{ m}$ . A multizone meshing strat-

egy is adopted to enhance the accuracy of the simulation. Specifically, a  $15 \text{ m} \times 60 \text{ m}$  region surrounding the model is discretized using unstructured grids with a cell size of  $0.1 \text{ m}$ , supplemented with global refinement. The remaining areas are meshed with a coarser resolution of  $1 \text{ m}$  (Figure 5(b)). The average skewness of the entire mesh quality is  $2.75 \times 10^{-2}$ , which satisfies the solution requirements for the turbulence model. Each case has a mesh count of approximately 180 000. For a sufficiently small time step and computational convergence accuracy, a time step size of  $1 \times 10^{-3}$  and 50 iterations per time step are selected after multiple iterations. These settings are implemented to ensure the accuracy of the grid division.

To improve the accuracy of numerical simulations, we set the upper and right boundaries of the model as pressure outlet conditions. The left boundary serves as a velocity inlet boundary, where the velocity varies based on specific wave conditions, and the remaining walls act as no-slip walls. Equations governing the cylindrical structure's phase transition dynamics are coded in C and integrated into Fluent via UDF. Figure 5(c) illustrates the numerical model, which depicts the cylindrical structure's water-exit motion. Here, the cylindrical structure's motion direction is defined horizontally to the right, with various time instants corresponding to the positional relationship between the cylindrical structure body and the free surface. The angle between the cylindrical structure body and the free surface is defined as  $\theta$ . Subsequent discussions will reference a deflection angle complementary to  $\theta$ . Table 2 details the specific settings used in Fluent. In subsequent analysis and discussion, displacement, velocity, and deflection angle are considered primary indicators for the quantitative assessment of the cylindrical structure's motion characteristics during the water-exit process. Displacement reflects the overall motion path and emergence extent of the cylindrical structure and serves as a key parameter in the evaluation of the water-exit performance. Horizontal and vertical velocities indicate the magnitude of hydrodynamic and inertial forces acting on the structure, which effectively captures the acceleration and deceleration trends caused by the interaction between currents and waves. The deflection angle is used to evaluate the postural change of the structure, which reveals the asymmetrical effects of fluid–structure interaction and the influence of flow-field disturbances on the motion stability of the cylindrical structure.

After the cylindrical structure exits the launch tube at certain vertical and deflection velocities as initial conditions, it proceeds to the water surface under the combined effects of gravity, fluid forces, and thrust. This stage is known as the underwater motion phase. During this phase, the cylindrical structure's trajectory experiences considerable changes due to variations in vertical velocity, deflection velocity, flow field structure, and flow conditions. The water-exit process involves two-phase media, and different

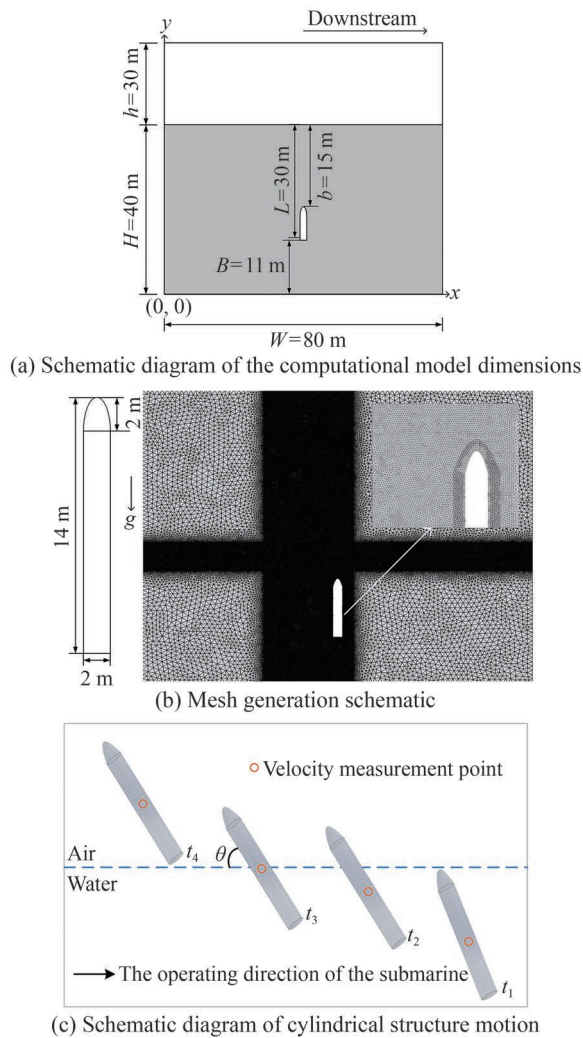


**Figure 5** Schematic of the calculation model

**Table 2** Fluent setup

| Project                           | Setting                                    |
|-----------------------------------|--------------------------------------------|
| Multiphase                        | Volume of fluid                            |
| Viscous model                     | SST $k-\omega$                             |
| Material                          | air (prime phase),<br>water (second phase) |
| Pressure velocity coupling method | PISO                                       |
| Pressure interpolation            | PRSTO!                                     |
| Dynamic mesh method               | Spring smoothing,<br>remeshing             |

near-surface speeds, cylindrical structure orientations, and sea surface conditions can affect the cylindrical structure's motion posture in various manners.

## 4.2 Mesh convergence analysis

To investigate the influence of mesh resolution on the accuracy of numerical simulation results, we employ three sets of meshes with different mesh sizes (Table 3). Numerical simulations are used to obtain the time-varying curves of displacement and velocity of the cylindrical structure

(Figure 6). Figure 6 adopts a dual y-axis representation, in which the solid and dashed lines correspond to the horizontal and vertical motion characteristics of the cylindrical structure, respectively. Under various mesh resolutions, relatively small deviations in horizontal velocity and displacement are observed, whereas significant differences are detected in vertical velocity and displacement. At  $t = 0.8$  s, the vertical velocities are 33.87, 29.97, and 28.71 m/s, respectively. An approximately 13% deviation is identified between the coarse- and medium-mesh results, whereas the difference between the medium- and fine-mesh results is approximately 4.3%. At  $t = 2$  s, the corresponding vertical displacements reach 62.97, 56.91, and 55.76 m, with a deviation of approximately 10.6% between the coarse and medium meshes and around 2% between the medium and fine meshes. A comparison of the simulation findings under different mesh densities reveals that discrepancies between results decrease as the mesh becomes finer. Considering computational accuracy and efficiency, the medium-resolution mesh is adopted for all subsequent numerical simulations in this study.

**Table 3** Mesh size setting

| Mesh type   | Mesh size                      | Mesh number |
|-------------|--------------------------------|-------------|
| Coarse mesh | $\Delta x = \Delta y = 0.2$ m  | 75536       |
| Medium mesh | $\Delta x = \Delta y = 0.1$ m  | 256995      |
| Fine mesh   | $\Delta x = \Delta y = 0.05$ m | 962068      |

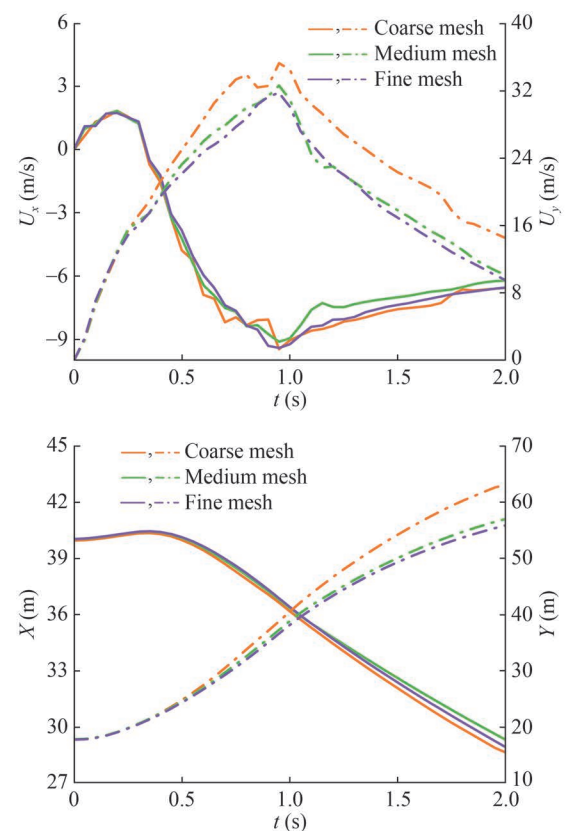


**Figure 6** Variation in cylindrical motion characteristics with time under different mesh densities

### 4.3 Influence of time step on simulation accuracy

Based on the analysis results of mesh convergence, a further investigation is conducted on the time step associated with the medium-resolution mesh during the simulation. Different time steps are selected for the analysis (Table 4). The motion characteristics of the cylindrical structure over time are obtained through numerical simulations (Figure 7).

**Table 4** Time step size setting

| Case   | Time step | Calculation time (h) |
|--------|-----------|----------------------|
| Case 1 | 0.1       | 2                    |
| Case 2 | 0.01      | 6                    |
| Case 3 | 0.005     | 10                   |

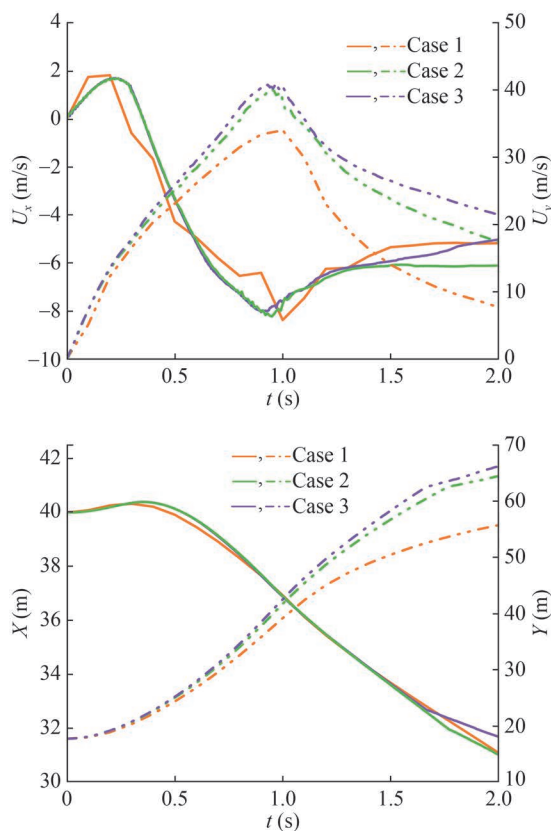


**Figure 7** Variation in cylindrical motion characteristics with time under different mesh densities

Figure 7 presents the motion characteristics of the cylindrical structure at various time steps. The figure employs a dual y-axis format, where the solid and dashed lines correspond to the velocity and displacement of the structure in the horizontal and vertical directions, respectively. Case 1 exhibits relatively small velocity fluctuations during the initial stage (Figure 7(a)). By contrast, cases 2 and 3, with smaller time steps, can capture more complex variations in velocity. At  $t = 1$  s, the horizontal velocities are  $-8.37$ ,

$-7.68$ , and  $-7.58$  m/s, and the vertical velocities are  $34.10$ ,  $38.49$ , and  $40.67$  m/s, respectively. The results on case 1 reveal significant deviation from the other two cases, whereas the difference between cases 2 and 3 is relatively small, with variations of approximately 1% and 5%, respectively. As illustrated in Figure 7(b), the horizontal displacement of the cylindrical structure among the three schemes reveals minimal differences. However, although vertical displacement is initially consistent across all cases, noticeable discrepancies emerge as the structure gradually emerges from the water. In this stage, the displacement curve of case 1 progressively deviates from those of the other two. The vertical displacements are  $64.50$  and  $66.29$  m, with a difference of approximately 2%.

Furthermore, the computational time required for each scheme varies considerably. Therefore, an appropriate time step must be selected to balance computational accuracy and efficiency. After a comprehensive evaluation of the influence of mesh resolution and time step on the simulation results, the medium-resolution mesh combined with the time step used in case 2 is selected for subsequent simulations.

### 4.4 Effect of slip-wall surface roughness

During the water-exit process of the cylindrical structure, the friction between the wall surface and surrounding fluid leads to a reduced flow velocity near the wall, which forms a velocity gradient. This section investigates the influence of surface roughness on the hydrodynamic behavior of the structure. Three different wall roughness heights are selected for comparison, and the detailed design parameters are listed in Table 5. Figure 8 shows the motion characteristic curves of the cylindrical structure under various wall surface roughness conditions. A dual y-axis format is adopted in the figure, where the solid and dashed lines represent the variations in horizontal and vertical motion characteristics of the cylindrical structure, respectively.

**Table 5** Design parameters of working conditions

| Wall conditions       | Roughness height (m) | Roughness constant |
|-----------------------|----------------------|--------------------|
| Smooth wall           | 0                    |                    |
| Moderately rough wall | 0.0005               | 0.5                |
| Highly rough wall     | 0.002                |                    |

Figure 8(a) displays the generally consistent initial variation trends of horizontal velocity under the three wall roughness conditions. In addition, these trends exhibit an initial increase followed by a decrease and then stabilization. During the period of  $t = 0.6$ – $1$  s, the high roughness wall exhibits the lowest horizontal velocity ( $-8.0$  m/s), and the smooth wall results in a small velocity drop. In terms of vertical velocity, the three curves nearly overlap in the early stage, which indicates that the variation in vertical motion

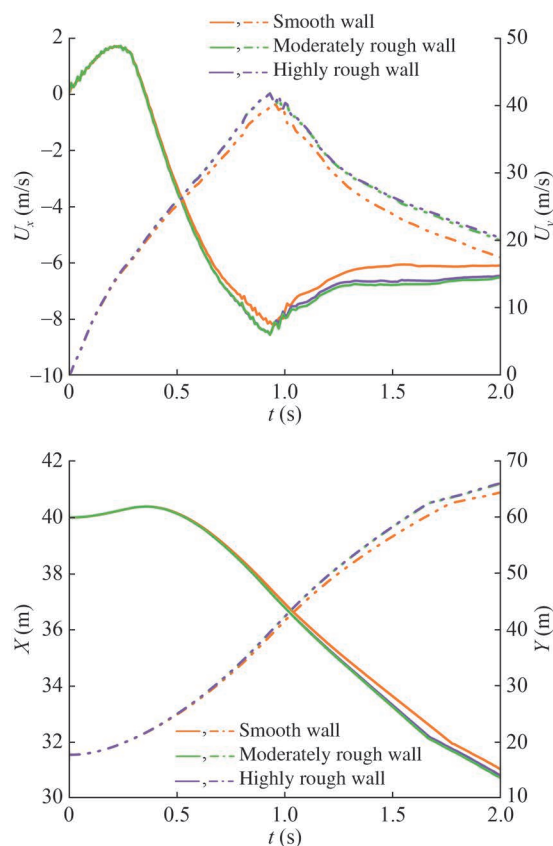


**Figure 8** Motion characteristics of the cylindrical structure under varying wall roughness

during the initial water-exiting phase is mainly governed by inertia, with negligible influence from surface roughness. After  $t = 0.6$  s, the effect of surface roughness becomes increasingly evident. The vertical velocity of the high roughness wall reaches a peak of 41.79 m/s, and the smooth wall shows a gradual change, which suggests a reduced resistance during motion. Figure 8(b) reveals the relatively small differences in displacement among the three cases. The final vertical displacements are 64.50, 66.07, and 66.16 m, which indicates that a rough surface leads to a fast ascent of the structure. Based on comparative analysis, although the high roughness wall yields strong dynamic responses in terms of vertical velocity and displacement, it also introduces intense local flow disturbances, which may compromise numerical stability. The medium-roughness wall exhibits premature attenuation in horizontal motion during certain periods, which implies a degree of interference with flow field development. By contrast, the smooth wall demonstrates stable variations in horizontal and vertical velocity and displacement, with relatively small discrepancies compared with the other cases. In addition, it ensures an improved convergence behavior during computation. Therefore, the smooth wall condition is selected for subsequent simulations in this study to ensure numerical stability and comparability of results.

## 5 Discussions

In real ocean environments, the conditions near the water surface are complex and involve wind, waves, and currents, with waves being the most influential factor. This chapter considers the effect of different wave levels, water-exit phases, and the combined effects of wave–current coupling on the cylindrical structure’s water-exit process. Numerical simulations are carried out based on the previously established basic motion model of submerged cylindrical structures and the wave environment. In the study on the effect of waves on the water exit process, the cylindrical structure is controlled to remain stationary as a fixed rigid body until the entire water surface is filled with waveforms, which prevents the premature release of the cylindrical structure.

### 5.1 Effect of wave levels on the hydrodynamic characteristics of the cylindrical structure

Three sea condition levels are considered in the study on the influence of wave levels on the cylindrical structure. For the research on the water-exit motion of a vehicle under wave action, Meng (2011) selected sea state parameters of different levels. Table 6 provides the wave parameters corresponding to different wave levels. Two scenarios are considered during the simulation: Case 1: Ignoring the effect of deflection velocity, the variation in cylindrical structure’s vertical exit motion characteristics under different wave levels; Case 2: in consideration of the effect of deflection velocity, the cylindrical structure’s motion process is simulated under different wave levels.

**Table 6** Wave parameters

| Wave levels | Wave height $H$ (m) | Wave length $L$ (m) | Wave period $T$ (s) |
|-------------|---------------------|---------------------|---------------------|
| Level 3     | 1.10                | 18                  | 3.40                |
| Level 4     | 1.80                | 27                  | 4.16                |
| Level 5     | 2.56                | 40                  | 5.06                |

#### 5.1.1 Ignoring the effect of deflection velocity

Figures 9(a) and (b) show the velocity and displacement curves during cylindrical structure motion, respectively, where solid lines represent vertical motion characteristics and dashed lines represent horizontal motion characteristics. In the presence of waves, the cylindrical structure’s height is relative to the free surface changes. Given wave velocity, the velocity of the cylindrical structure near the surface differs from that in still water as it approaches the free surface. The wave impact on the cylindrical structure’s velocity is primarily manifested in the horizontal velocity component. Without waves, the cylindrical structure’s horizontal velocity component fluctuates around zero. Under different wave levels, the velocity components exhibit varying motion directions. When the wave level is 3, the cylindrical structure has a velocity of 2.33 m/s along the posi-

tive  $x$ -axis after contacting the wave surface, and the cylindrical structure deflects 0.52 m in the positive  $x$ -axis direction. However, at wave levels 4 and 5, the cylindrical structure generates velocity components along the negative  $x$ -axis, with values of 1.39 and 2.54 m/s, respectively. After exiting the water, cylindrical structure eventually deflects 0.56 and 1.16 m in the negative  $x$ -axis direction. The vertical velocity component shows a similar trend; that is, it gradually increases over time, which causes the continued upward movement of the cylindrical structure. The numerical differences in the vertical velocity and displacement components under various wave levels are relatively small (Table 7). Figure 9(c) shows the cylindrical structure's motion trajectory change curve. In the absence of waves, the cylindrical structure trajectory approximates a straight line with no deflection throughout its motion. However, in the presence of waves, the trajectory exhibits deflection. Notably, although waves propagate in the positive  $x$ -axis direction, the cylindrical structure's deflection direction varies under different wave levels.

Figure 10 illustrates the velocity distribution and corre-

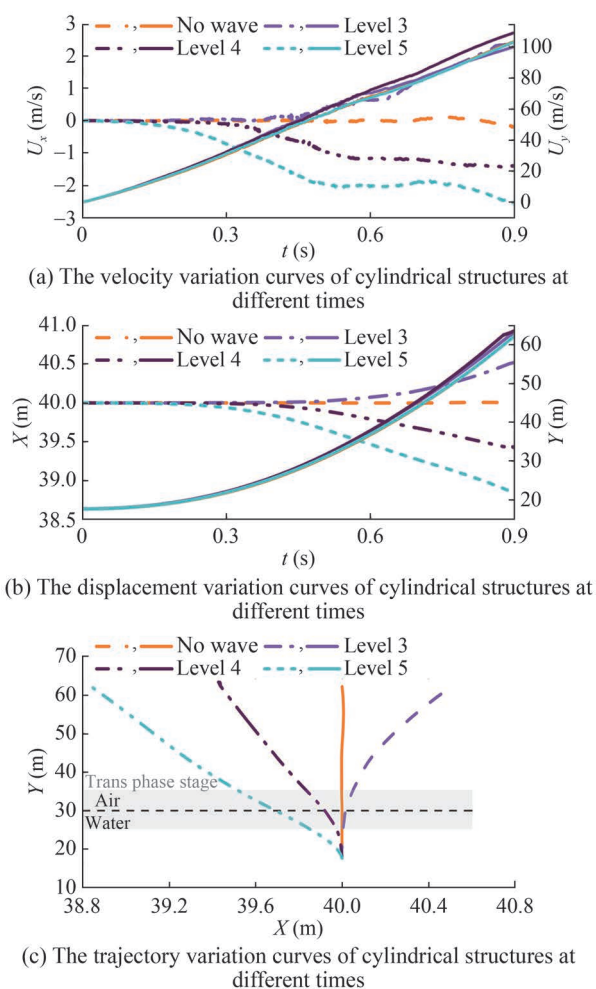


**Figure 9** Cylindrical structure hydrodynamic characteristics curves under different wave levels

**Table 7** Changes in cylindrical structure motion characteristics

| Wave levels | $\Delta U_x$ (m/s) | $\Delta U_y$ (m/s) | $\Delta x$ (m) | $\Delta y$ (m) |
|-------------|--------------------|--------------------|----------------|----------------|
| Level 3     | 2.33               | -3.28              | 0.52           | 0.55           |
| Level 4     | -1.39              | 5.74               | -0.56          | 1.27           |
| Level 5     | -2.54              | -0.22              | -1.16          | 0              |

sponding water-to-air phase distribution during the water-exit process of the structure under various wave levels. The black circles highlight the key regions, revealing the interaction of the structure with the free surface, which undergoes considerable deformation due to the disturbance caused by the emerging structure. As the wave level increases, the disturbance of the free surface intensifies, and the coupling effect between the structure and the waves improves.

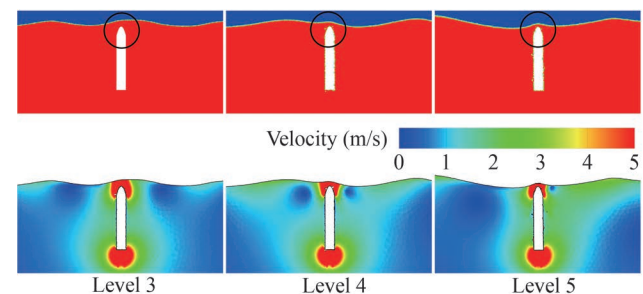


**Figure 10** Cylindrical structure water-exit process contour map

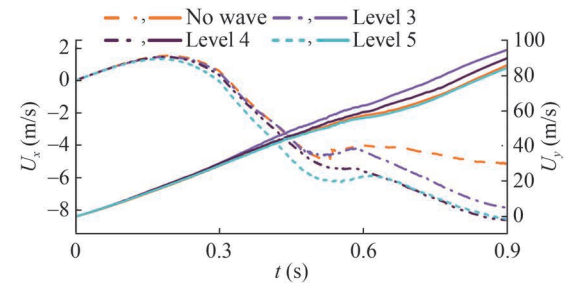
The velocity contours at the same emergence phase reveal the variation characteristics of the flow field around the structure. A distinct high-velocity jet region occurs near the top of the structure, and a strong wake region forms near the bottom. With the increase in sea state level, the velocity field exhibits great asymmetry and turbulence characteristics, with an intensified flow separation and an expanded high-velocity region. At wave level 3, the cylindrical structure emerges near the wave crest, whereas at wave levels 4 and 5, it emerges closer to the wave trough. Based on the characteristics of the second-order Stokes wave, the wave surface becomes steeper at the crest and flatter at the trough. At the crest, the horizontal velocity increases, which propels the cylindrical structure toward the positive  $x$ -direction, and at the trough, the horizontal velocity decreases, which slows down the structure's motion. Particularly, under wave level 5, wave-induced flow exerts significant influence, which results in violent free surface motion and a complex flow field around the structure. High wave levels substantially enhance the hydrodynamic characteristics during the water-exit process, which leads to strong surface disturbances and complex vortex structures in the surrounding flow field.

### 5.1.2 Considering the effect of deflection velocity

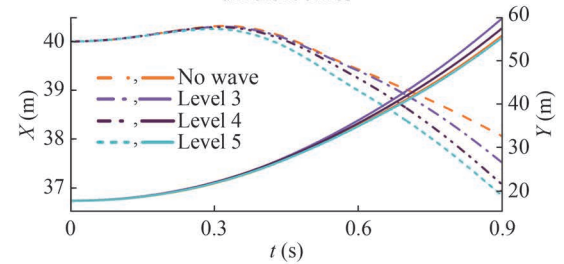
The water-exit characteristics of cylindrical structures under various wave conditions with deflection velocity are investigated.

As revealed in Figures 11(a) and (b), the solid lines represent the vertical motion characteristics of the cylindrical structure, and the dashed lines denote the changes in the horizontal motion. The overall trends of the motion characteristics remain consistent under various conditions. When  $t < 0.3$  s, the cylindrical structure proceeds through the underwater motion phase and is unaffected by waves. At this stage, the cylindrical structure slightly deviates in the positive  $x$ -direction, and the differences in cylindrical structure velocity and displacement are small. At  $t = 0.3$  s, the cylindrical structure forms specific deflection angles with the free surface, with values of  $88.5^\circ$ ,  $88.5^\circ$ ,  $88.48^\circ$ , and  $88.49^\circ$ . The cylindrical structure continues its motion toward the free surface, maintaining these deflection angles. In still water conditions, the cylindrical structure's vertical velocity is 85.84 m/s. As the wave level increases, the vertical velocity changes accordingly to 94.56, 89.74, and 84.38 m/s. As the effect of waves on vertical motion is relatively small, vertical velocity exhibits minor differences. The primary effect of waves on the cylindrical structure's motion occurs in the horizontal direction. In the absence of waves, the cylindrical structure's horizontal velocity component is 5.12 m/s, and the displacement in the negative  $x$ -direction is 1.95 m. In the presence of waves, the horizontal velocity components increase with the wave level, with values reaching 7.87, 8.58, and 8.60 m/s, which result in large displacement changes in the negative  $x$ -direction (2.5, 2.95, and 3.18 m, respectively). The cylindrical structure's motion deflection change also exhibits a positive correlation with wave conditions. Figure 11(c) depicts the cylindrical structure trajectory curve. Compared with the characteristics of the cylindrical structure's motion trajectory during vertical water exit, the cylindrical structure trajectory is now influenced by deflection velocity, which causes an initial deflection in the positive  $x$ -direction. Subsequently, the cylindrical structure continues its water-exit motion under thrust at a certain deflection angle. Therefore, when deflection velocity is considered, the cylindrical structure's motion during water exit is influenced by the deviation angle and wave surface changes.

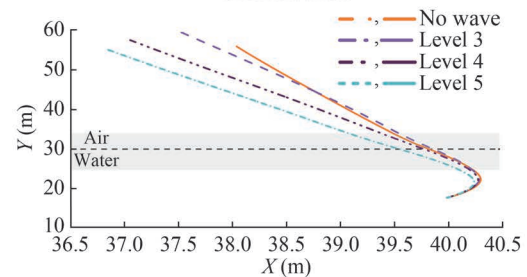
Given the influence of the offset velocity's duration and direction, the effect on the motion characteristics of the structure is primarily manifested in the horizontal direction during the underwater stage. To investigate the effect



(a) The velocity variation curves of cylindrical structures at different times



(b) The displacement variation curves of cylindrical structures at different times



(c) The trajectory variation curves of cylindrical structures at different times

**Figure 11** Hydrodynamic characteristics curve of the cylindrical structure under the influence of deflection velocity

of offset velocity, we analyze the vorticity field at  $t = 0.3$  s (Figure 12). In addition, the velocity, displacement, and deflection angle under different conditions are compared (Table 8).

Figure 12 shows the vorticity distribution of the structure under various wave levels and initial offset velocity conditions. Overall, with the increase in the wave level, the vorticity intensity during the structure's water entry process greatly strengthens, especially at wave level 5, where larger vortex regions form at the bottom and sides of the

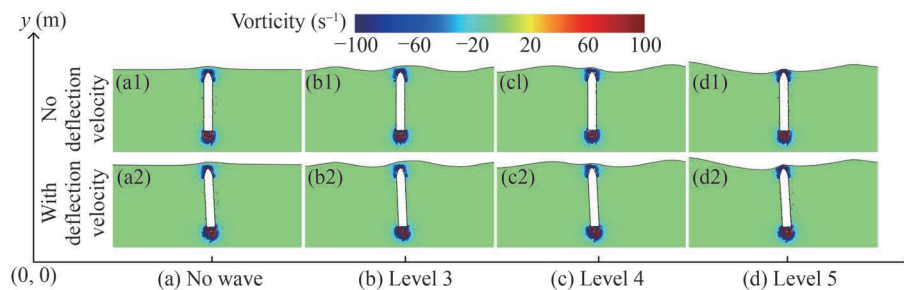


**Figure 12** Vorticity contours under different operational cases

**Table 8** Kinematic parameters

| Case   | Wave    | $U_x$ (m/s)          | $U_y$ (m/s) | $\Delta X$ (m) | $\Delta Y$ (m) | Deflection angle ( $^\circ$ ) |
|--------|---------|----------------------|-------------|----------------|----------------|-------------------------------|
| Case 1 | No wave | $6.6 \times 10^{-4}$ | 30.76       | -0.001         | 4.41           | 89.99                         |
|        | Level 3 | 0.061                | 32.46       | 0.003          | 4.60           | 89.96                         |
|        | Level 4 | -0.010               | 32.23       | -0.010         | 4.65           | 89.88                         |
|        | Level 5 | -0.726               | 31.29       | -0.061         | 4.50           | 89.22                         |
| Case 2 | No wave | 0.592                | 28.80       | 0.310          | 4.25           | 88.50                         |
|        | Level 3 | 0.502                | 30.12       | 0.297          | 4.40           | 88.50                         |
|        | Level 4 | 0.324                | 29.91       | 0.289          | 4.44           | 88.48                         |
|        | Level 5 | -0.062               | 28.88       | 0.254          | 4.29           | 88.49                         |

structure. These findings indicate that wave disturbances considerably intensify the unsteadiness of the flow field. In the case without deflection velocity, the vorticity distribution is relatively symmetrical and mainly concentrated at the bottom of the structure, which shows a typical vertical water entry feature (Figures 12(a1)–(d1)). By contrast, with a deflection velocity, the structure's movement deviates from the vertical direction, which causes an uneven vorticity distribution on both sides, with the vortex structure becoming asymmetric (Figures 12(a2)–(d2)). Moreover, the combined effect of waves and deflection velocity intensifies the flow near the free surface, which leads to more complex vortex structures in the subsequent water-exit motion.

In case 1, without waves and deflection velocity, the horizontal velocity is small, and the vertical velocity is large (Table 8). At this point, the deflection angle of the cylindrical structure approximates  $90^\circ$ , and the cylindrical structure almost maintains a straight upward trajectory during the water-exit process. When the wave level increases to 3, the horizontal velocity of the object considerably increases to 0.061 m/s, and the vertical velocity slightly increases to 32.46 m/s, with the deflection angle being  $89.96^\circ$ . Compared with the no-wave condition, the deflection angle slightly changes, which indicates the relatively small effect of the waves on the object. As the wave level increases further to level 4, the horizontal movement of the cylindrical structure becomes more noticeable. At this point, the deflection angle is  $89.88^\circ$ , which means a more evident deviation from the straight upward motion. Under the maximum wave level influence, the horizontal velocity increases considerably to 0.726 m/s, with a horizontal displacement at -0.061 m and the deflection angle decreasing to  $89.22^\circ$ . Under high wave levels, the horizontal displacement of the object increases tremendously, and the deflection angle decreases, making the deflection from vertical more pronounced. In case 1, the deflection angle is notably affected by waves, and it decreases as the wave level increases. In case 2, which has no waves but has the effect of initial deflection velocity, the cylindrical structure's velocity is relatively small. Without the influence of waves,

the main cause of the deflection of the structure is deflection velocity. Compared with the no-wave condition in case 1, the deflection angle is substantially reduced, and the angle between the cylindrical structure and the free surface increases accordingly. As the wave level increases, the horizontal velocity of the cylindrical structure decreases from 0.592 m/s to 0.062 m/s, and the corresponding horizontal displacement also decreases. When considering deflection velocity, relatively small changes in the deflection angle are observed under different wave levels.

## 5.2 Effect of wave phase on the water-exit process

Analysis from the previous section reveals that wave levels, or wave characteristic parameters, are the primary influencing factors of the cylindrical structure's water-exit process, with influence attained through a positive correlation between structural motion parameter variations and wave grades. In addition, the cylindrical structure's motion during water exit is affected by different wave phases. Phase-specific analysis indicates that at a designated wave level, the wave-phase dependency of cylindrical structure hydrodynamic loads deviates from a simplistic "high-intensity, low-weakness" pattern. Compared with wave levels, the effect of phase is more closely related to the variation in flow field characteristics as the position changes. Therefore, focusing on wave level 5, one wave period is selected as the research subject, and it is into  $60^\circ$  intervals, with the trough position at the  $0^\circ$  phase and the crest at the  $180^\circ$  phase (Figure 13). Two scenarios are considered in the simulation: Case 1: ignores the deflection velocity effect and observes the cylindrical structure's motion characteristics during vertical water exit at different water-exit phases; Case 2: considers the deflection velocity impact and simulates the cylindrical structure's motion process under the influence of different water-exit phases.

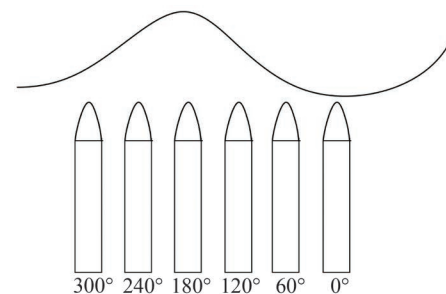


**Figure 13** Relationship between the water-exit phase and cylindrical structure position

### 5.2.1 Ignoring the effect of deflection velocity

This approach considers the hydrodynamic characteristics of the cylindrical structure's vertical water exit under the influence of various wave phases. For the fifth-level sea condition, the wave height, wavelength, and period are set to 2.56 m, 40 m, and 5.06 s, respectively, with the

wave parameters kept constant. The different wave phases are calculated based on the wave period, and for each phase, various cylindrical structure launch times are selected accordingly. Before the wave field stabilizes, the cylindrical structure is set as a fixed rigid body and not released.

Figure 14(a) illustrates the comparative analysis of horizontal velocity components at the cylindrical structure's center of mass under six phase conditions at wave level 5. As shown in the figure, the variation trends of the center-of-mass velocity closely correspond to those of the center-of-mass trajectory curves. From the onset of cylindrical structure motion, the horizontal velocity at its center of mass gradually increases from zero. This observation aligns with the trend shown in Figure 14(c), where the rate of lateral displacement in the center-of-mass trajectory increases with the rise in the vertical coordinate of the mass center. However, the rate of change of horizontal velocity initially increases and then decreases. As the cylindrical structure shifts from deeper water into the highly disturbed free surface area, the intensity of wave effects increases, which results in a continuous rise in its horizontal velocity component. When the cylindrical structure moves near and through the wave surface until it fully exits the water, the wave influence on cylindrical structure motion diminishes. Consequently, the growth in horizontal velocity essentially ceases, as evidenced by the near-vertical extension of the curve end in Figure 14(a), which indicates minimal variations in the horizontal velocity component during this phase.

The findings from the comparison of variations across various water-exit phases align with those of the analysis of the cylindrical structure's center-of-mass trajectory patterns. When the cylindrical structure exits at the wave crest, 120°, and 240° phases, the horizontal velocity component of its center of mass is oriented along the positive  $x$ -axis, reaching a maximum value of 4.60 m/s at the wave crest. Conversely, during exits at wave trough, 60°, and 300° phases, the horizontal velocity is directed along the negative  $x$ -axis, with a maximum magnitude of 3.66 m/s at the trough. At the wave crest, the increased horizontal velocity propels the cylindrical structure in the positive  $x$ -direction, and the opposite occurs at the wave trough, which results in a reduced motion velocity. Similar to the analysis of the cylindrical structure's vertical velocity component under different wave levels, the parameter variation curves reveal minimal differences across various phases within the same wave level. As the cylindrical structure's vertical velocity is orthogonal to the wave propagation direction, the wave impact mainly influences the horizontal direction. Therefore, the wave exerts a minimal influence on vertical velocity, which results in similar trends and numerical values for the cylindrical structure's vertical velocity changes at all water-exit phases.

Figure 14(c) illustrates the trajectory curves of the cylindrical structure's center of mass. After the underwater ver-

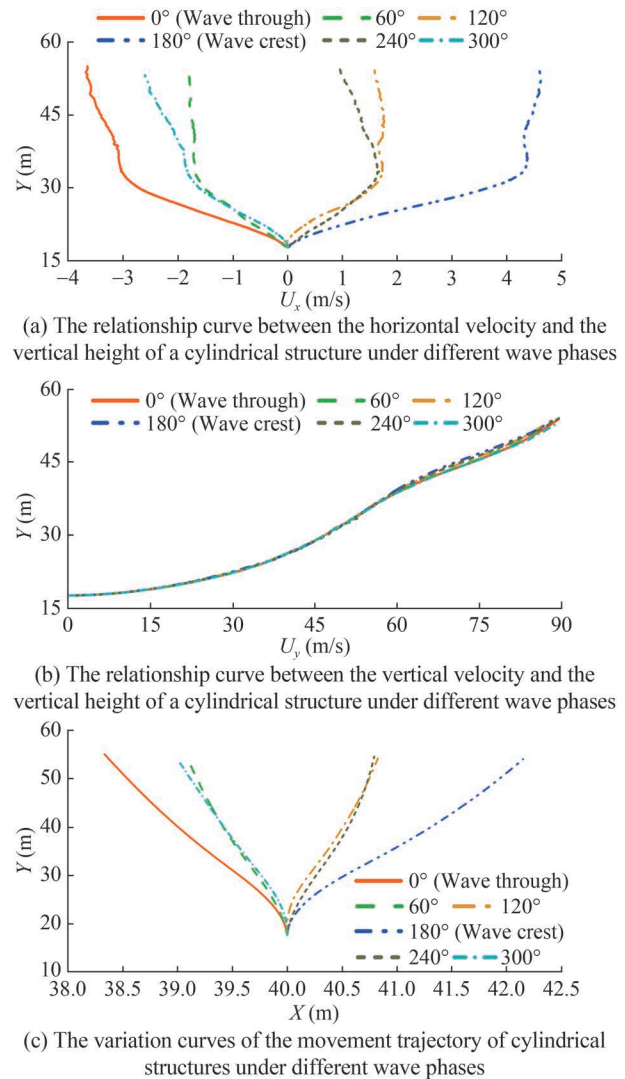


**Figure 14** Hydrodynamic characteristic curve of the cylindrical structure's vertical motion

tical acceleration phase, the cylindrical structure undergoes free upward motion, at which point wave effects become evident. The cylindrical structure exhibits varying lateral displacements in magnitude and direction when exiting at different phases. Notably, at opposing exit phases, lateral displacements of the cylindrical structure's center of mass move alternately with and against the wave propagation direction. Specifically, the directions of lateral displacement are opposite in the comparison of exits at wave crests versus troughs and similarly opposite in the comparison of exits at 60° versus 240° phases and 120° versus 300° phases. The lateral displacements align with the wave propagation direction during exits at wave crests, 120°, and 240° phases, and movements at 60°, 300°, and trough phases oppose the wave propagation direction. Furthermore, when the cylindrical structure's lateral displacement aligns with the wave propagation direction, specifically during water exit at the wave crest (0°), 120°, and 240° phase angles, the corre-

sponding lateral displacements measure 2.15, 0.83, and 0.79 m. By contrast, at the wave trough, 60°, and 300° phases, the lateral displacements reach 1.67, 0.88, and 0.98 m, respectively. The lateral displacement at the wave crest phase is considerably larger than that at the wave trough phase, and the displacement at the 120° and 240° phases is slightly smaller than that at the opposite water-exit phases. In the horizontal direction within the same period, the overall cylindrical structure “drift” direction induced by wave impact aligns with the particle-flow velocity direction. Notably, the maximum positive lateral displacement occurs during wave crest exit, and the maximum negative displacement transpires at wave troughs, although at a smaller magnitude than the crest-phase displacement.

Figure 15 presents the flow-field pressure contour map of the cylindrical structure at the same moment but with different water-exit phases. During the initial motion stage, the cylindrical structure is at a deeper location, and wave disturbance effects are minimal, which allows the cylindrical structure to maintain its original vertical upward trajectory. Upon contact with the free surface, the cylindrical structure’s motion begins to be affected by varying wave-field characteristics and wave forces at different exit phases. As the point of wave force application deviates from the cylindrical structure’s center of mass, which creates an unbalanced force distribution, the following effects become evident: During water exit at the wave crest, the cylindrical structure exhibits a clockwise rotational tendency, with its attitude angle progressively increasing along the positive  $x$ -axis, which results in lateral displacement in the direction of wave propagation (Figure 15(d)). Conversely, when the cylindrical structure exits at the wave trough, the attitude angle increases negatively along the  $x$ -axis, and the cylindrical structure undergoes a counterclockwise rotation with a smaller deflection and lateral displacement than when it exits at the wave crest (Figure 15(a)). For the other opposite phases, the cylindrical structure’s attitude change follows a similar pattern to the wave crest and wave trough exits but with smaller changes (Figures 15(b) and (e), 15(c) and (f)). Regarding the pressure contour map during the cylindrical structure water-exit process at different phases, Figures 15(a)–(f) confirm the conclusion of the previous analysis on the influence of wave level: Gravity is the main factor influencing flow-field pressure distribution, which results in a “layering” effect. The cylindrical structure’s nose, shoulder, and tail are high- and low-pressure regions. The variation patterns and causes of these pressures are consistent with those of previous analyses, where the wave’s characteristic parameters and particle parameters in the flow field cause no remarkable influence on pressure distribution.

### 5.2.2 Considering the effect of deflection velocity

Figure 16 illustrates the motion characteristics of the cylindrical structure under deflection velocity. Figure 16(a) displays the temporal evolution of the cylindrical struc-

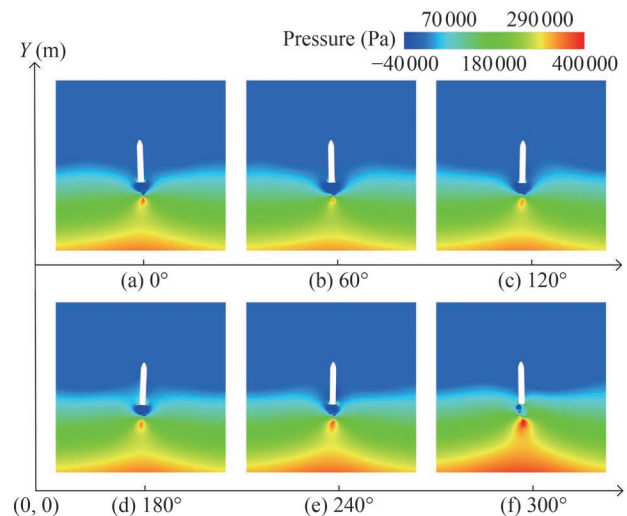


**Figure 15** Pressure contour map of the cylindrical structure during water exit at different wave phases

ture’s horizontal velocity. The velocity variations show a direct correlation with the observed displacement changes. During the initial motion phase, the deflection velocity enables the cylindrical structure to acquire a horizontal velocity component along the positive  $x$ -axis, and wave parameter effects remain negligible. As the deflection velocity gradually dissipates, the cylindrical structure develops a horizontal velocity component along the negative  $x$ -axis during the water exit. This horizontal velocity increases proportionally with the cylindrical structure’s vertical displacement, albeit with a relatively small rate of change. At the wave trough exit, the horizontal velocity reaches 9.71 m/s, which substantially exceeds the 4.36 m/s recorded at the wave crest exit. During this phase, the horizontal velocities at the wave trough, 60°, and 300° phases substantially surpass those at their corresponding opposite phases. The rate of change in horizontal velocity increases markedly as the cylindrical structure’s center of gravity traverses the free surface, with only the tail section remaining submerged. Notably, this rate of change exhibits greater magnitude at the wave crest, 120°, and 240° phases compared with the wave trough, 60°, and 300° phases. As illustrated in Figure 16(b), considering that wave effects predominantly manifest in the horizontal direction, the vertical velocity profiles exhibit minimal variation across various exit phases under identical wave level conditions.

In the underwater phase, the cylindrical structure deflects along the positive  $x$ -axis due to the deflection velocity. As the deflection velocity diminishes, the cylindrical structure emerges from the free surface with this deflected orientation, which causes its overall trajectory to deviate toward the negative  $x$ -axis (Figure 16(c)). In contrast to scenarios without the effects of deflection velocity, when the cylindrical structure exits at the wave crest, 120°, and 240° phases, it no longer exhibits horizontal displacement along the positive  $x$ -axis but consistently deviates toward the negative

x-axis. The corresponding horizontal displacements total 1.62, 2.84, and 2.45 m, respectively. For exits at the wave trough, 60°, and 300° phases, the cylindrical structure demonstrates an enhanced negative x-axis displacement compared with the cases without deflection velocity, with magnitudes of 4.53, 4.10, and 3.76 m, respectively. These values notably exceed the horizontal displacements observed at their opposing phases.

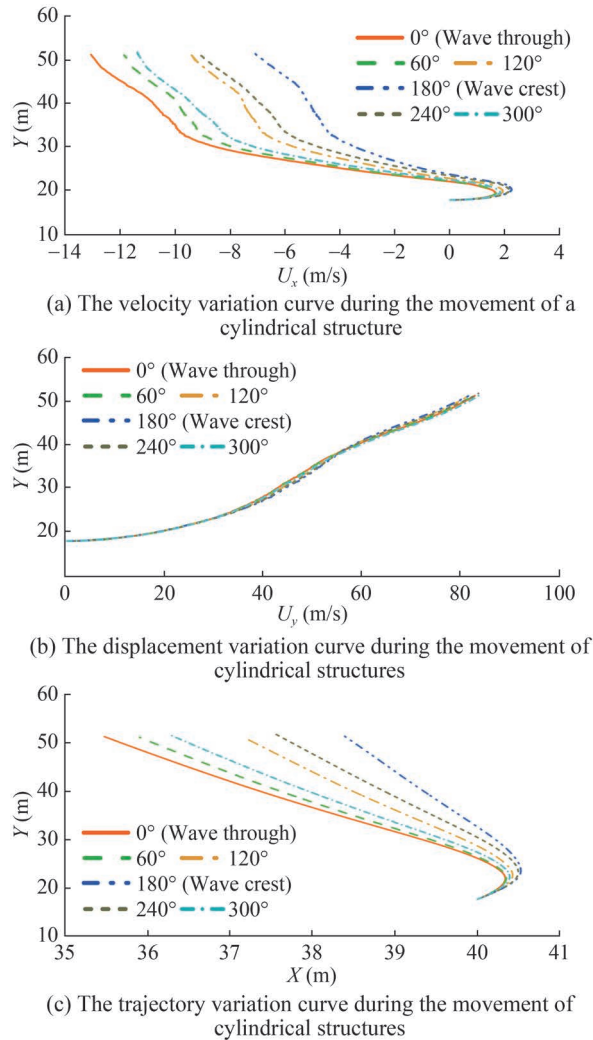


**Figure 16** Hydrodynamic characteristics curve of the cylindrical structure under the influence of deflection velocity

Figure 17 reveals the vorticity fields corresponding to various wave phases at  $t = 0.3$  s. Meanwhile, Table 9 provides a comparison of the motion characteristics under different scenarios. In the case without deflection velocity (Figures 17(a1)–(f1)), the cylindrical structure maintains a relatively vertical ascent posture, and symmetric vortex pairs form at the bottom of the structure during the water-exit process. As the wave phase increases from 0° (wave trough) to 180° (wave crest), the disturbed flow-field region above the cylindrical structure expands accordingly. When the structure emerges at the wave crest (Figure 17(d1)),

the vorticity intensity becomes slightly higher than that in other phases, which indicates that the upward motion of the wave exerts a stronger interference on the structure. This condition enhances the shear at the bottom boundary layer and results in more distinct vortex structures.

By contrast, under the condition with a deflection velocity (Figures 17(a2)–(f2)), the cylindrical structure exhibits a distinctly asymmetric vorticity distribution during the water-exit process. Given the horizontal offset trend during the underwater motion stage, the shear vortex structure at the bottom of the cylindrical structure is deflected toward one side, which leads to a spatial shift in the vortex distribution. When the structure emerges at the wave trough (Figure 17(a2)), the vorticity region on the right side becomes more prominent, which suggests that the horizontal deflection velocity enhances fluid shear on that side. This asymmetry persists across different wave phases and becomes most pronounced at the wave crest phase (180°), where the asymmetry of the vorticity field intensifies, and intersecting regions of positive and negative vorticities emerge locally.

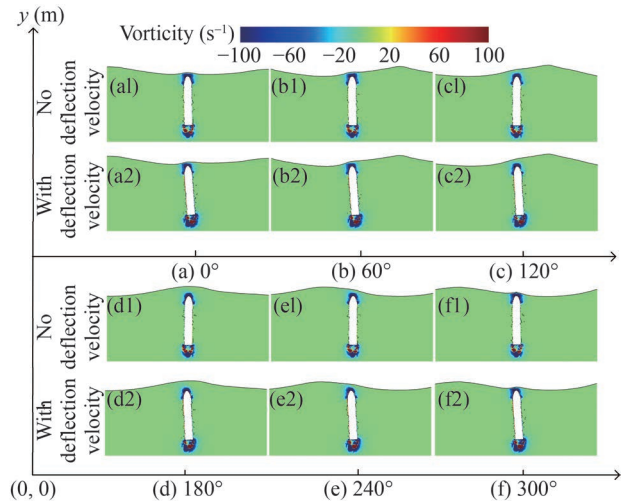


**Figure 17** Vorticity contours at different wave phases

**Table 9** Kinematic parameters

| Case   | Wave phase | $U_x$ (m/s) | $U_y$ (m/s) | $\Delta X$ (m) | $\Delta Y$ (m) | Deflection angle (°) |
|--------|------------|-------------|-------------|----------------|----------------|----------------------|
| Case 1 | 0°         | -0.725      | 27.581      | -0.061         | 4.133          | 89.15                |
|        | 60°        | -0.505      | 27.225      | -0.051         | 4.088          | 89.29                |
|        | 120°       | 0.221       | 26.688      | 0.007          | 4.019          | 89.90                |
|        | 180°       | 0.759       | 26.471      | 0.058          | 4.008          | 89.17                |
|        | 240°       | 0.472       | 27.051      | 0.045          | 4.081          | 89.37                |
|        | 300°       | -0.345      | 27.736      | -0.023         | 4.154          | 89.68                |
| Case 2 | 0°         | 0.576       | 25.600      | 0.334          | 4.001          | 85.23                |
|        | 60°        | 0.726       | 25.371      | 0.394          | 3.954          | 84.31                |
|        | 120°       | 1.380       | 25.012      | 0.341          | 3.899          | 85.00                |
|        | 180°       | 1.958       | 25.202      | 0.449          | 3.914          | 83.45                |
|        | 240°       | 1.731       | 25.686      | 0.440          | 3.989          | 83.70                |
|        | 300°       | 0.987       | 25.899      | 0.376          | 4.034          | 84.67                |

In case 1, the horizontal velocity of the cylindrical structure remains relatively small, with values ranging from  $-0.725$  m/s to  $0.759$  m/s, which indicates that the overall motion of the structure is primarily concentrated in the vertical direction (Table 9). The vertical velocity is consistently within the range of  $26$ – $28$  m/s, and the deflection angle remains close to  $90^\circ$ , which suggests that the cylindrical structure maintains a stable vertical trajectory during the underwater motion stage without deflection velocity. By contrast, in case 2, where the deflection velocity is considered, the horizontal velocity increases tremendously, reaching a maximum of  $1.958$  m/s, and remains positive across all wave phases. The horizontal displacement is also notably larger, with a maximum value of  $0.449$  m, which indicates a distinct lateral deviation of the structure. Although the vertical velocity slightly decreases compared with that in case 1, it maintains an upward motion trend. Under these conditions, the deflection angle decreases to  $83^\circ$ – $85^\circ$ , and the trajectory of the cylindrical structure deviates markedly from the vertical direction, which exhibits a strong asymmetry in its motion path.

### 5.3 Influence of the effect of wave–flow coupling on the water-exit process

During the underwater phase, water current velocity markedly influences the cylindrical structure's deflection angle during water exit, which subsequently alters its emergence posture. When they reach the free surface, wave forces further modify the cylindrical structure's trajectory. Comprehending the cylindrical structure's motion characteristics under these coupled wave–flow effects is crucial to ensure targeting accuracy, which holds substantial research significance. Typical ocean current velocities range from  $1$  knots to  $2$  kn (approximately  $0.5$ – $1.0$  m/s), with some extreme cases reaching  $4$ – $5$  kn (approximately  $2.0$ – $2.5$  m/s). Numerical analysis incorporates magnitude and directional components of flow velocity, with simulations conducted at  $\pm 1$  and  $\pm 2.5$  m/s. The flow velocity effects predominantly manifest along the  $x$ -direction. In downstream motion, the cylindrical structure experiences enhanced positive  $x$ -axis displacement and increased deflection angles. Conversely, reduced deflection angles are observed with upstream motion. The magnitude of trajectory deviation from still water conditions correlates directly with flow velocity magnitude. Wave effects primarily influence the cylindrical structure's orientation at the free surface interface, particularly during water exit and subsequent aerial phases. By contrast, flow effects are most pronounced during the underwater phase, where flow magnitude and direction greatly influence the cylindrical structure's trajectory and its approach orientation toward the free surface. These hydrodynamic conditions ultimately determine the cylindrical structure's motion characteristics during water exit.

Figure 18 illustrates the cylindrical structure's motion

characteristic curves under the combined effects of downstream current and varying wave conditions. The solid and dashed lines represent the vertical and horizontal motion characteristics, respectively. Flow-induced disturbances during the underwater phase generate oscillations in the horizontal velocity component, with oscillation amplitudes increasing proportionally with the flow velocity (Figures 18(a) and 18(d)). During the initial period ( $t \leq 0.3$  s), the deflection velocity induces a parabolic increase in the horizontal velocity component along the positive  $x$ -axis, which deflects the cylindrical structure in the positive  $x$ -direction. With the gradual dissipation of deflection velocity, the cylindrical structure maintains its deflection angle while continuing its upward trajectory. Throughout this phase, the horizontal velocity component progressively increases along the negative  $x$ -axis direction. Notably, the vertical velocity component exhibits minimal variation during the underwater motion phase.

At a flow velocity of  $1$  m/s, the cylindrical structure exhibits minor oscillations in its horizontal velocity component due to current-induced perturbations (Figure 18(a)). For  $t \leq 0.48$  s, the velocity and displacement variations remain generally consistent, with the cylindrical structure traversing in the negative  $x$ -axis direction at horizontal velocities of  $3.29$ ,  $3.15$ , and  $3.43$  m/s. During the water-exit phase ( $0.48$ – $0.6$  s), the horizontal velocity component experiences slight decrements of  $0.33$ ,  $0.43$ , and  $0.05$  m/s. Subsequently, during the aerial phase, free from hydrodynamic influences, the cylindrical structure maintains its trajectory at a fixed angle along the negative  $x$ -axis, with velocities progressively increasing to terminal values of  $5.74$ ,  $7.14$ , and  $5.26$  m/s. The minimal variations in horizontal velocity components correspond to negligible differences in negative  $x$ -axis displacements, with values of  $1.38$ ,  $1.7$ , and  $1.48$  m (Figure 18(b)). At an elevated flow velocity of  $2.5$  m/s, the current-induced oscillation amplitudes exceed those observed at  $1$  m/s (Figure 13(a)). Throughout the motion trajectory, wave levels 3 and 4 demonstrate minimal horizontal velocity differentials, with respective motion velocities of  $3$  and  $3.8$  m/s, respectively. However, wave level 5 induces a substantial increase in horizontal velocity; it reaches a peak of  $4.44$  m/s at  $0.23$  s, followed by a linear increase along the negative  $x$ -axis. Post  $0.6$  s, the growth rate diminishes, and it ultimately stabilizes at  $9.58$  m/s (Figure 18(d)). The horizontal displacement patterns correlate directly with velocity variations. Under identical flow conditions, wave levels 3 and 4 result in modest negative  $x$ -direction displacements of  $0.07$  and  $0.14$  m, respectively. By contrast, wave level 5 generates a considerably enhanced deflection, which culminates in a negative  $x$ -axis displacement of  $1.51$  m.

Figures 18(c) and (f) show the cylindrical structure's trajectory curves. Initially, under the combined influence of the deflection velocity and flow speed, the cylindrical struc-

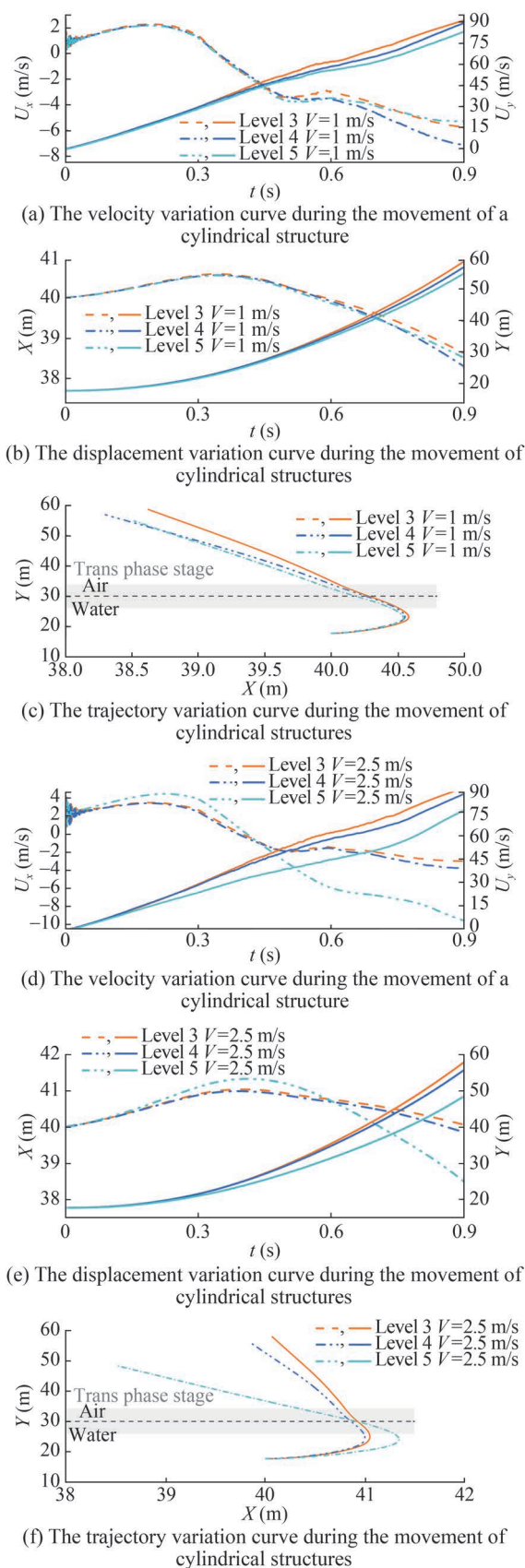


**Figure 18** Hydrodynamic characteristics curve under the influence of different wave levels during downstream flow

ture moves in the positive  $x$ -direction, with the cylindrical structure body having a certain deflection angle relative to the free surface. The cylindrical structure then continues moving toward the free surface at this deflection angle and exits the water. Given the influence of different initial motion conditions, variations in the final impact points of the cylindrical structure's trajectory are observed. As shown in Figure 18(c), during the water-exit phase, the cylindrical structure's deflection angle gradually increases with the wave level. This finding implies that at higher wave levels, the cylindrical structure exits the water at a flatter angle, which results in a lower impact point. In addition, at wave level 4, the cylindrical structure, which has a large horizontal velocity component, moves in the negative  $x$ -direction, and the final impact point is 38.3 m. At the water flow speed of 2.5 m/s and wave levels 3 and 4, the difference in the final impact points is relatively small. However, when the wave level is 5, remarkable changes occur in the cylindrical structure's motion. The flow direction, combined with the deflection velocity, causes intensification of the cylindrical structure's motion in the positive  $x$ -direction. Figure 18(f) shows the very small angle formed between the trajectory curve and the free surface and considerable horizontal movement of the cylindrical structure during the subsequent motion, with a noticeable decrease in the vertical height.

Figure 19 presents the specific values of the vertical motion characteristics of the cylindrical structure under various launch environments. Under varying wave conditions, as the current velocity increases, the vertical velocity of the cylindrical structure decreases substantially compared with that in still water. Specifically, when the flow velocity is 1 m/s, the vertical velocities are 91.22, 89.24, and 83.07 m/s. When the flow velocity increases to 2.5 m/s, the vertical velocities are 90.62 and 86.73 m/s, which are relatively close to the values at 1 m/s. However, under wave level 5, the vertical velocity drops considerably to 76.17 m/s, which indicates that high sea states exert a pronounced suppressive effect on the vertical motion of the structure. In addition, when the current direction is opposite, the overall vertical velocity is slightly higher than that in still water, with values reaching 95.87, 90.65, and 86.4 m/s. Nevertheless, the trend of decreasing velocity with the increase in wave level remains evident. The vertical displacement of the cylindrical structure generally decreases with the increase in flow velocity, with the effect being more pronounced under higher wave levels. When the flow velocity is 2.5 m/s, the vertical displacement is 58.02 m under wave level 3 and decreases to 48.59 m under wave level 5.

In summary, the results shown in Figure 19 indicate that the combined effect of wave level and flow velocity has a crucial effect on the water-exit motion of the cylindrical structure. Higher wave level exerts a stronger inhibitory effect on the vertical motion characteristics of the structure, which leads to reduced motion stability.

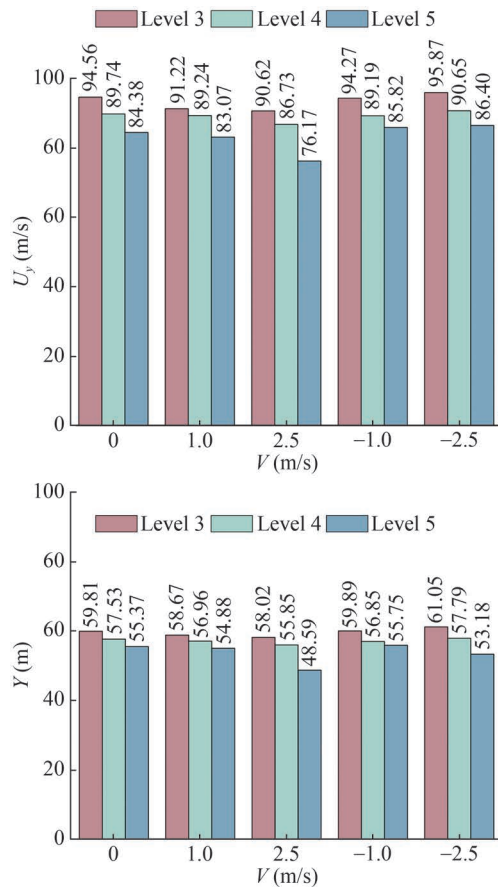


**Figure 19** Comparison of vertical motion characteristics during cylindrical structure movement

Figure 20 illustrates the hydrodynamic characteristics of the cylindrical structure under different wave levels in an upstream flow. As displayed in Figure 20, the solid line represents the vertical motion changes in the cylindrical structure, and the dashed line indicates the horizontal motion characteristics. In the upstream water flow direction, the cylindrical structure is affected by water flow disturbances, which results in oscillations in the horizontal direction. As the water flow speed increases, the amplitude of these oscillations also increases (Figures 20(a) and (d)). As the fluid direction is opposite to that of the initial deflection velocity, it impedes the cylindrical structure's motion. The cylindrical structure's horizontal velocity component represents the sum of the water flow speed and deflection velocity. As shown in Figure 20(a), when the flow speed is  $-1$  m/s, between 0 and 0.3 s, the cylindrical structure reaches its maximum horizontal velocity at 0.196 s, with velocities of 0.7, 0.62, and 0.59 m/s. During this process, the cylindrical structure's horizontal deflection reaches 0.022, 0.005, and  $-0.001$  m. Afterward, the cylindrical structure's speed in the x-direction continuously increases and ultimately reaches 8.81, 7.82, and 7.82 m/s. When the flow speed is  $-2.5$  m/s, as the flow speed exceeds the deflection velocity (1.8 m/s), the cylindrical structure's horizontal velocity at

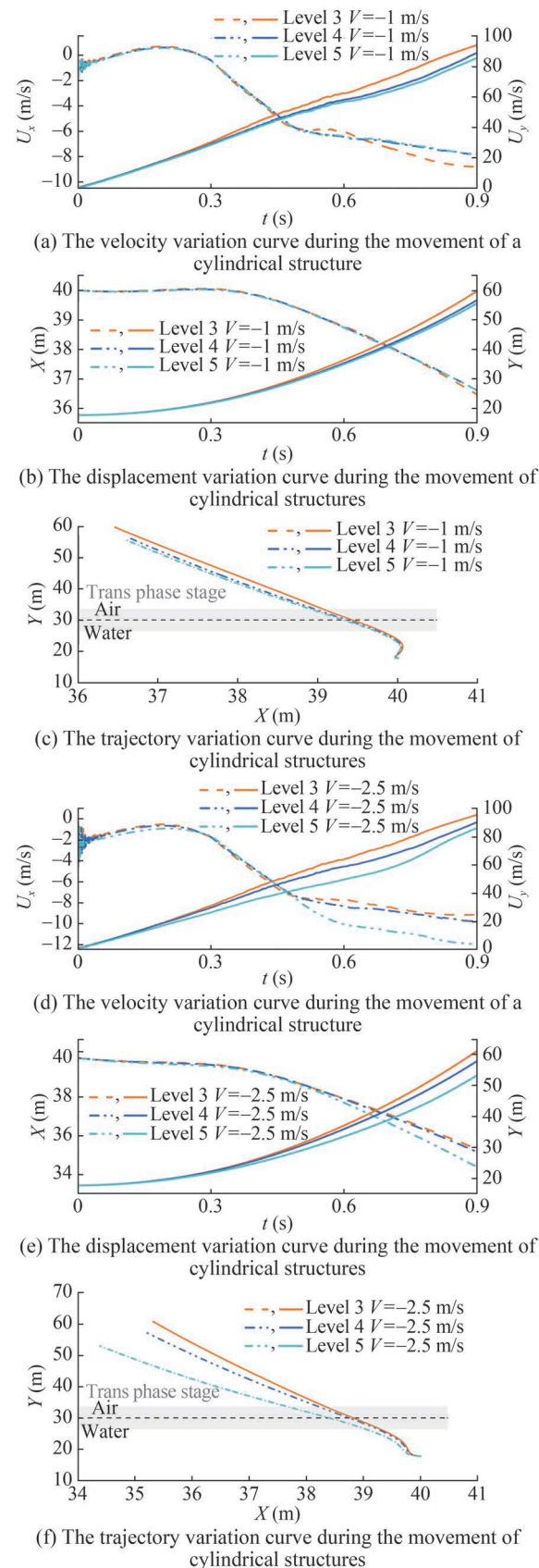


**Figure 20** Hydrodynamic characteristics curve under the influence of different wave levels during upstream flow

0.3 s amounts to 1.76, 1.77, and 1.67 m/s (Figure 20(d)). At this point, the cylindrical structure no longer deflects positively along the  $x$ -axis but moves in the negative  $x$ -direction. The cylindrical structure's horizontal deflection reaches  $-0.32$ ,  $-0.35$ , and  $-0.41$  m. Under the influence of current, the cylindrical structure's overall motion trajectory is mainly affected in the horizontal direction, with less effect in the vertical direction (Figures 20(b) and (e)). When the flow speed is  $-1$  m/s, the vertical velocity decreases with the increase in wave levels at 94.27, 89.19, and 85.82 m/s. Correspondingly, the vertical displacement decreases, with values of 59.89, 56.85, and 55.75 m. When the flow speed increases to  $-2.5$  m/s, the differences in the cylindrical structure's vertical motion characteristics under various wave levels become more significant. At wave levels 3 and 4, the vertical velocities and displacements are 95.87 and 90.65 m/s and 61.05 and 57.79 m, respectively. However, at sea level 5, the cylindrical structure's vertical motion characteristics decrease substantially, with the speed and displacement reaching 86.4 m/s and 53.18 m, respectively (Figure 19). According to Figure 20(f), under the combined effect of large flow speed and wave level 5, the cylindrical structure's posture at the water exit is close to the free surface. As a result, the cylindrical structure's overall motion trajectory experiences a large horizontal deflection, and the vertical displacement exhibits a noticeable reduction compared with other conditions.

Figure 21 unveils the cloud diagram of the cylindrical structure's state when it is stationary underwater ( $t = 0$  s). Given the influence of flow velocity, the waveform within the computational domain changes compared with still water, and the wave speed is also affected by flow velocity. At the flow velocity of 1 m/s, as the wave level increases, the degree of waveform decreases. At wave level 3, the waveform changes remarkably, and the wave surface flattens (Figure 21(a1)). However, when the wave level is 5, the effect on the wave surface is small at the flow velocity of 1 m/s (Figure 21(a3)). As the flow velocity increases, the influence on the waveform becomes more pronounced. When the flow velocity is 2.5 m/s, and the wave levels are 4 and 5, the effect on the free surface intensifies, and the upper liquid surface near the cylindrical structure appears nearly horizontal (Figures 21(b2) and (b3)). This condition causes alterations in the cylindrical structure's motion characteristics during its movement through the wave surface during water exit. When the water flow direction is opposite to the direction of wave propagation, the waveform changes are not significantly different from those during downstream flow. However, the change in flow direction has a noticeable influence on the cylindrical structure's horizontal motion characteristics as it exits the water.

For the cylindrical structure's motion process, with the case of wave level 3 and flow velocity of 1 m/s as an example, the motion process is visualized (Figure 22). From 0 s

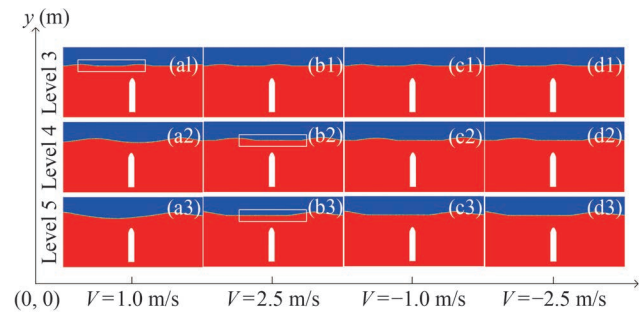


**Figure 21** Initial state cloud diagram of the cylindrical structure

to 0.3 s, the cylindrical structure is affected by the deflection velocity, that is, it experiences a small deflection toward the negative  $x$ -axis due to the deflection velocity and then moves toward the water surface in this state (Figure 22(a1)). From 0.34 s to 0.64 s, the cylindrical structure undergoes the water-exit phase. As the motion continues, at  $t = 0.34$  s, the cylindrical structure's nose contacts the free surface, and the fluid around it moves upward due to its effect  $e$ , which causes the liquid surface to lift (Figure 22(a2)). At  $t = 0.39$  s, the cylindrical structure's nose reaches the water surface boundary, which indicates that it is preparing to initiate the water-exit process. At this moment, the water surface rises considerably, with some fluid staying at the cylindrical structure's nose and adhering to the cylindrical structure's surface after the water exit (Figure 22(a3)). As the cylindrical structure continues to move out of the water, from 0.45 s to 0.53 s, the cylindrical structure passes through the water–air interface, with more than half of its body emerging from the water (Figures 22(a4) and (a5)). Figure 22(a6) indicates that at  $t = 0.64$  s, the cylindrical structure's tail completely leaves the water surface and enters the atmosphere, which completes the entire water-exit process. After the water exit, the cylindrical structure continues to move upward (Figure 22(a7)). Given the relative velocity between the cylindrical structure and the water and the water's viscosity, a significant wake is generated when the cylindrical structure exits the water. The wake follows the cylindrical structure as it continues to move. As the cylindrical structure's motion finishes, the wake gradually detaches from the cylindrical structure's tail, which affects the water surface, and this condition results in the formation of a noticeable vortex.

Figure 23 shows the pressure contour maps at the cylin-

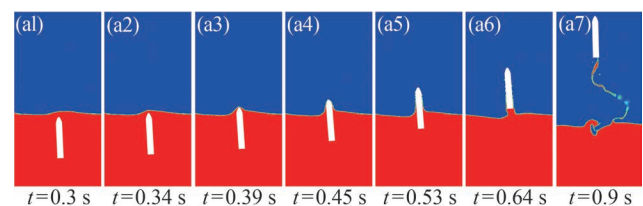


**Figure 22** Cloud diagram of the cylindrical structure's water-exit motion

drical structure's water exit in different wave levels and water flow velocities. From the overall flow field, the pressure exhibits a layered distribution, with varying pressure distributions observed around the cylindrical structure's body. Once the cylindrical structure initiates movement, as its speed increases, localized high-pressure regions appear at the cylindrical structure's nose and tail, and a low-pressure region forms at the shoulder. After the local pressure zones stabilize, they maintain their respective shapes. During the air phase of the cylindrical structure's nose, the high- and low-pressure regions at the nose and shoulder rapidly diminish. Once the cylindrical structure is completely above water, the localized pressure area at the tail gradually decreases, and it eventually disappears as the cylindrical structure's height increases. These pressure variations can be explained by the relationship between incompressible flow velocity and pressure. Based on relative motion, the cylindrical structure's movement through the fluid can be considered the fluid flow around the cylindrical structure. At the cylindrical structure's nose, the flow velocity stagnates, and pressure rises greatly. With the decrease in the flow area, the fluid accelerates, and pressure drops, which creates a localized low-pressure region at the cylindrical structure's shoulder. In the cylindrical structure's middle structure, where the flow velocity changes minimally, no localized pressure regions form. At the cylindrical structure's tail, the flow area increases, which causes a decrease in flow velocity and a subsequent rise in pressure. This condition creates a high-pressure region at the tail. At this point, the range of pressure

variation at the cylindrical structure's shoulder increases, and the negative pressure region expands considerably.

As shown in Figure 23(a), at the flow speed of 1 m/s, the pressure variation at various wave levels can be compared. Under different wave levels, the generation and decay trends of high- and low-pressure regions at the cylindrical structure's nose, tail, and shoulder are consistent, and the range of pressure variations is roughly the same, with minimal differences in the peak and trough values of localized pressure. These findings indicate that during the water-exit process, the pressure distribution is mainly determined by the static pressure of the liquid under gravitational force and changes in fluid particle parameters during the fluid–structure relative motion, with the characteristic parameters of the waves exhibiting a secondary influence. As shown in Figure 23(b), with an increase in flow speed, a comparison of pressure changes at different wave levels shows that at the flow speed of 2.5 m/s and wave level 5, the negative-pressure region at the cylindrical structure's shoulder is substantially reduced in the underwater region (Figures 23(b11) and (b12)). The cylindrical structure's effect on the entire flow field's pressure is minimal, and pressure effects are mainly concentrated around the cylindrical structure. The pressure influence in the flow field occurs primarily around the cylindrical structure's nose and tail.

Before 0.34 s (during the underwater motion phase) and from 0.34 s to 0.64 s (during the water-exit phase), pressure change at the cylindrical structure's nose is particularly noticeable. A high-pressure zone appears at the cylindrical

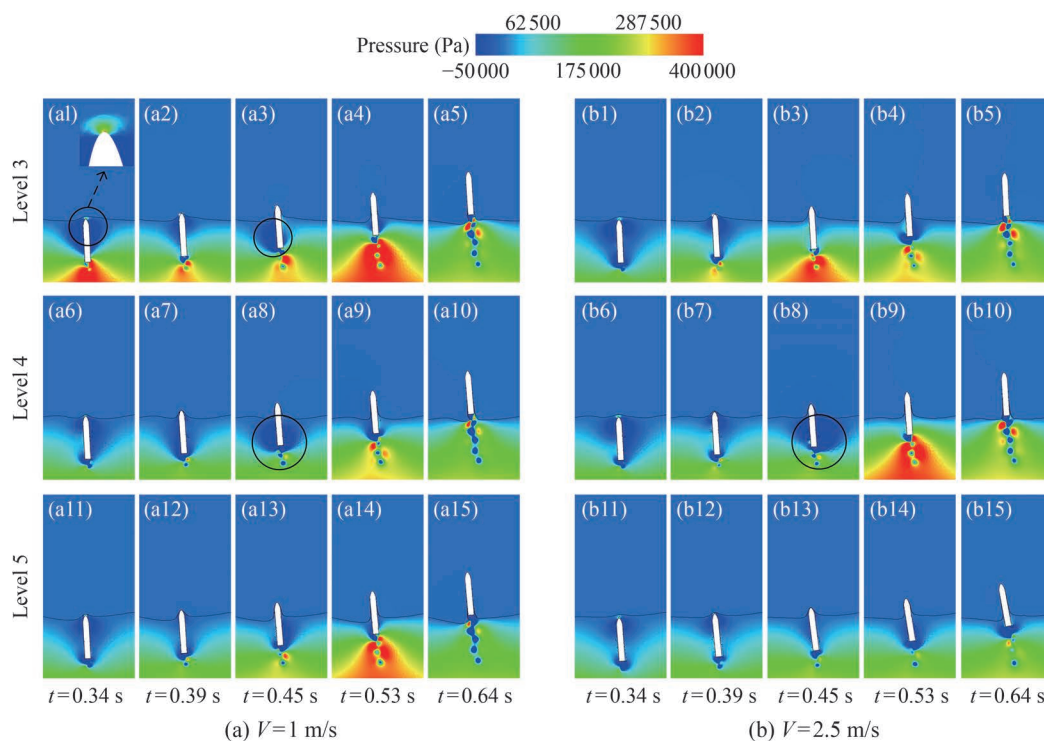


**Figure 23** Pressure contour diagram during the cylindrical structure's water-exit process

structure's nose, and a low-pressure zone is present at the cylindrical structure's shoulder (Figure 23(a1)). As the water flow speed increases, the pressure decreases, a phenomenon explained by Bernoulli's equation. At 0.45 s, the cylindrical structure breaks the water surface, and negative pressure appears at the lower part of the cylindrical structure body. Given the opposing direction of the waves and the cylindrical structure's motion, the cylindrical structure constantly affects the wave surface, which causes wave surface disturbances. As the cylindrical structure is a solid surface, fluid motion stagnates at the cylindrical structure's surface. The kinetic energy of the fluid is converted into pressure potential energy. As the cylindrical structure continues to move, the fluid's velocity increases, and the pressure potential energy is converted back into kinetic energy, which causes the fluid's velocity to reach its maximum. As a result, a noticeable low-pressure region exists at the cylindrical structure's surface (Figures 23(a3), (a8), and (b8)).

The pressure distribution diagrams reveal that after water exit, the pressure around the cylindrical structure body equilibrates with atmospheric pressure. As shown in Figures 23(a5), (a10), (a15), and (b5), (b10), (b15), a consistent trend of pressure variation around the cylindrical structure body is observed after it fully exits the water. After the water exit, the cylindrical structure's tail creates notable disturbances on the free liquid surface. As fluid velocity increases, negative pressure develops at the cylindrical structure's tail, and the wake moves along with the cylindrical structure until it dissipates. Given an air density of approximately  $1.29 \text{ kg/m}^3$ , which is 1/800th of the density of water, despite similar effects between air and water on the cylindrical structure, according to Bernoulli's equation, the smaller air density results in a pressure reduction of 800 times compared with underwater conditions. Therefore, after the cylindrical structure exits the water, changes in the pressure field around its body are minimal.

Figure 24 illustrates the velocity field evolution for the case under wave level 4 and a current velocity of 2.5 m/s. The velocity contour distribution exhibits asymmetric characteristics throughout the cylindrical structure's water-exit process, with the asymmetry aligning with the cylindrical structure's trajectory due to its deflection velocity. The cylindrical structure's kinematic state varies with different flow velocities, which results in substantial deviations in x-directional displacement due to current effects.

In the downstream flow direction, the cylindrical structure's trajectory in the x-direction deviates more compared with that in still water. On the other hand, when the flow direction is upstream, as a result of the hindrance caused by water flow, the cylindrical structure's displacement in the x-direction decreases, and its deflection amplitude diminishes. In addition, the velocity distribution at the cylindrical structure's nose and tail becomes more complex. During the cylindrical structure's water-exit process, the cylin-

drical structure body is surrounded by a layer of fluid, and as a result of viscosity, this fluid continuously maintains a relative velocity with the cylindrical structure. As the motion progresses, the relative velocity between this fluid and the cylindrical structure increases (Figures 24(b) and (c)). The velocity at the cylindrical structure's nose expands outward in a semicircular shape (Figures 24(d) and (e)). The maximum water flow velocity region occupies the cylindrical structure's tail, and as the motion continues, the tail flow region grows longer. In this region, water flow velocity changes in response to the cylindrical structure's speed. During motion, water flow velocity constantly dissipates, but the region with a higher flow velocity in the tail flow continues to follow the cylindrical structure's motion (Figure 24(f)). The further the tail flow is from the cylindrical structure, the smaller the water flow velocity. Once the cylindrical structure has water exited, the higher-velocity water in the tail flow separates from the cylindrical structure's tail and forms a high-velocity region underwater. The cylindrical structure's influence on the fluid is mainly concentrated in the tail flow region, which alters the potential and kinetic energy of the fluid in that region. As the motion continues, a part of the energy is dissipated due to the fluid's viscosity and eventually converted into the fluid's internal energy.

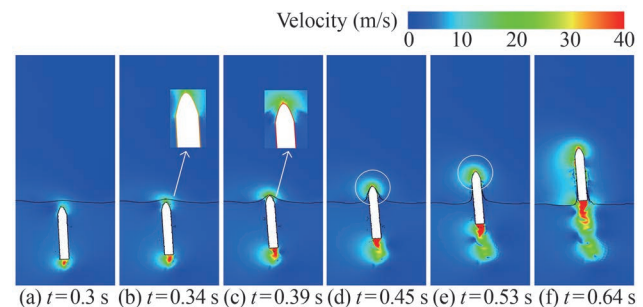


**Figure 24** Velocity field contour map during the cylindrical structure water-exit process

## 6 Conclusions

Based on the established high-precision numerical wave tank, this study employed appropriate numerical calculation methods to construct a multi-DOF model for cylindrical structure water-exit motion. Simulations were conducted to analyze the cylindrical structure's water-exit process under various conditions, including different wave levels, wave phases, and coupled wave–current effects. The investigation focused on the hydrodynamic characteristics of the cylindrical structure under various launch environments and examined phase diagrams, pressure field contours, and velocity field distributions during the cylindrical structure's motion. Furthermore, the research explored variations in

motion characteristics when the cylindrical structure exits at different phases under identical wave level conditions.

1) The spatiotemporal matching between the wave phase and cylindrical structure emergence position determines the directionality of the horizontal velocity component. In the wave crest region, horizontal flow acceleration occurred at a velocity of 2.33 m/s and wave level 3, which resulted in a positive displacement deflection of 0.52 m. By contrast, the wave trough exhibited flow separation effects, with velocities ranging from  $-1.39$  m/s to  $-2.54$  m/s at wave levels 4 and 5, which caused negative displacement offsets ranging from 0.56 m to 1.16 m. According to the velocity-phase distribution characteristics derived from second-order wave theory, when the wave level exceeded a critical threshold (wave level 4), the system experienced a dynamic transition from wave crest energy amplification to wave trough energy dissipation. This phenomenon prompted trajectory control systems to prioritize horizontal perturbation suppression and optimize water-exit stability through phase synchronization between deflection velocity and wave profiles.

2) This study elucidated the nonlinear coupling mechanisms between wave-phase dynamics and cylindrical structure water-exit kinematics at wave level 5. Phase-resolved analysis of Stokes wave horizontal velocity fields demonstrates critical phase-dependent momentum transfer: wave crests ( $180^\circ$  phase) and troughs ( $0^\circ$  phase) induced maximum opposing horizontal flow velocities with  $+4.60$  m/s and  $-3.66$  m/s, respectively, which generated lateral displacement discrepancies of 3.82 m. Symmetrical phase groups ( $60^\circ/240^\circ$ ,  $120^\circ/300^\circ$ ) displayed mirrored sign-reversal characteristics in displacement vectors. The deflection velocity induced a dynamic superposition inversion effect, which reversed the wave crest phase displacement from  $+2.15$  m to  $-1.62$  m while amplifying the wave trough phase displacement to 4.53 m. This phenomenon primarily arose from the nonlinear interactions between the cylindrical structure and the wave velocity field.

3) This work also focused on the nonlinear dynamic mechanisms governing cylindrical structure trans-phase motion under wave–current coupling effects. During the underwater phase dominated by N–S hydrodynamics, a downstream current ( $+2.5$  m/s) induced the nonlinear amplification of horizontal velocity to 9.58 m/s, which generated a maximum horizontal displacement of 1.51 m, and an upstream current ( $-2.5$  m/s) suppressed lateral deflection by 74.3% through momentum equilibration. Transitioning to the water-exit phase governed through reverse wave–current interactions under wave level 5, the expansion of the bow negative-pressure zone precipitated vertical velocity attenuation to 76.17 m/s, which ultimately shaped a trajectory with minimized inclination angles under  $12^\circ$  through coupled phase synchronization between wave profile dynamics and cylindrical structure kinematics.

These conclusions reveal that the motion attitude and

hydrodynamic characteristics of the cylindrical structure are affected by complex marine environments. In addition, the above studies were carried out in a 2D environment, which can provide data reference for further research on 3D environments.

**Funding** Supported by the National Natural Science Foundation of China (Grant Nos. 52171248, 52171278), the Guang Chuan Joint Fund of the Zhejiang Provincial Natural Science Foundation of China under Grant No. LGEY25E090002.

**Competing interest** The authors have no competing interests to declare that are relevant to the content of this article.

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