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Vortex shedding around a near-wall circular cylinder induced by a solitary wave

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This study developed a two-dimensional generalized vortex method to analyze the shedding of vortices and the hydrodynamic forces resulting from a solitary wave passing over a submerged circular cylinder placed near a flat seabed. Numerical results for validation are compared with other numerical and experimental results, and satisfactory agreement is found. A series of simulations were performed to study the effects of gap-to-diameter ratio and incident wave height on vorticity pattern as well as the forces exerted on the cylinder. The range of the heights of incident waves is from 0.3h to 0.7h, where h is the still water depth. The range of the gap-to-diameter ratios is from 0.1 to 0.8. The results indicate that the flow pattern and the pressure distribution change significantly because of the close proximity of the seabed where the vorticity flux on the seabed-side surface of the cylinder is suppressed. Placing the cylinder nearer the seabed increases the drag and the positive lift on the cylinder. When the gap-to-diameter ratio increases, the pattern of vortices changes because of the interaction between the main recirculation zone and the shear layers separated from the gap. The maxima of drag, lift and total force increase linearly with the height of the incident wave.

1. Introduction

With the development of marine engineering, installing subsea pipelines alongshore has become a common marine construction. Subsea pipeline constructions, such as those for telecommunications, power cables, crude oil transportation, running water transportation, and optical networks, are extremely relevant to people's lives. Nevertheless, waves and ocean currents in the marine environment are constantly scouring the seabed, frequently damaging subsea pipelines. For example, in 2003, a total of approximately 175 m of spanning was found in the subsea gas pipelines installed by the Chinese Petroleum Corporation (Taiwan) in the open waters of Tung Shiau, with a maximum spanning length of approximately 100 m. Subsequently, the pipelines were backfilled using the riprap method. However, an inspection conducted in 2004 found that a portion of the pipelines were again exposed and spanning, with an average spanning height of 0.4–0.5 m. Therefore, understanding the hydrodynamic phenomena surrounding subsea pipelines and the mechanism of destruction is vital in the field of marine engineering.

In addition to the pressure gradient resulting from surface waves, the creation and shedding of vortices surrounding pipelines generate significant stresses that affect subsea pipelines. When gaps occur between pipelines and the seabed, the

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vortex effects increase in complexity. Previous studies examining this issue have yielded numerous findings regarding the flow fields of uniform and oscillating flows passing through cylinders. By contrast, few studies have simultaneously analyzed the surface waves and the vortices formed by flows passing through cylinders.

Because of the determining effects of vortices in this issue, overlooking viscous effects during analysis may limit the practicality of the results. For example, Li and Cheng (1999) employed potential flow theory to simulate the scour that results from unidirectional flows passing through offshore pipelines. In their study, the interactions between flow fields and topography was conducted by interaction, and the interactions among flows, pipelines, and the bed were considered. The results showed that the predicted maximum scour depths approached the depth yielded by the empirical equation only during clear-water scouring. Analysis indicated that the difference occurred because vortex effects were neglected in the potential flow model.

Because potential flow theory cannot be used to analyze vortex effects, the majority of relevant studies have applied viscous flow theory. For example, Dipankar and Sengupta (2005) used the stream function-vorticity formulation of the Navier–Stokes equations. They employed an improved overset grid method to simulate uniform flows passing through cylinders located above the bed, and compared the results yielded by different ratios of cylinder diameter (D) and pipeline-bed gap (G). The results showed that the lift force and drag force coefficients approached the experimental data when the G/D ratio was 0.5 and 1.5. Liang and Cheng (2005) used turbulence models such as the k–ε model and Smagorinsky subgrid-scale model to simulate the bed scouring below a pipeline resulting from waves. In this study, waves were simulated using sinusoidal oscillatory flows; therefore, the interaction between fluctuations in the water surface and the pipelines was not analyzed. An et al. (2011) simulated the flow field around a cylinder near a bed boundary in oscillating flows, and used the 2D Reynolds-averaged Navier–Stokes equations and the finite element method to solve the k–ε turbulence model. This study examined the flow fields surrounding cylinders when the Stokes number was 196, the KC number was between 2 and 30, and the ratio of the gap between the cylinder and the bed boundary (G/D) was between 0 and 3. The results showed that steady flow positions were affected by the KC number and the gap-to-diameter ratio.

Regarding experimental observations, Sumer et al. (1991) conducted an experiment that involved placing a cylinder on a plane in an oscillating flow field and examining the instantaneous pressure distribution surrounding the cylinder when the Reynolds number was relatively large ($\mathrm{Re}=10^5$) and the flow field of vortex motion when the Reynolds number was relatively small ($\mathrm{Re}=10^3$–10^4). The results indicate that vortex streets disappeared when $7<KC<13$. As the KC number declined, vortex shedding existed when the gap-to-diameter ratio was small, and as the gap-to-diameter ratio declined, the Strouhal frequency increased. Lin et al. (2005) investigated the flow fields surrounding cylinders at $\mathrm{Re}=780$ and the gap ratios for the planar boundary differed. The results showed that the plane had no influence on the vortex shedding frequency when $G/D>3.0$; however, the frequency increased as the G/D declined from 3.0 to 0.6, and decreased when $G/D<0.6$. Qi et al. (2006) conducted a series of experiments regarding shallow water turbulences passing through cylinders of varying height. The results indicated that unshedding occurred in the vortex structure when the cylinder contacted the bed and the free surface, and that vortex shedding occurred with variations in cylinder height. Researchers have conducted experiments to observe the scour mechanisms surrounding pipelines. For example, Chiew (1990) explored the primary effects that unidirectional flow fields have on the scouring mechanism. The experimental results indicated that the contact between the pipeline and stagnation eddy causes the deposition of non-cohesive soil and subsequently local scour, thereby initiating the scouring mechanism, the key factor of which is the flotation gradient of the seabed deposition. Specifically, a depth-to-diameter ratio higher than 3.5 is unlikely to result in scour. However, when the hydraulic gradient caused by the pipeline exceeds the flotation gradient of the seabed deposition, upstream stagnation eddy is likely to result in scour.

Studies examining the vortex flow fields resulting from waves passing through cylinders placed on an even seabed have rarely focused on solitary waves as the research subject. Solitary waves, which possess single peaks and infinitely long wavelengths, can be used to simulate alongshore storm surges and tsunamis. This study used solitary waves as the subject and developed a two-dimensional generalized vortex method to analyze the flow field and the hydrodynamic forces resulting from a solitary wave passing through a submerged circular cylinder placed near an even seabed. The effects that the gap between the cylinder and the seabed and the incident wave height have on vortex types and drag were also investigated.

2. Governing equations and boundary conditions

The problem of interest concerns the calculation of the two-dimensional flow of a solitary wave over a near-wall circular cylinder in a uniform channel. The viscous effects as well as the generation of vorticity at the free surface are ignored. The x-axis lies in the undisturbed free surface and the y-axis points vertically upward with unit vectors $\hat{\mathbf{e}}_x$ and $\hat{\mathbf{e}}_y$, respectively (see Fig. 1). The corresponding fluid velocity components are u and v, respectively, and $\mathbf{u}$ is the fluid velocity vector. The motion of the fluid is governed by the incompressible Navier–Stokes equations:

$$\nabla\cdot\mathbf{u}=0, \tag{1}$$

$$\frac{\partial\mathbf{u}}{\partial t}+\mathbf{u}\cdot\nabla\mathbf{u}=-\frac{1}{\rho}\nabla p-g\hat{\mathbf{e}}_y+\nu\nabla^2\mathbf{u}, \tag{2}$$