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Reduction of internal-solitary-wave-induced forces on a circular cylinder with a splitter plate

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ABSTRACT

Internal solitary wave (ISW) of depression type widely exists in stratified water, with upper layer having a lower density caused by salinity or temperature. The ISW-induced force on the pile is different from that induced by pure current due to the feature of different flow directions between these two layers. The question remains whether the method commonly used for reduction of forces acting on a pile under pure current can still be applied in case of ISW propagation. In this study, a splitter plate deployed upstream of the pile with its frontal face normal to the wave propagation is used to explore the reduction of forces on an erected cylindrical pile. The ISWs-induced forces acting on a pile with different splitter plates are simulated by means of the large eddy numerical simulation. Extra laboratory experiments on the propagation of the ISWs around an erected cylindrical pile without a splitter plate are carried out for verifying the numerical models. It is found that the splitter plate has prominent influences on the force distribution of the pile in the upper layer. However, it hardly has an effect on the counterpart in the lower layer during the propagation of the ISWs of depression type. In addition, the pattern of vortex structures existing behind the splitter plate does play an important role in reducing the forces on the frontal side of the pile. Numerical results also reveal that the length of the splitter plate and the distance between the splitter plate and the frontal side of the pile characterize the feature of vortex structures around the pile. It is important to restrain the parameters of splitter plates at an appropriate level. Otherwise, over-reduction would occur and the ISWs-induced forces acting on a pile with the splitter plate would be unexpectedly larger than forces on the single pile without a splitter plate.

1. Introduction

Environmental flow with stable stratification widely exists in oceans, estuaries and lakes while fluid density changes with the depth because of the variations in temperature, salinity and other environmental factors (Hu et al., 2001). Internal solitary waves (ISWs) are usually generated by a tiny or weak disturbance at the interface of such stable stratified fluid, and their amplitudes and periods are usually larger than those of surface waves (Zhang et al., 2013). Strong underwater current caused by the ISWs could be a serious threat to underwater structures, such as oil drilling platforms or supporting cylinders (Osborne and Burch, 1980).

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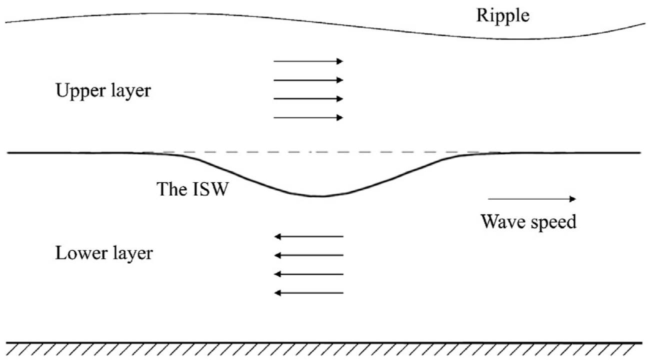

Fig. 1. Schematic diagram for propagation of an ISW with depression type.

In hydraulic and marine engineering, cylindrical structures are fairly common such as piers (Wang, 2014). Previous studies on the stabilities of single cylinder under the propagation of the ISWs have been done extensively. Zhou et al. (2005) found that the alternate vortex shedding behind the cylinder not only leads to increase of the streamwise force, but also results in the oscillating lift force acting on the cylinder. Han (2011) reported that such oscillating force threatens the underwater structures and causes fatigue damage accordingly.

As a result, many researchers, such as Achenbach (1968) and Gu et al. (2012), paid attention to reducing the fluid forces acting on structures by means of suppressing the flow separation and vortex shedding. Morel and Bohn (1980) performed some physical experiments on flows over two circular cylinders set in tandem arrangement, revealing that the forces acting on both of the two cylinders are smaller than single one. Many methods for reducing flow forces are based on this point of view. Lesage and Gartshore (1987) reduced both the average flow forces and the oscillating fluid forces acting on the cylinder by settling an object upstream of the cylinder to suppress the vortex shedding in the flow. Overall, a splitter plate is a proper way to reduce the forces acting on a cylinder and actually the flow field induced by a splitter plates is similar to the cases of flow over the tandem cylinders. Alam investigated the Strouhal numbers, forces and flow structures in the wake of two tandem cylinders of different diameters (Alam and Zhou, 2008). Chen used immersed boundary method to study vortex induced vibrations of three tandem cylinders (Chen et al., 2018). In terms of the ISWs, Wang carries out numerical experiments to study ISWs over two tandem cylinders (Wang et al., 2016), finding that the distance between the two cylinders plays an important role in forces acting on the two piles.

Up to date, many studies were focused on reduction of the flow-induced forces on the cylinders subjected to flow with uniform density. While, there are few studies on reduction of flow-induced forces in the stratified environment, especially under the propagation of the ISWs. In fact, the flow field induced by the propagation of the ISWs is quite different from that in the pure current (Geodäsie, 2012). As seen in Fig. 1, the ISW exits at the pycnocline and is a result of disturbance from winds near the free surface or complex topographies at the bottom. The pycnocline is usually a result of the thermocline or the halocline in the sea. When an ISW of depression type propagates, the flow velocity in the lower layer is opposite the direction of that in the upper layer and the latter is the same as the direction of wave speed. The differences in velocity between two layers in stratified environment do not exist in the pure current condition, which results in the fact that ISW-induced force on the pile is different from that induced by the pure current. So it is necessary to study how to reduce the flow-induced forces on the cylinders under this condition.

In the present study, with reference to the methods used to reduce fluid forces acting on cylinders in uniform density flow, a series of numerical experiments on ISWs the propagating over the circular cylinder with a splitter plate placed upstream of the cylinder were conducted to study reduction of the flow-induced forces on cylinder. The numerical models and verifications are introduced in Sections 2 and 3 respectively. In Sections 4 and 5, numerical simulated results and discussions about the effect of a splitter plate on the forces induced by the ISWs are addressed. Finally, the conclusions are drawn in Section 6.

2. Numerical models

2.1. Momentum equations and continuity equation

Applying continuity assumption, the motion of three dimensional (3D) unsteady incompressible flow governed by Navier–Stokes equations can be described as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial \left(\rho u_i u_j\right)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial x_j}\right) + f_i \tag{2}$$