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Experimental study of flow structures of a solitary wave propagating over a submerged thin plate in different angles using PIV technique

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ABSTRACT

This research presents an experimental investigation into the interaction of a solitary wave and a submerged thin plate under different angles. Experiments are conducted to measure both velocity and vorticity by using the Particle Image Velocimetry (PIV) technique. Effects of changing the thin plate angle on the wave height and wave speed are analyzed through the use of wave height gages. Vortices are generated when the solitary wave is transmitted over the obstacle. Understanding the formation and location of the vortices will help analyze the obstacle effect on the flow. In the initial stage, a thin plate is located vertically, and flow structures are visualized. The plate is then deviated from the vertical direction towards positive angles (the direction of wave propagation) and towards negative angles in the opposite direction. In order to study the effects of the plate angle on the flow structures, experiments are carried out for three positive and three negative angles. Comparison of the formed vortices at different angles shows the formation of an additional vortex near the bottom of the channel for positive angles, as opposed to negative angles. The larger the angle is, the less the formation time of the vortex at the bottom of the channel will be. The study of the clockwise vortices formed behind the obstacle shows that increasing the plate angle in both directions decreases their strength. The clockwise vortices of negative angles are stronger than those of positive angles. In addition, changing the plate angle to the negative direction causes more wave height and wave speed reduction than changing it to the positive direction.

1. Introduction

The study of wave transmission over obstacles has always been an important subject in the field of marine engineering. These obstacles are either fully or partially embedded in the water. Flow patterns formed on the obstacle, directly impact the changes in the wave and wave energy, which is crucial to the design of a submerged breakwater. However, vortices formed around the obstacle, and the fluctuations created by them are very effective in absorbing energy from waves.

The study of solitary wave propagating over a submerged obstacle has been carried out in numerous ways. Since early times, the study of solitary wave propagation over submerged cylinders has been important because of its application in costal engineering and the petroleum industry (Ogilvie, 1963; Cooker et al., 1990; Chian and Ertekin, 1992; Xiao et al., 2013). Purpose of most numerical and experimental researches on other submerged obstacle was often two important issues: study on wave reflection, transmission, and dissipation (RTD) coefficients (Mei and Black, 1969; Seabra-Santos et al., 1987; Silva et al., 2000; Chang et al., 2001; Lin, 2004) and, the generation and evolution of vortices in the vicinity of a submerged obstacle under solitary waves (Zarruk et al., 2015; Hsieh et al., 2015).

Recent experimental research has focused primarily on vortex shedding and evolution induced by a solitary wave propagating over submerged cylindrical structures and other obstacles By using PIV and laser induced florescent (LIF) methods (Zarruk et al., 2015; Chang et al., 2012). Zhuang and Lee (1996) studied the interaction of a solitary wave and a submerged dike both numerically and experimentally. A four-beam laser Doppler velocimeter was used to measure the water particle velocities. The flow separation behind of block was visualized by tracing the motion of injected dye in a laboratory flume (Tang and Chang, 1998). Chang et al. (2001) used Particle Image Velocimetry (PIV) technique to measure the velocity field in the vicinity of the obstacle which was induced by interactions of a solitary wave and a submerged rectangular obstacle. Also, the numerical and experimental vortex shedding results at the corners of the obstacle were compared that had good agreement with each other. Chang et al. (2005) studied the generation and evolution of vortices in the vicinity of a submerged rectangular obstacle under cnoidal waves. Lin et al. (2006) studied the gener-

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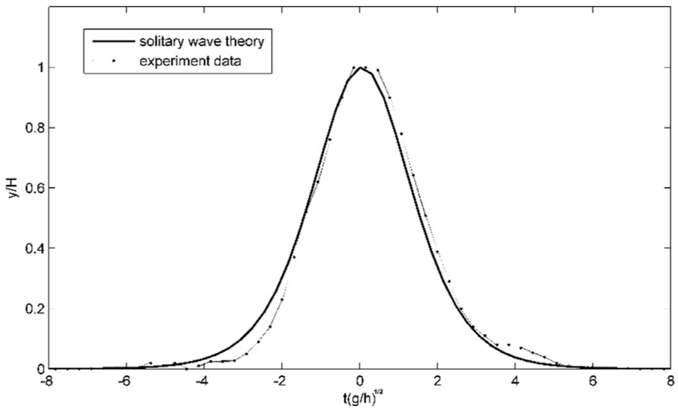

Fig. 1. Comparison of free surface profile between the solitary wave gauge measurement and the theoretical equation results.

ation and evolution of vortices induced by a solitary wave passing over a bottom mounted rectangular dike by using three visualization techniques, Particle Image Velocimetry (PIV), laser-induced fluorescence (LIF), and particle tracing. Unlike most of the previous reports that found only one vortex generated at each side of the dike, they reported six vortices at the weather side of the dike and seven vortices on the lee side of the dike. The interactions between a solitary wave and a submerged vertical bottom-mounted barrier were investigated experimentally and numerically (Wu et al., 2012). The solitary wave has also been studied in a two-layered fluid system, known as the internal solitary wave (Hsieh et al., 2015; Ermanyuk and Gavrilov, 2005). The fluorescent injection has been used in investigations to better visualize flow patterns and stratified mixing caused by internal solitary waves in two-layered fluid systems (Chen, 2007).

Because of the simple geometry and similarity to breakwater, the rectangular obstacle was used in many numerical and experimental studies. Ting and Kim (1994) was the first person to compile both experimental (LIF) and numerical methods to detect flow separation during when a solitary wave passes over a submerged rectangular (Ting and Kim, 1994). The solitary wave propagation process and its interaction with submerged rectangular obstacles have been studied under both numerical methods and various laboratory environments (Mei and Black, 1969; Chang et al., 2001; Lin, 2004; Zarruk et al., 2015; Chang et al., 2012; Zhuang and Lee, 1996; Tang and Chang, 1998; Chang et al., 2005; Lin et al., 2006a) and (Ting and Kim, 1994; Huang et al., 2003; Decheng and Guoxiong, 1998; Huang and Dong, 2001; Lin and Huang, 2010; Zhou et al., 2014; Rey et al., 1992). In all of the above studies, length of the rectangular obstacle was seen to have the same or even greater than its height.

The study conducted by Lin et al. (2005a,b) showed the length of the flow pattern near the rectangular obstacle to be much smaller than its height, and typically represented by a vertical plate (Lin et al., 2006b, 2005a). While their primary focus lay on the formation of the separated shear layer and its comparison to the tick rectangular (Lin et al., 2005b), Chang Lin et al neglected angle variation influences of the plate on flow pattern and vortex shedding.

In this study, the PIV technique is used on the transmission of a solitary wave over a thin vertical plate fully imbedded in water, in order to investigate the procedure of vortex formation, as well as the flow pattern behind and in front of the plate. The same was conducted on different plate angles of 30, 45 and 60° in both positive and negative directions. Moreover, wave gages were used to study the angle change effect of a thin plate on the wave height and wave celerity.

2. Experiment setup

PIV tests are carried out in an open water channel with 7 m long and 0.3 m width, and have a transparent Plexiglas wall. A piston wave maker, which is installed at the end of the channel, generates a solitary wave with a height of 9 cm through a water depth of 26 cm. The water free surface displacement can be obtained from the following equation (Lin and Huang, 2010):

$$\eta(x,t) = Hsech^2\left[\sqrt{\frac{3H}{4h^3}}(x-ct)\right] \quad (1)$$

where η denotes the free surface elevation above the still water level based on location (x) and time (t) parameters. H is the maximum wave height and c is the wave celerity that can be calculated theoretically from Eq. (2):

$$c = \sqrt{g(H+\mathrm{h})} \quad (2)$$

The generation of solitary waves by a piston type wave maker can be repeated. The comparison depicted in Fig. 1 shows good agreement between the generated solitary wave, measured by the wave gauge and the theoretical equation obtained from Eq. (1).

Akaminna wave height gauges (AWP_300Series) are used to measure the wave height. Following the placement of two wave height gages on both sides of the plate, the changing effects of the plate angle on wave celerity and wave height are studied (see Fig. 2) (Wave height gauge AWP-24-3 model, Acamina Company 2001).

The PIV experiment in this study includes a CMOS camera, a continuous laser and tracer particles with 10 and 20 µm diameters. The green light laser (DPSS), with 532 nm wavelength is adjusted to 9 W of power, and a cylindrical lens is located in front of the laser to create a light sheet on the flow. The shutter speed is performed at 450 fps, with a 1280*1024 resolution to take sequential photos from the flow. Finally, the PIV images are analyzed

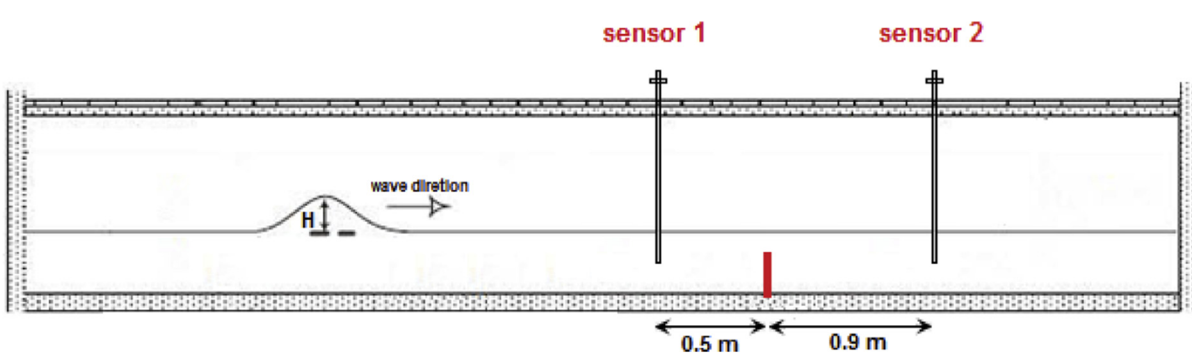

Fig. 2. Schematic diagram of the location of wave height gages.