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Vortex transportation and wave deformation after the interaction of a solitary wave with an inclined bottom mounted plate

Chih-Hua Chang[a,b,*], Keh-Han Wang[c], Chang Lin[d], Jassim M. Jaf[e]

[a] Department of Information Management, Ling-Tung University, No.1, Ling-Tung Rd., Taichung, 408, Taiwan, ROC
[b] Natural Science Division in General Education Center, Ling-Tung University, No.1, Ling-Tung Rd., Taichung, 408, Taiwan, ROC
[c] Department of Civil and Environmental Engineering, University of Houston, Houston, TX, USA
[d] Department of Civil Engineering, National Chung Hshin University, Taichung, 402, Taiwan, ROC
[e] Department of Civil Engineering, University of Kirkuk, Kirkuk, Iraq

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ABSTRACT

This study is aimed to investigate numerically and experimentally the interaction between a solitary wave and a thin submerged plate with various inclinations. The obtained results on wave deformations and formed vortex patterns are analyzed. To extend the very limited study on a solitary wave encountering an inclined plate, the developed streamfunction-vorticity formulations with free surface (SVFS) model is applied to compute the flow field, wave profiles, and induced forces. In addition, the experimental measurements of wave elevations and flow visualizations using particle image velocimetry (PIV), particle-tracking, and planar laser-induced fluorescence (PLIF) were conducted. This paper presents qualitative and quantitative comparisons between numerical solutions and experimental data, including the recorded images. The agreements are generally good. The influence of tilting angle, ranging from -60° to 60°, on the flow patterns, formed vortices, and free-surface elevations are examined and discussed. For a given incident wave and the setting of the same vertical level of the plate tip, it is found that the wave attenuations under a plate with a downstream tilting angle (positive angle) is larger than that when a plate is placed with an upstream tilting angle (negative angle). Also, the occurrence of maximum intensity of the main vortex is observed to be within the tilting angles of -30° to -10° depending on the setting of the plate height. In terms of hydrodynamic forces, when keeping the same tilting angle, the results suggest the maximum horizontal force per unit width on a downstream tilting plate is larger than that on an upstream tilting plate.

1. Introduction

The modeling of wave deformation due to submerged obstacles is vital to the hydrodynamic analyses of those coastal structures. Additionally, the wave induced vortex flows around a bottom -mounted structure may be critical to the constructed marine structures and their foundation stability. Relatively, the finite-thickness breakwater in the large ocean scale can be regarded as a thin obstacle, like a plate. Therefore, this simple physical geometry has been assumed in the past for obtaining either the analytical or numerical solutions to describe the complex fluid-structure interaction problems. The linear wave interacting with an infinitely thin vertical plate was studied by researchers, such as Evans [1] and Porter and Evans [2] for a single plate, and Evans and Morris [3] and Newman [4] for multiple tandem plates. Most of the problems were solved either by obtaining closed-form solutions with or without using the asymptotic perturbation methods or through computational procedures. Different from the vertically upward position, the wave encountering a plate with an inclination is another interesting problem worthy of investigation. This issue can be related to breakwaters with side surfaces facing wave-induced motions in a tilted position. Also, for the design consideration, more effective and better looking breakwaters in the coastal environment are sought. A recently built flooding defense device named MOSE system [5] in Venice, Italy was an example of barriers that can be rotated from the submerged bottom position into a setting as an inclined above water-level breakwater to block the rising water entering the city. Waves interacting with an inclined wall in general is more difficult to obtain the exact solutions mathematically. Potentially, the breakwater with a proper inclined angle can be more effective in attenuating the incoming waves. Rao et al. [6] studied experimentally the influence of a submerged inclined plate on wave transmission. They found that a plate type breakwater with inclinations of $+60^\circ$ and -60° (0° as the referenced vertical

* Corresponding author.
E-mail address: changbox@teamail.ltu.edu.tw (C.-H. Chang).

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position) can reduce, within a large range of relative depths, the monochromatic wave height by about 40%. Recently, Koutandos and Karambas [7] investigated through wave-tank tests the interactions between waves and a partially immersed vertical/inclined thin breakwater. They concluded that the lowest transmission coefficient mostly occurs when the plate was either at the -30° or $+30^{\circ}$ position. In contrast, a breakwater with 0° inclination (a vertical breakwater) presents the highest wave transmission. Therefore, the plate's inclination is a very important design factor as it influences greatly the effectiveness of a breakwater. Additionally, only limited studies on the interaction between nonlinear waves and inclined structures have been reported.

A solitary wave is a unique nonlinear wave that in propagation is balanced with its dispersive property in shallow waters. One of the problems among the solitary waves interacting with thin structures is the case considering a solitary wave encountering a submerged horizontal plate. In shallow waters, it is shown that the submergence of a plate apparently plays a significant role on the wave scattering [8]. The results have also been discussed by others (e.g [9,10].). The studies related to the interactions between a solitary wave and other types of structures can also be found in literatures. As the present study mainly concerns about the flow patterns and vortices induced at the interaction between a solitary wave and a bottom connected tilted plate, the following literature review intends to focus more along this aspect. Some researchers have studied the encountering of a solitary wave with a thin vertical plate analytically. For example, Sugimoto et al. [11] investigated the reflection and transmission of a solitary wave passing over a thickless plate using the edge-layer theory. Later, this theory was extended by Jeffery and Ramollo [12] to study the internal wave propagation. In addition to the wave nonlinearity, the vortex shedding caused by the interaction between a solitary wave and structures has also been the focus of many studies (e.g [13–15].). Considering a propagating solitary wave against plates, Liu and Al-Banaa [16] numerically studied the problem of a solitary wave encountering a partially submerged vertical plate using RANS (Reynolds Averaged Navier-Stokes) model. They also conducted PIV (Particle Image Velocimetry) measurements for the visualization of wave induced flow motions. A more detail experimental investigation for a solitary wave propagation over a bottom mounted plate was conducted by Lin et al. [17], where the PIV measurements and particle tracing technique were used to reveal the flow patterns. Recently, Jaf and Wang [18] adopted the Fourier integral method to derive analytical solutions describing a solitary wave propagating over a submerged vertical plate and conducted experimental measurements to verify their solutions. They also examined the effect of breakwater height on the peaks of reflected and transmitted waves. As for the inclined barriers, the studies of their effects on an approaching solitary wave have been very limited. Zaghian et al. [19] experimentally analyzed a solitary wave interacting with a tilted plate using the PIV method. Their visualization photos were adopted to compare to the present numerical results.

In this study, an extension of Chang's modeling approach [20] on a solitary wave interacting with a submerged vertical plate is carried out to investigate the interaction process, including the formed vortices, between a solitary wave and an inclined plate with a set tilting angle. The enhanced SVFS (Streamfunction-Vorticity formulations with Free Surface) model is applied to simulate the free-surface deformation and associated vortex motions as a solitary wave passes over a bottom inclined plate. For the validation of the numerically generated streamline patterns and the trajectories of vortex cores, the work of particle-tracing visualizations and PIV measurements were conducted in a laboratory flume. To further the comparisons, a series of experiments with the use of a planar laser-induced fluorescence (PLIF) technique were carried out to record the visualized evolution of the induced vortices. Additionally, the free-surface elevations of the reflected and transmitted waves were recorded for comparison with the numerical results. Basically, the comparisons considering either quantitatively or qualitatively between the simulated and measured flow characteristics are in good agreements. After the verifications of the numerical model, a series of numerical results showing the effect of plate inclination on the wave transformation and induced flow pattern are also presented and discussed.

2. Equations and numerical procedures

The numerical method is based on the streamfunction (ψ)-vorticity (ω) with free surface (SVFS) model, which was initially developed by Tang and Chang [21] and later improved by Chang et al. [22]. In this study, the SVFS model is further extended and adjusted to simulate a solitary wave encountering an inclined bottom mounted plate. This is a two-dimensional unsteady wave motion problem considering incompressible fluid with non-breaking surface waves. Also, the surface tension effect is ignored. The mathematical formulations and numerical method are summarized below.

The describing formulations of the fluid motions are expressed originally in the Cartesian-grid $O(x, y)$ system. To conform the moving free surface and to fit the inclined plate, a boundary-fitted curvilinear coordinate grid $O(\xi, \eta)$ system is employed. The physical variables are nondimensionalized with the length scaled by the constant undisturbed water depth H^{*} and the time by H^{*}/C_0^{*}, where $C_0^{*} = \sqrt{gH^{*}}$ is the linear-long-wave celerity, g is the constant acceleration due to gravity, and the variables with superscript symbol "*" represents the dimensional physical quantities. In terms of water depth its dimensionless symbol H (See Fig. 1) is equal to one. The flow motions are governed by the Poisson equation of streamfunction and the vorticity transport equation; they are given in terms of curvilinear forms as

$$\left.\begin{aligned} \nabla^2\omega &= \mathrm{Re}(\omega_\tau + U\omega_\xi + V\omega_\eta) \\ \nabla^2\psi &= -\omega \end{aligned}\right\}, \text{ inflow domain} \tag{1}$$

The subscripts with respect to the coordinates (ξ, η) and the corresponding time τ denote the partial derivatives. In Eq. (1), Re is the Reynolds number defined as $H^{*}\sqrt{gH^{*}}/\upsilon$, where υ is the kinematic viscosity. The variables U and V are the contra-variant components of the fluid velocities given as

$$U = (-x_\tau y_\eta + y_\tau x_\eta + \psi_\eta)/J;\; V = (-y_\tau x_\xi + x_\tau y_\xi - \psi_\xi)/J, \tag{2a, b}$$

The symbol ∇^2 is the Laplacian operator, which is defined as

$$\nabla^2 = g^{11}\frac{\partial^2}{\partial\xi^2} + 2g^{12}\frac{\partial}{\partial\xi}\frac{\partial}{\partial\eta} + g^{22}\frac{\partial^2}{\partial^2\eta} + f^1\frac{\partial}{\partial\xi} + f^2\frac{\partial}{\partial\eta} \tag{3}$$

where

$$g^{11} = (x_\eta^2 + y_\eta^2)/J^2, \tag{4a}$$

$$g^{22} = (x_\xi^2 + y_\xi^2)/J^2, \tag{4b}$$

$$g^{12} = -(x_\xi x_\eta + y_\xi y_\eta)/J^2, \tag{4c}$$

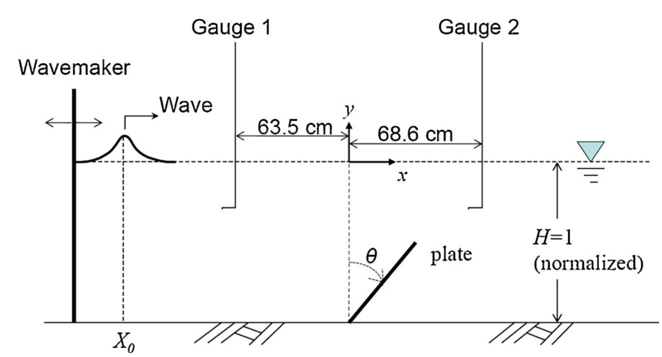

Fig. 1. Schematic diagram of the physical problem.