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An experimental study of steep solitary wave reflection at a vertical wall

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ABSTRACT

Until now very few experimental investigations have been conducted to study the reflection of steep solitary waves at a vertical wall whereas many theoretical analyses and numerical simulations have been developed in the past. The use of experimental techniques to capture the waveform and associated phenomena during the short-time head-on collision of two solitary waves (or the reflection of a solitary wave by a vertical wall) is not an easy task. Solitary waves with amplitude $a/h \leq 0.556$ are experimentally generated by a piston type wavemaker. We have used a high speed camera and our experimental results were compared with previous studies, including both theoretical investigations and numerical simulations.

Experimental values of attachment and detachment times, wall residence time, maximum run-up time and phase shift due to reflection at the wall as a function of solitary wave amplitude are new results. In addition, we found that previous theoretical results underestimate wave run-up characteristics (maximal run-up amplitude, attachment and detachment times, wall residence time), except the third-order result of Su and Mirie (1980) who calculated maximal run-up which is in good agreement with experiments. Within the range of solitary wave amplitude considered experimentally, present measurements are in excellent agreement with numerical results of Cooker et al. (1997) and Chambarel et al. (2009).

For very steep solitary waves we found numerically the occurrence of a Rayleigh–Taylor instability on the top of the jet due to the head-on collision. A theoretical proof of the existence of this instability is given. Furthermore, the occurrence of this instability is corroborated by numerical computations of the vertical gradient of underwater pressure during the collision of the solitary waves.

1. Introduction

Assuming that the water depth is constant and the flow is inviscid, the solitary wave reflection phenomenon at a vertical wall is equivalent to the head-on collision of two equal solitary waves. Maxworthy [1] conducted experiments on head-on collision of two solitary waves and reflection of a solitary wave at a vertical wall. In his study, solitary waves were generated by pulling a flat plate in a tank with water level differences and the results were in qualitative but not in quantitative agreement with available theories. However, his results serve as reference for further studies. Experimental studies on head-on collision are quite sparse, namely for steep solitary waves. On the opposite, many analytic and numerical studies have been devoted to the run-up of a solitary wave at a vertical wall and the collision of two solitary waves. Herein, we can cite Chan & Street [2], Byatt-Smith [3,4], Oikawa & Yajima [5], Temperville [6], Su & Mirie [7], Mirie & Su [8], Fenton & Rienecker [9], Power & Chwang [10], Renouard et al. [11], Cooker et al. [12], Bona & Chen [13], Pelinovsky et al. [14], Lubin et al. [15], Craig et al. [16], Chambarel et al. [17]. For a more detailed and exhaustive review one can refer to Chambarel et al. [17]. More recently Park et al. [18] have reported a series of experiments of solitary wave reflection at a vertical wall and focused their investigation on the interaction between the free surface motion and the wall boundary layer in the vicinity of the moving contact line. Very recently Touboul & Pelinovsky [19] have considered numerically the bottom pressure distribution under solitonic waves reflecting at a vertical wall. Using two different approaches they emphasized the role of

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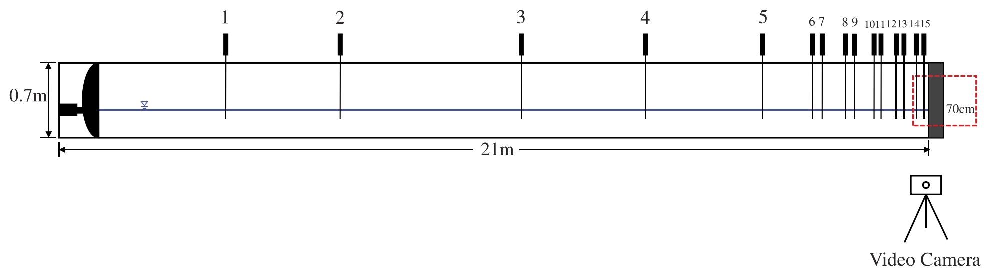

Fig. 1. A schematic description of the THL facility. The frame in red represents the field of view of images and blue line corresponds to the still water level.

dispersion in the case of traveling or fully reflected waves. Note that Carbone et al. [20] considered a different problem that is the run-up of wave groups on a vertical cliff. Due to combined effects of nonlinearity and dispersion they obtained numerically a maximal run-up six times larger than the initial amplitude of the wave group.

Measurement techniques of water particle trajectories have been well developed for many years. For this study, previous trajectory measurements and image processing techniques are used to capture solitary wave profiles. To ensure the capture and then the analysis of the wave profile by a high speed camera, a rectangular grid was located in the observation area schematized by a frame in red color in Fig. 1. Chen et al. [21] and Hsu et al. [22,23] developed several image techniques applied to experimental investigations of water particle trajectories. Consequently, a lot of errors during the experimental process can be reduced. The above techniques are used to obtain accurate experimental results.

The numerical method (BIEM) presented in the papers by Chambarel et al. [17] and Touboul & Kharif [24] is used to perform the numerical simulations that are then compared to the experiments. The experimental results are compared with theories, too.

For very steep dimensionless amplitude a/h larger than 0.60 we found numerically the occurrence of an instability on the top of the jet due to the head-on collision of two solitary waves. The parameters a and h are the wave amplitude and depth, respectively. This instability was observed numerically by Chambarel et al. [17], too. Herein, we give a theoretical explanation of the occurrence of this instability.

The experimental set-up is presented in Section 2 and a very brief description of the numerical method is given in Section 3. Results are discussed in Section 4 and a conclusion is given in Section 5.

2. Experimental methodology

The experiments are carried out in a wave tank at Tainan Hydraulic Laboratory of National Cheng Kung University, Taiwan. This tank is 21 m long and 0.7 m deep, with a width of 0.5 m, and its glass sidewalls facilitate the recording with a camera and permit the visual observation of the evolution of waves. A schematic diagram of the experimental setup is shown in Fig. 1. The arrangement of the measurement apparatus is deployed with wave gauges and high-speed camera. The elevation of the local water surface is recorded by employing 15 capacitance-type wave gauges with a sample rate of 20 Hz. All wave gauges were calibrated through a standard method which concerns the change of water level to adjust the response voltage of each gauge before and after the experiments to ensure its linearity and stability. The linearity of gauge response is given by a correlation coefficient of $0.9997 \sim 0.99991$. A high-speed digital camera (Canadian photonic labs. Inc., MS55k2) with a frame acquisition rate of 500 Hz at 1280×1020 pixels was used to qualitatively observe the wave front evolution during the reflection of solitary wave. The position of the wave front as a function of time was determined from digitized pictures, allowing a quantitative comparison between laboratory imagery and numerical results.

Pushing or withdrawing a given volume of water within a fixed duration is the basic idea to generate a solitary wave. In this study, the waves are generated by a hydraulically driven, dry back, piston type wavemaker with a maximum stroke of 1.0 m. A programmable controller that can be accessed easily by a PC controls the motion of the wave-board at 25 Hz through a 16 bits AD/DA card. Different wave-board motions can be prescribed by the computer. Target solitary waves are generated at one end of the flume. Among the two existing nonlinear algorithms developed respectively by Goring [25] and Synolakis [26], the former is employed here to generate solitary waves. A series of 19 tests were conducted, corresponding to solitary waves of normalized amplitude a/h ranging from 0.147 to 0.556. Test conditions are listed in Table 1. The still water depth was measured after each test to maintain the same initial condition. Repeatability of all experiments was satisfactory with a maximum deviation in reference wave amplitude of approximately 3% between repetitions. The experimental data were synchronized before analyses. A transparent acrylic-plastic sheet (1 m $\times$ 70 cm $\times$ 1 cm) plotted with 5 mm $\times$ 5 mm square grids was placed in the still water, centered along the tank width and then photographed before being removed from the tank. The photographed network grids were programmed into computer and used to analyze the continuous images of solitary wave profiles captured by the high-speed digital camera.

3. Numerical method

From the numerical point of view, the problem is solved by assuming that the fluid is inviscid, incompressible, and the motion irrotational. The Laplace equation is solved within a domain bounded by the free surface and solid boundaries of the numerical tank. The impermeability condition on the solid boundaries is applied and a Lagrangian description of the free water surface is used. The dynamic boundary condition states that the pressure at the free surface is equal to the atmospheric pressure. A Boundary Integral Equation Method (BIEM) is used to solve numerically the system of equations with a mixed Euler–Lagrange (MEL) time marching scheme. For more details about this numerical method one can refer to the papers by Chambarel et al. [17] and Touboul & Kharif [24].

4. Results and discussion

4.1. Wave profile

To test the ability to generate experimentally steep solitary waves, a comparison with fully nonlinear solutions obtained numerically by Tanaka [27] is shown in Fig. 2 for $a/h = 0.556$, where a is the amplitude and h the depth. One can observe an excellent agreement between the experimental and numerical solutions. Note that, the experimental profile presents a very weak dispersive tail. For comparison, the Green–Naghdi solitary wave is plotted, too.