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Experimental study of head-on and rear-end collisions of two unequal solitary waves

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ABSTRACT

The features of two unequal solitary waves during an interaction were experimentally investigated by optical and particle-tracer methods. To estimate the temporal colliding-wave profiles and phase shift during the head-on collision, the water surface variations were measured using two wave gauges. In addition, the spatial surface profiles were analyzed by combining particle mask correlation (PMC) with an image-thresholding method that detects the air–water interface as a set of locally extreme luminance values. The experimental surface displacement of the colliding wave was compared with the corresponding shape of a third-order perturbation approximation. Applying a particle image velocimetry (PIV) method, the kinetic features of right-running, left-running, and colliding waves were measured in head-on collisions, and in cases of shorter, taller, and compound waves in rear-end collisions. The PIV technique accurately measured the water velocity spatially induced by the nonlinear solitary wave interactions. The paths of the water particles were also successfully tracked by this method. Finally, to understand the effects of the interactions, the dynamic pressure was measured by tiny pressure transducers placed at horizontal locations throughout the water depth.

1. Introduction

Geophysical events, such as earthquakes, landslides, volcano eruptions, and other catastrophic mechanisms, generate successive tsunami waves that omnidirectionally propagate, maintaining an extremely large wavelength. The amplitudes of these waves considerably increase at the shoreline, and some waves may travel opposite to the river flow, causing serious damage to neighboring areas. Tsunamis undergo sudden changes induced by the reflection from coastal structures, interactions with flows, and collisions among counter-propagating waves. Tsunami research has expanded following the 2004 Indian Ocean tsunami and the 2011 Tohoku tsunami. To accurately predict the appearance of a tsunami, we must understand how small surface disturbances evolve into exceptionally powerful waves that exert devastating forces as they enter an estuary or coastal area. According to Japan's Earthquake Research Promotion agency (Cabinet Office 2013), there is a 40–50% chance that a high magnitude earthquake will occur within the next 30 years in the Kanto–Tokai area. The Tokyo Bay is vulnerable to a tsunami from the south–west region. Major fault lines run along the stretches of the Nankaido and Tokaido regions of Honshu (the Nankai Trough) and from the Sagami Bay to the areas off the Boso Peninsula (the Sagami Trough). In both the troughs, the Philippine Sea plate subducts beneath the North American plate and the European plate. In the inner part of the Nankai Trough, large earthquakes occur at a frequency of one every 100–150 years. The Hoei earthquake in 1707 (M 8.4–9.3) was historically the biggest earthquake ever recorded. It resulted in more than 20,000 fatalities from direct damages, collapses, fire, tsunamis, and secondary damages. In addition, two large earthquakes, namely, the Genroku Earthquake (M 8.2) in 1703 and the Taisho Earthquake (M 7.9) in 1923, occurred along the Sagami Trough. It is important to consider how the Tokyo Bay could be affected by the tsunamis that result from large earthquakes. The Tohoku earthquake in 2011 occurred 400 km northeast off the Miyagi Prefecture and led to the tsunami that entered the Tokyo Bay. The maximum wave height was recorded as 2.84 m in the Funabashi fishery port (north shore).

The tsunami lifted the column of water above the slippage. Increased seismic energy was released in parts where the ocean was deep. Hence, enormous energy was released outwards from the epicenter because the depth along the Nankai Trough is very high (approximately 3500 m). The average water depth outside the southwestern facing mouth of the Tokyo Bay is approximately 500 m. In contrast, the average depth on the Tokyo Port side is only 20 m. Wave energy is subjected to concentrations by shoaling and refraction as it moves toward the north shore through the mouth. Moreover, the southwestern facing mouth of the Tokyo Bay is V-shaped. Tsunamis arrive at the funnel opening and concentrate the energy into a narrow mouth before it is released into the bay. Each tsunami wave heads

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Nomenclature

The following symbols are used in this paper:

A	maximum trajectory of wave paddle;
a	wave amplitude
a_L	wave amplitude of left-running wave;
a_R	wave amplitude of right-running wave
c	wave celerity;
c_L	wave celerity of left-running wave;
c_R	wave celerity of right-running wave;
g	gravity acceleration;
h	water depth;
p	pressure;
u	horizontal velocity;
w	vertical velocity;
x	horizontal distance;
z	vertical distance from bottom;
ε_1	nondimensional amplitude of target wave;
ε_2	nondimensional amplitude of incoming wave;
ε_L	nondimensional amplitude of left-running wave ($=a_L/h$);
ε_R	nondimensional amplitude of right-running wave ($=a_R/h$);
ζ_L	nondimensional left-running wave profile;
ζ_R	nondimensional right-running wave profile;
η	surface elevation;
$\eta_{\max}$	maximum run-up elevation;
θ_L	phase shift of left-running wave;
θ_R	phase shift of right-running wave; and
ρ	water density.

toward the inner coasts and is refracted by the bathymetric change and deflected from a few reclaimed islands. Vertical coastal structures such as flood barriers are also of concern, because they reflect seismic energy. The colliding tsunami wave height is amplified by a factor of two at the point where it hits a vertical wall or floodgate head-on. Reflected wave energy can concentrate, thus increasing the risk toward other areas. The Koto ward is located in a low ground district known as the Koto Triangle between the Sumida River and the Arakawa River. Currently, two-third of the total area of the Koto ward is lower than the average sea level of the Tokyo Bay, and the area as a whole is protected by a number of water gates, levees, and seawalls. Thus, average tsunami heights up to a few meters could be reached following a large seismic event. This translates into a height of several meters if the tsunami hits a vertical structure at right angles. Nakajima and Umeyama (2015) revealed that to deal with water-related disasters in the area, exemplified by floods, the solution is not provided by constructing massive structures such as dams, dikes, and seawalls, but by utilizing an indirect approach, particularly, by constructing floating structures, which minimize the impact of water and the effect of water-related disasters more economically. Although this is a pending problem, it is necessary to expand the existing knowledge with respect to tsunami mechanics in an enclosed bay.

Phenomena such as tsunami transmissions, run-ups over sloping bottoms, and landward inundations are hydrodynamically similar to solitary waves, and hence are commonly computed by solitary-wave approaches (Lin et al., 1999; Carrier et al., 2003; and Lin et al., 2014). Although the study of solitary-wave interactions has an old history, dating back to the nineteenth century, several problems remain unsolved (Drazin and Johnson, 1989; Johnson, 1997; and Constantin, 2011). This paper investigates certain collisions of two solitary waves with different amplitudes, focusing on the colliding wave behavior after the interaction. The data are compared against theoretical predictions of the wave characteristics such as surface displacement, maximum water-surface elevation, phase shift, and pressure variation. The solitary-wave generating system was operated in a sophisticated manner. The water surface displacements were measured using two methods: (i) by wave-gauge measurements in a larger test section and (ii) by combining particle mask correlation (PMC) with the image-thresholding method in a smaller test section. The water-particle velocities and trajectories of the solitary and colliding waves were also investigated using a new PIV system that improves the spatial resolution of the precedent set reported by Umeyama et al. (2014). This study includes several new expressions for the investigation of head-on and rear-end collisions. In the head-on case, water surface displacements for right-running and left-running solitary waves and colliding wave profiles were obtained from three different tests and were spatially plotted together in a panel. The colliding and single wave profiles were compared with the corresponding shapes based on a third-order perturbation approximation because the surface variation of each single wave during the collision has not been investigated to date. To resolve the phase shift problem, the velocity fields of the right-running, left-running, and colliding waves were measured individually for the first time using a combined PMC and image-thresholding method. The method was applied to several experiments to demonstrate the role of the proposed procedure in understanding the effect of wave kinematics on phase shifts. The phase shift and maximum water-surface elevation were evaluated against the dimensionless target and oncoming wave amplitudes ε_R and ε_L. In addition, the essential features of the head-on and rear-end collisions and the structure of the small trailing residual were identified by spatially measuring the dynamic pressure fields using transducers.

2. Literature Review

The interactions among multiple solitary waves might be interesting to coastal engineers who study inner-bay tsunami waves by analytical and numerical models. Byatt-Smith (1971) obtained a second-order analytical solution for the nonlinear interactions induced by solitary-wave reflection at a vertical wall. The Boussinesq equation admits a solution for the combined motion of incident and reflected solitary waves, each satisfying an appropriate Korteweg–de Vries (KdV) equation. This second-order solution includes an interaction term that separates the two solitary-wave terms into functions of their respective phase variables. Miles (1977) theoretically investigated the nonlinear interactions between counter-propagating dual solitary waves, decomposing the interaction term into transient and phase-shift terms. Su and Mirie (1980) and Mirie and Su (1982) developed perturbation and numerical solutions to a higher-order Boussinesq equation. The third-order perturbation solution showed that the profile of two solitary waves colliding head-on becomes asymmetric during the interaction; however, both the waves eventually stabilize with a phase shift. A third-order dispersive tail appeared but a change in wave amplitude was not supported. An amplitude change was observed in numerical simulations, which also confirmed the predicted dispersive tail. Using a Fourier series method to solve the fully nonlinear Euler equations, Fenton and Rienecker (1982) developed a numerical model for dual solitary wave interactions and examined the maximum run-up height at the center of the collision and the post-interaction phase shifts. The numerical run-up elevation agreed with that obtained from the third-order perturbation solution, but the phase shifts of the crests were slightly smaller than the analytical values. Unfortunately, Fenton and Rienecker could not discern the secondary waves within the accuracy of their numerical scheme. Byatt-Smith (1987) investigated higher-order solitary-wave interactions by an extended KdV equation. He adopted the Benjamin–Bona–Mahony (BBM) equations in a perturbation technique based on inverse scattering. The numerical evidence indi-