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Harbor resonance induced by subaerial landslide-generated impact waves

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ABSTRACT

Past studies of harbor resonance have mainly been restricted to the quasi-steady oscillations induced by steady wave conditions. This paper investigates the response of a rectangular harbor to subaerial landslide-generated impact waves based on physical models, in order to compare the oscillations induced by steady and transient waves. In response to steady incident waves, oscillations within the harbor need to experience a long process to obtain their maximum value before the input energy and the losses are balanced. Landslide-generated impact waves usually include components with solitary wave characteristics and also components with dispersive wave characteristics. Each component travels with a different celerity. Usually, solitary wave components propagate faster, and arrive in the harbor first. Oscillations attain their maximum status as soon as these components arrive. The subsequently arriving components with dispersive characteristics do not enhance the resonance oscillations. So the waves with solitary characteristics are considered to play an important role in harbor resonance. Numerical experiments, using the FUNWAVE model, were conducted in order to further verify these conclusions.

1. Introduction

The resonance of a harbor to oceanic waves is a problem that has already attracted the attention of many investigators for several decades. Oscillation in a harbor is caused by the amplification of waves at the natural frequencies. Analytical, numerical and laboratory models are typically used to determine the amplification factors of the wave energy within the harbor relative to the constant long-wave energy outside it (Miles and Munk, 1961; Mei, 1983; Lee, 1971). During the design of a harbor, the geometry with the minimum amplification factor can be determined.

The majority of past studies on harbor resonance have been restricted to the stationary oscillations induced by steady wave conditions. In response to periodic forcing waves, oscillations within the harbor at their natural frequencies increase significantly in magnitude before the energy input from the external source is balanced by losses owing to frictions, boundary absorption and radiation from the entrance. Waves and swell induced by winds or storms have short periods ($O(10\,\mathrm{s})$), however, for many harbors, the most important natural modes have rather long periods, ranging from several minutes to an hour. So significant oscillations could not be directly induced by these short-period forces. Tsunamis have been shown to drive these oscillations (Kulikov et al., 1996). The effects of resonance excited by them in partially enclosed harbors can cause a surprisingly large amount of damage, and sea walls that are constructed for defense against storm surges may actually make the problem worse when a tsunami overtops them (Gisler, 2008). However, tsunamis are transient wave processes, and it is impossible for these short-duration motions to offer a long response time for the harbor resonance. Our study was motivated by the desire to address the issues of: how the resonance of the harbor is induced by these transient waves, and the differences between the resonance induced by a transient forcing and a stable wave forcing.

Tsunamis may be caused by landslides, volcanic activities or earthquakes. Many authors have studied impact waves generated by landslide, their propagation and inundation. Several empirical formulas related to the landslide parameters were proposed to predict the wave characteristics (Fritz et al., 2004; Carvalho and Carmo, 2007). In order to further investigate the impact wave generating mechanism, particle image velocimetry (PIV) was used to the unsteady three phase flow consisting of landslide, air and water (Fritz, 2002). Numerical models, based on shallow-water equations, Boussinesq-type equations and Navier–Stokes equations, have been developed to reproduce these impact waves' generation and propagation (Carvalho and Carmo, 2006; Gisler, 2008; Lynett and Liu, 2002).

Although harbor resonance is one of the major aspects of the problem associated with tsunami, which can be seen from that the word tsunami is taken from the Japanese and translates literally to "harbor waves", has its significant hazards to life and

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property induced by inundation, most previous studies focused on the generation and propagation of waves and their impact on coastal areas, and only a few of them were concerned with harbor oscillations (Lepelletier, 1980; Zelt, 1986). Furthermore, the study of these phenomena, including waves' generation, propagation and their resonance in the harbor should be integrated. In this work, laboratory experiments were conducted to comprehensively investigate these phenomena, and hope to remedy some of the limitations of previous work.

Surface elevations recorded by gauges provide the time-domain signals. However, in many cases the most significant information is hidden in the frequency spectrum, which provides the energy associated with each frequency. In coastal and ocean engineering, the Fourier transform (FT) is usually used to obtain the frequency spectrum. The FT provides information on the number of frequency components, but not when (in time) the particular frequency components occur. Such information is sufficient for the stationary signals as their frequency contents do not change over time and all the frequency components exist all the time (Massel, 2001). Landslide-generated impact waves are transient phenomena. There is energy transfer and dissipation through nonlinear interaction between different wave components in the propagation. We need to obtain information on the change of frequencies in the time domain. The wavelet transform (WT) can provide the time localization of the spectral components. Panizzo et al. (2002) have illustrated in detail its capability to analyze aerial landslide-generated waves. Considering the advantages of the WT for analyzing such non-stationary processes, it was chosen as the analysis method in our study.

This paper is organized as follows: Section 2 describes the experiments. The evolution of wave trains and spatial spectra are investigated in Section 3. Section 4 investigates eigen oscillations in the flume. Harbor resonance induced by landslide-generated impact waves is discussed in Section 5. In order to further illustrate our conclusions, numerical experiments are conducted with the FUNWAVE model in Section 6. Conclusions are drawn in Section 7.

2. Description of the experiments

The experiments were carried out in the wave flume at the State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, China. The experimental setup is shown in Fig. 1. The flume is 50.0 m in length and 4.0 m wide. A rectangular harbor (3 m long and 0.3 m wide) made of concrete is located at the centre of the flume at a distance of 38.5 m from the left wall. All the edges of the harbor and the flume are represented by vertical walls, which could be considered to perfectly reflecting boundaries. Impact waves are generated by a rigid block dropping vertically from the still-water surface into the left end of the wave flume. The block is a wooden, squared parallelepiped filled with concrete (length λ, width w and height δ). The water depth h remains at 0.3 m everywhere throughout the experiments.

The characteristics of the impact waves mainly depend on the non-dimensional parameters λ/h and δ/h. Basically, four types of impact waves will be observed successively as the ratios λ/h and δ/h increase gradually: (1) leading wave with oscillatory wave characteristics, (2) leading wave with solitary wave characteristics, followed by a trough connecting it with the dispersive wave pattern, (3) leading wave being a single wave with solitary wave characteristics, separated by the dispersive wave pattern and (4) solitary wave with complex form (Panizzo et al., 2002). However, the initial free surface will evolve into one component with solitary wave characteristics traveling in front and the other component with dispersive wave characteristics following after a long period of propagation. In 1995, the tsunami from the Chile earthquake propagated across the Pacific Ocean and was recorded at tide gauges in Japan (Ruegg et al., 1996). Such long distance dissipates most of the energy of the dispersive waves, so tsunamis often emerge as series of solitary waves. This study aims at investigating the resonance of the harbor induced by far-field landslide-generated waves rather than the characteristics of the falling body generated waves, so the initial wave type is not so important. Therefore, only two different blocks were used in our experiments (see Table 1): impact waves mainly characterized by solitary waves were expected to be generated by the big block (BB), and a wave packet mainly characterized by dispersive waves was hoped to be trigged by the small block (SB). The response of the harbor to the two distinctive wave components was investigated.

The surface elevations were sampled simultaneously at 100 Hz (time interval Δt=0.01 s) by means of resistance wave gauges, characterized by an absolute accuracy of the order of ± 1 mm. The positions of these gauges are shown in Fig. 1. The gauges were calibrated immediately before each run, and each test was conducted three times in order to check for repeatability. When impact waves are generated at the left end of the flume, they will propagate downstream and be reflected by the external boundary of the harbor. These reflected waves will be reflected back again by the left end of the flume. In order to eliminate the effect of these reflected waves, a total recording time of 65 s was established.

3. Evolution of impact waves

The time histories of impact waves induced by the BB and the SB at different gauges are shown in Fig. 2, and the corresponding

Table 1
Specifications of rigid dropping blocks.

Block	λ (m)	w (m)	δ (m)	ρ (kg/m^3)
BB	3.9	0.15	0.3	1740
SB	3.9	0.15	0.15	1740

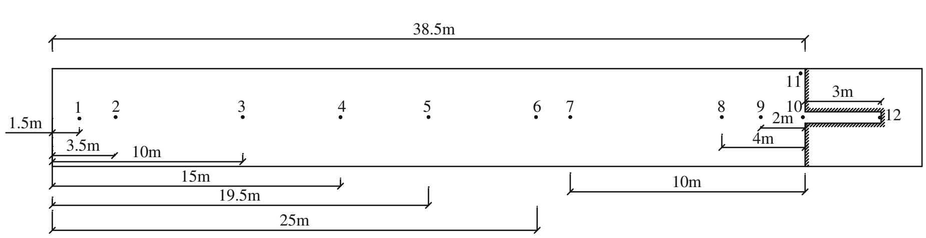

Fig. 1. Schematic drawing of experimental setup. Positions of gauges are indicated by dots and numbers.