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Experimental investigation of tsunami bore impact force and pressure on a square prism

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ABSTRACT

The 2004 Indian Ocean tsunami and the recent 2011 Japan tsunami have highlighted the need to investigate the interaction between tsunamis and coastal structures. Although some efforts have been made to determine tsunami loads on structures, there are discrepancies between the limited number of published design guidelines. This study comprises an experimental investigation of a tsunami bore interaction with an inland structure. Physical modelling of the tsunami bore in the laboratory allowed study of the impact of tsunami bores on a square prism model having different orientations to the flow direction. The use of common geometrical shapes simplifies experiments and increases the reliability of results. The experiments were conducted in a 14 m long, 1.2 m wide and 0.8 m deep wave flume equipped with an automatic gate designed to generate a tsunami bore. Measurements were made of the forces and pressures exerted on the model structure and of the bore heights and velocities. The vertical pressure distribution was measured on what was initially the structure's front wall, with the front wall at 0°, 30°, 45°, 60°, 90° and 135° to its original alignment. A relation between bore velocity and bore height is presented. The measured maximum forces in the stream-wise and upward directions were numerically modelled successfully, and relevant drag coefficients were determined for the structure at different orientations.

1. Introduction

Tsunamis are large ocean waves that are caused by a variety of natural phenomena such as earthquakes, landslides (sub-areal and submarine), volcanic eruptions and comets. Their effects on coastal communities are often catastrophic, as recently demonstrated by the 2004 Indian Ocean and 2011 Japan tsunamis.

Severe damage or collapse of structures and large loss of human life from the 2004 Indian Ocean tsunami illustrate the destructive nature of tsunamis (Fritz et al., 2006; Ghobarah et al., 2006; Saatcioglu et al., 2006; Tomita et al., 2006). More recently, the 2011 Japan tsunami killed thousands of people and destroyed coastal infrastructure (Foytong et al., 2013; Fritz et al., 2012; Liu et al., 2013; Shimozono et al., 2012). These recent tsunami events highlight the need to advance investigation of the interaction between tsunamis and coastal structures. Coastal areas in the seismically active Pacific Rim are experiencing rapid development of residential and tourist infrastructure, resulting in a significant increase in the number of coastal structures at risk of tsunami damage. As a consequence, better understanding of tsunami interaction with coastal structures is vital.

Depending on location and tsunami characteristics, some tsunamis break off shore and transform into a tsunami bore (Yeh, 1991). A bore is a broken wave with uniform depth and infinite wavelength, characterized by a turbulent but relatively gently sloping wave front (Hibberd and Peregrine, 1979). As the tsunami bore approaches the shoreline, the water velocity approaches the wave propagation velocity, resulting in an accumulation of turbulence at the front of the bore. Yeh (1991) proposed that this turbulence is increased by a momentum exchange between the bore and a small wedge of initially still water in front of the bore. The energy of this high turbulence is released on the dry shore and can cause extensive damage (Yeh, 1991). Kihara et al. (2015) proposed that the main body of the flow profile can be described using the ideal flow model of Ritter (1892), but in the leading edge or tip region of the bore flow resistance is important and the profile in this region is better described by a real fluid model (e.g. Chanson (2006)).

The inland tsunami flow depth and velocity are highly variable. During the 2004 Indian Ocean tsunami, the flow depth at the southern part of Khao Lak reached between 4 and 7 m (Dias et al., 2006; Matsutomi et al., 2006). The tsunami flow velocities were estimated at between 3 and 4 m/s at Kumala beach and 6 to 8 m/s at Khao Lak (Rossetto et al., 2007). Tsunami flow velocities have been calculated to be as high as 8 m/s, or estimated at up to 16 m/s (Ramsden, 1993). For the 2011 Japan tsunami, reported maximum flow depths were 8 m at Kamaishi City (Fraser et al., 2012), and 6 m at Arahama Town (Suppasri et al.,

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2012). In Sendai, the tsunami flow velocities reached approximately 8 m/s at about 1 km inland of the shoreline (Hayashi and Koshimura, 2013). In another area close to the Sendai Airport, the tsunami flow velocity was about 10 to 13 m/s (Jaffe et al., 2012).

The flow generated from rapid release of water from a sluice gate or a radial gate is similar to a tsunami bore (Chanson, 2006; Cross, 1967; Yeh, 2006), and has been adopted in tsunami–structure interaction studies by various researchers (Arnason, 2005; Nistor et al., 2011; Nouri, 2008; Rahman et al., 2014). Accordingly, in the present study, a tsunami bore was simulated by the almost instantaneous opening of a sluice gate which impounded a large volume of water.

Many experiments have been carried out in laboratory flumes to investigate tsunami bore impact on (a) a vertical wall blocking the flume width (Cross, 1967; Kihara et al., 2015; Linton et al., 2013; Mizutani and Imamura, 2001; Robertson et al., 2011; Robertson et al., 2013; Santo and Robertson, 2010), and (b) low rise coastal structures with wave overtopping (Asakura et al., 2000; Iizuka and Matsutom, 2000; Rahman et al., 2014; Thusyanthan and Madabhushi, 2008). However, the interaction between a tsunami bore and a three dimensional structure where the flow does not overtop the structure has received limited attention because of the complexity of tsunami bore flow around such a structure (Wijatmiko and Murakami, 2012). Research that has been carried out has been restricted to the investigation of tsunami bore impact on the front wall (perpendicular to the flow) and side wall (parallel to the flow) (Chinnarasri et al., 2013; Fujima et al., 2009; Nouri et al., 2010; Palermo et al., 2012; Palermo et al., 2009; Robertson et al., 2008).

Previous studies have produced both similar and contradictory results for the tsunami induced pressure. For example, Nouri et al. (2010) investigated the pressure distribution on the front wall and side wall of a square prism structure due to a tsunami bore. Their study identified two types of exerted pressure: (a) an impulsive pressure with a short duration (order of milliseconds) and (b) a quasi-steady pressure with a longer duration than impulsive (order of seconds). Recently, Kihara et al. (2015) studied the impact of a tsunami bore on a vertical wall and similar observations for the impulsive pressure phase similar to that of Nouri et al. (2010). However, Nouri et al. and Kihara et al. have dissimilar observations for the quasi-steady phase pressure as compared with the hydrostatic pressure at the bore height. Nouri et al. (2010) reported quasi-steady phase pressures greater than hydrostatic pressure while Kihara et al. (2015) reported pressures almost equal to the hydrostatic pressure.

The following types of tsunami forces have been identified by researchers: (a) horizontal forces, including impulsive, hydrostatic, and hydrodynamic forces; and (b) vertical forces, including impulsive, hydrodynamic drag, hydrodynamic lift, and buoyant forces (Yeh, 2007). Cross (1967) investigated tsunami bore propagation in a flume and measured the bore-induced stream-wise force on a vertical wall. Cross found that, for the case of uniform steady flow impinging on a vertical wall and for a bore front slope of less than 15°, the total stream-wise force is the summation of a hydrostatic force and a hydrodynamic force. This statement of Cross (1967) is used as a basis in this study for evaluating the bore force on a rectangular prism structure. The previously cited have provided useful information for designing coastal structures (e.g. seawalls and buildings) in tsunami prone regions. The results and findings have contributed to the preparation of tsunami design guidelines.

Specific tsunami design guidelines for coastal structures have been prepared by authorities in the United State of America (USA). The City and County of Honolulu (CCH) specified equations for estimation of the forces affecting buildings due to coastal flooding, including hydrostatic, hydrodynamic (drag), surge and buoyant forces (CCH, 2000). The Federal Emergency Management Agency (FEMA) stated that tsunami loadings may be treated in the same way as wave loading and flood loading but on a much larger scale (FEMA, 2011). However, in guidance for design of tsunami vertical evacuation shelters, FEMA states that there are significant differences between a tsunami and flooding or storm surge (FEMA, 2012). Amongst these guidelines, there are significant differences amongst the estimates of tsunami force on the structures. In spite of the guidance outlined above, there are significant shortcomings in the field of tsunami design. For example, until the recent Japan 2011 tsunami, it was assumed that reinforced concrete structures would withstand tsunamis. However, during the Japan tsunami many reinforced concrete structures collapsed because of the unexpected magnitude of tsunami loads (Yeh et al., 2013).

Lloyd and Rossetto (2012) and Cawley (2014) reviewed the existing design guidelines and found that the guidelines have not used unified notation for characterising tsunami waves, and have not addressed the load combinations consistently. Cawley (2014) stated that most guidelines have addressed tsunami forces based on their own experimental results. Consequently, Cawley (2014) emphasised the need for further investigation of the effect of building shape and orientation in estimating tsunami loadings, and for definition of the flow depth and velocity.

Measurements of the action of a tsunami bore on a square prism structure at different orientations to the flow direction are presented. The bore height and velocity were measured in the flume upstream the structure, and an empirical relationship between the bore height and velocity was derived; the empirical relationship was compared with those from previous studies. To study the effect of structure orientation on the bore induced pressure, the vertical distribution of the pressure on the front wall of the structure was measured at 0°, 30°, 45°, 60°, 90° and 135° to the flow direction. In most of the previous studies, pressures were measured at only 0° and 90°. In addition, the bore induced stream-wise and upward forces, and moments, were measured at the base of the structure. The findings by Cross (1967) were used to compute the stream-wise force theoretically, and the theoretical calculation was validated using the experimental results. The additional orientations allow drag coefficients to be proposed for all orientations of a square prism structure. The upward force on the structure due to the bore impact was theoretically computed assuming the total upward force being due to the buoyancy, and the results were validated using the experimental data. Concurrent measurement of force allowed evaluation of the pressure measurement technique and of the integration of the pressures to give a total force.

2. Experimental set-up

2.1. Facility

A 14 m long, 1.2 m wide and 0.8 m deep wave flume, connected to a reservoir 11 m long, 7.3 m wide and 0.6 m deep, was used (Fig. 1). The flume is equipped with an automatic gate to generate a tsunami bore. The flume has concrete block side walls and a horizontal bottom of moderately smooth concrete to enable simulation of tsunami bore propagation over a plane dry bed. The flume is emptied using the drain gate and drain channel.

The 1.20 m wide and 0.9 m high automatic gate consists of a sliding gate and a shutter gate, both of which open rapidly, providing near-instantaneous water release (Fig. 2). The vertical-rise sliding gate controls water release, while the shutter gate ensures uniform flow distribution across the flume. The sliding gate opening is automatic; it is timed to remain open for 4 seconds before automatically closing. The sliding gate is rapidly lifted by a hydraulic piston actuated through a computer program. The shutter gate opening is also automatic. It is almost instantaneously opened by a pneumatic cylinder; after manual initiation of opening on an electronic signal from the opening of the sliding gate it is also timed to remain open for 4 s before automatically closing. The simultaneous operation of the two gates facilitates the generation of a stable bore with a reasonably smooth water surface. In addition, the combination of the gate and shutter minimises any leakage of water into the flume before gate opening. The sliding gate opening height is