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# Instant tsunami bore pressure and force on a cylindrical structure

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## ABSTRACT

This study investigates tsunami bore impact on a cylindrical structure. A physical study was carried out in a large wave flume with a horizontal floor. Experiments covered a range of bore heights (140–210 mm) and bore velocities (1.98–2.45 m/s). The vertical and angular distributions of the applied pressure were measured using a vertical array of pressure sensors. The cylindrical structure was rotated so that the sensors were orientated at several angles between 0° and 135°, giving in effect a three-dimensional pressure distribution around the structure. The total stream-wise force was computed as a summation of the hydrostatic and hydrodynamic forces. A hydrodynamic coefficient of 0.65 was found to be appropriate for this study. The height of the centre of effort of the force on the cylinder surface was estimated by dividing the measured moment by the measured force, and was found to be proportional to the actual water height at the front face of the cylinder.

## 1. Introduction

Coastal engineers' interest in tsunami was heightened by the recent 2011 Japan tsunami. Even though Japan is well prepared for earthquakes, the catastrophic effect of the 2011 tsunami was unexpected; this demonstrates that the risk of tsunami damage is no less significant than the risk of earthquake damage. In the 2011 tsunami, the magnitude of the tsunami flow was greater than expected. A flow depth of up to 8 m was reported at Kamaishi City (Fraser et al., 2012), in an area containing 2–3 storey multi-use commercial and residential buildings, and 5–6 m at Arahama Town (Suppasri et al., 2012). In Sendai, the tsunami flow velocities reached approximately 8 m/s at about 1 km inland from the shoreline (Hayashi and Koshimura, 2013). In another area close to the Sendai Airport, the tsunami flow was about 10–13 m/s (Jaffe et al., 2012). Various types of cylindrical structures were affected by the Japan tsunami, such as oil storage tanks (Hatayama, 2015; Naito et al., 2013). Also, a cylindrical building is a possible geometrical shape for tsunami evacuation structures (Hasumi et al., 2015). A cylindrical structure was chosen for investigation of its performance under a tsunami bore impact.

The height of a tsunami wave increases as it approaches the shoreline, and may break offshore and transform into a tsunami bore (Yeh, 1991). A bore is a broken wave with uniform depth and infinite wavelength, characterized by a sloping and turbulent front (Hibberd and Peregrine, 1979). A tsunami bore can apply very large forces on coastal structures (Yeh, 1991). Knowledge of the interaction between a tsunami bore and structures is a pre-requisite for developing strategies for mitigating damage from tsunamis. For laboratory studies, a tsunami bore can be generated by rapid release of water from a sluice gate (Chanson, 2006; Cross, 1967; Yeh, 2006). This method of tsunami bore generation 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 that impounded a large volume of water.

Early research on tsunami-structure interaction focused on wave impact on a cylindrical structure (e.g. Goda et al. (1966); Sawaragi and Nochino (1984)). Goda et al. (1966) investigated the maximum force of a wave impact on a single cylinder, and proposed a formula for calculating the maximum force. In their formula, the maximum force is the summation of an initial impact force and a hydrodynamic force. Sawaragi and Nochino (1984) identified an additional hydrostatic force resulting from water level differences between the front and rear of the cylinder. They modified the formula proposed by Goda et al. (1966) by considering the additional hydrostatic force observed in their study.

Arnason (2005), Sakakiyama et al. (2009), Nouri et al. (2010), Al-Faesly et al. (2012), and Wijatmiko and Murakami (2012) investigated the interaction between a tsunami bore and a cylindrical structure. Arnason (2005) identified a resistance force and a hydrostatic force induced on the cylindrical structure. He defined a resistance coefficient, similar to the standard drag coefficient, based on the measured total bore force induced on the structure. Arnason (2005) found that the resistance coefficient is a function of the relative bore height (i.e. the ratio of bore height to the object width) and the relative structure

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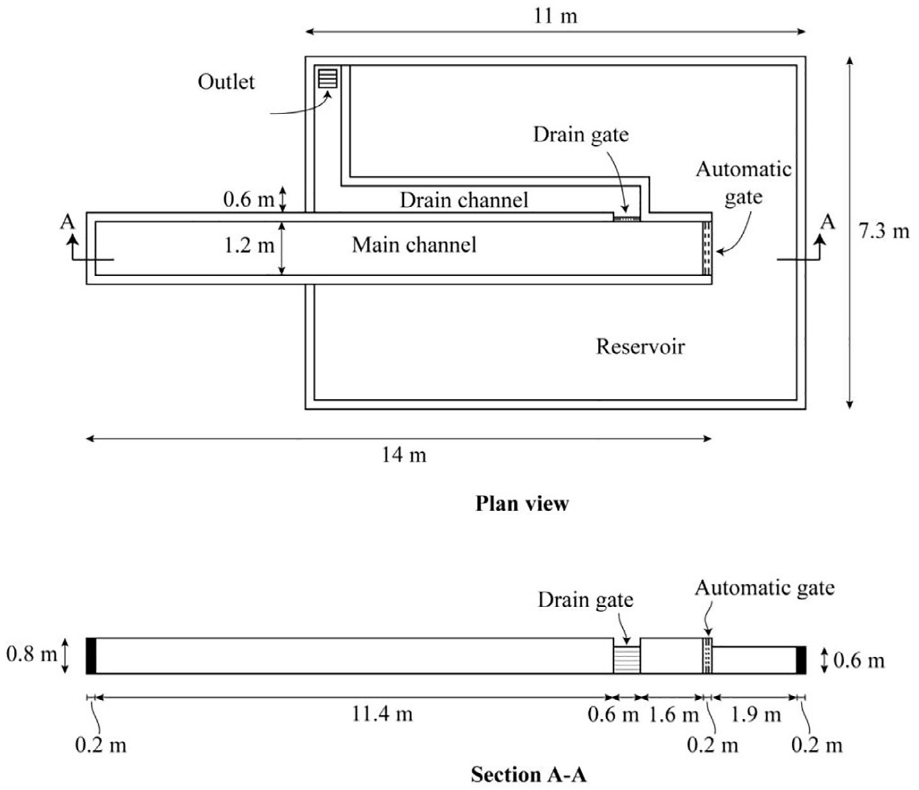

**Fig. 1.** Experimental set-up (Shafiei et al., 2016).

blockage (the width of the structure to the width of the flume); Arnason found that the coefficient decreased with both increasing relative bore height and increasing relative structure blockage. For various relative bore heights and relative cylinder blockage, Arnason (2005) measured resistance coefficients ranging from 0.89 to 2.06. These resistance coefficients had approximately the same values for cylindrical, diamond and square prism structures, which is inconsistent with the commonly accepted variation of drag coefficient with shape of structure.

Sakakiyama et al. (2009) reported drag coefficients ranging from 0.7 to 2, for cylindrical models of oil storage tanks and for supercritical flow. Their results indicated that the drag coefficient in a supercritical flow is smaller than in critical and subcritical flows because the difference between the water levels at the front and rear of the structure becomes smaller.

Nouri et al. (2010) divided the bore force into two phases, the initial impact and quasi-steady (named post impact in their study). For the quasi-steady phase, Nouri et al. recommended combination of the hydrodynamic (drag) and hydrostatic forces. They found that the hydrodynamic force was the larger of the two forces, and that it was slightly larger than the initial impact force. In addition, Nouri et al. (2010) investigated the vertical pressure distribution at the front and side of a cylindrical structure. Their results indicated a positive (inward) pressure at the front and a negative pressure (outward) at the side of the cylinder. Al-Faesly et al. (2012) used the same wave flume and equipment as Nouri et al. (2010) and reported results similar to those obtained by Nouri et al. (2010). Al-Faesly et al. (2012) recommended that further investigation of the bore-structure interaction is required in order to develop and validate more accurate formulas for estimating tsunami bore forces.

Wijatmiko and Murakami (2012) investigated vertical and angular (from 0° to 90° orientation to the flow direction) pressure distributions and induced forces on a cylindrical structure due to a tsunami bore. They reported a positive (inward) angular pressure distribution around the bottom of the frontal half of the cylinder. Also, the pressure was uniform around the bottom and decreased up the vertical height of the cylinder. This observation is in contrast with that by Nouri et al. (2010) who reported a negative (outward) pressure at the side of the cylinder.

Recently, Han and Cho (2014) carried out a series of experiments to investigate a tsunami wave impact on a cylindrical structure, in which the tsunami wave was represented by a solitary wave. They measured the vertical distribution of the pressure, which was uniform up the vertical height of the cylinder. In addition, they measured the angular distribution of the pressure at 45° intervals. In their study, the pressure decreased from 0° to 90°, being largest at 0° and smallest at 90°. The pressure increased from 90° to 180°, but the pressure at 180° was less than at 0°. The pressure magnitudes were positive (inward) at all places up and around the cylinder, which is inconsistent with the results reported by Nouri et al. (2010) and Wijatmiko and Murakami (2012). In addition, Han and Cho (2014) normalised the measured pressures by the equivalent hydrostatic pressure from the wave height. They compared their normalised pressures with those from Goda et al. (1966) and found them to be similar.

Review of the previous studies shows that there remains some disagreement about the vertical and angular pressure distributions on a cylindrical structure from a tsunami bore impact. In addition, this literature review suggests the need for a further investigation to develop more accurate equations to estimate tsunami induced forces on a cylindrical structure (Al-Faesly et al., 2012; Han and Cho, 2014). Most of the previous studies have concentrated on the stream-wise component of the tsunami induced force. This study was primarily concerned with the investigation of the vertical and angular (from 0° to 135°) distributions of the tsunami bore pressure on a cylindrical structure. In addition, the total stream-wise and upward forces from tsunami bore impact were measured and the main components of each of these forces were determined, so that reliable calculation of design loads on a vertical cylinder can be made. Based on the measurements in this study, the hydrodynamic force coefficient for a cylindrical structure was determined. The experiments were conducted over nearly dry-bed conditions, representing a cylindrical structure located near coastline. The authors have published a study on the impact of tsunami bore on a square prism (Shafiei et al., 2016). The same experimental set-up and