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Mitigation effects of onshore perforated barriers on inundation and forces induced by tsunami and tsunami-driven objects

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ABSTRACT

The hydraulic performance of onshore barriers in response to tsunami and a tsunami-driven shipping container was examined experimentally. For the barriers subjected to tsunami up to twice their designed height, experiments with various barrier permeability were conducted to assess the mitigation effect and the concurrent forces on the barrier. The perforated barrier with 30% porosity reduced the momentum flux of the inundation flow behind the barrier by 40–60% even when the water overflowed the barrier. Below the overflow limit, the barrier reduced the fluid force acting on it by 40% of the corresponding force on the impermeable barrier. The force on the perforated barrier was close to half the momentum flux of the incoming inundation. The low-permeability barrier buffered the impact of the drifting shipping container and reduced the impact force on the barrier. The total force induced by the inundation flow associated with the driftage was reduced with decreasing permeability of the barrier. The inverse relation between the impact forces acting on the high- and low-porosity barriers was in contrast to that of the fluid forces. The permeability of wall-type structures has an important influence on inundation mitigation and reduction of the fluid force and the impact force.

1. Introduction

In tsunami-prone areas, it is important to consider the complexity and resilience of the coastal defense structures as well as effective plans for evacuation and land use, based on the magnitude of the tsunami and the land-use status and trends. An extremely large tsunami will cause serious damage to coastal areas, not only from the tsunami wave over the land but also from tsunami-driven objects (e.g. Takahashi et al., 2011; Suppasri et al., 2012; Naito et al., 2014). Boats, shipping containers, cars, timber, and the like can drift into ports and coastal areas and cause damage to the surrounding areas in addition to that inflicted by the tsunami wave, and obstruct the recovery effort. Thus, measures to prevent damage from tsunami-driven objects must be implemented along with prevention and mitigation of tsunami overland flow. To ensure minimum safety standards in tsunami-prone areas, comprehensive multiple defenses against tsunamis and development of tough and resilient coastal defense structures are required.

This study focuses on the hydraulic performance of onshore perforated wave barriers, which captured boats, shipping containers, and timber that drifted into a number of Japanese ports and harbors after the huge tsunami caused by the 2011 Great East Japan Earthquake (Fig. 1). The perforated barriers were installed along the coast and outside ports where roads, railways, and buildings are located very close to the shore. This type of barrier is used to reduce wave splash and spray over the top of seawalls and as a shield against wind and dust. The structure consists of a wall of perforated sheet metal, with holes a few cm in diameter creating a porosity of 30–40%, supported by columns. The tsunami-height dataset of the 2011 Tohoku Earthquake Tsunami Joint Survey Group (Mori and Takahashi, 2012) shows that the perforated barriers were subjected to extremely high tsunami waves (see Fig. 1); however, while the perforated barriers captured tsunami-driven objects, they did not suffer any structural damage. Thus, the permeability of the perforated barriers may act to lessen the force of the tsunami wave and reduce the damage caused by the wave and the tsunami-driven objects.

While perforated barriers can protect against waves and tsunamis, they are also compact and do not block the view of the ocean, which is important for evacuation management. Unlike high solid walls, perforated barriers have the advantage of retaining an open-space feeling. Therefore, perforated barriers can be part of a multi-system protection scheme which uses existing coastal facilities and different methods of coastal disaster prevention. Some field observations (e.g. Kamikubo et al., 2009; Hirano et al., 2013; Fig. 1) suggest that perforated wave

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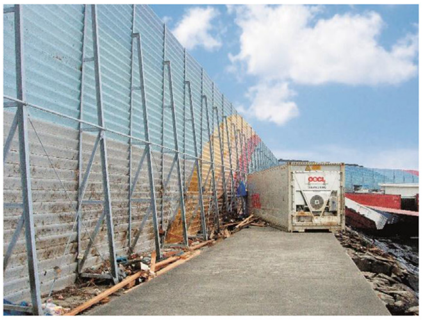

(a)

(b)

(c)

Fig. 1. Perforated barriers that captured driftwood, containers, and boats during the 2011 Tohoku earthquake and tsunami. The tsunami height was estimated at about (a) 5.4–7.1 m at the port of Sendai, (b) 5.0–5.4 m at the port of Hachinohe, and (c) 7.5–8.0 m at Ooharahama, Ishinomaki, based on the survey of the 2011 Tohoku Earthquake Tsunami Joint Survey Group.

barriers can be used as an effective measure to prevent and mitigate coastal flooding disasters. However, there have been no reports of a quantitative assessment of the mitigation effects of onshore perforated barriers on tsunami inundation and on the forces generated by tsunamis and tsunami driftage.

The effect of the impact forces of water-driven objects on slender structures such as columns has been studied through experimental and theoretical research. Matsutomi (1993, 1999, 2009) investigated the collision behavior and impact forces of tsunami-driven wood logs and proposed a practical evaluation formula for the impact force on a column. Haehnel and Daly (2002, 2004) performed steady flow experiments and showed that the maximum impact force of woody debris was a function of the impact velocity, debris mass, and the effective stiffness of the collision. Laboratory experiments of a shipping container exposed to tsunami flow over land were conducted by Mizutani et al. (2005) who investigated the fluid force on a shipping container on a wharf, the drift velocity, and the impact force on a slender column. Considering that the impact force is influenced by the material property and structural rigidity of the impacting and impacted objects, Arikawa et al. (2007) measured the impact force between a large-scale model of a concrete wall and a steel shipping container and found that the empirical formula based on the Hertzian method was useful to evaluate the impact force. Recently, Ko et al. (2015) conducted large-scale experiments on the impact forces caused by in-air and in-water collisions between a column and a 1:5-scale shipping container. They compared the results from the in-air and in-water tests to quantify the hydraulic effects on the debris impact force and duration. A numerical investigation on the response of reinforced concrete columns to the impact of shipping containers was carried out by Madurapperuma and Wijeyewickrema (2013). However, estimating the impact force of tsunami-driven objects on a structure is complex because it is influenced by the various properties of the driftage and the structure (Haehnel and Daly, 2004). Insufficient knowledge exists on the impact force of tsunami waves and driftage on permeable-wall type structures and the hydraulic performance of the structures in response to these forces.

The forces acting on impermeable walls and columns as a result of simple tsunami overland flow with no driftage have been studied since the 1960s (e.g. Fukui et al., 1963; Cross, 1967; Ramsden, 1996; Fujima et al., 2009; Nouri et al., 2010). Recently, several studies were conducted on the mitigation effects of various types of coastal defense structures. Oshnack et al. (2009) and Thomas and Cox (2012) investigated low-lying seawalls that helped reduce building damage in the 2004 Indian Ocean Tsunami. They conducted systematic experiments to quantify the reduction of the tsunami run-up and force on a building behind a low-lying seawall. Linton et al. (2013) investigated the interaction between a solitary tidal bore and a wood-frame wall at full scale using a large wave flume to understand how a flexible structure performs when subjected to tsunami overland flow and to evaluate the fluid force acting on the wall. However, inadequate investigations examined the interaction between tsunamis and perforated onshore structures though many studies were conducted on the interaction between storm waves and perforated coastal structures (e.g. Li et al., 2006; Huang et al., 2011; Elbisy, 2015).

Many aspects regarding the interaction between tsunami overland flow, tsunami-driven objects, and permeable structures such as perforated barriers are still unknown. For effective mitigation of tsunami disasters in coastal areas, a good understanding of the changes in the characteristics of the fluid forces and impact forces acting on permeable structures installed on land is needed. The permeability of perforated barriers will change the characteristics of tsunami propagation, including the reflection, transmission, and attenuation of the wave, which affects the dynamic response and impact force of the tsunami driftage as it collides with the barriers. In general, high permeability decreases reflection and attenuation of wave, and increase transmission. The relations between wave propagation and force on barriers are not fully understood. Understanding of characteristics of inundation and impact is particularly important for design of barriers and development of effective defense from tsunami-driven objects. It is therefore necessary to understand the fundamental characteristics of the interactions between various structures and tsunami-driven objects. However, almost no quantitative evaluations have been conducted on mitigating inundation and capturing tsunami driftage by onshore perforated barriers. Furthermore, better