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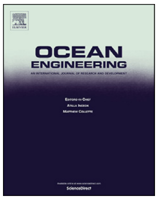

Effectiveness of a compound defense system of sea embankment and coastal forest against a tsunami

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ABSTRACT

The Great East Japan tsunami revealed the limits of using only a sea embankment for defense. Therefore, a compound defense system combining a coastal forest and sea embankment for a tsunami overflowing the embankment is proposed to mitigate damage. This study was conducted to clarify the changes in overflow volume from an embankment due to the location and thickness of a coastal forest. The effect of tree overturning was also investigated in relation to changes in wave height. A flume with a gate quickly lifted by air pressure to create an unsteady tsunami-like bore was used to investigate the changes in overflow volume and the reflection characteristics of various compound-defense models. The results show that a landward forest has the advantage of decreasing the fluid force behind the forest, and seaward forest can reduce overflow volume landward. Even when the sea-side forest is thin, the change in flow pattern in front of the embankment increases its total reflection and decreases the overflow volume by approximately 10%, although the forest itself does not increase the reflection. A thin seaward and overturned forest also decreases the overflow volume when the approaching tsunami height was less than the embankment height.

1. Introduction

The 2011 Great East Japan tsunami largely exceeded the designed level of coastal defense. The tsunami extensively destroyed parts of sea walls (tsunami gates, large embankments) (Tappin et al., 2012) and coastal forests (Tanaka et al., 2013), and thus it caused catastrophic damage to people and buildings in the Tohoku and Kanto districts of Japan (Udo et al., 2012; Suppasri et al., 2013). After the 2011 tsunami, the Ministry of Land, Infrastructure, Transport and Tourism, Japan (MLIT) classified tsunamis as level 1 and level 2. The return period of the magnitude for level 1 tsunamis is defined as around 100 years interval, while that for level 2 tsunamis is within hundreds to a thousand years. The goal of the coastal defense against a level 2 tsunami changes from 'disaster prevention' to 'disaster mitigation.' The method is also changed from 'line defense' to 'compound defenses.' One of the important lessons of the 2011 tsunami is that the effect of a forest as a bioshield was not negligible compared with that of a sea embankment in the mitigation of fluid force (Tanaka et al., 2014) and protection of buildings by trapping floating debris (Tanaka, 2012; Pasha and Tanaka, 2016), although the coastal forest was destroyed.

Many previous studies recognized the effectiveness of coastal vegetation in mitigation of water-borne disasters like tsunamis in post-disaster surveys after the 1998 Papua New Guinea tsunami (Dengler and Preuss, 2003), 2004 Indian Ocean tsunami (Danielsen et al., 2005; Tanaka et al., 2007; Mascarenhas and Jayakumar, 2008), and 2011 Great East Japan tsunami (Nandasena et al., 2012; Tanaka, 2012; Tanaka et al., 2014), although the effectiveness and limitations had already been discussed in Shuto (1987). Attempts to evaluate the effectiveness of a coastal forest were also conducted in numerical simulations that changed the tsunami and forest characteristics (Hiraishi and Harada, 2003; Harada and Imamura, 2006; Nandasena et al., 2008). Not only for tsunamis but for storm surge mitigation, the effectiveness was also examined in Vietnam (Mazda et al., 1997) and Bangladesh (Tanaka, 2008). On the other hand, the limitations of the tsunami mitigation capacity of a coastal forest were also discussed in terms of the destruction of the coastal forest itself (Tanaka et al., 2007), production of driftwood (Dengler and Preuss, 2003; Cochard et al., 2008), and channeling of the flow into a gap in a coastal forest (Thuy et al., 2009; Tanaka, 2009; Nandasena et al., 2012).

The effectiveness of an embankment in the Great East Japan tsunami was also considered in post-tsunami surveys and numerical simulations considering the inundation area and fluid force (Dao et al., 2014; Tanaka et al., 2014). However, not many studies of multiple defenses composed

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of embankment, coastal forest, and/or ditches were conducted except for the post-tsunami surveys and their evaluation. To design future coastal zones, it is very important to clarify the effects of a coastal forest combined with other artificial structures like an embankment or a natural system such as sand dunes or a lagoon. Recently, the number of studies of the compound defenses using embankment with a coastal forest (Tanaka et al., 2007, 2014; Tokida and Tanimoto, 2014), sand dunes (Tanaka et al., 2006), the combination of hollow topography, embankment, and coastal forest (Usman et al., 2014), and a second embankment (Tanaka and Igarashi, 2016) is increasing; however, much is still unknown.

Not only field surveys but also physical experiments and/or numerical simulations indicated the effectiveness of vegetation for decreasing the run-up heights of a tsunami (Irtem et al., 2009; Ismail et al., 2012), and for increasing reflection and decreasing transmission of a solitary wave (Huang et al., 2011). Noarayanan et al. (2012) proposed new parameter for expressing vegetation resistance that combines the structural rigidity of the individual model stem, flow parameters, and vegetation parameters. However, most of the experiments were conducted using a physical model of only a coastal forest and were not combined with an embankment.

As the arrangement of a coastal forest and embankment, a continuous landscape structure of a sand beach, sand grasses, and a coastal forest is natural, and an embankment behind a coastal forest is ecologically beneficial. A coastal forest also can partially reflect a tsunami (Irtem et al., 2009; Iimura and Tanaka, 2012; Ismail et al., 2012); thus, a forest in front of an embankment may increase the reflection. However, coastal forests without embankments were damaged more in the 2011 Great East Japan tsunami because they received the tsunami fluid force directly (Tanaka et al., 2013), and forests in front of steep slopes received a large fluid force due to reflection by steep hills in the 2010 Mentawai tsunami (Huang et al., 2013).

On the other hand, a coastal forest behind an embankment also has a disadvantage because large amounts of coastal forest were destroyed by erosion of the substrate and the forest produced large amounts of driftwood (Tappin et al., 2012; Tanaka, 2012). Moreover, a coastal forest behind an embankment cannot be expected to decrease the overtopping flow from the embankment. Considering the advantages and disadvantages, it is very important to quantitatively estimate the effect of relative positions of coastal forest and embankment. Considering that the land available on which to construct a green belt is limited (Tanaka et al., 2011), and the fact that trees have a high probability of being broken (in fact, most were bent at the Great East Japan tsunami (Tanaka et al., 2013)), the effectiveness of a coastal forest combined with an embankment should be clarified, especially paying attention to the thin coastal forest and that fact that broken trees, as inclined cylinders, can also provide resistance (Poulin and Larsen, 2007; Thuy et al., 2012).

Therefore, the objectives of this study were to clarify the effectiveness of a compound defense system combining a coastal forest and sea embankment. The flow structure and overflow volume when a tsunami current overflowed or passed through the physical model combining forest and embankment model were investigated. This study focused on the location on the coast and number of rows of trees in front of or behind an embankment to obtain the optimal compound defense system with changes in the magnitude of surge-type flow. An overturned tree model was also used to evaluate the effectiveness more realistically in a disaster situation.

2. Materials and methods

2.1. Experimental apparatus and procedures

Fig. 1 shows the experimental flume setup. A water flume 18 m in length and 0.4 m in width with a quickly lifting gate, which is similar to that of Yeh et al. (1989), was used at Saitama University. Yeh et al. (1989) showed that a single bore can be generated by a lifting gate that initially separates the quiescent water on the model beach from the deeper water behind the gate. The gate used in this study can be lifted 15, 20, and 25 cm in 0.384, 0.512, and 0.640 s, respectively, by the operating air pressure of 0.65 MPa. In the experimental channel, a constant 1/10 slope was set from the gate. The model scale was set at 1/100 and Froude similarity was used. In the coastal forest affected by the 2011 Great East Japan tsunami, the diameter of tree trunks at breast height, tree height, and tree density were 0.2–0.5 m (including broken trees), 18 m, and 0.20 trees/m^2, respectively. Considering the real scale, the diameter, height, and spacing were 0.4 cm, 18 cm, and 2.3 cm, respectively.

In many previous studies, trees were usually modeled using vertical

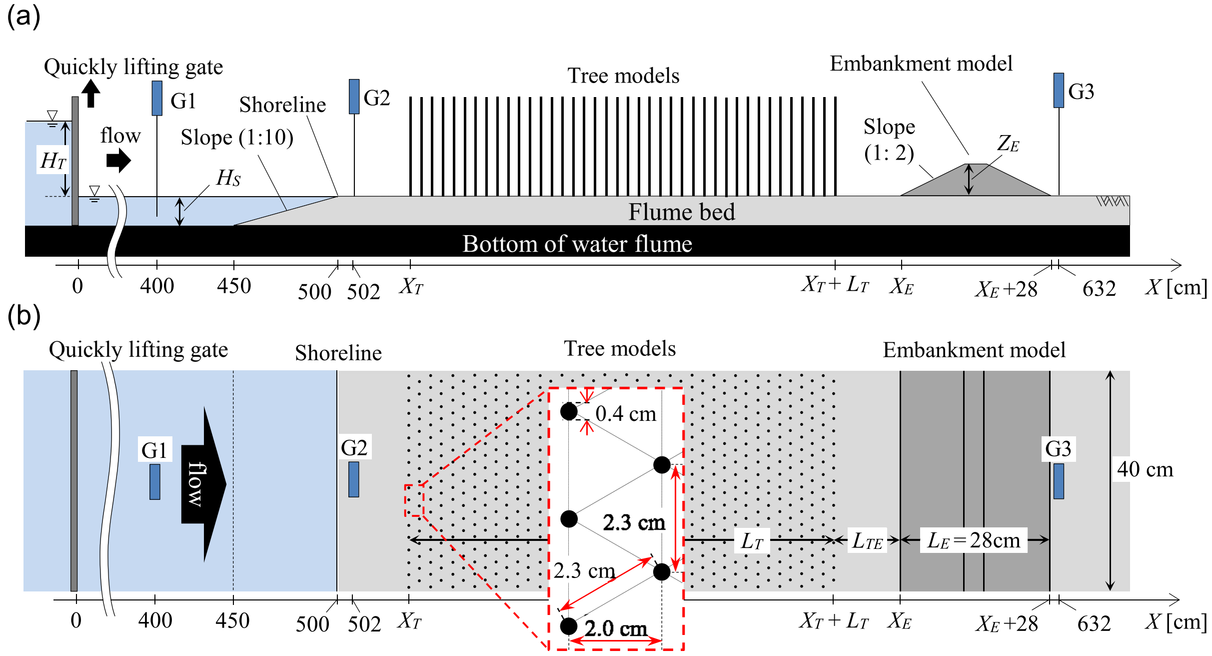

Fig. 1. Experimental apparatus and model setting. (a) In a side view (Case T$_{40\mathrm{B}}$E), the tree model was set in a staggered arrangement, (b) in a plan view, G1–G3 indicate the locations of wave meters.