Ocean Engineering 164 (2018) 722–732

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Changes in flow structures and energy reduction through compound tsunami mitigation system with embankment and lined piles

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ARTICLE INFO

Keywords:
Energy reduction
Hydraulic jump
Overflow from embankment
Compound defense

ABSTRACT

For mitigating tsunamis that overtop an embankment, flume tests were conducted to clarify the energy reduction of a tsunami due to a compound defense system by a combination of a sea embankment and lined vertical piles behind the embankment. The relationship between the flow structure and energy reduction was investigated with changing pile height, spacing, and number of rows. The flow structure was classified into 10 types, and the patterns were classified into two. The energy reduction increased with smaller spacing between lined piles, and the reduction of energy and fluid force behind piles gradually decreased when the piles were submerged. In some cases, energy reduction became very low or energy was locally concentrated because standing waves were generated behind the piles. Two important parameters were proposed, $ResP^*$, consisting of pile spacing, pile diameter, and number of lines of piles in the downstream direction, and Ps^*, comprising overflowing water depth, pile height, and embankment height. Ps^* discriminates whether the piles are emergent or submerged, and $ResP^*$ classifies the change in the flow structure pattern. Recommended design criteria to reduce tsunami energy and to prevent the formation of the standing waves downstream of piles were elucidated by these two parameters.

1. Introduction

The 2011 Great East Japan tsunami extensively destroyed parts of sea walls (tsunami gates, large embankments) (Tappin et al., 2012) and coastal forests (Tanaka et al., 2013). Thus, the tsunami caused catastrophic damage to people and buildings in the Tohoku and Kanto districts of Japan (Udo et al., 2012; Suppasri et al., 2013) and revealed the limits of using only a sea embankment as defense. After the tsunami, the Ministry of Land, Infrastructure, Transport and Tourism, Japan (MLIT) classified tsunamis as level 1 and level 2. The recurrence period of the magnitude for level 1 tsunamis is defined as around 100 years, while that for level 2 tsunamis is within hundreds to a thousand years. Because a level 2 tsunami overtops an embankment, a compound defense system is proposed for level 2 tsunamis to mitigate damage to the hinterland. However, the optimum compound defense system for mitigating a level 2 tsunami is still unknown. Recently, the number of studies that propose compound defense systems, i.e., embankment with coastal forest (Tanaka et al., 2014; Tokida and Tanimoto, 2014; Igarashi and Tanaka, 2016), forest and moat (Usman et al., 2014), moat behind embankment (Mineura et al., 2013; Tsujimoto et al., 2014), dune and canal (Niimi et al., 2013; Rahman et al., 2016, 2017), barrier behind embankment (Matsuyama et al., 2012), hybrid system with low embankment and forest (Temmerman et al., 2013), and double embankments (Tanaka and Igarashi, 2016) has increased.

When a forest is introduced in the downstream part of an embankment, the forest can reduce the tsunami energy by resistance. If the resistance provided by a forest is large enough to change the flow from supercritical to subcritical, it also can decrease the tsunami energy by causing a hydraulic jump. However, not many studies have been conducted for that objective. In a double embankment system (Igarashi and Tanaka, 2016), the second embankment has the risk of being washed out by a tsunami if it is made of soil. Even in that case, reduction of the energy of a tsunami can still be expected when piles are set inside the second embankment and appear after the second embankment was eroded and washed away. To decrease the erosion of an embankment and behind it, hidden piles or short but dense plants such as bushes also have the capacity to increase the resistance to erosion. Thus, it is very important to investigate the effectiveness of a narrow width forest or piles behind an embankment for reducing the energy that overtops an embankment.

The effect and limitation of coastal forests had already discussed in Shuto (1987) before the 2011 tsunami. In addition, there are many

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https://doi.org/10.1016/j.oceaneng.2018.07.003
Received 25 December 2017; Received in revised form 29 June 2018; Accepted 6 July 2018

studies of numerical simulations to evaluate the effects of a coastal forest when tsunami and forest characteristics are changed (Hiraishi and Harada, 2003; Harada and Imamura, 2006; Nandasena et al., 2012). Hiraishi and Harada (2003) also carried out experiments and showed that a greenbelt composed of tropical trees reduces the tsunami water level, flow velocity, and pressure. Tanaka et al. (2014) compared the mitigation effect of an embankment and forest during the 2011 Japanese tsunami and revealed the importance of the forest by their post-tsunami survey and numerical study. Similar effects can be expected for piles. If the spacing of piles or small bush-type trees is close enough to affect the flow upstream of piles, a hydraulic jump may be generated. It is widely known that a hydraulic jump can dissipate tsunami energy (Ahmed et al., 2014; Moussa et al., 2016; Pasha and Tanaka, 2016, 2017). It is also known that a ski jump-type of flow can dissipate energy (Wu et al., 2016). If a free nap flow of a ski jump-type is generated around the piles or trees by resistance, tsunami energy can be dissipated due to collision with the downstream bed of piles or trees although no hydraulic jump is generated.

The resistance of circular cylinders changes with changes in the spacing of the cylinders (Takemura and Tanaka, 2007) and their arrangement (Li and Shen, 1973). In addition, the combination of sparse and dense cylinders affects the reflection of the tsunami (Iimura and Tanaka, 2012). Irtem et al. (2009) showed that the tsunami run-up height for a slope with wooden cylinders placed in a staggered arrangement was decreased compared with that of cylinders in a rectilinear arrangement. However, few experimental studies of supercritical flow against circular cylinders have been reported. In addition, more knowledge about conditions for generation of a hydraulic jump around lined cylinders is needed.

Therefore, a flume study was conducted to clarify the relationship between the energy reduction and the flow structure when a tsunami passes through a compound defense system, i.e., a combination of embankment and piles (lined cylinders) towards the land side.

2. Materials and methods

2.1. Experimental apparatus and procedures

Fig. 1 shows the experimental setup. The compound system was proposed to reduce the energy of overflowing tsunami water by a hydraulic jump and/or resistance of piles. This study changed the pile height, pile spacing, and number of lined piles and investigated the relationship between the flow structure and energy reduction. As a first step, a steady flow condition was set in an open channel flume with the energy reduction ratio for various compound defense models on a physical scale of 1/100 and 1/50, as shown in Fig. 1. The flume length and width were 14 m and 0.5 m, respectively. For setting hydraulic conditions, Froude similarity was used.

For the model experiments on a physical scale of 1/100, a wooden embankment model 14.5 cm high was set on the flume bottom. For the pile models, wooden circular cylinders 0.4 cm in diameter were used, and they were set in a single row at regular intervals along the embankment or they were placed in two rows in a staggered arrangement. One and two rows of piles were selected, as shown in Fig. 1a and b, respectively. The spacings between cylinders for one and two rows (Sp) were set as 0.3, 0.6, and 0.9 cm, and 0.6 and 0.9 cm, respectively. These five cases were named M100R1SD, M100R1SI, M100R1SS, M100R2SI, and M100R2SS. As the convention for case names, M100 indicates that the model scale is equal to 1/100. R1 and R2 indicate that the number of rows is 1 and 2, respectively. SD, SI, and SS indicate that the pile spacings are dense, intermediate, and sparse, respectively. For each of these five cases, three pile heights (H_P) were selected (1, 2, and 4 cm). The distance from the embankment toe to the front-line of the piles was constant at 33 cm.

In addition, two cases, M50R1SI and M50R2SI, both of whose physical scale are 1/50, were tested to confirm the effects of physical scale on flow structures. In cases M50R1SI and M50R2SI, only the small pile height (2 cm) was conducted due to the limitation of the pump flow rate. To investigate the effect of pile diameter, two pile diameters (0.4, 0.8 cm) were additionally tested in cases M50R1SI and M50R2SI under the number of rows of lined piles and non-dimensional pile spacing (Sp/D) were kept constant. Moreover, only the embankment case (Case M100R0 and M50R0) was tested for comparing the effectiveness of the compound system cases. The experimental condition is summarized in Table 1.

2.2. Parameters used in this study

Using the model and hydraulic parameters shown in Fig. 1, five non-dimensional parameters were defined in this study. Non-dimensional pile spacing (Sp^*) was defined as $Sp^* = Sp/D$, where Sp and D are the spacing between the piles and the diameter of a pile, respectively. Sp^* was set as 0.75, 1.5, and 2.25. Non-dimensional pile height ($H_P{}^*$) was defined as $H_P{}^* = H_P/H_E$; where H_P and H_E are the pile height and embankment height, respectively. $H_P{}^*$ were set as 0.07, 0.14, and 0.28. For comparison of results, non-dimensional overflow water depth ($h_c{}^*$) was defined as $h_c{}^* = h_c/H_E$, where h_c is the critical depth on top of the embankment. In cases in which the physical scale of the model was 1/100 or 1/50, the flow structure was investigated in relation to $h_c{}^*$ in the range of approximately 0.08–0.37 or 0.08 to 0.22, respectively.

2.2.1. Non-dimensional arrangement of lined piles ($ResP^*$)

Resistance of lined piles affects the flow structure behind piles. Therefore, the non-dimensional arrangement of lined piles ($ResP^*$) was defined as:

$$\mathrm{Re}\,sP^* = \frac{D}{Sp + D} + \alpha\left(\frac{D}{Sp + D + L}\right) \tag{1}$$

where α is 0 or 1 when the number of rows is 1 or 2, respectively, and L is the distance in between the row of lined piles, as shown in Fig. 1.

On the right hand side of Eq. (1), the first term means the ratio of a unit length in the direction along the embankment ($Sp + D$) and the diameter of a pile in the first row (D). The second term also means the ratio, but it includes the effect of L. When L approaches 0 while keeping α as 1 (two row condition), $ResP^*$ approaches to $2D/(Sp + D)$. It correctly expresses the one row and double density condition. In addition, $ResP^*$ shows that the effect of lined piles of the second row becomes 0 when L becomes infinite.

2.2.2. Non-dimensional parameter on whether piles are emergent or submerged (Ps^*)

The relationship among pile heights, overflow water depths, and embankment heights affects whether piles are emergent or submerged. So, a non-dimensional pile and water surface parameter, Ps^*, was defined as:

$$Ps^* = \frac{h_c^*}{(H_p^*)^\beta} = \frac{(h_c/H_E)}{(H_P/H_E)^\beta} \tag{2}$$

where β is a constant that expresses the backwater rise due to piles.

The effect of $H_P{}^*$ is smaller than that of $h_c{}^*$ because the backwater rise around piles due to changing $H_P{}^*$ is smaller than the rise of water level around piles by changing $h_c{}^*$. Therefore, β in Eq. (2) should be less than 1.0.

2.3. Methods for evaluating reduction of tsunami energy

The overflow water depth from the embankment (h_c) and water depth behind the piles (h_2) were measured in all cases. In some cases, fluctuations in the water surface were observed behind the piles with time and space, and hence maximum and minimum h_2 were measured and their average value was calculated. For estimating the tsunami