Optimum Second Embankment Structure behind Sea Embankment for Energy Dissipation of the Overtopping Flow of Level-2 Tsunami

Y. Igarashi$^1$ and N. Tanaka$^2$

$^1$Graduate School of Science and Engineering, Saitama University
255 Shimo-okubo, Sakura-ku, Saitama, Saitama, JAPAN

$^2$International Institute for Resilient Society, Saitama University
255 Shimo-okubo, Sakura-ku, Saitama, Saitama, JAPAN

E-mail: tanaka01@mail.saitama-u.ac.jp

Abstract: The 2011 Great East Japan tsunami has revealed the limit of hard solution when it is composed of only sea embankment. So the tsunami mitigation for level-2 tsunami (recurrent cycle is around several hundreds to one thousand years) is discussed by multiple defense system; not only by using a single sea embankment but by a combination of several hard and soft solutions. The objective of this study is to clarify the effectiveness of double embankment system for dissipating tsunami energy where the second inland embankment is smaller than the first seaside embankment. Flume tests were conducted to deduce the optimal arrangement and height of inland embankment in comparison with single embankment system. Hydraulic jump is generated in between the two embankment system which greatly reduces the energy of flowing water. When the flow passes the second embankment, it becomes a supercritical condition, and no hydraulic jump occurs, thus energy loss is comparatively low. However, even without a hydraulic jump, the overflow from the second embankment is like a free nap flow and still it involves high energy dissipation due to collision with the ground surface.

Keywords: level 2 tsunami, multiple defense, flume experiment, energy dissipation, hydraulic jump.

1. INTRODUCTION

The 2011 Great East Japan tsunami largely exceeded a designed level of coastal defense. After which the Ministry of Land, Infrastructure, Transport and Tourism, Japan (MLIT) classified it into two types i.e Level-1 and Level-2. Level-1 tsunamis are thought to recur over a period of around 100 years while Level-2 evolves over 100s – 1000s of years. The target of the coastal defense for Level-2 tsunami is changed from ‘disaster prevention’ to ‘disaster mitigation’. The method is also changed from ‘line defense’ to ‘multiple defense’. Recently, the number of studies on the multiple defense using embankment with coastal forest (Tanaka et al., 2007; Tanaka et al., 2014), sand dune (Tanaka et al., 2006), and second embankment (Tanaka & Igarashi, 2016) increases, however, much is still unknown. Therefore, this study selected double embankments system for the multiple defense system, and flume tests were conducted in steady condition as a first step. The flow structure and energy dissipation mechanism is investigated when tsunami current overflows the embankment system. The difference of energy head is measured and calculated at the top of the first embankment and after passing the multiple defense system. This study focuses on the height of the second embankment height for obtaining the knowledge of optimal multiple system with changing of the overtopping flow depth.

2. HYDRAULIC MODEL STUDY

As a tsunami is an unsteady and non-linear flow, physical experiment is usually conducted using a flume with a sudden opening gate. However, very large scale facility is needed to simulate the flow and realize the overtopping phenomenon. As the time period of a tsunami is very long, and can be considered quasi-steady except for the initiation of the inundation, this study conducted flume experiments in a steady condition as a first step. Froude similarity was applied to set the flow condition for the model scale (1/100) of the physical experiment. A multiple defense structure using one or two embankment model was set in a flume of 0.5m in width as shown in Figure 1. Case S is for single embankment system, and Cases D1-D3 are for double embankment system. Details of the experimental conditions are shown in Table 1. Upstream and downstream embankments are defined...
as first and second embankment, respectively. The length \((L)\) in between two embankments was set to a constant value of 30 cm. The height of the first embankment \((EH_1)\) was set as 14.5 cm considering the actual scale (14.5 m) in Iwate Prefecture, Japan. For Cases D1-D3, the sea side slope of the second embankment was set steep (1:1) for making hydraulic jump easy. The heights of second embankment \((EH_2)\) were set 1.8 cm, 3.6 cm, and 5.4 cm, which are 0.125, 0.25, and 0.375 times of the first embankment for Cases D1, D2 and D3, respectively. In all model cases, 11 values of overtopping flow depth \((h_c)\) were selected which are: 1.3, 1.8, 2.3, 2.8, 3.3, 3.8, 4.3, 4.8, 5.3, 5.8, 6.0 cm. Where, overtopping flow depth is the critical depth measured on the top and near the shoulder of the first embankment.

![Figure 1 Experimental setup (S:single, D:double)](image)

**Table 1 Experimental conditions**

<table>
<thead>
<tr>
<th>Exp case</th>
<th>(EH_1) [cm]</th>
<th>(EH_2) [cm]</th>
<th>(L) [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case S</td>
<td>14.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case D1</td>
<td>14.5</td>
<td>1.8</td>
<td>30</td>
</tr>
<tr>
<td>Case D2</td>
<td>14.5</td>
<td>3.6</td>
<td>30</td>
</tr>
<tr>
<td>Case D3</td>
<td>14.5</td>
<td>5.4</td>
<td>30</td>
</tr>
</tbody>
</table>

3. RESULTS AND DISCUSSION

3.1. Change of the Flow Structure around Multiple Embankment System

3.1.1. Classification of the Water Level State

The flow structure after overtopping the first embankment can be classified into four types, as shown in Figure 2. In Type c, a hydraulic jump was generated near the first embankment when it flowed into the stored water in between the two embankments. With increasing water depth, the flow structure was changed to Type b, where the hydraulic jump became strong and occurred not only near the first embankment but in the entire region between the two embankments. By further increasing the water depth, the retained water was washed away, and Type a1 was generated. In this type, the flow jumped on the upstream slope of the second embankment followed by a free nap flow and ultimately collided with the downstream bed. With increasing the \(h_c\) further, the free nap flow was terminated and the flow passed the second embankment as a supercritical flow (Type a2).
3.1.2. Characteristic of Each Water Level State

Tsunami energy can be dissipated in Type c because a hydraulic jump is generated between the two embankments. Besides, stored water in between the two embankments acts like a cushion, and the scour at the toe of first embankment is more likely to be decreased. In addition, the destruction risk of the second embankment becomes low because the seaside flow of the second embankments is subcritical. Type c is in ideal condition, when the second embankment and the length \( L \) in between two embankments are sufficient enough condition to generate a hydraulic jump.

In Type b, dissipation of tsunami energy is also expected like in Type c, because a hydraulic jump is generated in between two embankments. However due to the turbulent nature of the flow in between the two embankments, it involves greater risk of scouring of the first embankment toe and destruction of the second embankment in comparison with the Type c.

In Type a1, a hydraulic jump isn’t generated between the two embankments. The flow in between the two embankments is supercritical flow. Furthermore, it is assumed that the destruction risk of scouring of first embankment toe and the second embankment becomes higher, because the flow in between the two embankments becomes a supercritical condition, hence the shear stress is assumed to increase in the place. Therefore, it is necessary to plan the second embankment height so that Type c or Type b is generated. However, even without a hydraulic jump, the overflow from the second embankment is like a free nap flow which dissipates considerable amount of energy when it collides with the ground surface.

In Type a2, tsunami energy dissipation cannot be expected because a hydraulic jump isn’t generated between two embankments and the collision to the ground surface isn’t occurred. In addition, the destruction risk of scouring of first embankment toe and the second embankment is supposed to be higher because of the high velocity current around the embankments.

3.2. The Tsunami Mitigation Effect by the Second Embankment

For estimating the tsunami mitigation effect by the second embankment, relationship between energy reduction rate [%] and non-dimensional overflow water depth \( h' \) are shown in Figure 3. Where, non-dimensional overflow water depth \( h' \) is defined ‘overflow water depth \( h \) over the first embankment height \( EH_1 \) (14.5cm)’. In addition, energy reduction rate [%] is defined as

\[
\text{Energy reduction rate} \% = \frac{E_1 - E_2}{E_1} \times 100
\]
Where, $E_1$ is the energy at the measurement position I, and $E_2$ is the energy at the measurement position II as shown in Figure 1. $E_1$ and $E_2$ are calculated from Bernoulli’s theorem.

Figure 3 shows that the energy reduction rate is higher for Cases D1-D3 as compared to Case S. Figure 3 shows that energy reduction rates in Case S and D3 gradually decrease from 81% to 38% for $h_c'$ of 0.09-0.41, and from 85% to 61% for $h_c'$ of 0.09-0.39, respectively. For Case D2, energy reduction rate gradually decreases from 82% to 60%, although the flow structure is changed from Type b to Type a1 after when $h_c'$ becomes higher than 0.23. About Case D1, Figure 3 shows that energy reduction rate decreases notably when $h_c'$ becomes higher than 0.23, and it almost coincides with Case S when $h_c'$ increases more than 0.33. In Case D1, the flow categorizes as Type b when $h_c'$ is less than 0.23, Type a1 when $h_c'$ is ranged 0.23-0.33, and Type a2 when $h_c'$ is more than 0.33 (Figure 4).

As mentioned above, Type a1 can be expected to dissipate tsunami energy by the collision to the ground surface. Therefore, Type a1 for two embankment system dissipates greater energy by up to approximately 22% in maximum than single embankment system. However, when free nap flow approaches horizontally in Type a1 condition, the energy reduction rate gradually decreases. On the other hand, in Type a2, energy reduction rate increases approximately 5% in maximum than single embankment system.
3.3. Change of the Flow Structure by the Second Embankment Height

For classifying the flow type in relation to the second embankment height, relationship between non-dimensional overflow water depth $h_c'(\text{ratio of } h_c \text{ and } EH_1)$ and non-dimensional second embankment height $EH_2'(\text{ratio of } EH_2 \text{ and } EH_1)$ are investigated (Figure 4). Figure 4 shows that, for a constant value of $EH_2'$, with increasing $h_c'$, flow structure type changes from c to b, a1 and a2. From Figure 4, it can be deduced that the second embankment height should be such that the flow structure type becomes Type b-c for expected $h_c$.

4. CONCLUSIONS

The results are summarized as following:

1) Double embankment system dissipated 5-22% greater energy than single embankment system when non-dimensional overflow water depth was larger than 0.12, however the difference was low for small overflow depths.

2) In case of double embankment system, the flow structure between the two embankments can be classified into four types. Type b and c dissipate tsunami energy by up to approximately 21% in maximum than single embankment system, because a hydraulic jump is generated between the two embankments. Type a1 can be expected to dissipate tsunami energy (up to 22% in maximum) by the collision with the ground surface. However, when a free nap flow approaches horizontally, the energy reduction rate gradually decreases, and the difference of energy loss becomes 7-12 %. Type a2 cannot be expected to dissipate tsunami energy because a hydraulic jump is not generated between the two embankments and neither is there any collision with the ground surface.

ACKNOWLEDGMENTS

This study was supported in part by a JSPS Grant-in-Aid for Scientific Research (No. 15H02987), and by Grant for Environmental Research Projects from The Sumitomo Foundation.

REFERENCES


Tanaka, N. and Igarashi, Y., 2016, ‘Multiple defense for tsunami inundation by two embankment system and prevention of oscillation by trees on embankment’, Proc. of 20th IAHR-APD, Colombo, Sri Lanka (abstract is accepted)