Stability of geotextile-reinforced coastal dykes against overflowing tsunami

Takeru Kobayashi\(^i\), Keisuke Fukatsu\(^i\), Yoshiaki Kikuchi\(^i\), Taichi Hyodo\(^i\), Yasuo Nihei\(^i\), Yuki Kurakami\(^i\) and Fumio Tatsuoka\(^i\)

\(^i\) Graduate Student, Department of Civil Engineering, Graduate School of Tokyo University of Science, 2641 Yamazaki, Noda 278-8510, Japan. ii) Professor, Department of Civil Engineering, Tokyo University of Science, 641 Yamazaki, Noda 278-8510, Japan. iii) Assistant Professor, Department of Civil Engineering, Tokyo University of Science, 641 Yamazaki, Noda 278-8510, Japan.

ABSTRACT

In the Tohoku Pacific Ocean Earthquake in 2011, many coastal dykes were destroyed due to overflow of tsunamis which height were higher than the crown heights of coastal dykes. It is shown by previous studies that the GRS coastal dykes covered with crushed stone and panels are strong against overflow of tsunami. In this study, we studied the effects of slope inclination and the water flow inside of the dyke against overflow resistance of dykes. The height of the model dykes were 100 mm. Stepwise increasing water flow rate experiments and bore type water flow experiment with extremely high level of water rate experiments were conducted to the model dykes. The inclinations of slope used were 1:2 and 1:0.5. For performing the water flow through the model dyke, gaps between the panels were made with using paste plastic tapes. Followings were concluded in this study. (1) Effect of slope inclination: To improve the overflow resistance, inclination of seaside slope should be milder than 1:2 and inclination of landside slope should be steep as inclination of 1:0.5. (2) Influence of the water flow through the dyke: The water flow through the dyke has a large effect to the resistance of the dykes against overflow of tsunami, because if the water comes through the dyke, sand or embankment materials will be outflowed from the dyke.

Keywords: coastal dykes, tsunami, geosynthetics, overflow

1 INTRODUCTION

The role of embankment is to protect the human life and the property in the coastal hinterland from tsunamis, tidal waves and waves as well as to prevent erosion of land. The tsunami caused by the Tohoku Pacific Ocean Earthquake in 2011 overflowed the coastal dykes. And many coastal dykes were collapsed. Also, the damage of human and material have become enormous. And they were outburst by overflowing tsunamis. Tsunamis will come many times when once they occurred. Therefore, it is necessary to avoid collapsing dykes by overflow of tsunami. Figure 1 shows the damage of coastal dykes which was overflowed by tsunami in 2011 earthquake. If the coastal dyke was broken by the first tsunami attack, it is hard to protect hinterland by the second attack of tsunami. Therefore coastal dykes should be safe against overflow of tsunami. In other words, coastal dykes should be tenaciously strong against tsunami overflow.

The authors proposed to use geotextile reinforced soil coastal dykes (GRS coastal dykes), which have high ability to resist the overflow of tsunami. From the results of series of model experiments, it was found that reinforcing coastal dykes with geotextiles improve the resistance against overflowing tsunami (Yamaguchi, S. et al. 2012, Yamaguchi, S. et al. 2013, Matsushima, K. et al. 2014). In addition, as the overflow experiments of embankments such as railway embankments and river levees experiments have been conducted (Watanabe, K. et al. 2014, Aoyagi, Y. et al. 2014, Kurakami, Y. et al. 2014). Fukatsu, K. et al. (2015) showed GRS dykes covered with panels and crush stones have high
resistance ability against tsunami overflow by conducting a series of overflow experiment with step increasing quantity of flow.

In this study, effects of structure difference of coastal dykes to the resistance against tsunami overflow were examined. Model dykes used in this study were based on model dykes used in the series of experiments conducted by Fukatsu, K. et al. (2015). In particular, effects of the slope gradient and the gap between cover panels were focused on the impact on the resistance to erosion of the coastal dykes at the time of the overflow.

2 EXPERIMENTAL OUTLINE

2.1 Experimental apparatus

In this study, a series of experiments were conducted with a small circulation channel and a wave-making channel.

Figure 2 shows a schematic diagram of a small circulation channel with dimensions of 1800 mm in length x 410 mm in height x 205 mm in width. Figure 3 shows a schematic diagram of a wave-making channel with dimensions of 36 m in length x 1.2 m in height x 1.0 m in width. In the wave-making channel, a shutter for making a bore was set at 25.5 m from the offshore side end of the channel. And a channel floor was inclined in 1:20 in 4 m from the shutter. The channel floor becomes level at an altitude of 0.21 m from the channel floor of the position of the shutter. The model dyke was constructed at the position of 4 m from the shutter. Running water beyond the model is drained away from the onshore side end of the channel.

In all experimental cases, model dyke height was 100 mm, and the crest width was 100 mm, and the length of the model was the same as the channel width. In addition, the one of the side wall of each channel was made of acrylic resin for observing the state of flow and a dyke model during the experiment.

The model dykes were constructed on the plywood which was the surface of each channel floor. In this series of experiment, foundation ground of the model dyke was not considered, and scouring of each end of slope was not considered.

In the small channel experiments, overflow of circulating water was performed by seven submersible pumps. The flow rate was increased progressively from 0.098 m³/min/m to 6.05 m³/min/m. In the wave-making channel, bore flows were made. The bore flow was made by rapid opening of the shutter with a water level difference between in front and behind shutter. The water level difference was increased from 30 cm to 85 cm in stepwise.

2.2 Experimental cases

Figure 4 shows a cross sectional image of model dykes used in this series of experiments.

As shown in the figure, the central part of the dyke was constructed by silica sand. Silica sand was covered by crushed stone with 30 mm thickness and metal panels with 5mm thickness. The silica sand and crushed stone were reinforced with geogrid. Number of layers of geogrid was 6. The crushed stone was wrapped by geogrid. Also, geogrid and panels were attached with glue. There were gaps between the panels. The gaps between the panels were controlled with paste plastic tape. Paste plastic tapes were attached to the front side and the rear side of the upper and lower ends of the slopes panel.

Silica sand used was Tohoku Silica sand No.6 \((\rho_s = 2.65 \text{ g/cm}^3, D_{50} = 0.34 \text{ mm})\). The sand was compacted to dry density \(\rho_d\) of 1.50 g/cm³, which was a degree of compaction on the standard Proctor of 95 %, in water content ratio w of 11.9 %, which was optimum moisture content. Physical properties of crushed stone were \(\rho_s\) of 2.66 g/cm³, grain size of from 4.75 mm to 9.5 mm, and \(D_{50}\) of 6.05 mm. Crushed stone was compacted to \(\rho_d\) of 1.56 g/cm³ with water content ratio of 0.03.
w of 5%. The model geogrid used to embankment reinforcement was tarp screen #2014 (5 mm grid spacing). Metal panels used for the cover were those made by duralumin of thickness 5 mm.

Table 1 shows the cases conducted in this series of experiments.

In case of from Case 1 to Case 4, slope inclinations of land side and sea side were changed. In each case, the gaps between the panels were 0.3 mm except in Case 5 in which gap between panels were 0.9 mm. Experiments of Case 6 and Case 7 were carried out in the wave-making channel. The width of wave-making channel was five times of that of the small circulation channel. As the width of the model dykes were five times as those in the small circulation channel, five rows of panels were used in these cases. The inclination conditions of the experiments conducted in wave-making channel were 1:2 in sea side slope, and 1:0.5 in land side slope, as these conditions showed the highest overflow resistance among the experimental condition conducted in this series of experiment in small circulation channel. In Case 6, gaps between the panels were 0.3 mm. This condition is the same as in Case 4. In case of Case 7, no gaps were prepared between the panels.

During the experiment of each case, the displacement of the cover panels, erosion of the model dyke, the deformation of the dykes were observed and recorded by digital video cameras.

Table 1. Experiment case.

| Case | Top width (mm) | Slope gradient land said / sea said | Gap between the panels (mm) | Reinforcement | Channel used |
|------|----------------|------------------------------------|----------------------------|---------------|--------------|
| 1    | 100            | 1:2/1:2                            |                            |               |              |
| 2    |                | 1:0.5/1:0.5                        | 0.3                        | Overall reinforcement | Small circulation channel |
| 3    |                | 1:2/1:0.5                          |                            |               |              |
| 4    |                | 1:0.5/1:2                          | 0.9                        | Overall reinforcement | Wave-making channel |
| 5    |                |                                    |                            |               |              |
| 6    |                |                                    |                            |               |              |
| 7    |                |                                    | 0                          |               |              |

3 EXPERIMENT RESULTS AND THEIR ANALYSIS

3.1 Effect of slope gradient

Figure 5 shows the relationship between overflow elapsed time and the remaining cross sectional area ratio and the relationship between the amount of flow rate and overflow elapsed time in the experiment from Case 1 to Case 4. The remaining cross-sectional area ratio is the ratio of remaining cross sectional area observed through acrylic wall against the initial cross sectional area. In Fig. 5, solid lines show the remaining cross sectional area ratio, and dotted line shows unit width flow rate.

Fig. 5. Remaining cross sectional area ratio and unit width flow rate against elapsed overflow time (From Case 1 to Case 4).

The model coastal dyke used in Case 4 had the slope of 1:2 in sea side and 1:0.5 in land side. When the unit width flow rate increased, slight sand outflow from the model dyke was observed. And the deformation and outflow of sand were very little after the maximum flow rate condition as shown in Fig. 6. In the case, the overall failure was never observed.

In contrast, the model coastal dykes collapsed with some level of flow rate in from Case 1 to Case 3. In these cases, outflow of sand from the model dykes were significant, and it led to the total failure and large displacement of panels.

6.05 m³/min/m

Fig. 6. Maximum overflow rate in Case 4 (upper left shows the flow rate).

Three reasons are considered on high resistance capacity in Case 4.

First, it was the structure that coastal dykes materials were hard to be flow out because it was the coastal dykes which covered by panels and crushed stone (Fukatsu, K. et al. 2015).

Second, because of the inclination of sea side slope was mild, the vertical component of the water pressure acting on the seaward slope is large compared to horizontal water pressure acting on the slope. It makes
the ratio of "horizontal force acting on the base of the channel under the dyke", F, to "vertical force acting on the base of channel under the dyke", L, small, when total vertical force is summation of submerged dyke weight and vertical component of water pressure. If coefficient of friction \( \mu \) between plywood and sand is higher than 0.5, slope inclination of 1:2 is always satisfying \( \mu L \geq F \) regardless of the weight of the embank body. In other words, it is stable against for the water pressure if an inclination of sea side slope is 1:2. On the other hand, if the inclination of seaside slope is 1:0.5, the condition of \( F \geq \mu L \) can be happen when the flow rate increased to some extent.

Third, running water flow velocity is lowered in the inclination of land side slope was 1:0.5 compared to in the slope inclination of 1:2. This lower water flow velocity reduced the lowering the water pressure of land side slope and it reduced the possibility of outflow of sand from the dyke. It helped not to be broken the dyke from the landside slope.

3.2 Effect of difference of the gap between the panels

Figure 7 shows the same relationships as Fig. 5 in Case 4 and Case 5. In Case 4 and Case 5, only difference was the gaps between panels. The gaps between the panels were 0.9 mm in Case 5. The outflow of sand from a model dyke occurred even from the smallest flow rate in Case 5, and it was collapsed at the unit width flow rate of 2.68 m³/min/m. At the collapse, all panels were removed. Because of the amount of water flow through dyke increased, the dyke was easily collapsed. It was because of the larger gaps between the panels.

The cross sectional condition of Case 6 was the same as that in Case 4. The gaps between panels were 0.3 mm. In Case 6, the model dyke sustained up to the water level difference of 50 cm as shown in Fig. 8. And at that time, the maximum unit flow rate of this condition was almost 35 m³/min/m and the maximum water depth of seaside crown was 216 mm. Therefore, it may be said that the model dyke of Case 4 sustain its performance up to 35 m³/min/m of unit flow rate.

The model dyke of Case 7 had no gaps between panels. Other structural conditions inside of the model dyke were the same as those in Case 6. In case of Case 7, there were almost no deformation or no outflow of sand observed even the water level difference was 85 cm which was the maximum water level difference can be made in the channel. During the flow in this condition, the maximum unit flow rate was almost 67 m³/min/m and the maximum water depth of seaside crown was 395 mm. In this way, resistance against overflow of the coastal dykes increased dramatically if no water flow inside of the dyke is permitted. Reality, it is difficult to perform such a condition. However, there is a big effect in minimizing amount of water flow penetrate through the coastal dykes for improving the resistance against overflow of the coastal dykes.

![Fig. 8. Overflow in Case 6.](image8)

![Fig. 9. Overflow in Case 7.](image9)

3.3 Extra large amount of water flow rate experiment

The experiment of Case 6 and Case 7 were conducted in wave-making channel. In both experimental case, water level difference was 30 cm in the first flow experiment. Water difference was increased in 10 cm each in following flow experiment.

4 CONCLUSIONS

In this study, effects of slope inclination and the water flow inside of the dyke to overflow resistance of
dykes were discussed. In this study, model dykes were covered with crushed stone and panels and they are reinforced by geogrid. Followings are the main conclusions of this study.

(1) Effect of slope inclination
To improve the overflow resistance, inclination of sea side slope should be milder than 1:2 and inclination of landside slope should be steep as inclination of 1:0.5. This combination of slope inclinations seems to be hydraulically reasonable.

(2) Influence of the water flow through the dyke
If the gaps between the panels were large, the overflow resistance of the dyke was not enough. If there were no gaps between the panels, the overflow resistance of the dyke dramatically improved. This difference was because of the difference of the water flow inside of the dyke. And if the water comes through the dyke, sand or embankment materials will be outflowed from the dyke. It will weaken the overflow resistance of the dykes.

REFERENCES
1) Aoyagi, Y., Kawabe, S., Kikuchi, Y., Fujii, M., Watanabe, K., Nonaka, T., Iijima, M. and Tatsuoka, F. (2014): GRS by small scale model tests overflow stability of Coastal dykes, Japanese Geotechnical Society Special Symposium -Beyond East Japan Earthquake Disasters-, 623-627 (in Japanese).
2) Fukatsu, K., Kikuchi, Y., Hyodo, T. and Tatsuoka, F. (2015): Evaluation of the resistance of GRS coastal dykes against overtopping Tsunami current, Proc. of Geosynthetics, 30, 51-58 (in Japanese).
3) Kurakami, Y., Nihei, Y., Itakura, M., Morita, M., Yoshimori, Y., Otsuki, J., Kawabe, S., Kikuchi, Y. and Tatsuoka, F. (2014): GRS coastal dykes penetration and cleaning moats characteristics, Japanese Geotechnical Society Special Symposium -Beyond East Japan Earthquake Disasters-, 644-650 (in Japanese).
4) Matsushima, K., Mouri, S., Tatsuoka, F., Kikuchi, Y., Watanabe, K. and Ohugushi, K. (2014): Special strong coastal dykes to rest tenaciously teleseismic wave, Japanese Geotechnical Society Special Symposium -Beyond East Japan Earthquake Disasters-, 651-659 (in Japanese).
5) Watanabe, K., Fujii, M., Matsushima, K., Nonaka, T., Kudou, A., Iijima, M., Yamaguchi, S., Aoyagi, Y., Furukawa, D., Kawabe, S. and Kikuchi, Y. (2014): Overflow periods of reinforced soil experimental study on the resistance of structures, Japanese Geotechnical Society Special Symposium -Beyond East Japan Earthquake Disasters-, 628-636 (in Japanese).
6) Yamaguchi, S., Yanagisawa, M., Kawabe, S., Tatsuoka, F., and Nihei, Y. (2012): Stability against a variety of retaining wall by small scale model tests over-flow tsunami evaluation, Proc. of Geosynthetics, 27, 61-68 (in Japanese).
7) Yamaguchi, S., Obayashi, S., Kawabe, S., Tatsuoka, F., Kikuchi, Y. and Nihei, Y. (2013): An experimental study on the tsunami tide crest reinforcement technology, test papers, Proc. of Geosynthetics, 28, 245-250 (in Japanese).