Resistance of geosynthetics reinforced coastal dykes against over-topping tsunami

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ABSTRACT: In the 2011 off the Pacific coast of Tohoku Earthquake, at many places, coastal dykes fully collapsed by deep over-topping tsunami. In this study, the resistance of coastal dyke against deep over-topping tsunami was examined by conducting a series of model experiments. In the model dykes, inclination of upstream and downstream slopes, covering system of the dyke such as the thickness of surface gravel layers or the opening size between the slope protection panels, way of reinforcing by geogrids such as length of the geogrids inside of the dykes were changed. In the model experiments, the height of the model dykes was 10cm, width of the flume was 20cm. Flow rates applied in the experiment were increased step by step. The over-flow depth against dykes increased with increasing unit water flow rate. It was found that GR coastal dykes having the following structures can exhibit high resistance against erosion of the backfill caused by deep over-topping tsunami: the inclination of the upstream slope is gentle while it of the downstream slopes is steep; the cover system should include gravel and panels; and the geogrid layers are arranged over the full width of the embankment and the reinforcement layers are connected to the panels.

Keywords: coastal dykes, tsunami, geosynthetics, overflow

1 INTRODUCTION

The tsunami caused by the Tohoku Pacific Ocean Earthquake in 2011 over-flowed the coastal dykes. And many coastal dykes were collapsed. The tsunamis height of which exceeded the height of the crown of coastal dykes attacked many coastal dykes. And they were outburst by overflowing tsunamis. The damage of human and material have become enormous where the hinterland of broken dykes.

The role of coastal dykes is to protect hinterland from wave disasters such as high waves or tsunamis. From this reason, coastal dykes are very important structures preventing from coastal disasters. They should be tenaciously strong against hazardous actions.

Tsunamis will come surged many times when once they occurred. Therefore, it is necessary to avoid collapsing dykes by overflowing tsunamis. 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 strong against overflow of tsunamis. 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 tsunamis. From the results of series of model experiments, it was found that reinforcing coastal dykes with geotexitiles improve the resistance against overflowing tsunami (Yamaguchi et al. 2012, Matsushima et al. 2014). In addition, as the overflow experiments of embankments such as railway embankments and river levees experiments have been conducted (Watanabe et al. 2014, Aoyagi et al. 2014, Kurakami et al. 2014).

In this study, effects of structure difference of coastal dykes to the resistance of tsunami overflow were examined. Model dykes used in this study were based on model dykes used in the series of experiments conducted by Fukatsu et al.(2015,2016). In particular, effects of the slope inclination and the length of geogrid were focused on the impact on the resistance to erosion of the coastal dykes at the time of the overflow.

2 EXPERIMENT

2.1 *Apparatus*

In this study, two series of experiments were conducted with a circulation channel. Figure 1 shows schematic diagram of a circulation channel. The model channel in dimensions with 1800 mm in length x 410 mm in height x 205 mm in width. The model dykes were constructed on the plywood which was the surface of the channel floor. In these series of experiments, foundation ground of the model dykes was not considered, and scouring of each end of slope was not considered.

Overflow experiments by circulating water using seven submersible pump having different capacity were performed. The flow quantity increased it progressively from 0.098 m^3/min/m to 6.05 m^3/min/m.

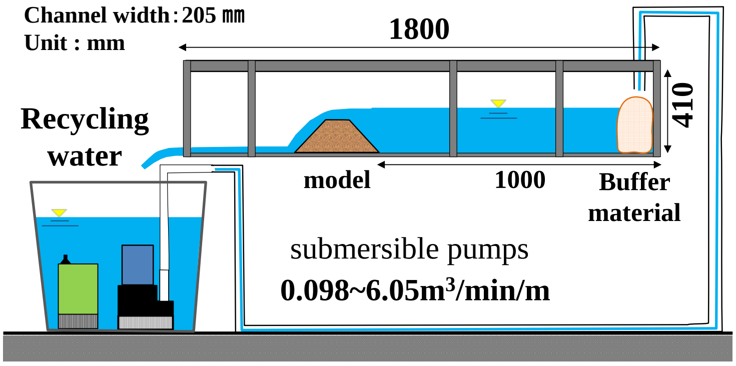


Figure 1. Diagrammatical view of the small circulation channel.

2.2 *Experimental cases*

Height of model dykes were 100 mm, length of the crown of them were 100 mm, and width of them were 205 mm which was the same as the width of the channel.

Experiments were separated to two series. Table 1 shows experimental cases in series 1 (Fukatsu et al., 2015). In this series, effect of cover system to the resistance of dykes against overflow was examined. Table 2 shows experimental cases in series 2(Fukatsu et al., 2016). In this series, effects of slope inclination and geogrid installation to it were examined. Maximum unit water flow rate was 6.05 m^3/min/m, and the relationship between elapsed time and unit water flow rate used in the experiments is shown in Figure 2. Maximum unit water flow rate in the series 1 was 2.68 m^3/min/m, because of the limitation of number of pumps in this series. But the relationship between elapsed time and unit water flow rate up to 2.68 m^3/min/m in each experimental case in series 1 was the same as that used in series 2.

Table 1. Experimental conditions in series 1

Case	Slope inclination		Crown width (cm)	Cover material used		Geogrid
	Land side	Sea side		Gravel	Panel	
1-1	1:2	1:2	10	○	-	-
1-2					○	-
1-3				○	○	-
1-4	1:0.5	1:0.5		○	○	○

Figure 3 shows cross sectional image of a model dyke used in Case 1-3. As shown in the figure, the central part of the dyke was constructed by silica sand. Silica sand was covered by crushed stone with 30mm thickness and metal panels with 5mm thickness. There were gaps between the panels in slopes. Gaps between the panels were controlled to 0.3 mm 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. Usually even if dykes are covered with panels, gaps between panels are inevitably occurred because of un-even settle-

Table 2. Experimental conditions in series 2

Case	Slope inclination		Crown width (cm)	Cover material used		Geogrid
	Land side	Sea side		Gravel	Panel	
2-1	1:2	1:2	10	○	○	Fully installed
2-2	1:2	1:0.5		○	○	
2-3	1:0.5	1:2		○	○	
2-4	1:0.5	1:0.5		○	○	
2-5	1:0.5	1:0.5		○	○	Partial (long)
2-6	1:0.5	1:0.5		○	○	Partial (short)

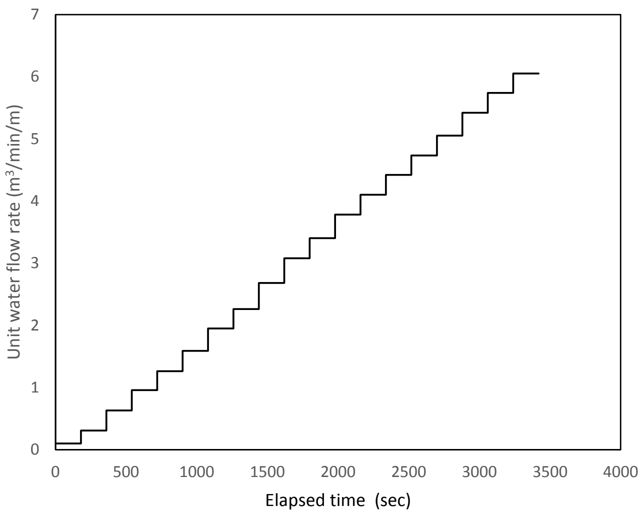


Figure 2. Relationship between elapsed time and unit water flow in series 2.

ment or other reasons. From considering the scale of the model dykes considered, the gap of more than 1.5 cm in the proto type was considered.

As shown in the figure, the central part of the dyke was constructed by silica sand. Silica sand was covered by crushed stone with 30mm 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.

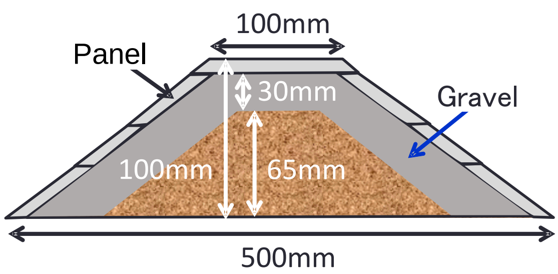


Figure 3. Cross sectional image of a levee in Case 1-3

Figure 4 shows cross sectional image of a model dyke used in Case 2-3. Geogrids were used to reinforcing dykes and maintaining steep slopes in Case 1-4 and all cases in series 2. In these cases, 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.

Figure 5 shows the image of partial reinforced by geogrids. As seen in the figure, embedded length of geogrid was different in Case 2-5 and Case 2-6. Usage of geogrid was different in Case 2-3 and Case 2-5. The crushed stone of sea side was wrapped in Case 2-3, but it was not wrapped in Case 2-5.

Silica sand used was Tohoku sand No.6 (ρ_s = 2.65 g/cm^3 , D_{50} = 0.34 mm). The sand was compacted to dry density ρ_d of 1.50 g/cm^3 ,which was a degree of compaction on the standard Proctor (Ec 1) D_c of 95 %), in water content ratio of 11.9 %, which was optimum moisture content. Physical properties of crushed stone were ρ_s of 2.66 g/cm^3, grain size of from 4.75 mm to 9.5 mm, and D_{50} of 6.05 mm. Crushed stone was compacted to ρ_d of 1.56 g/cm^3 with water content ratio of 5 %. The model geogrid used to embankment reinforcement was tarpo screen #2014 (5 mm grid spacing). Metal panels used for the cover were those made by duralumin of thickness 5mm.

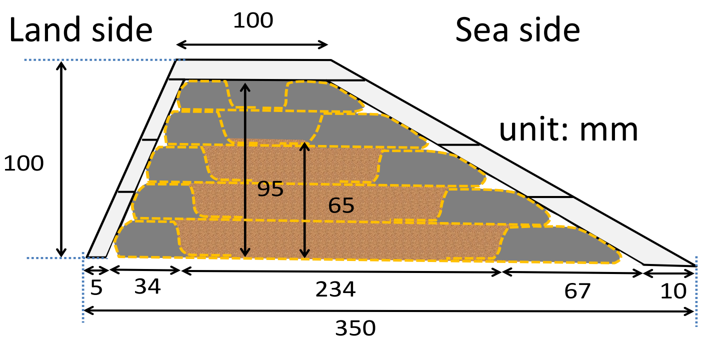
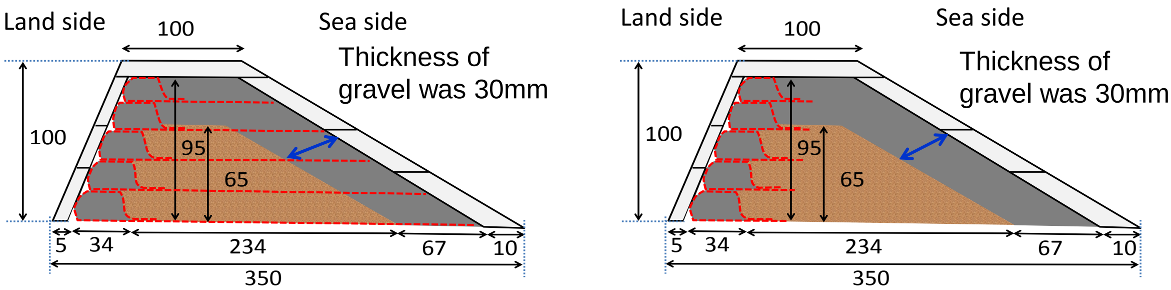


Figure 4. Cross sectional image of a levee in Case 2-3



(a) Case 2-5 (b) Case 2-6

Figure 5. Cross sectional image of levees in Case 2-5 and 2-6.

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.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 *Effect of cover system*

Figure 6 shows the relationship between unit water flow rate and remained cross section rate. Remained cross section rate was observed cross section area of a model dyke through acrylic resin divided by original cross section area of the dyke. In the figure, plotted remained cross section ratio was the end of each unit water flow rate. Duration of one step of unit water flow rate was set to 30 seconds as shown in Figure 2.

Comparing the results of Case 1-1 or Case 1-2 and Case 1-3, combination use of gravel and panels for cover system dramatically improved the resistance of reducing cross section of model dykes against overflow. As seen in Photo 1 (a), a model dyke covered with only gravel eroded from the crown of the dyke just after over flow started. This phenomena was similar to the dyke without any cover system. As seen in Photo1 (b), a model dyke covered with only panels was sucked out sand from gaps between panels at first, then panels were suddenly slide down the slope. As seen Photo 1 (c), a model dyke covered with gravel and panels was never eroded from the crown because of existing of panels nor was less sucked out sand from gaps because of existing of gravel.

The model dyke in Case 1-4 had steep slopes with geogrid. It maintained its original height and small suck was observed up to unit water flow rate of 1.59 m^3/min/m. But as seen in Photo 1(d), large deformation of it and sliding were observed at the unit water flow rate of 1.95 m^3/min/m. This is because of lack of sliding resistance of the dyke against horizontal force originated from water pressure based on the depth of the water. Water pressure acted on the slope of sea side was normal to the slope and it was separated to vertical force and horizontal force. When the slope was 1:0.5, horizontal force was twice of vertical force. When the water depth of sea side was increased, sliding safety factor was decreased. When the slope was 1:2.0, horizontal force was a half of vertical force. Even if the water depth of sea side was increased, sliding safety factor was increased if considering coefficient of friction between sand and plywood was 0.6.

From above results, following two points are clarified. Firstly, the resistance of a dyke against overflow can be increased with double cover of panels and gravel. Secondly, when slope inclination of sea side should be mild, sliding safety factor is maintained.

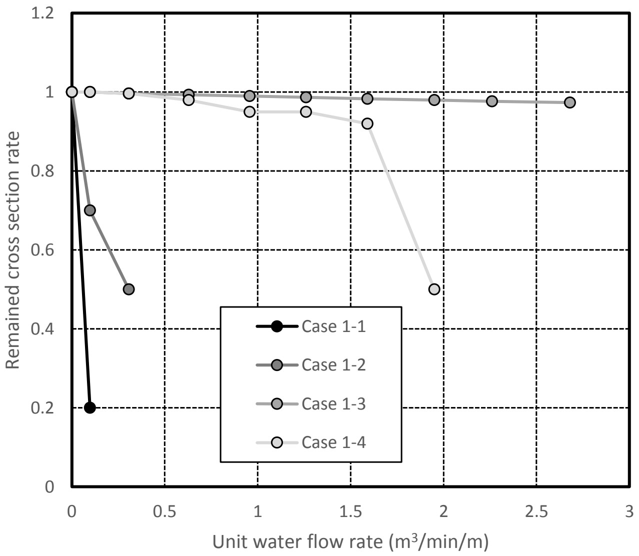
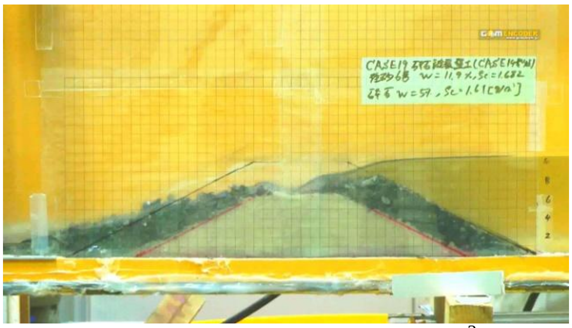


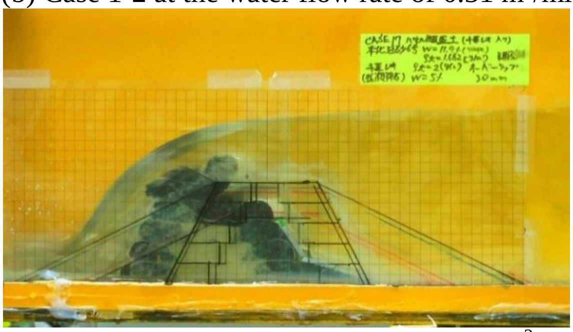
Figure 6. Relationship between unit water flow rate and remained cross section rate in series 1.



(a) Case 1-1 at the water flow rate of 0.10 m^3/min/m

(b) Case 1-2 at the water flow rate of 0.31 m^3/min/m

(c) Case 1-3 at the water flow rate of 2.68 m^3/min/m



(d) Case 1-3 at the water flow rate of 1.95 m^3/min/m

Photo 1. Deformation of levee in series 1.

3.2 *Effect of slope inclination*

Figure 7 shows the relationship between unit water flow rate and remained cross section ratio from in Case 2-1 to Case 2-4. Sea side slope inclinations of Case 2-2 and Case 2-4 were 1:0.5 and model dykes were failed in sliding mode as seen in Photo 2 (b) and (d) even if the unit water flow rate at the failure was different. Referring to the results of Case 1-4, steep slope of sea side made the model dyke unstable because of reducing sliding safety factor with increasing the water depth.

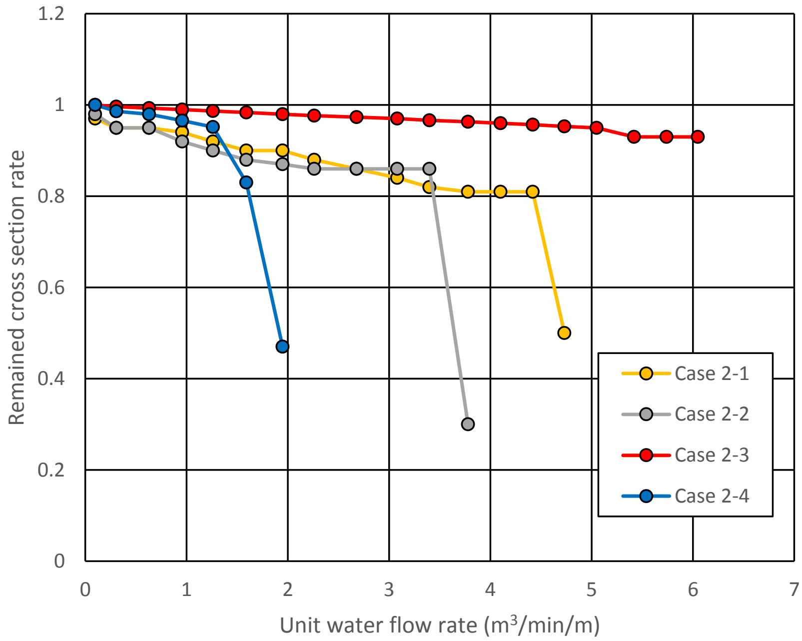
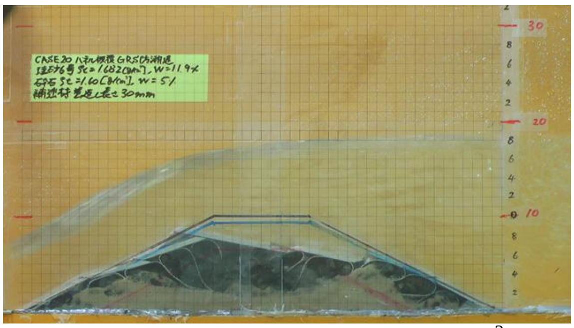


Figure 7. Relationship between unit water flow rate and remained cross section rate in Cases from 2-1 to 2-4. In these cases, slope inclinations of sea side and land side were changed. Most strong case was Case 2-3, in which the slope of seaside was 1:2.0 and it of land side was 0.5:1.

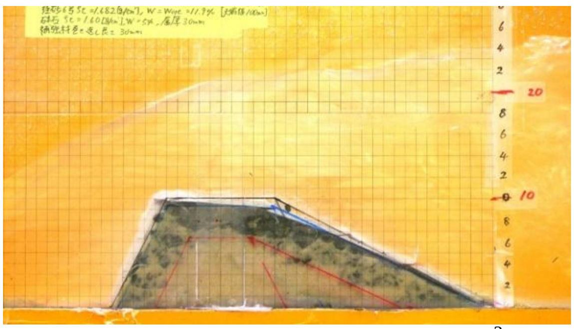
When slope inclinations of sea side were 1:2.0, there were no sliding mode of failure in Cases 2-1 and 2-3 as seen in Photo 2 (a) and (c).

In Case 2-1, the model dyke was failed because of suck of sand and removal of panels of land side. In Case 2-3, small deformation of the model dyke was observed. It is because small amount of sand was sucked out in this case. The slope of land side was different between in these cases. As seen in Photo 2 (a) and (c), water depths on land side slopes were different in these cases and it means the water flow velocity on each slope was different. It was large in Case 2-1 and this difference made the difference of sucking sand out from the body of the dyke.

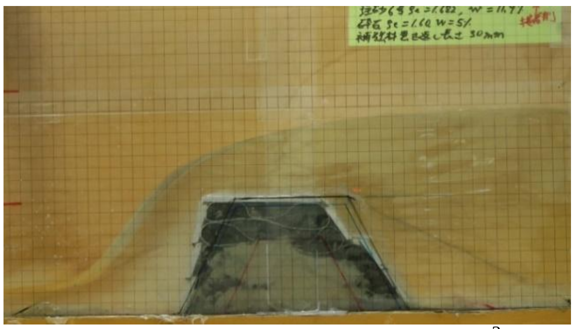


(a) Case 2-1 at the water flow rate of 4.42m^3/min/m.

(b) Case 2-2 at the water flow rate of 4.73m^3/min/m.



(c) Case 2-3 at the water flow rate of 6.05m^3/min/m



(d) Case 2-4 at the water flow rate of 1.59 m^3/min/m.

Photo 2. Deformation of levee in series 2 with different slope inclination cases

3.3 *Effect of Reinforcement with Geogrid*

As seen in 3.2, to have high resistance against overflow, slope inclination of sea side should be maintained mild and it of land side slope should be maintained steep. In this section, usage of geogrid was changed and sea side and land side slope inclinations were fixed as 1:2.0 and 1:0.5 respectively.

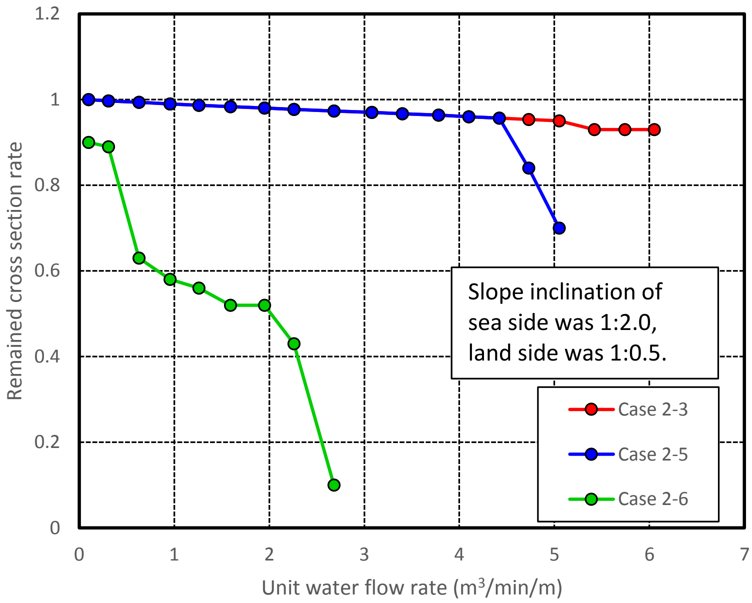
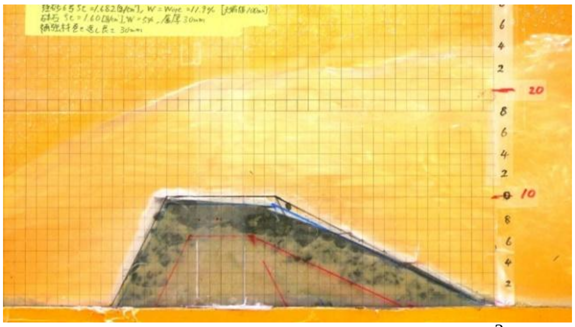
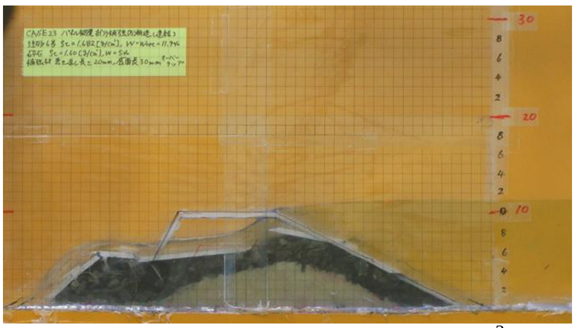


Figure 8. Relationship between unit water flow rate and remained cross section rate in Cases 2-3, 2-5, and 2-6. In these cases, installation of geogrid was different as shown in Figures 4 and 5. When the length of geogrid was short, resistance against overflow was rather small.



(a) Case 2-3 at the unit water flow rate of 6.05m^3/min/m

(b) Case 2-5 at the unit water flow rate of 5.05m^3/min/m



(c) Case 2-6 at the unit water flow rate of 0.63 m^3/min/m

Photo 3. Deformation of levee in series 2 with different geotextile length.

Figure 8 shows the relationship between unit water flow rate and remained cross section ratio in Cases 2-3, 2-5, and 2-6. Difference of usage of geogrid was shown in Figure 4 and 5. As explained in 3.2, small deformation was observed in Case 2-3 even at the maximum unit water flow. But in Cases 2-5 and 2-6, the model dykes failed at smaller amount of unit water flow rate. The crown panel was removed at first, then sand were sucked out and panels on land side slope were removed in Case 2-5. Differences of usage of geogrid in Cases 2-3 and 2-5 were whether sea side gravel was wrapped or not and whether sea side slope panels were glued with geogrid or not. From this difference, unification of panels and geogrid is important to increase the resistance of dykes against overflow.

Looking at the difference of failure mode in Cases 2-5 and 2-6, land side slope deformed largely in Case 2-6 as seen in Photo2 (c), otherwise deformation of deeper part of land side slope was small in Case 2-5 as seen in Photo 2(b). This difference was because of the difference of embedment length of geogrid. Longer geogrid embedment will increase the resistance of dykes against overflow.

4 CONCLUSIONS

Many coastal dykes were collapsed by tsunami caused by the Tohoku Pacific Ocean Earthquake in 2011, because of overflow of the coastal dykes. Finding high resistance dyke structure against overflow of tsunami was the aim of this research.

As for the cover system of dykes, double cover of panels and gravel is largely effective to improve resistance of overflow. It is considered that panels work as reducing the water flow inside of the dyke and gravel works as reducing the water flow through inside sand. Both effects reduced the erosion of dykes.

As for the slope inclination of dykes, the highest resistance against overflow was performed with slope inclinations of 1:2.0 in sea side slope and of 1:0.5 in land side slope. Mild inclination of sea side slope maintains the sliding safety factor high. Steep inclination of land side slope reduces the water flow velocity of land side slope and reduces the sand sucking from the dyke.

As for the usage of geogrid, when geogrid wraps both side of gravel and geogrid and panels are unified, the resistance of dykes against overflow is increased. On the other side, small embedment length of geogrid increases the resistance small.

As mentioned in the introduction, foundation ground of the model dykes was not considered, and scouring of each end of slope was not considered in this research. Effect of these points should also be considered to improve the coastal dykes against overflow of tsunami.

ACKNOWLEDGEMENT

Part of this research was supported by the grants-in-Aid for Scientific Research (A) (Responsible researcher: Yasuo Nihei). The authors express their great acknowledgement to this support.

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