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Effect of River Levee with Geosynthetic-Reinforced Soil against Overflow Erosion and Infiltration

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ABSTRACT

Overflows from huge floods have caused levee breaches in a great number of places, including Japan. To prevent such destruction and thereby increase the resistance of armored levees to overflow erosion, we examined the performance of Geosynthetic-Reinforced Soil (GRS) levees against overflow erosion under various conditions, such as reinforcement, back slopes, and geo-grid layers. In addition, we investigated the effect of geo-grid layers on the infiltration of levees. The model tests revealed that 1) with scour protection in front of the toe of the back slope, the GRS levee exhibits much higher resistance against overflow erosion than the armored levee, and 2) the armored levee with a steep back slope (= 1:0.5) collapsed faster than that with a normal slope (= 1:2). However, the GRS levee with a steep back slope of 1:0.5 maintained high resistance against overflow erosion after the target time. 3) The GRS levee with partial and full reinforcements had a comparably high resistance against overflow erosion. 4) The GRS levee using a small-sized geo-grid maintained a high residual ratio of the cross-sectional area over a long period. 5) The infiltration discharge of the GRS levee was less than that of the levee with no reinforcement due to the reduction in infiltration erosion in the GRS levee. These facts suggest that the GRS levee with partial reinforcement can be applied to the reinforcement of existing levees, and appropriately sized geo-grid layers should be selected.

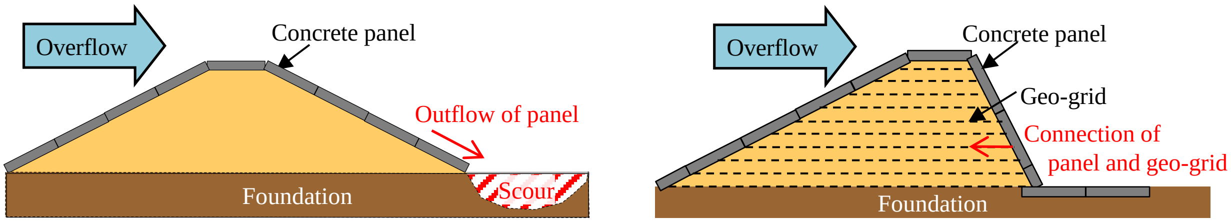
Keywords: *river levee, overflow, infiltration, GRS, erosion, flood*

1. INTRODUCTION

River levees are generally designed to protect against scour, infiltration, and earthquakes for water levels below the designated high water level (HWL). Therefore, overflows exceeding the HWL are not generally taken into account. Earthen levees made up of sediments, including sand and clay, are typical in the world because river levees are originally semi-natural structures made of sediments transported from upstream regions. However, earthen levees have the potential of failure due to overtopping flows (e.g., Powledge et al., 1989). Therefore, levee failures have occurred in a great number of places around the world when water levels exceeded the HWL because of severe flooding, tsunamis, and storm surge. On September 10, 2015, an extreme flood by typhoon nos. 1518 caused a levee breach in the Kinugawa River, Japan, mainly due to overflow, thereafter causing huge flood damage in Joso City, Ibaragi Prefecture.

Armored levees, which are covered with concrete panels on the top and side slopes, have been introduced as a measure to protect against overflow erosion (Figure 1 (a), Hughes 2008). However, such levees have still collapsed due to overflow erosion when the panels were swept away by the current created by a flood. In armored levees, the concrete panels maintained their positions thanks to the weight of the panels. To increase the resistance of the armored levee to overflow, it is necessary to increase the weight of the panel, but the stability of the armored levee against earthquakes is reduced with an increase in the panel weight. It is therefore necessary to develop a new reinforcement technology to protect river levees from overflow erosion and earthquakes.

To prevent such destruction and thereby increase the resistance of armored levees to overflow erosion, Kurakami et al. (2013) introduced a river levee with geosynthetic-reinforced soil (GRS; Tatsuoka et al. 1997) in which the



(a) (b)

Figure 1. Schematic views of armored levee (a) and GRS levee (b).

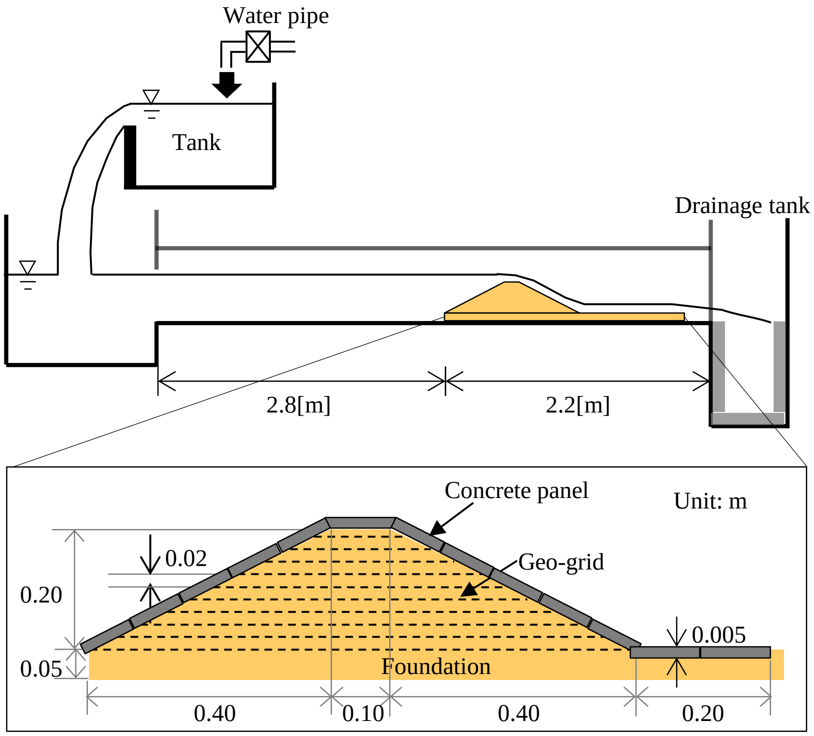


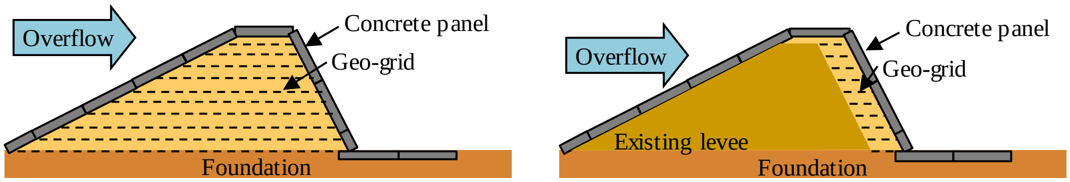
Figure 2. Schematic views of open channel used in overflow model tests and cross-sectional shape of the levee model.

concrete panels are connected to geo-grid layers reinforcing the sand. The geo-grid layers, with their high tensile strength, should help to keep the concrete panels in place and, thus, increase the resistance of the levee to overflow erosion (Figure 1 (b)). GRS structures and walls have been widely used to strengthen levee stability against earthquakes (Tatsuoka et al., 1997; Tatsuoka et al., 1998; Tatsuoka et al., 2009). Kurakami et al. (2013) conducted fundamental tests to evaluate the resistance of the GRS levee to overflow erosion and showed that the GRS levee can survive during prolonged overflow conditions. However, the experimental conditions were limited. Furthermore, it is necessary to confirm the influences of infiltration on the GRS levee because the formation of a water path is a fundamental issue in relation to GRS structures.

In this study, we examined the performance of a GRS levee against overflow erosion under various conditions, such as reinforcement, back slopes, and geo-grid layers. In addition, we investigated the effect of geo-grid layers on the infiltration of levees. For these tests, we conducted a laboratory model test on overflow erosion and infiltration. As the experimental condition to verify the fundamental form of the GRS levee, we tested GRS and conventional armored levees with and without scour protection. In this series, we chose a 1:2 slope, which is used in general levees. In addition, to improve the performance of the GRS levee, we set up three cases: 1) to reduce the area of the cross section of the levees, we tested the GRS levee with a steep back slope (1:0.5 slope), 2) we introduced partial-

Table 1. Experimental conditions of overflow erosion.

No.	Levee	Reinforcement condition	Back slope	Scour protection	Geo-grid size	D_c[%]
1-1	Armored	Panels only	1:2	×	-	85
1-2				○		
1-3			1:0.5			90
2-1	GRS	Full-length reinforcement	1:2	×	Medium	85
2-2				○		
2-3			1:0.5	○	Coarse	90
2-4					Medium	
2-5					Fine	
3-1		Parial-length reinforcement	1:0.5	○	Coarse	90
3-2					Medium	
3-3					Fine	



(a) Full-length reinforcement (b) Partial-length reinforcement

Figure 3. Reinforcement condition

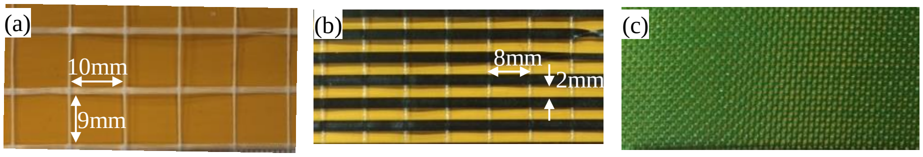


Figure 4. Three grid sizes of geo-grid layer; (a) Coarse (9 * 10 mm, 56 D_{50} * 63 D_{50}), (b) Medium (2 * 8 mm, 12 D_{50} * 50 D_{50}), (c) Fine (0.6 * 0.6 mm, 4 D_{50} * 4 D_{50})

length geo-grid layers to examine the application of the GRS technique to existing levees (Figure 3), and 3) we set three geo-grid sizes to verify the appropriate grid size of the geo-grid layer. In the infiltration experiment, we set the model levee with the same conditions as in the overflow experiment in the water tank, and water level of the waterside land was kept constant.

2. METHODS

2.1. Outline of Overflow Experiments

In this study, we tested a GRS levee against overflow by conducting laboratory model tests in an open channel that was 5 m long, 0.2 m wide, and 0.35 m high, as shown in Figure 2. Model levees at 0.2 m high, with a 0.1 m crest width, and back slopes of 1:2 and 1:0.5 were created by compacting Toyoura sand, which is a well-sorted fine sand in which the mean grain size is 0.16 mm and the optimum water content w_{opt} is 16.0%. The model scale in this test was set to 1/25, and the height of the model levee corresponds to a 5 m prototype levee. The overflow depth on the levees was set to 0.06 m, corresponding to 1.5 m in the prototype using the model scale (= 1/25); Froude similarity was used. The overflow discharge Q was 5.61×10^{-3} m^3/s. At this overflow depth, the prototype levee is assumed to take 50 min to collapse based on Yoshikawa (2008). With the Froude similarity, it corresponds to 10 min for the model levee, which is the target overflow time in our experiment. Model levees were set on a 0.05 m thick

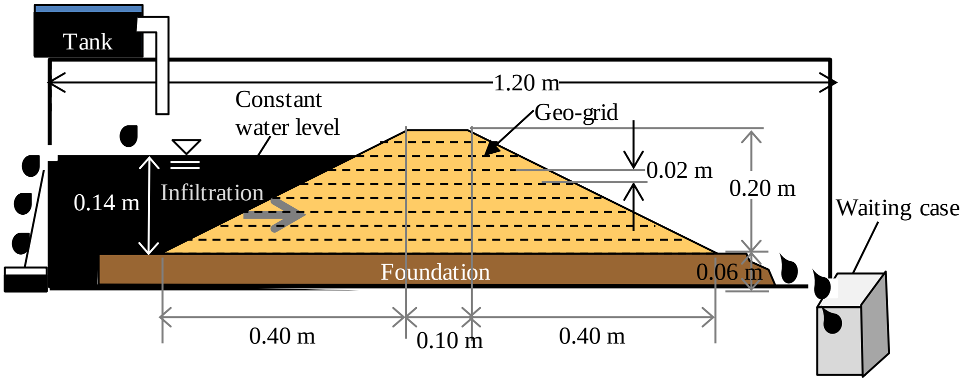


Figure 5. Schematic view of water tank used in infiltration model tests and cross-sectional shape of the levee model.

Table 2. Conditions of infiltration experiments.

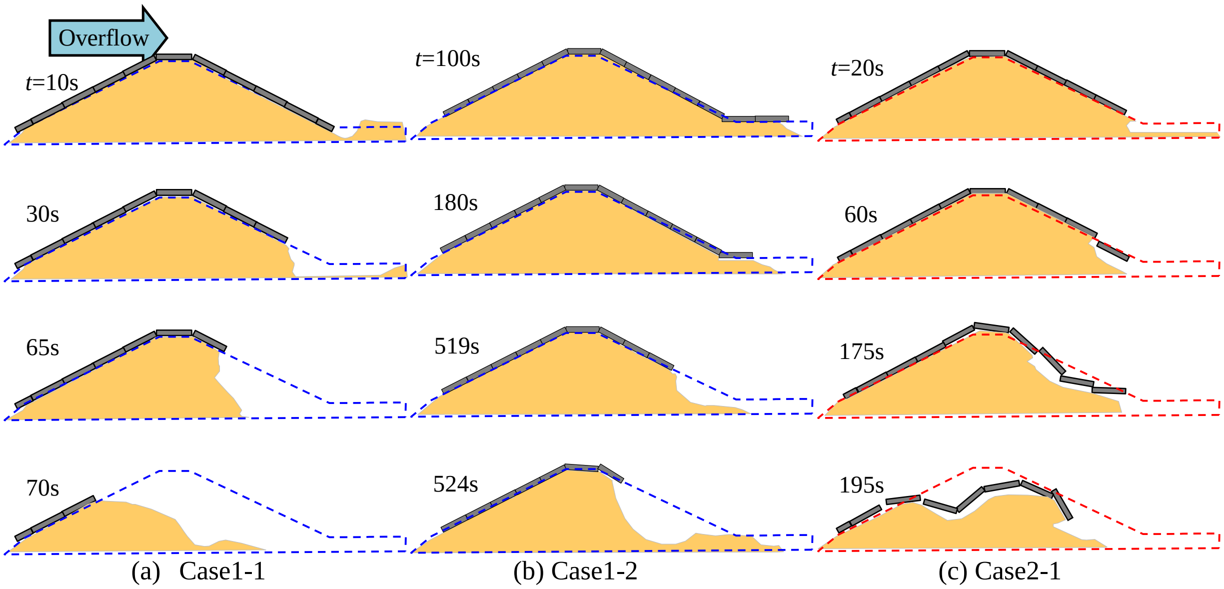
No.	Levee	Reinforcement	Back slope	Geo-grid size	D_c[%]
A	Earthen	-	1:2	-	90
B	GRS	Geo-grid layers without panels		Coarse	
C				Medium	
D				Fine	

foundation to account for the effects of scouring at the toe of the back slope of the levee, which is a key factor in the overflow erosion of levees.

Table 1 lists the experimental conditions of overflow erosion. We compared the effects of scour protection for armored and GRS levees with and without scour protection. To improve the performance of the GRS levee, we conducted further model tests. To examine the influence of the back slope of the levees, we compared the armored and GRS levees with 1:2 and 1:0.5 back slopes. To examine the full- and partial-length reinforcements of the GRS levee, we compared the full reinforcements in Case 2-4 and the partial reinforcements in Case 3-2 with 1:0.5 back slopes. Finally, to understand the influences of the grid sizes of geo-gird layers, we used three types of geo-grids: 9 mm * 10 mm, 2 mm * 8 mm, and 0.6 mm * 0.6 mm, corresponding to coarse, medium, and fine sizes, respectively (Figure 4). The full- and partial-length reinforcements with three kinds of geo-grids were set in this experiment. The geo-grid layers were laid at 0.02 m intervals. Digital video (DV) images of the side and top views of the levees were recorded to examine the erosion of the levees. Herein, we used a DV camera (HDR-XR550V, SONY, Ltd.).

2.2. Outline of Infiltration Experiments

We conducted an infiltration experiment with a model levee to grasp the influence of the geo-grid layer on the infiltration capacity of the levees. The infiltration experiment was conducted using a water tank that was 1.2 m long, 0.2 m wide, and 0.45 m high, as shown in Figure 5. We set the model levee at 0.2 m high, with a 0.1 m crest width and a 1:2 slope, which are the same conditions as in the overflow experiment. The model levee was set on the foundation at 0.06 m thick. The model levee and foundation were created by compacting Silica sand No. 6 (D_c = 90 %), which is a well-sorted fine sand (mean grain size 0.26 mm) with the optimum water content: w_{opt} = 16.0%. The infiltration coefficient k of Silica sand No. 6 is 1.70×10^{-4}. To conduct a constant head permeability test, the water level on the river side of the levee remained constant with a depth of h = 0.14 m.



(a) Case1-1 (b) Case1-2 (c) Case2-1

Figure 6. Time variations of the levee shape and position of concrete panels.

Table 2 lists the conditions of the infiltration experiments. An earthen levee and a GRS levee without panels are selected for the reinforcement conditions of the infiltration experiments. For the GRS levees, we used three kinds of geo-grids, where the grid sizes were 9 mm * 10 mm, 2 mm * 8 mm, and 0.6 mm * 0.6 mm, which were the same sizes as in the overflow experiment. The geo-grid layers were laid at 0.02-m intervals. To visualize the infiltration behavior inside the levees, the water was colored using Indian ink. DV images for the side and top views of the levees were recorded to examine the infiltration behavior in the levees and the erosion processes of the levees. To this end, we also used a DV camera (HDR-XR550V, SONY, Ltd.). In addition, to measure the seepage discharge and erosion rate of the levees, we collected the water and sediment at the toe of the back slope of the levees, as shown in Figure 5.

3. RESULTS AND DISCUSSION IN OVERFLOW EXPERIMENT

3.1. Effect of Scour Protection

To verify the effects of scour protection on overflow erosion, Figure 6 indicates the temporal variations in the cross-sectional shapes for the armored levee without scour protection (Case 1-1), the armored levee with scour protection (Case 1-2), and the GRS levee without scour protection (Case 2-1). In the figure, the initial levee surface is drawn with dashed lines. The positions and directions of the concrete panels are also drawn. The geo-grids laying in the GRS levee are omitted from the figure. In addition, note that while the GRS levee with scour protection in Case 2-2 maintained its whole sectional shape beyond the target time, the result of Case 2-2 is omitted from the figure. The result of the armored levee without scour protection indicates the foundation near the toe of the back slope was locally scoured at t = 10 s (t: time from start of overflow). Then, the concrete panels near the toe of the levee were swept away and the levee sediments eroded at t = 30 s. After the erosion surface reached the crest of the levee at t = 65 s, the levee had mostly collapsed at t = 70 s. A comparison of the cross-sectional shapes in Cases 1-1 and 1-2 indicates that scour protection can effectively prevent the scour at the toe of the back slope. This means that scour protection improved the resistance of the armored levee against overflow erosion. However, after losing the scour protection, the levee in Case 1-2 was rapidly eroded, showing a pattern similar to that in Case 1-1.

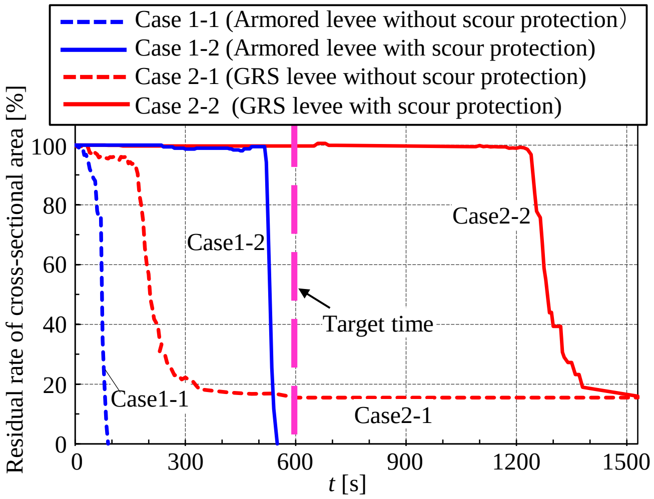


Figure 7. Time variations of residual rate of cross-sectional area in Case 1-1, 1-2, 2-1 and 2-2.

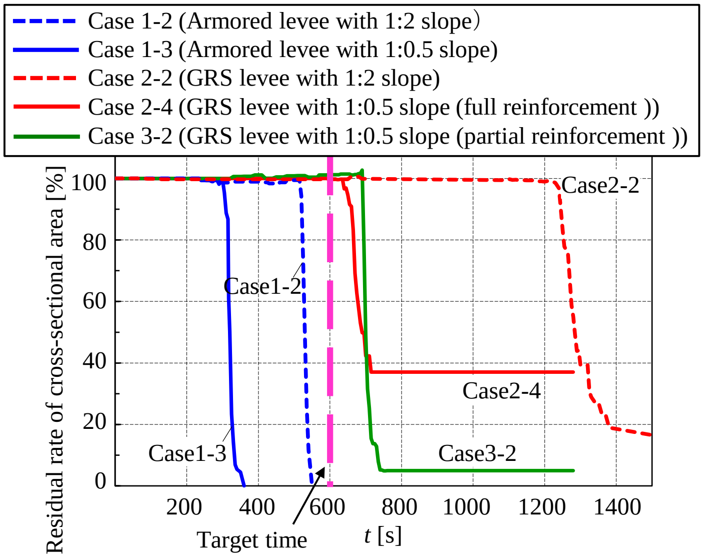


Figure 8. Time series of residual rate of cross-sectional area in Case 1-2, 1-3, 2-2, 2-4 and 3-2.

Figure 7 shows the residual rates of the cross-sectional areas in Cases 1-1, 1-2, 2-1, and 2-2. The residual rate of the cross-sectional area is evaluated with the cross-sectional area at any time divided by the initial cross-sectional area. These results were obtained from the motion picture of the DV camera. The result of the armored levees shows that the residual rates of the cross-sectional areas were 90% in the armored levees with and without scour protection at $t = 50$ s and 525 s, respectively. This indicates that scour protection can maintain the cross-sectional shape of the levees during lengthy overflow conditions. However, even with scour protection, the armored levee collapsed completely before reaching the target time (= 600 s). On the other hand, in the GRS levee, the scour protection also improved the resistance against overflow erosion. Furthermore, the GRS levee with scour protection maintained its whole sectional shape for 20 min beyond the target time. These facts demonstrate that it is necessary to introduce scour protection to maintain the fundamental form of the GRS levee.

3.2. Influence of Steep Back Slope and Partial-Length Reinforcement

To examine the influence of back slope on the overflow erosion of the armored and GRS levees, Figure 8 shows the residual rates of the cross-sectional areas of the armored and GRS levees with 1:2 and 1:0.5 slopes. The results in

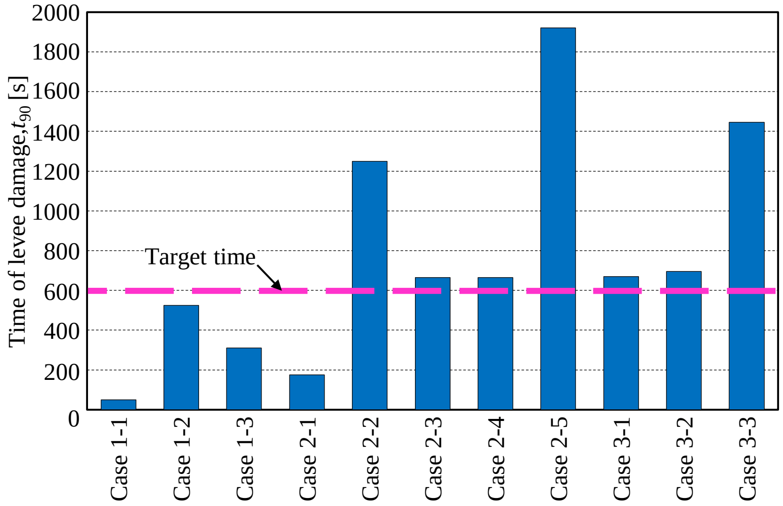


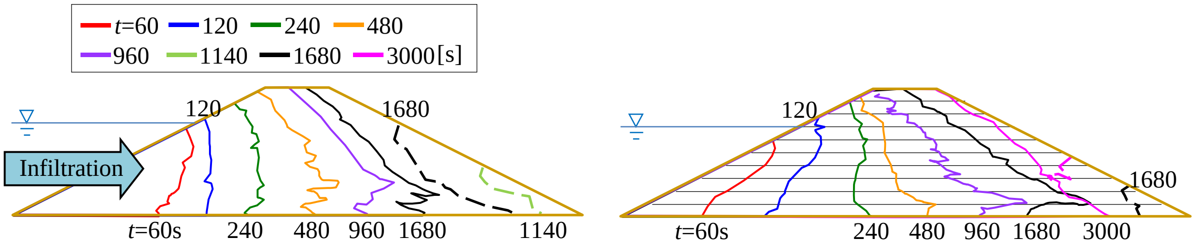
Figure 9. Time of levee damage t_{90} for all of cases.

the GRS levee with a 1:0.5 slope with full- and partial-length reinforcements are shown in the figure. Focusing on the armored levee, the resistance against overflow erosion was reduced by steepening the back slope from 1:2 to 1:0.5. In particular, after losing the scour protection, the residual rates of the cross-sectional areas rapidly decreased in Cases 1-2 and 1-3, and, finally, the armored levee collapsed before the target time. On the other hand, in the GRS levee with a 1:0.5 slope, the residual rate of the cross-sectional shape of the GRS levee was almost 100% even at the target time. This means the GRS levee with a steeper back slope can maintain a high resistance against overflow erosion beyond the target time. Therefore, the GRS levee can significantly improve the resistance against overflow erosion even at a smaller cross section.

A comparison of the results in the GRS levees with full- and partial-length reinforcements shows that the residual rate of the GRS levee with partial-length reinforcement was comparable to that with a full-length reinforcement. The GRS levee with both partial- and full-length reinforcements has a comparably high resistance against overflow erosion, showing that partial reinforcement is also useful to increase the resistance of the levee to overflow erosion. This means the GRS levee with partial reinforcement can be applied to reinforce existing levees.

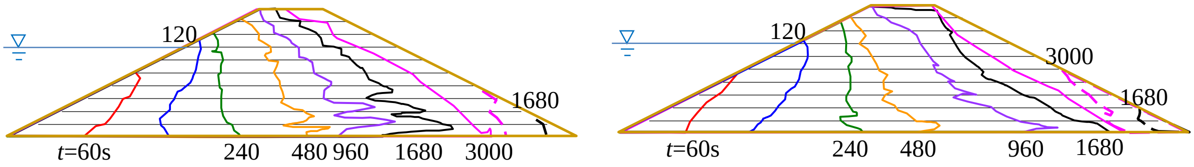
3.3. Effect of Grid Size on Geo-Grids

Figure 9 indicates the times of levee damage, t_{90}, for all cases. Here, the time of levee damage t_{90} is defined as the time when the residual rate of the cross-sectional area was 90%. To examine the effects of the grid sizes of geo-grid layers on the resistance against overflow erosion, we here focus on the results of the GRS levees with coarse (Cases 2-3, 3-1), medium (Cases 2-4, 3-2), and fine (Cases 2-5, 3-3) geo-grids. Although the resistance against overflow erosion for the GRS levee with a 1:0.5 slope was lower than that for the 1:2 slope, all cases of GRS levees with a 1:0.5 slope could maintain high resistance against overflow erosion beyond the target time. In the GRS levees with full- and partial-length reinforcements, the t_{90} in the fine geo-grid was larger than those in the coarse and medium geo-grids. The GRS levee using a small-sized geo-grid can maintain a high residual ratio of the cross-sectional area over a long period. Therefore, it is useful to select an appropriate geo-grid layer size for increasing the resistance of the levee to overflow erosion. These results demonstrate that the GRS levee can be a cost-effective measure to increase the resistance against overflow erosion at a small cross-section.



(a) Case A

(b) Case B



(c) Case C

(d) Case D

Figure 10. Temporal variation of seepage lines with solid lines and levee erosion with broken lines.

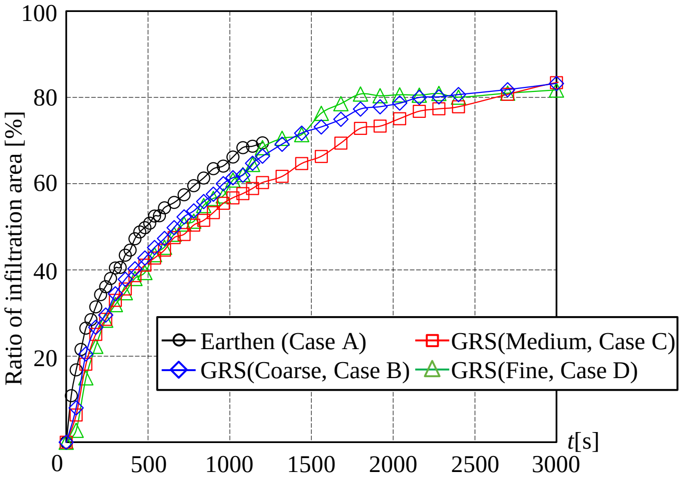


Figure 11. Time series of the ratio of infiltration area.

4. RESULTS AND DISCUSSION IN INFILITRATION EXPERIMENT

To verify the fundamental property of the infiltration into the earthen and GRS levees, Figure 10 shows the temporal variations of seepage lines in all cases of the infiltration experiment. The solid lines show the seepage lines obtained through visualization with Indian ink. The eroded levee shapes are also shown by the broken lines in the figure. The results indicate that the seepage lines were vertically steep initially and transitioned to a milder inclination over time in all cases. This means that the infiltration flows in all cases go toward the toe of the back slope, and the velocity of the infiltration flow is relatively larger near the foundation. The seepage lines were not straight, and the unevenness of the seepage lines appeared not only in the earthen levee, but also in the GRS levees. Furthermore, the height of the unevenness of the seepage lines in the GRS levees did not necessarily correspond to the geo-grid layer. This fact indicates that the water path along the geo-grid layers was not found in this experiment. The eroded area of the earthen levees indicates the erosion near the toe of the back slope started at t = 1,140 s and the eroded area increased at 1,680 s. In contrast, the eroded area in the GRS levee with three kinds of geo-grids was smaller than that in the earthen levee, which means the geo-grid layers can function to resist the initial erosion of the levee (Kurakami et al., 2013).

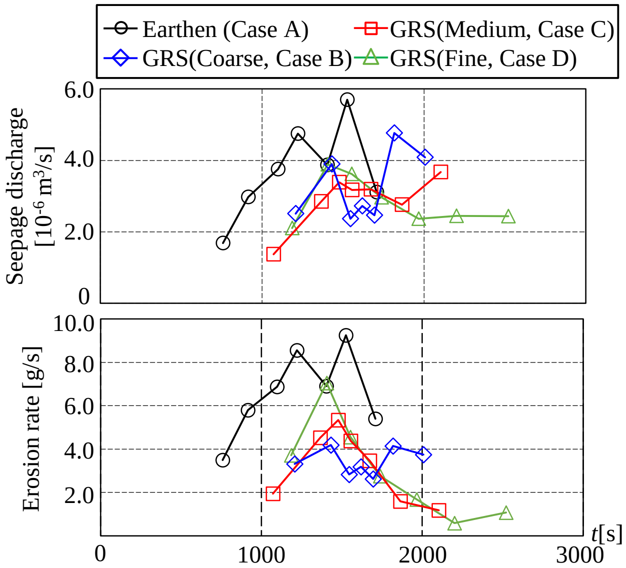


Figure 12. Time series of seepage discharge and erosion rate of the levees.

Figure 11 shows the time series of the ratio of the infiltration area obtained from a motion picture in each case to quantitatively grasp the infiltration property. The ratio of the infiltration area is evaluated with the infiltration area at any time divided by the initial cross-sectional area. These results show that although there were no significant differences in the ratio of the infiltration area among all cases, the ratios of the infiltration areas in the GRS levees were slightly lower than those in the earthen levees, mainly due to the difference in the eroded area.

A time series of the seepage discharge and erosion rate of the levees measured at the downstream end of the water tank is shown in Figure 12. The results indicate that the seepage discharge and erosion rate in the earthen levee were greater than those in the GRS levees. The seepage discharges of the GRS levees were less than those of the earthen levees due to a reduction in the infiltration erosion in the GRS levees.

5. CONCLUSION

In this study, a new type of river levee, a GRS levee, was proposed, and its performance for overflow erosion and infiltration was studied using a series of laboratory model tests. The present study obtained the following conclusions:

1) Scour protection is highly effective both in preventing erosion at the toe of the back slope and in maintaining the stability of the panels covering the levee. Although the armored levee still collapsed before reaching the target time (= 600 s) with scour protection, the GRS levee maintained its whole sectional shape for 20 min, which means the scour protection worked with the GRS levee effectively. Therefore, it is necessary to introduce scour protection to maintain the fundamental form of the GRS levee.
2) The armored levee with a steep back slope (= 1:0.5) collapsed faster than that with a normal slope (= 1:2). However, the GRS levee with a steep back slope maintained a high resistance against overflow erosion after the target time. The GRS levee with partial- and full-length reinforcements has a comparably high resistance against overflow erosion, showing that partial reinforcement is also useful to increasing the resistance of the levee to overflow erosion. This means the GRS levee with partial reinforcement can be applied to reinforce existing levees.

3) The GRS levee using a small-sized geo-grid can maintain a high residual ratio of the cross-sectional area over a long period. Therefore, it is useful to select an appropriate geo-grid layer size for increasing the resistance of the levee against overflow erosion.
4) The infiltration discharge of the GRS levee was less than that of the levee with no reinforcement due to reduction in infiltration erosion in the GRS levee. Introducing a geo-grid was not a disadvantage to making a water path, but it contributed to making the back slope more stable against slope failure.

However, the results shown in this paper were obtained from small-scale model tests, so the reliability of the measured data might not necessarily be exact. More experimental tests under different conditions will be needed to study the details. In addition, it is difficult to satisfy the similarity law completely because in this study, we used various materials composed of concrete panels and geo-grids. Therefore, large-scale model tests with a levee height of more than 1 m should be conducted in the near future.

6. ACKNOWLEDGEMENTS

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