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PREVENTION OF SOIL OUTFLOW FROM THE GROUND AROUND BRIDGE ABUTMENT USING CEMENT SOIL STABILIZATION

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ABSTRACT: In recent years, heavy rains have frequently occurred in Japan, and a large amount of soil, rocks, and trees that were dislodged by landslides have flowed into rivers, causing damage to bridges. When a bridge is blocked by driftwood and boulders, the river water overflows onto and around the bridge abutment and the back face banking of the abutment is eroded, rendering the bridge impassable. We propose cement soil stabilization as a countermeasure to the erosion for the back of abutments. In this study, channel experiments on a 1:15 scale into the effect of cement soil stabilization were carried out. It was observed that erosion started from the downstream corner of the abutment when the overflow water returned to the river at the downstream point. In addition, when the back face banking of the abutment was strengthened with the minimum additional amount of concrete (set as 50 kg/m3) and cured for approximately two days, erosion was inhibited in both the reinforced back face banking and the unimproved levee.

Keywords: Cement soil stabilization, Erosion, Overflow water, Back of the abutment

1. INTRODUCTION

In recent years, large-scale rainfall has increased in Japan due to the effects of climate change. It has been reported that trees and rocks have flowed into rivers from collapsed slopes due to heavy rainfall, causing damage to bridges. Driftwood and boulders accumulate between the bridge piers and balustrades that block the flow of rivers, causing the inundation of bridges, erosion of levees by overflow water, and erosion of road embankments adjoining the back faces of bridges by overflow water. Bridges are vital parts of roads and railways; when they are damaged, traffic obstacles occur, which significantly affect evacuation, isolate villages, and hinder post-disaster recovery. For example, the Yuyabashi Bridge over the Ohmata River in Kumano City, Mie Prefecture, was damaged by Typhoon Talas in 2011. Drifts were deposited on the bridge, and water overflowing from the upstream embankment eroded the ground. On the embankment adjoining the abutment, the ground was eroded by up to approximately 5 m, making the bridge impassable, as illustrated in Fig. 1.

In this study, we focus on the erosion of the embankment adjoining the abutment by overflow water. Abutments are generally constructed by excavating a space enclosed by inserted steel sheet piles, and this space is then backfilled with on-site soil, as depicted in Fig. 2. Because the enclosed working space is narrow and the abutment is a hindrance, backfill soil is difficult to compact and tends to be a weak spot. backfill soil is difficult to compact and tends to be a weak spot.

Therefore, we propose the use of cement soil stabilization for the shallow ground to improve the ground strength of the embankment adjoining the abutment, thereby preventing erosion. In this paper, we clarify the erosion process due to overflow water by a basic water channel model experiment, and also examine the erosion prevention effect of the ground improvement.

Fig. 1 Erosion at the left bank of the Yuya bridge
(Photo was provided by Dr. Kenji Okajima)

Fig. 2 Construction space by excluding water using steel sheet pile

2. PREVIOUS STUDY

Various damages have occurred at the back face ground of bridge abutments, such as the subsidence of embankment caused by an earthquake at the boundary between the bridge abutment and back face banking of the abutment, and erosion of the ground around the bridge abutment caused by tsunamis or floods.

Kawajiri et al. observed the erosion process of the ground around the bridge abutment by the reproduction experiment using a water channel, focusing on the runoff damage of the back of the bridge abutment due to heavy rainfall in Hokkaido in 2016 [1] [2]. Furthermore, Kawajiri et al. conducted two experiments to verify the effects of their proposed countermeasure work. In one of these experiments, a stone filled net and geogrid were used for slope protection. The other experiment involved the use of geocell for slope protection work. In these experiments, although both types of countermeasure constructions caused partial collapse and runoff of the filling material, etc., they concluded that the constructions were useful because the runoff of the embankment did not cause the sinking of the back of the abutment [3]. Onmayashiki et al. conducted verification experiments for the effect of geogrid. They compared two cases of experiments. One of these cases involved the use of a stone filled net, and the other case involved the use of a stone filled net and geogrid. It was confirmed that the geogrid was effective in providing protection against corrosion [4]. In their experiments, the water flow over the embankment due to the blockage of the bridge was modeled to flow in the vertical direction from the front of the embankment. Therefore, it is desirable to clarify the erosion process under actual water flow conditions, because the water flow in the experiments conducted by Kawajiri et al. and Onmayashiki et al. differ from the actual water flow situations. Additionally, we think it is desirable to propose a relatively easy-to-construct and low-cost countermeasure.

Ikemoto et al. devised a method of creating a column-like reinforced body using cement-based material as a measure to prevent the settling of the rear surface of the abutment during earthquakes and verified the effect by shaking table tests [5]. Takizawa estimated the behavior of a column-like reinforced body back of the bridge abutment after vibration by three-dimensional dynamic elastoplastic [6]. Their studies have been put to practical use in JR East as a method for preventing subsidence back face banking of abutments on railroad bridges, and show the effectiveness of ground improvement using cement-based materials. However, the effects of erosion are not discussed in their study. Therefore, it is necessary to separately consider the effectiveness of the ground surface erosion prevention which this study targets, the construction range of the improvement body, and the construction method.

There are approximately 700,000 road bridges over two meters in length and approximately 160,000 road bridges over 15 meters in length in Japan; half of them will have existed for 50 years or more by the mid-2020s [7]. Therefore, the development of effective measures with excellent workability and economy should be promoted. Considering that there are a large number and age range of existing bridges, it is desirable to upgrade to a structure that is resistant to disasters as efficiently as possible while maintaining and managing them. In this study, when considering countermeasure works, we placed emphasis on three points: (1) low material cost; (2) low construction cost; and (3) the possibility of implementation at the same time as routine maintenance. We propose the soil cement stability at the surface layer around bridge abutment as countermeasure work. The surface of the abutment approach section is often asphalt-paved, and the pavement is subjected to repair work such as replacement over a fixed period as it deteriorates. Therefore, the above three points may be satisfied by constructing the shallow ground in the lower part of the road body at the same time as the renovation of the pavement.

3. EXPERIMENTAL OUTLINE

3.1 Purpose of experiment

The experiments aim to clarify the following: the erosion process of the embankment around the bridge abutment by overflow, the effect of cement soil stabilization for soil outflow on the back face of the bridge abutment, and the difference in erosion by the three cases of flow rates.

3.2 Experiment model

The experiment simulated the upper part of the embankment in the cross-section of the river to investigate the influence of the rising water level and overflow on the erosion of the embankment, especially around the abutment. The open channel used for the experiment had a length of 13,000 mm, width of 500 mm, height of 350 mm, and slope of 5°. A 1,333 mm section was closed to simulate a bridge with a width of 333 mm and the upper part of the left bank levee. The experiment model had a 1:15 scale. Therefore, it had a length of 20.0 m and a width of 5.0 m in actual scale. The inclination at the bottom of the channel was 5°; however, we simulated the embankment such that the surface was horizontal.

The bridge model, constructed in this study, combined the following four parts depicted in Fig. 3: the wall of the inverted T-abutment modeled in a simple box shape, bridge girder, panel simulating a blockage between the bridge pier and abutment, and floorboard of the channel width. The bridge model was placed at the center of the experimental section in the lengthwise direction and fixed to the bottom of the water channel.

The part of the free board of the levee, which is the revetment top end to the levee top end, and the surface of the embankment was assumed to be bare ground, and the embankment surface was assumed to be horizontal. The image of the experimental model on the actual embankment is depicted in Fig. 4, and the experimental model is illustrated in Fig. 5.

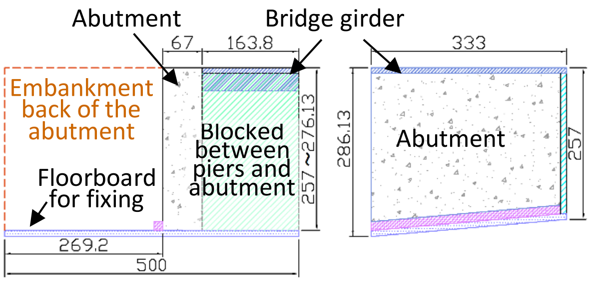

Fig. 3 Bridge model

Fig. 4 Revetment and free board of a levee

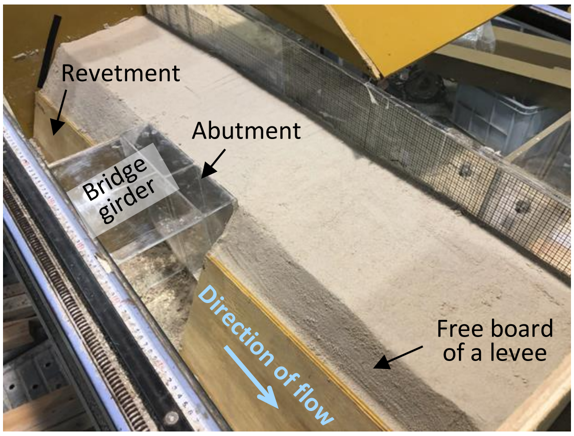

Fig.5 Experimental model (Case 1)

3.3 Experiment cases

In this paper, we report four cases of experiment. The differences in the four cases are presented in Table 1. In all the four cases of the experiment, the process of erosion was examined. In Case-1 and Case-2, the effect of the countermeasure was considered based on the difference in the erosion process with and without the countermeasure with a similar flow rate. Additionally, in Case-2, Case-3, and Case-4, the influence of the flow rate was considered based on the difference in the erosion process at the same condition of ground improvement part when the flow rate was different. The pump used in these experiments caused an error in the flow setting depending on the water supply condition. Therefore, the flow rate was measured in each case to clearly understand the effect of flow rate on erosion.

Blast furnace cement type B was used as the stabilizer for ground improvement, and the amount to be added was set to 50.0 kg/m3, which was considered the minimum additional amount necessary to ensure an accurate mix of stabilizer and untreated soil [8]. The improvement range was the entire back face banking of the abutment, and the improvement depth was 80 mm, which was equivalent to actual scale 1.2 m. The usual method of mixing requires a stabilizer to be spread onto the target ground and mixed with the ground material using a shovel-loader. However, in this experiment, the soil of the ground improvement target area was placed in a bucket and mixed thoroughly with the stabilizer. Subsequently, the prescribed amount of improved soil was returned to the target area and compacted. If the cement setting time, which is approximately 2 h, is exceeded, the cement stabilized soil loses a considerable amount of strength. Therefore, it is desirable for the time from mixing to compression to be within approximately 1 h. Consequently, the ground improvement was conducted in a timely manner. Generally, it takes seven days for the strength development of the stabilizer to become stable; however, we set the curing time between two and three days to impose a more severe condition in these experiments.

The flow velocity was targeted at approximately 3.0 m/s according to references [9] and [10]. Based on equation (1), the flow amount was adjusted so that the overflow water depth around the bridge center was approximately 60 mm, and the design standard flow amount simulating a flood was 2.00 × 10-2 m3/s. In Case-3 and Case-4, the flow rate was set to lower velocity than the target value at a flood.

$$v = \sqrt{gh} \tag{1}$$

$$\frac{h_m}{h_p} = L_r \tag{2}$$

in which v is the average flow velocity (m/s), g is gravitational acceleration (m/s^2), and h is water depth (m), h_m is the water depth of the model (m), h_p is the water depth of the prototype (m), L_r is the model scale.

Table 1 Main difference between the four cases

	Soil stabilization	Curing period (days)	Flow rate (m^3/s)
CASE-1	Without	–	2.00×10^{-2}
CASE-2	With	2	1.77×10^{-2}
CASE-3	With	3	2.34×10^{-3}
CASE-4	With	3	2.18×10^{-4}

3.4 Measuring equipment

To quantitatively evaluate the amount of displacement of the embankment, inclinometers were installed at symmetrical positions on the upstream and downstream sides, centering on the center of the bridge abutment. The two-dimensional diagram of the inclinometer installation position is illustrated in Fig. 6. Ten inclinometers were installed in Case-1, and eight inclinometers were installed in Case-2, Case-3, and Case-4. These inclinometers are the PMP-S5HT manufactured by Midori Sokki co, Ltd and can detect inclination from –5° to +5° in one direction by the leaf spring pendulum method. They were installed with the condition that when they incline toward the downstream side, the output change is positive; their bases were embedded to a depth of 100 mm. If the output is positive, the erosion is considered to be scraped from the ground surface. In addition, if the output is negative, it is considered that slip failure or progressive erosion or erosion from deep position occurs. The external dimensions and interpretation of the direction of inclination are depicted in Fig. 7 [11].

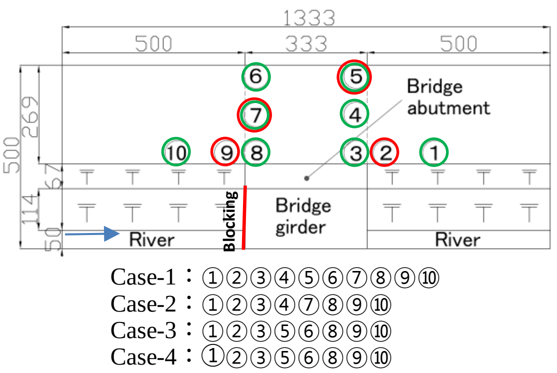

Fig. 6 Tilt sensor arrangement plan

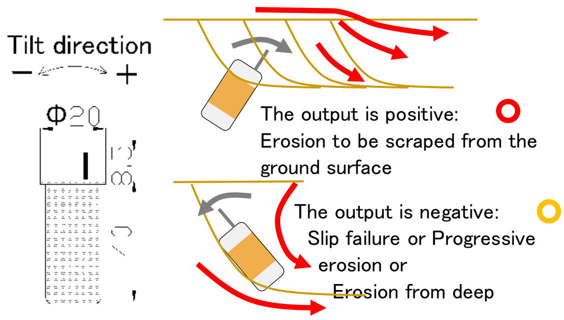

Fig. 7 Tilt direction and interpretation of results

4. RESULTS AND DISCUSSION

4.1 The results of Case-1

The state after the water flow is depicted in Fig. 8, and the tilt fluctuation around each measurement point is depicted in Fig. 9. The overflow water reached the end of the downstream embankment adjacent to the abutment 6 s after the onset of the overflow, and the erosion started approximately 1 s after that. The 2nd inclinometer initially started to move. The erosion expanded from the end of the downstream embankment, which was adjacent to the abutment. The downstream embankment flowed out 17 s after the start of overflow. Subsequently, the eroded area expanded downstream and upstream. All the inclinometers leaned within 60 s. The red circle in Fig. 6 indicates that the upper part of the inclinometer fell toward the downstream side. The inclination direction of the inclinometer at each point was uneven, and the characteristic tendency was not observed in the erosion direction.

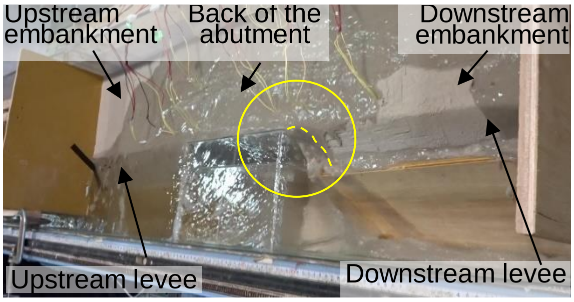

Fig. 8 Start of erosion (After 6 s from the onset of overflow)

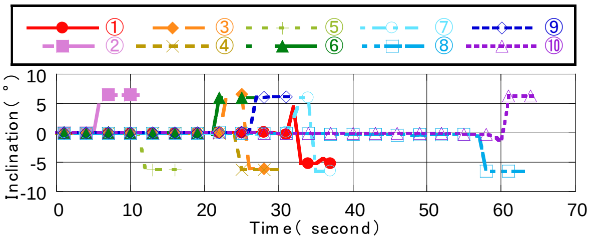

Fig. 9 Tilt fluctuation (Case 1)

4.2 The results of Case-2

The state after the water flow is depicted in Figs. 10 and 11, and the tilt fluctuation around each measurement point is depicted in Fig. 12. The overflow water reached the end of the downstream embankment adjacent to the abutment 7 s after the onset of the overflow, and the erosion of the embankment started after approximately 1 s as in Case 1. However, the subsequent erosion process differed from that in Case 1, and the erosion near the back face of the abutment did not progress rapidly.

The downstream levee without cement soil stabilization was notably eroded by the surface flow, and the erosion progressed slowly at the boundary between the ground improvement part adjoining the abutment and downstream embankment depicted in Fig. 10. Furthermore, the erosion of the upstream embankment progressed, as indicated by the yellow arrowed line in Fig. 11. Then, the embankment just below the improved part was washed away. Inclinometers of the improved part, which are inclinometers No. 3, No. 4, No. 5, and No. 6, indicated by the red points in Fig. 11, started to gradually incline at approximately 2 min and 40 s from the start of overflowing, and they significantly inclined downstream all at once after 3 min and 27 s. Because the four inclinometers demonstrated the same behavior simultaneously, it is clear that the ground improvement part became integrated, as indicated by Fig. 12. Inclinometer No. 8, represented by the blue point in Fig. 11, in the upstream embankment part continues to incline gently from approximately 2 min and 27 s to the end of the experiment. In comparison with Case 1, in which the same position embankment was washed away 60 s after the start of overflow, this result demonstrates that the unimproved embankment on the upstream side increased its resistance to erosion.

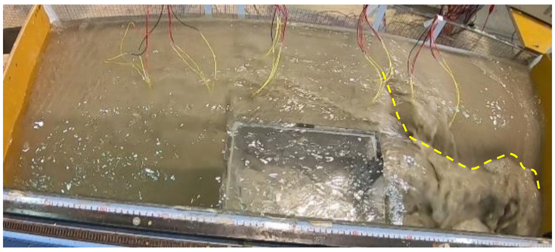

Fig. 10 Erosion at the boundary between the improved part and levee embankment on the downstream side

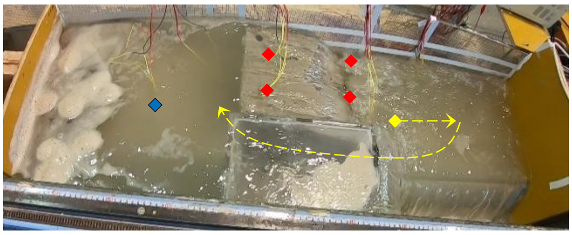

Fig. 11 Broken ground improvement part and process of displacement (After 3 min 40 s from the start of overflow)

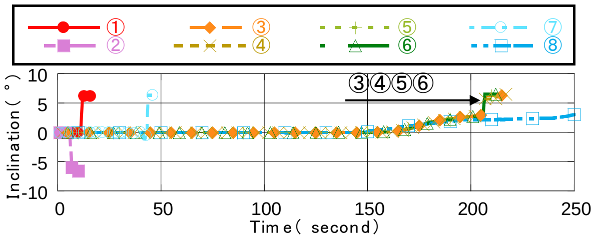

Fig. 12 Tilt fluctuation (Case 2)

The direction of the inclination of the inclinometers was analyzed to consider the state of erosion. The green circle in Fig. 6 indicates that the upper part of the inclinometer fell toward the downstream side when the inclinometer started to move. With only inclinometers No. 2 and No. 9 close to the improved part, the lower parts of the inclinometers fell toward the downstream side. It is inferred that they moved along with the sliding soil due to the strong flow from upstream to downstream. In the case of the other inclinometers, their upper parts fell toward the downstream side. It is inferred that deep progressive erosion was suppressed, and the influence of erosion from the ground surface was greater than the influence of deep progressive corrosion.

4.3 The results of Case-3

In Case-3, a significant amount of time passed before the water level rose and an overflow occurred, because the flow rate was low. In consequence, the penetration and erosion of the upstream levee in comparison with other areas preferentially progressed. It is thought that the erosion was accelerated because the formwork moved by compaction energy at the time of formation of the embankment and the ground adjoining the revetment loosened. The erosion gradually progressed at the boundary between the improved part and levee embankment on the downstream side until approximately 1 min and 20 s after the start of overflow. Subsequently, the erosion area did not expand because the water continuously flowed through the tunnel, which was formed under the improved part.

The inclination of inclinator No. 7, which was displaced first approximately 4 min after the overflow, is depicted in Fig. 14. Inclinometers of the improved part, which are inclinometers No. 3, No. 4, No. 5, and No. 6, indicated by the red points in Fig. 13, had not displaced even approximately 8 min after the overflow when the experiment ended. Thus, the effect of soil cement stabilization was also confirmed in the Case-3 experiment.

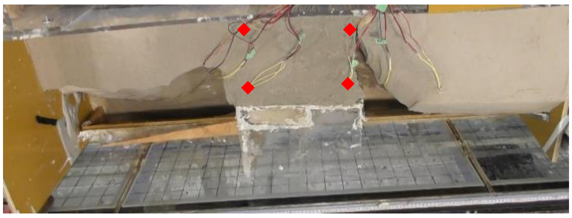

Fig. 13 Scour-like erosion and flow at the upstream side

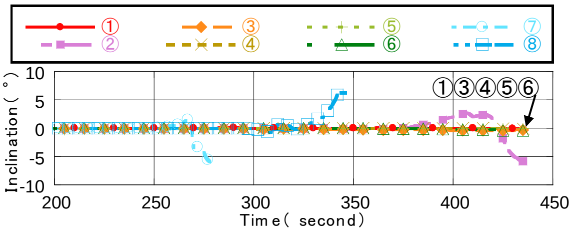

Fig. 14 Tilt fluctuation (Case 3)

4.4 The results of Case-4

In Case 4, a more considerable amount of time passed before an overflow occurred because of the low flow rate as in Case 3. The erosion started from the upstream levee. After the erosion area approached the bottom of the upstream levee, the unimproved ground immediately below the improved ground adjoining the abutment was eroded in the downstream direction, and water flowed analogous to a tunnel penetrated underneath the improved part, as depicted in Fig. 15. The results demonstrate that when the flow volume is low, that is, the flow velocity is low, the embankment erosion by the penetration on the upstream side is notable, and the erosion progresses in the riverbed direction. Additionally, because the amount of overflow water is small, the amount of erosion at the downstream embankment is small. The erosion gradually progressed at the boundary between the improved part and levee on the downstream side until approximately 2 min and 30 s after the start of overflow. Subsequently, the downstream embankment was completely washed away by the water flow; thus, the experiment ended approximately 40 min after the start of the experiment.

The inclinometers No. 3, No. 4, and No. 5, in the improved part had not displaced, as depicted in Fig. 16. The cause of displacement of inclinometer No. 6 in the improved part close to the upstream revetment is that the base of the improved part was slightly eroded by the water flow.

Fig. 15 Improved soil after the experiment

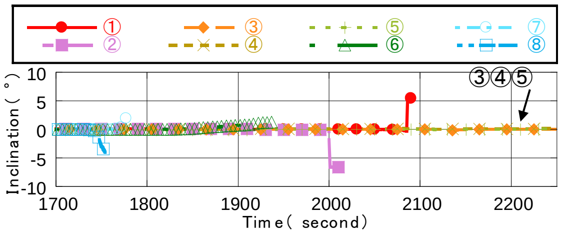

Fig. 16 Tilt fluctuation (Case 4)

4.5 Effectiveness of ground improvement

Case 2 was conducted under the conditions of minimum amount of cement addition and two days of curing. From the results of Case 2, it was confirmed that the ground improvement was integrated, and the erosion was suppressed more than that in Case 1, which was without improvement. Although the improved part settled and inclined because the foundation ground supporting the improved ground had been lost, if the foundation ground remained, there is a fair possibility that it would maintain its function as a road on the embankment adjoining the abutment. There is room for consideration of the improvement ground range, such as the downstream embankment adjacent to the abutment, because the erosion proceeds from weak areas, such as the boundary between the abutment and the embankment, or the boundary between the improved part and the unimproved embankment.

The result of improving the ground of the embankment adjoining the abutment was that the unimproved embankment became more resistant to erosion. It was considered that the cause of this phenomenon was affected by the following: (1) The resistance to erosion of the improved part increased in comparison with the case without improvement. (2) The penetration of the improved part was suppressed. Moreover, because the improved part was not eroded, the flow of the overflow water and progress of erosion was reduced in comparison with the unimproved case.

5. CONCLUSIONS

In this study, four cases of experiment were investigated to clarify the erosion process of the embankment around the bridge abutment by overflow, to clarify the difference of erosion by the different flow rates, and to clarify the effect of cement soil stabilization for soil outflow on the back of the bridge abutment.

The overflow water from the river embankment due to the blockage of the bridge significantly eroded the downstream embankment, especially near the abutment. In the case of high flow volume, the erosion after overflow occurred from the end of the downstream embankment adjacent to the abutment, and progression of erosion at the boundary between the ground improvement section and embankment was confirmed.

In the case of low flow volume, the erosion started from the end of the upstream embankment adjacent to the abutment and expanded to the bottom of the water channel and downstream direction. If the flow rate is small, the risk of seepage failure on the levee increases on the upstream side. Therefore, countermeasures for the upstream and downstream levee near the abutment are also desirable.

Under the conditions of this experiment, it was found that to conduct ground improvement of the embankment adjoining the abutment, erosion at the improved area can be suppressed, the ability to maintain function as a road can be improved by suppressing the erosion at the back of bridge abutment, and the erosion of the surroundings of the levee embankment can be suppressed.

In the future, under the condition that the foundation ground does not run off, it is necessary to consider the amount of cement to be added, curing conditions, and ground improvement range, to resist against relatively large flow rates and long overflow times.

6. ACKNOWLEDGMENTS

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