FLUME EXPERIMENTS ON REVETMENT FAILURE DUE TO BED DEFORMATION DURING FLOOD

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ABSTRACT

In alluvial rivers, revetments have an important role in protecting banks and levees from lateral erosion. In general, revetments are designed and constructed in consideration of riverbed degradation and local scouring at a toe of a revetment. In 2016 August, numerous flooding events and countless revetment failures due to heavy rain are observed in tributaries of the Tokachi River in Hokkaido, Japan. One of the noticing points with those revetment failures in these events was that they were caused not only by local scouring in low-water channels, but by erosion on high-water channels. In this study authors focused on the mechanism of revetment failure caused by scouring along a revetment on high-water channel and carried out some flume experiments to replicate and examine these patterns of revetment failures. Results of experiments showed some points of view regarding revetment failures. In a straight channel, there is some possibility that a local scouring happens at the end of a revetment, inducing erosion on high-water channel along the revetment. On the other hand, in a meandering channel an overtopping and an erosion on high-water channel happened along a revetment and this erosion seemed to induce the revetment failure. Through a PIV analysis, this erosion was caused by not only a rapid overtopping flow along the revetment.

Keywords: *revetment, flume experiment, PIV analysis, riverbed deformation*

1. INTRODUCTION

As banks and levees are usually made from riverbed material: sand and gravel, they are easily eroded by river flow. To protect them from river flow's lateral erosion effect, a revetment is installed on bank slope (Figure 1). Especially at an outer bend of a meandering channel where strong lateral erosion would happen during flood events, a robust revetment of concrete blocks is installed to avoid a levee breach.

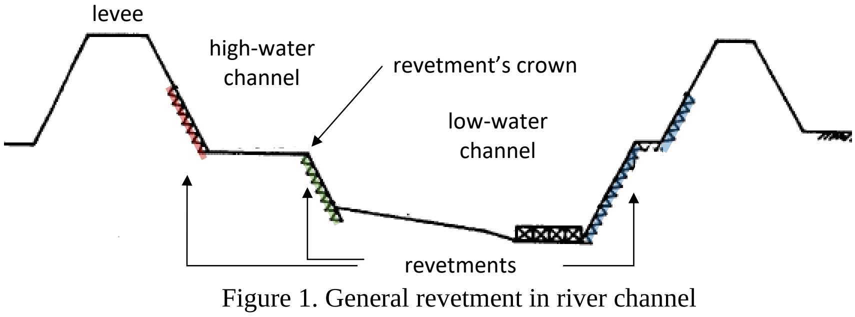

Figure 1. General revetment in river channel

Figure 2. A revetment failure with high-water channel erosion in Otofuke River

According to Yamamoto (2003), failure of a revetment during a flood event is generally caused by bed degradation and local scouring of low-water channel in front of the revetment. Those degradation and local scouring bring damage to a revetment's foundation, resulting in revetment's collapse. For this failure pattern, reinforcing the foundation by piling works is mostly one of effective countermeasures.

However, in a flood event of eastern Hokkaido in August 2016, one of the noticing points was that many of revetment failures were with high-water channel erosion and their foundations weren't damaged severely. Figure 2 shows an example of revetment failures in Otofuke River which is one of tributaries of Tokachi River in eastern Hokkaido. In Figure 2, The revetment is turned over from its back to front and lateral erosion nearly reached to levee's toe. From a report by Hokkaido Development Bureau (2016), some of levees with this revetment failure pattern were in danger of a levee breach while a water level was not so high.

So far there have been some reports on this failure pattern. According to Yamamoto (2003), the process of the failure pattern is shown as below: when flood flow drops down from high-water channel to low-water channel or when overtopping to high-water channel happens, sometimes a rapid flow around revetment's crown can happen and the rapid flow erodes high-water channel. However, the detail of the rapid flow's mechanism is not explained.

We interpreted this Yamamoto's explanation and hypothesized that the revetment failure due to overtopping to high-water channel would go through a process below: first, overtopping flow on high-water channel happens during large-scale flood events. Subsequently, as the flow rate further increases, a rapid flow returns from high-water channel to low-water channel (main flow path) due to the channel planform, inducing erosion of a high-water channel behind the revetment. Finally, it leads to a turnover of revetments from its back to front toward the main flow channel.

However, a detailed mechanism relating to revetment failures and channel migration, various changes of flow discharge, water level, and sediment transport remains unclear. As there are various factors with revetment failures, in this study we focused on the following two factors relating to riverbed deformation; "1. Collapsed by local scouring" and "2. Turned over by high-water channel erosion". To replicate these failure patterns and investigate relation between failures and characteristics of riverbed deformation around a revetment, we carried out three flume experiments. The experiments are classified into straight channel cases and a meandering channel case.

2. EXPERIMENTAL SETUP

2.1 Straight Flume Setup and Experimental Procedure

Figure 3 shows a sketch of the straight channel. The experiments were carried out in a flume of 10 m in length and 0.8 m in width. A flume bed was consisted with silica sand (average diameter = 0.765 mm), initial slope was set at a gradient of 1/120, and was formed into a high and low-water channel as in Figure 3.

Two experiment were carried out in the straight channel flume (Case1 and Case2). A hydrograph in Case1 and Case2 shown in Figure 4 was designed to make the channel dynamic equilibrium state as followings: first we set discharge as low as 0.003 m^3/s and checked that a bedform reached the equilibrium state. Subsequently, we increased the discharge to 0.018 m^3/s to let water level rise on the high-water channel.

On the slope between two channels, a series of revetment miniatures were set from upstream end to middle of the flume as in Figure 3. These experimental revetments were made of aluminum plates (1 mm in thickness) in Case1 (Figure 5a) and flexible aluminum mesh sheets in Case2 (Figure 5b).

2.2 Meandering Flume Setup and Experimental Procedure

We hypothesized that a remarkable failure by overtopping occurs in the location of meandering bends more than that of straight. To replicate a revetment failure by overtopping like Otofuke River, we made the following meandering channel flume suggested in Figure 6.

In this flume, there was a meandering low-water channel with 2 waves and 40 cm width. A wavelength was 2.2 m, a meandering angle was 40 degree. Bed material was same silica sand as in Case1 and Case2. There were embankments on right and left ends of a riverbed to avoid flowing along the flume wall. Water discharge was 0.005 m^3/s and kept constant.

We used mosaic tile sheets as a revetment miniature in Case3. The sheets were inserted into a riverbed to its bottom along a straight channel's bank slope as shown in Figure 6. A top end of sheets was rolled into high-water channel as an actual revetment has a protection work on its crown. To prevent bed material slipping through the sheet's gap, every sheet was connected by a thin fabric sheet on its back.

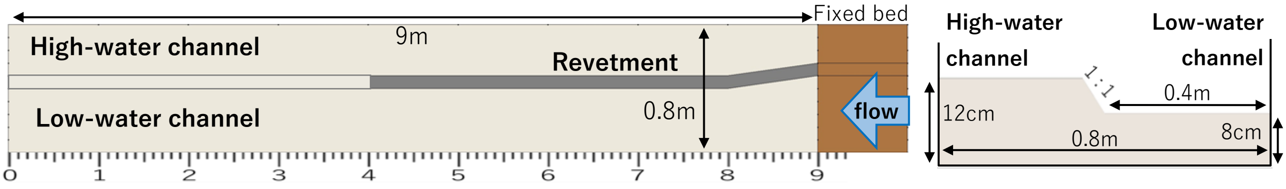

Figure 3. Straight flume channel in Case1 and Case2

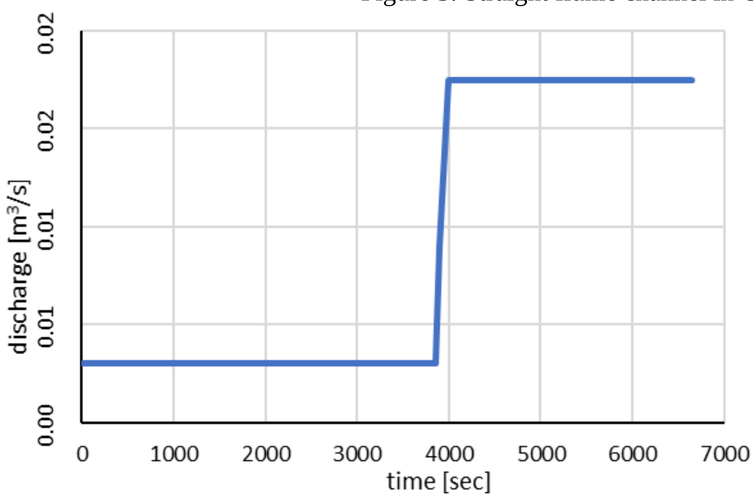

Figure 4. Hydrograph in Case1 and Case2

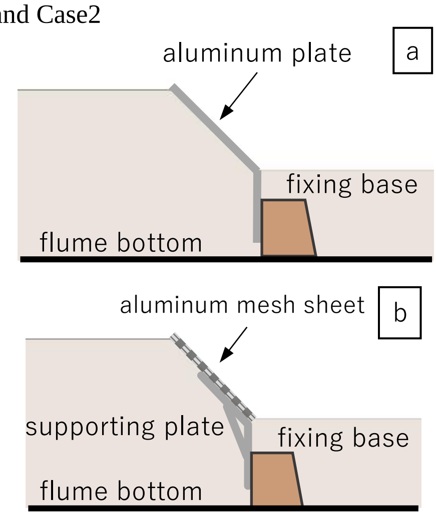

Figure 5. Revetment in Case1 (a) and Case2 (b)

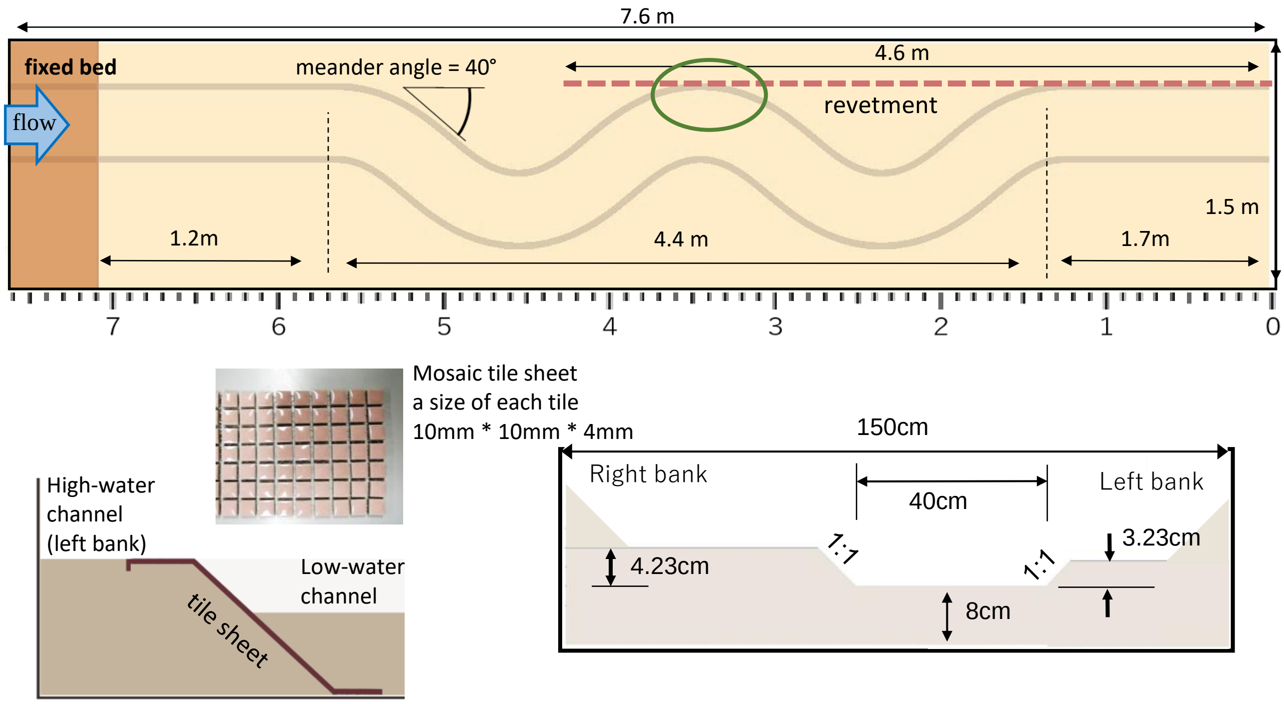

Figure 6. Meandering channel flume and a revetment in Case3

In Case3, we designed that an overtopping flow would occur at the outer bend of meandering as shown by a circle in Figure 6. A height of a left bank was set lower than a right bank by 1cm so as to make water flow easily cross over the revetment.

2.3 Data collection

We took overview photographs and cross-sectional elevation data with a laser displacement measure of the flume before and after each case and calculated bed elevation changes. Additionally, we performed Particle Image Velocimetry (PIV) analysis with each case to check flow velocity around the revetment.

3. RESULTS AND DISCUSSION

3.1 Straight channel

3.1.1 Bed deformation in Case1 and Case2

Figure 7 shows contour maps of riverbed elevation before and after the experiment and a contour map of elevation change in Case1. On the low-water channel in middle area of the flume, alternative bars of about 1.6 cm wave height were formed. At some points of the alternative bars' front edge, local scourings in front of the

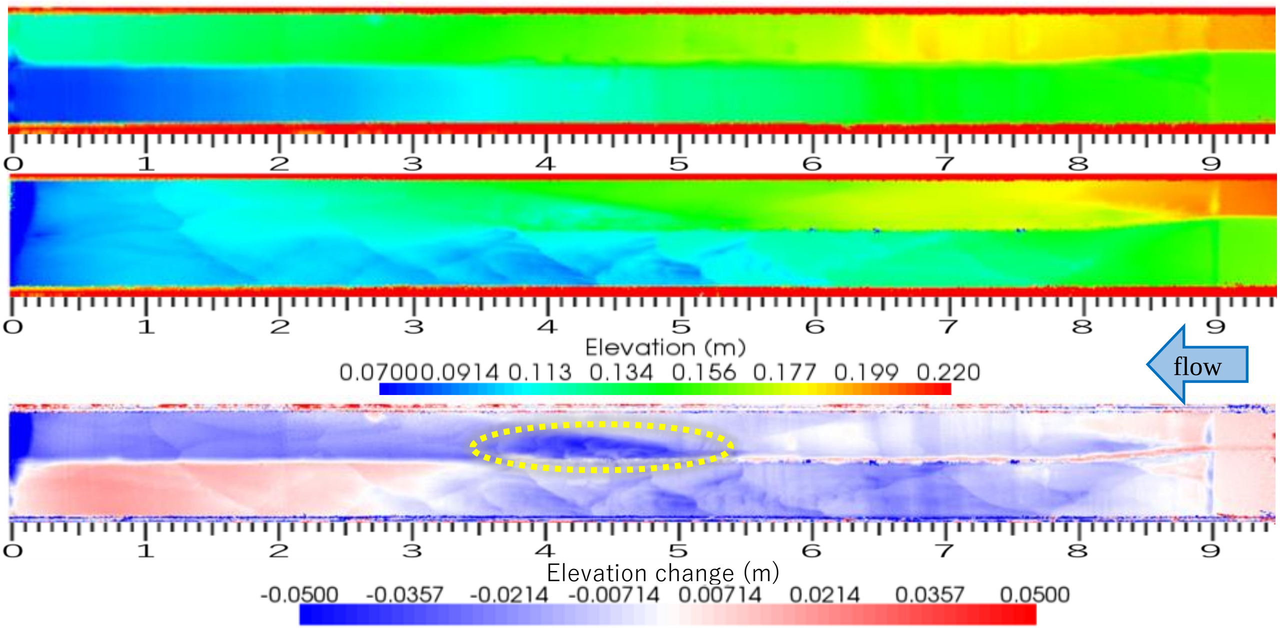

Figure 7. Ccontour maps of bed elevation before (top) and after (middle), and elevation change (bottom) in Case1

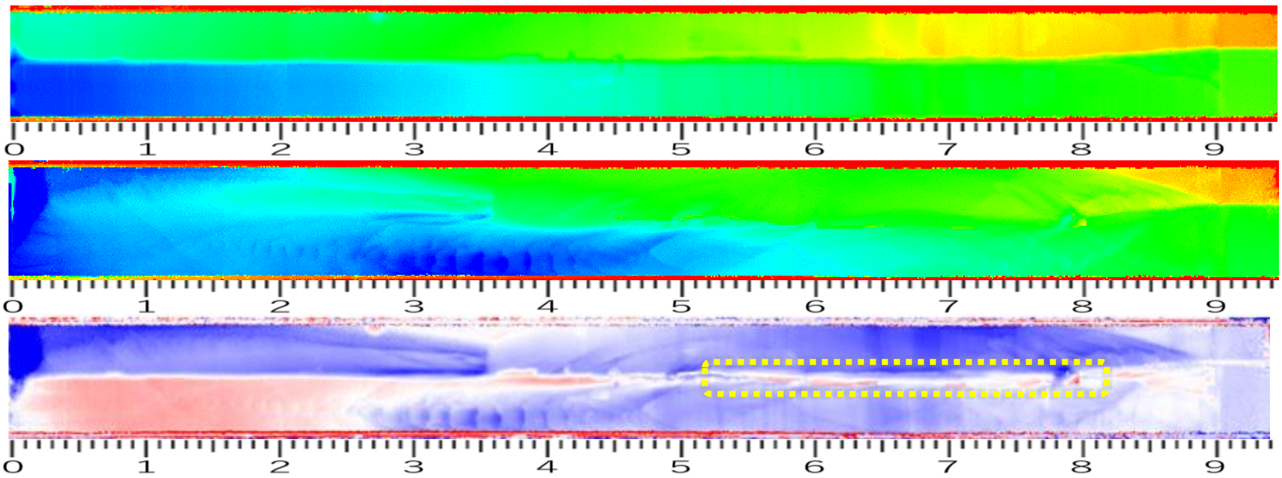

Figure 8. Contour maps of bed elevation before (top) and after (middle), and elevation change (bottom) in Case2 (the color-scales are same as in Figure 7)

revetment were observed, but those depth were not so deep as the revetment's foundation. On the high-water channel beside the bars, a bed degradation was observed as shown by a yellow circle in Figure 7.

In Case2 about 5 minutes after the discharge increase and the flow flooded on the high-water channel, some parts of the aluminum mesh sheet, shown by yellow rectangle in Figure 8, were lifted up. After a few minutes more, those lifted sheets got turned over toward low-water channel. Behind the turned over sheet, wide bed degradation on high-water channel was observed as indicated in Figure 8. Furthermore, there were a dropping flow and sediment transport from highwater channel to low-water channel through gaps between turned over sheets and remaining sheets. This flow and transport appeared to promote the bed degradation on high-water channel.

3.1.2 PIV analysis in Case1 and Case2

We performed PIV analyses every 10 minutes after the discharge increase. Figure 9 shows one of PIV results which performed about 30 minutes after the discharge increase. From those PIV results in Case1, though there were not prominent overtopping flows crossing the revetment toward the degradation area, a flow on the high-water channel concentrated to the degradation area as shown in Figure 9. By examining time series of PIV results, this degradation took place from the revetment's downstream end. It suggested that the degradation was not caused by a rapid flow or an overtopping flow on the high-water channel along the revetment, but by local scouring at the revetment's end.

Figure 10 shows velocity vectors by PIV analysis performed 20 minutes after the discharge increase in Case2. In Figure 10a, velocity vectors in upstream area indicates that their velocity was over 0.6 m/s on low water channel and 0.5 m/s on high water channel. As can be seen from Figure 10b, the dropping flow from the high-water channel concentrated in the gap by the mesh deformation. However, its velocity was about 0.4 m/s at most and not so high in comparison with upstream area of the flume.

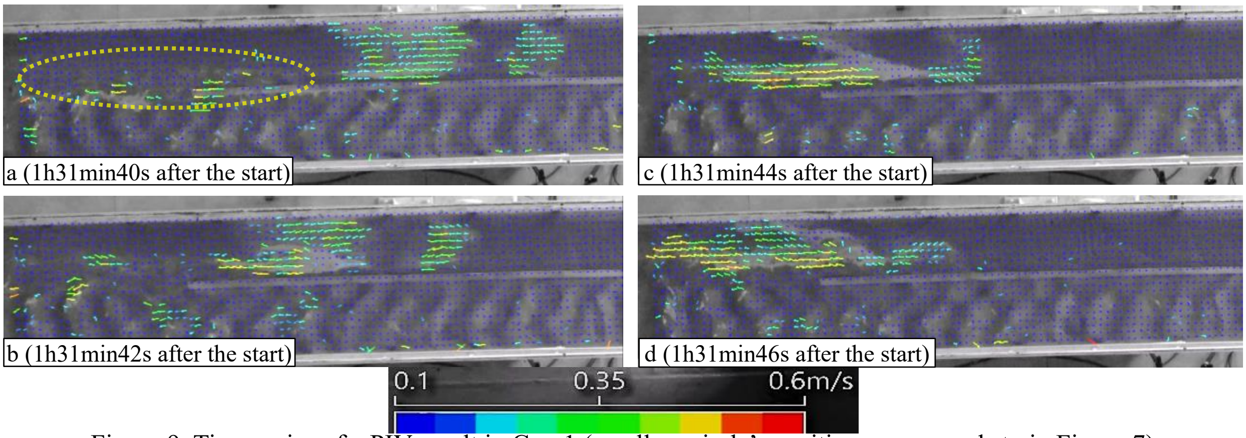

Figure 9. Time series of a PIV result in Case1 (a yellow circle's position corresponds to in Figure 7)

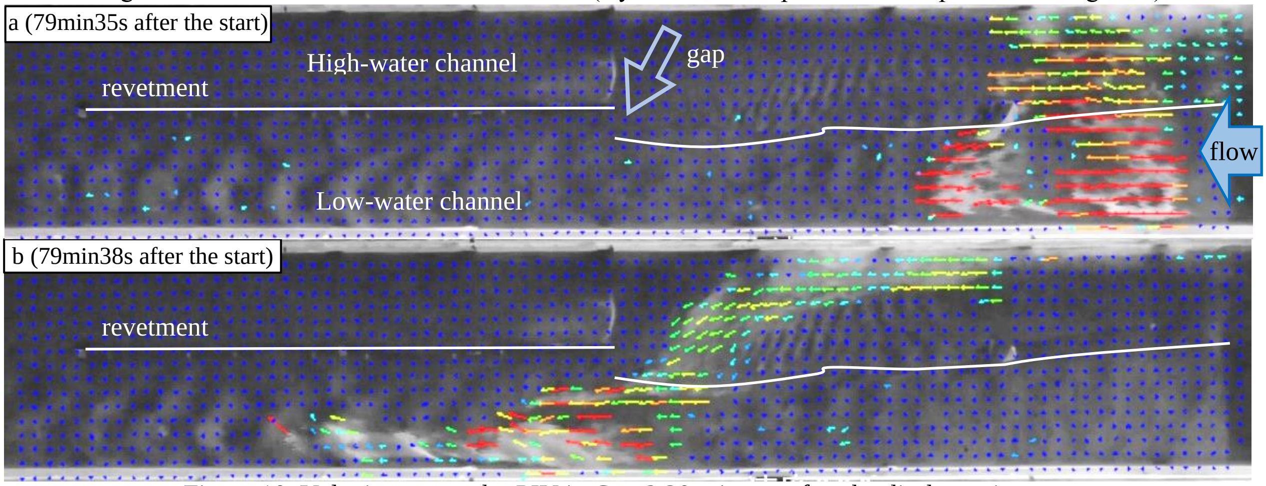

Figure 10. Velocity vectors by PIV in Case2 20 minutes after the discharge increase
(the color-scales are same as in Figure 9)

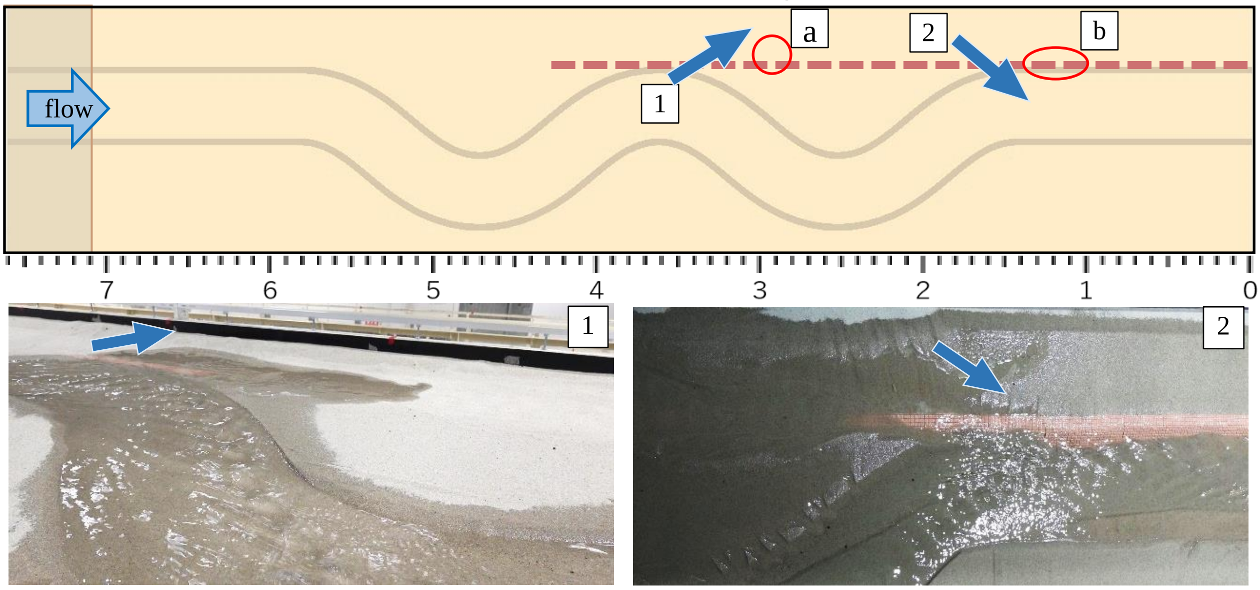

Figure 11. points where overtopping happened in Case3 and photographs of them

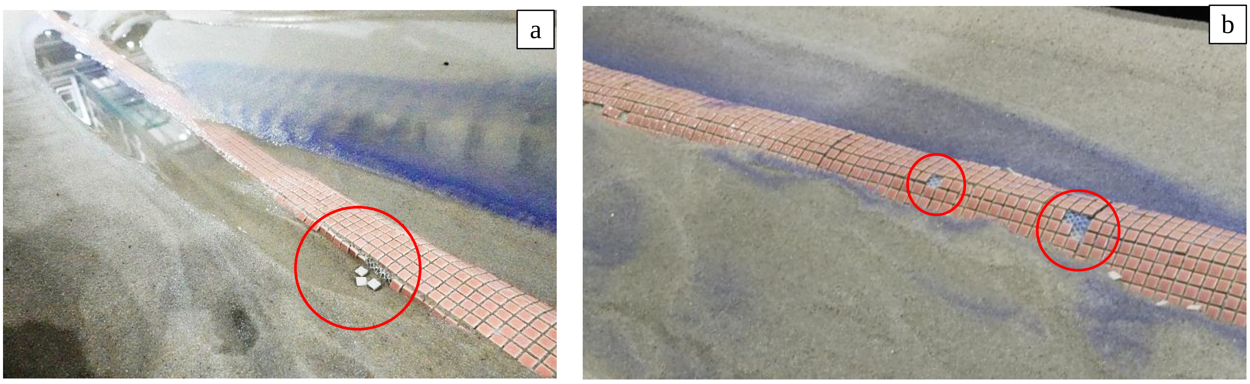

Figure 12. damage to top end and tile blocks' falling out in Case3

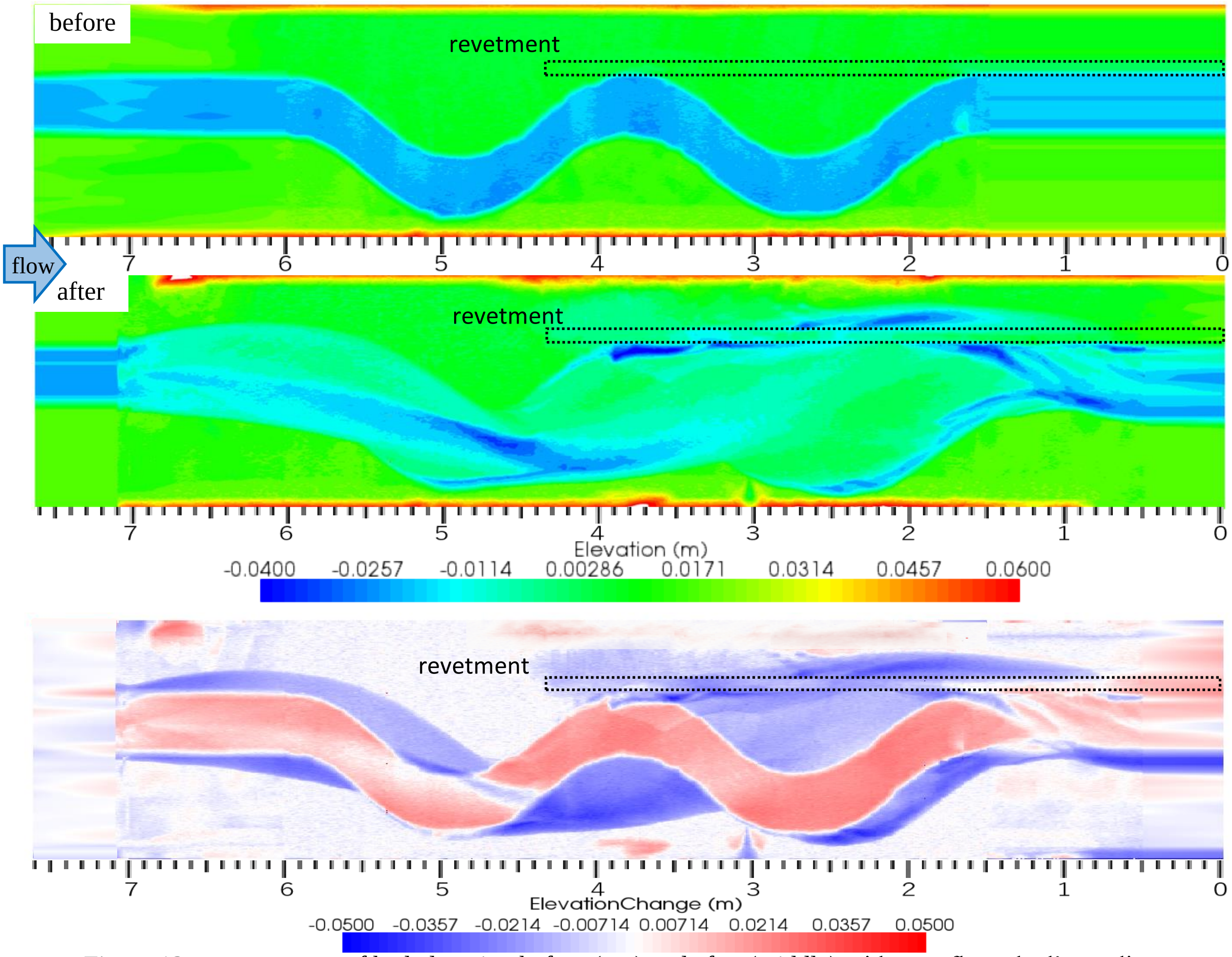

Figure 13. contour maps of bed elevation before (top) and after (middle) without a flume bed's gradient, and elevation change (bottom) in Case3

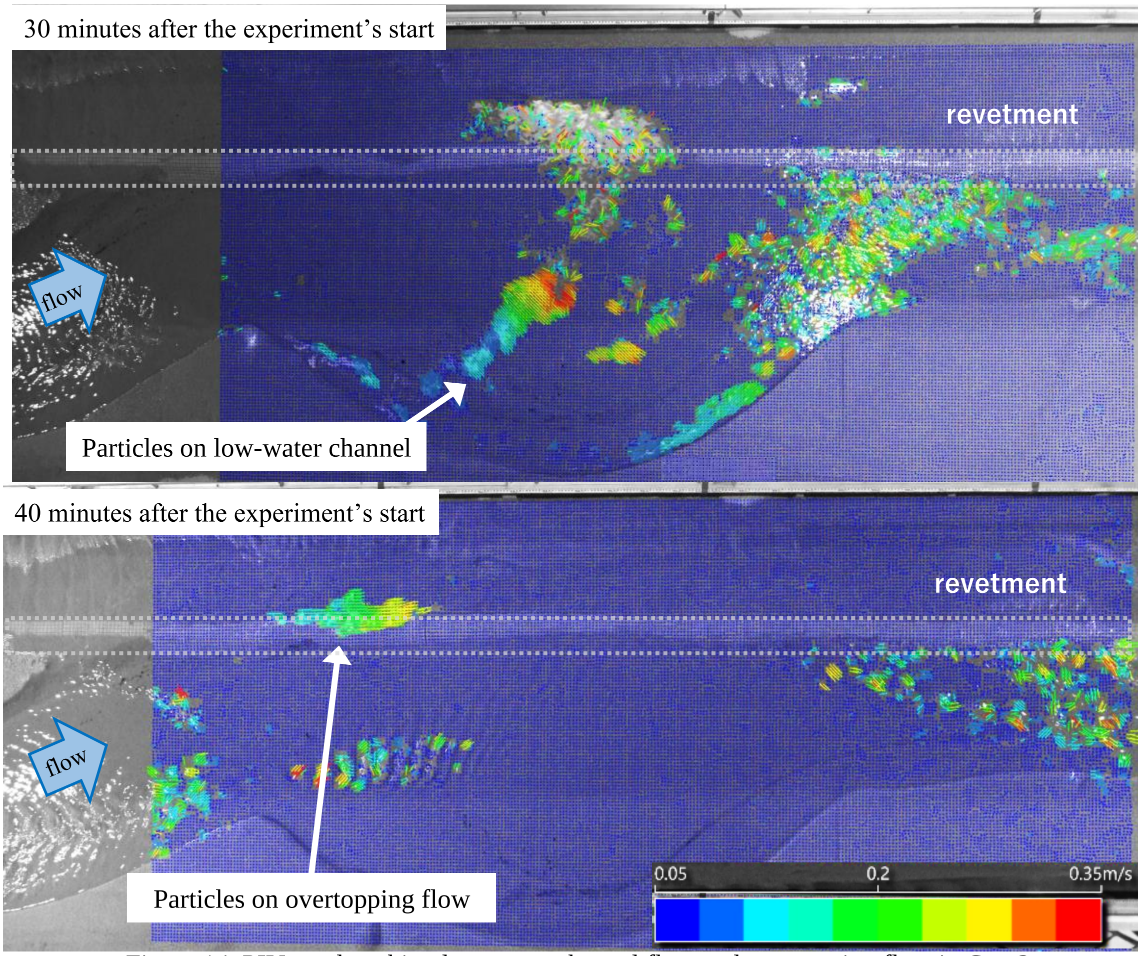

Figure 14. PIV results taking low-water channel flow and overtopping flow in Case3

3.2 Meandering channel

3.2.1 Bed deformation in Case3

This experiment continued for an hour and a half. A few minutes after the experiment started, water flow crossed over the revetment at some points including the outer bend of meandering on left bank side. Figure 11 shows points where overtopping happened. The overtopping flow streamed along the revetment and returned to the low-water channel at the downstream straight channel. There was some damage to the top end of tile sheets and some of tile blocks were fell out around where overtopping happened as shown by a red circle in Figure 12.

Figure 13 shows riverbed elevation contour maps without a flume's gradient before and after the experiment and an elevation change contour map of Case3. As can be seen from Figure 13, the meandering channel transformed as below; the meandering channel gradually migrated toward downstream with a decrease of meandering angle. Also, we can observe from the elevation map a remarkable scouring along the back of the revetment around 2 m from a downstream end. This scouring was 50 mm at most and near where the overtopping flow returned to the low-water channel.

3.2.2 PIV analysis in Case3

Figure 14 shows two PIV results performed in 30 and 40 minutes after an experiment's start. Though there are some noises on a downstream area, we can see the velocity of a low-water channel flow and an overtopping flow. According to the Figure 14, a velocity of the overtopping flow was about 0.3 m/s at most, while a velocity on low-water channel was partly over 0.3 m/s. This characteristic of overtopping velocity indicates that there wasn't a rapid flow inducing the scouring behind the revetment shown in Figure 13.

4. CONCLUSION

As mentioned above, according to Yamamoto (2003) a process of the revetment failure with high-water channel erosion is thought to be caused by an overtopping and a rapid flow along the revetment's crown.

From results of Case1 and Case2, in a straight channel there is little possibility of erosion on a high-water channel causing the failure pattern. In a straight channel with a fixed revetment as in Case1, there was not a prominent overtopping flow crossing the revetment nor a rapid flow around a revetment's crown. Although there was a bed degradation area on a high-water channel, that was formed from a local scouring at the end of a revetment, not caused by erosion due to an overtopping flow or a rapid flow.

In regard to Case2 with a movable revetment, a large-scale bed degradation took place on a high-water channel, but a rapid flow crossing the revetment wasn't observed. Compared with the result of Case1, the degradation in Case2 appears to have been caused by the revetment's turning over, not to be the reason of the turning over.

In a meandering channel as in Case3, we observed several phenomena which would cause a failure pattern of "turned over by high-water channel erosion": an overtopping flow, severe erosion along a revetment and several damage to a revetment. Nevertheless, the velocity of the overtopping flow was not so remarkable as we expected. Thus, it was found through experiments in this study that the failure pattern with high-water channel erosion is not necessarily caused by a rapid flow along revetment's crown.

ACKNOWLEDGMENTS

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