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Shimada, T.; Yokoyama, H.; Hirai, Y.; Tsuji, T.

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LEVEE BREACH EXPERIMENT BY OVERFLOW AT THE CHIYODA EXPERIMENTAL CHANNEL

T. Shimada[1], H. Yokoyama[2] , Y. Hirai[3] and T. Tsuji[4]

Abstract: *The mechanism of three-dimensional levee breach by overflow (i.e., lateral overflow with consideration of river flow riverside land) has not been clarified in past studies. Elucidation of this mechanism is very important for disaster prevention as well as for the future progress of studies on levee breach by overflow.*
Levees were built in the Chiyoda Experimental Channel in 2009, and a three-dimensional experiment on levee breach by overflow was conducted using two types of soil. The results revealed the conditions required for a sudden increase in levee width, and also clarified differences in the widening processes involved in levee breach depending on soil types.
The findings of the experiment are as follows: After the beginning of overflow, levee breach widening did not begin until after most of the levee section had collapsed. When the soil used for the levee had a high fine-grain content, the time between overflow and levee breach widening was longer. When the levee body had a high gravel content, levee breach widening progressed with repeated widening of the levee bottom following widening of the top to a certain degree. When the levee had a high fine-grain content, its top and bottom collapsed at the same time during the progress of levee breach widening.

Keywords: *Chiyoda experimental channel; levee breach by overflow; breach process*

1. INTRODUCTION

The increased occurrence of storm disasters caused by typhoons and local downpours in recent years has given rise to concerns over the possibility of large-scale floods resulting from river overflow. Levee breaches cause particularly severe damage, and more than 80% of such accidents in the past have been attributed to overflow. Studies on levee breach by overflow have been conducted from various viewpoints using diverse methods. However, many aspects of the phenomenon remain unclear (especially concerning the three-dimensional mechanism of levee breach by overflow on a real scale), so understanding the problem is very important for the future progress of related studies. The results of clarifying these points are also expected to be useful in improving risk control technologies and restoring breached levees, as well as for enhancing the accuracy of hazard maps.

1 Researcher , Civil Engineering Research Institute for Clod Region, PWRI
Hiragishi 1-3-1-34, Toyohira-ku, Sapporo, 062-8602, Japan, Email: osaka.shimada@gmail.com
2 Senior Researcher , Civil Engineering Research Institute for Clod Region, PWRI
Hiragishi 1-3-1-34, Toyohira-ku, Sapporo, 062-8602, Japan
3 Team Leader Researcher , Civil Engineering Research Institute for Clod Region, PWRI
Hiragishi 1-3-1-34, Toyohira-ku, Sapporo, 062-8602, Japan
4 Administrative officer, Hokkaido Development Bureau, Obihiro Development and Construction Department
Nishi 4-jo Minami 8-chome, Obihiro, 080-8585, Japan

The Hokkaido Regional Development Bureau (under the Ministry of Land, Infrastructure, Transport and Tourism) and the Civil Engineering Research Institute for Cold Region conducted a real-scale, two-dimensional levee breach experiment involving front overflow in the Tokachi River's Chiyoda Experimental Channel in 2008 to clarify the widening process of levee breach. However, as actual levee breaching is caused by lateral overflow under the influence of river flow riverside land, the widening process here is thought to be different. It is also important to clarify differences in the breach process depending on levee materials, since many actual levees are built using materials generated on site.

Fig. 1. Levee constructed in the Chiyoda Experimental Channel

In 2009, levees using different materials were built in the Chiyoda Experimental Channel as shown in Figure 1, and a levee breach experiment involving lateral overflow (as seen in the actual phenomenon) was conducted to clarify differences in the widening processes involved in levee breach depending on soil types.

2. OVERVIEW OF THE LEVEE BREACH EXPERIMENT

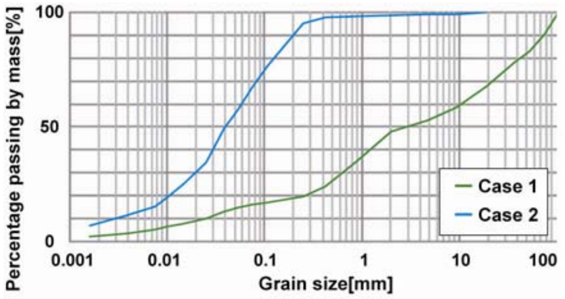
2.1 Overview of the vertical levees

Levees measuring 2.5 m in height and 3 m in levee crown width with a slope gradient of 50% were built in the Chiyoda Experimental Channel, and a levee breach experiment involving lateral overflow with consideration to river flow riverside lands was conducted twice (on April 30 (Case 1) and June 30 (Case 2)).

Figure 2 shows an overview of the experiment. A notch measuring 0.5 m in depth, 3 m in top width and 1 m in bottom width was cut to initiate levee breach. The levee materials used were as shown in Figure 3, and the fine-grain content was around 15% in Case 1 and 67% in Case 2. However, the materials adopted in Case 1 were used up to 0.6 m above the riverbed in Case 2 for convenience of construction. To prevent levee erosion caused by water flow, blocks were placed on the front slope of the breach section (P567 – 647) and vinyl sheets were placed on the front and back slopes of the non-breach section.

2.2 Overview of the observation

As shown in Figure 2, the main observation items during the period of water flow were water level (recorded with a water level gauge), related conditions (by camera/video), time-series progress of the levee profile (with an acceleration sensor) and flow (by pile wire-type ADCP and electric wave-type flowmeter). The observation methods and other details were the same as those in previous studies by the authors, with an electric wave-type flowmeter newly introduced for flow observation. The observation and flow rate calculation methods were as described below.



Item		Case1	Case2
General	Soil-grain density ρ_s[g/cm^3]	2.685	2.624
	Natural water content w_s[%]	8.02	31.24
Grain-size composition	Gravel(2~75mm) [%]	52.0	1.2
	Sand(0.075~2mm) [%]	32.0	31.4
	Silt(0.005~0.075mm) [%]	11.9	54.8
	Clay(~0.005mm)[%]	4.1	12.6
	50% grain size[mm]	2.7	0.037
Compaction	Maximum dry density ρ_{dmax}[g/cm^3]	2.615	1.304
	Optimum water content w_{opt}[%]	7.2	29.3
	Compaction[%]	93.3	93.0

Fig. 3. Grain-size distribution and soil test results for the levee materials

Since the overflow discharge from a levee is estimated based on the difference between the flow rates upstream and downstream of the breached section, detailed time-series flow data are needed. When using an ADCP, observation must be conducted while moving repeatedly in the transverse direction of the channel. It is difficult to obtain continuous data in this regard, although it is possible to measure the riverbed profile and detailed flow velocity in a cross-sectional area of the flow in real time. An electric wave-type flowmeter was therefore used to obtain surface flow velocity data (obtained every second, with the average for each 60-second period used as one data point) from the center of the direction transverse to the channel, and time-series flow rates were calculated by multiplying these flow velocity values by the cross-sectional area of the flow (based on measurements taken using the water level meter and observation of the riverbed profile before and after water flow).

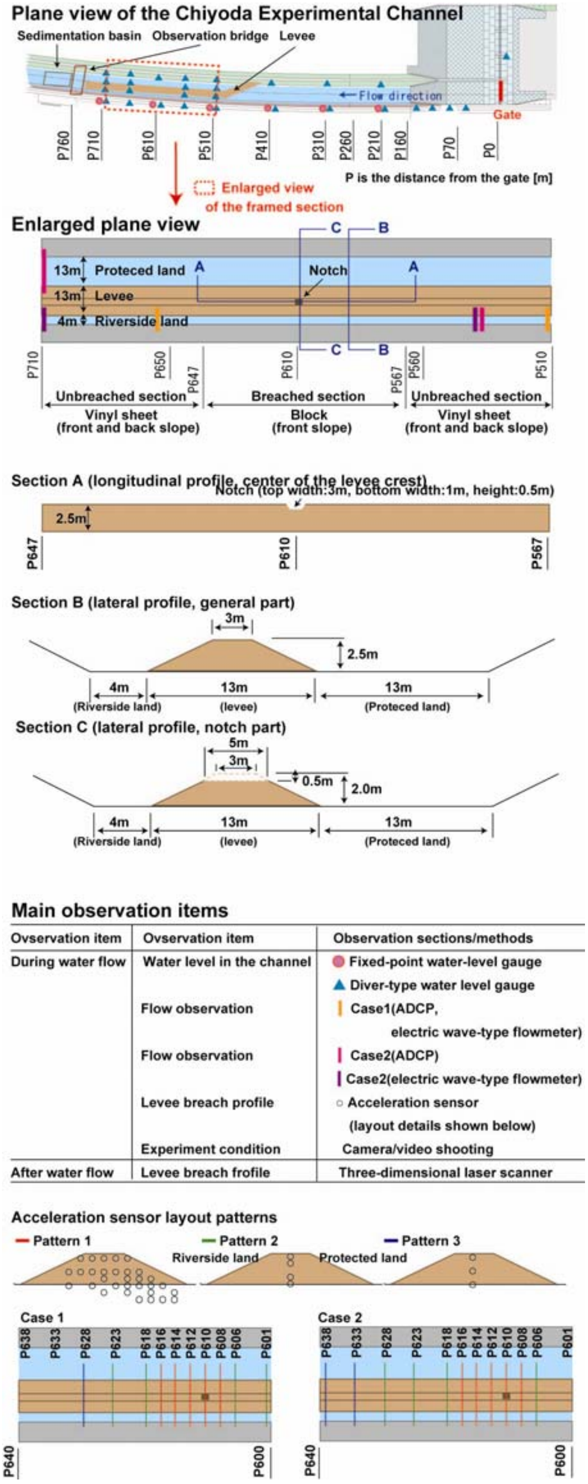


Fig. 2. Overview of levee breach by overflow

However, since the flow velocity data were obtained at a single point on the water surface, correction may have to be made as necessary by comparing them with the flow data obtained by ADCP observation.

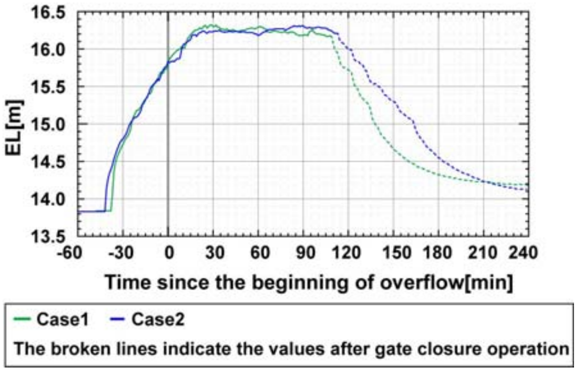


Fig. 4. Water level riverside land at ap-point 100 m upstream of the notch part (P510)

2.3 Overview of flowing water

In both Cases 1 and 2, the flow rate was increased until the overflow depth from the notch reached 30 to 50 cm (determined based on past cases), and a steady flow was maintained thereafter (the steady flow rate was around 75 m3/s). Figure 4 shows the water levels riverside land measured at P510 (located 100 m upstream of the notch part). While the changes in water level were similar in Cases 1 and 2, there was a difference in the time required for the water level to decrease after the gate was closed to stop the water flow. The comparison of the experiment results below covers the time until the gate closure operation.

3. EXPERIMENT RESULTS (HYDRAULIC QUANTITY)

3.1 Experiment conditions

Figure 5 shows images videotaped during the experiment. In both cases, erosion of the surface and top of the back slope began after the onset of overflow. While erosion and recession of the crest progressed from the inside to the outside of the levees and collapse of the levee bodies centering around the notches was observed, the time required seemed to be longer in Case 2 than in Case 1. The overflow condition was the same as that in the case of front overflow, and no levee breach widening was observed at this stage.

Breach widening began approximately 30 minutes after the onset of overflow in Case 1 and after 75 minutes in Case 2. Subsequently, the overflow condition changed from the vertical to the orthogonal direction in relation to the levees, and breach widening toward the downstream side began. In this experiment, no breach widening toward the upstream side was observed in either case.

3.2 Water levels inside and riverside land (notch part)

Figure 6 shows the water level observation results and the differences in water levels outside (left bank of the channel) and inside (right bank of the channel) the levees at P610 on the transverse section of the notch part. Looking at the results for the area riverside lands, the water level exceeded the height of the notch part at the same time as the beginning of overflow, indicating that the accuracy management of levee construction was appropriate in both cases.

While the water levels continued to be uniform after increasing to an overflow depth of 50 cm, sudden decreases were observed approximately 30 minutes (Case 1) and 75 minutes (Case 2) after the beginning of overflow. These times corresponded with those at which the progress of levee breach widening was observed in the video images of the experiment. Fluc-

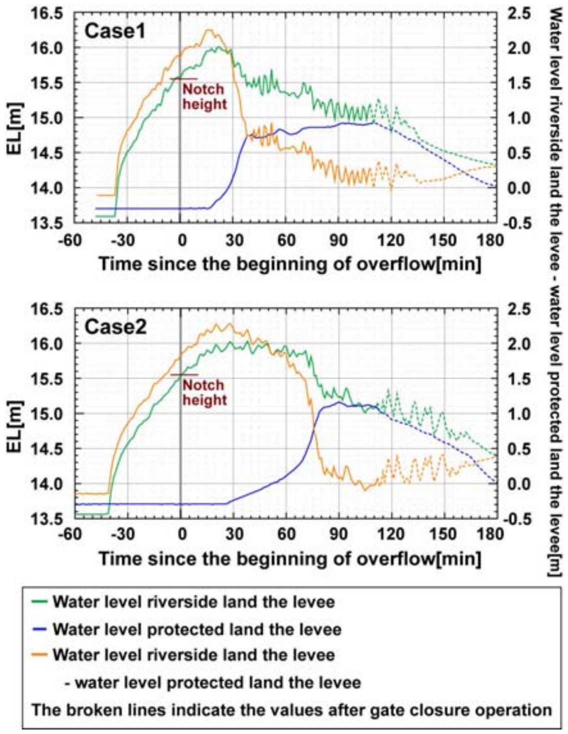


Fig. 6. Water level protected and riverside land the level (P610) and difference between them

tuations in water levels were especially significant after the decrease in water levels riverside lands, indicating the influence of levee breach on the conditions in the river channel. The contrast between Cases 1 and 2 here is the difference in water levels between the areas inside and riverside lands. While this difference decreased gradually until 90 minutes after the water level receded riverside land in Case 1, it disappeared immediately in Case 2. This phenomenon shows differences in hydraulic quantities during the breach process, meaning that discussion of the levee breach widening process (to be described below) cannot be based simply on differences in soil type.

3.3 Estimation of overflow discharge

Figure 7 shows the results of the flow observation conducted upstream and downstream

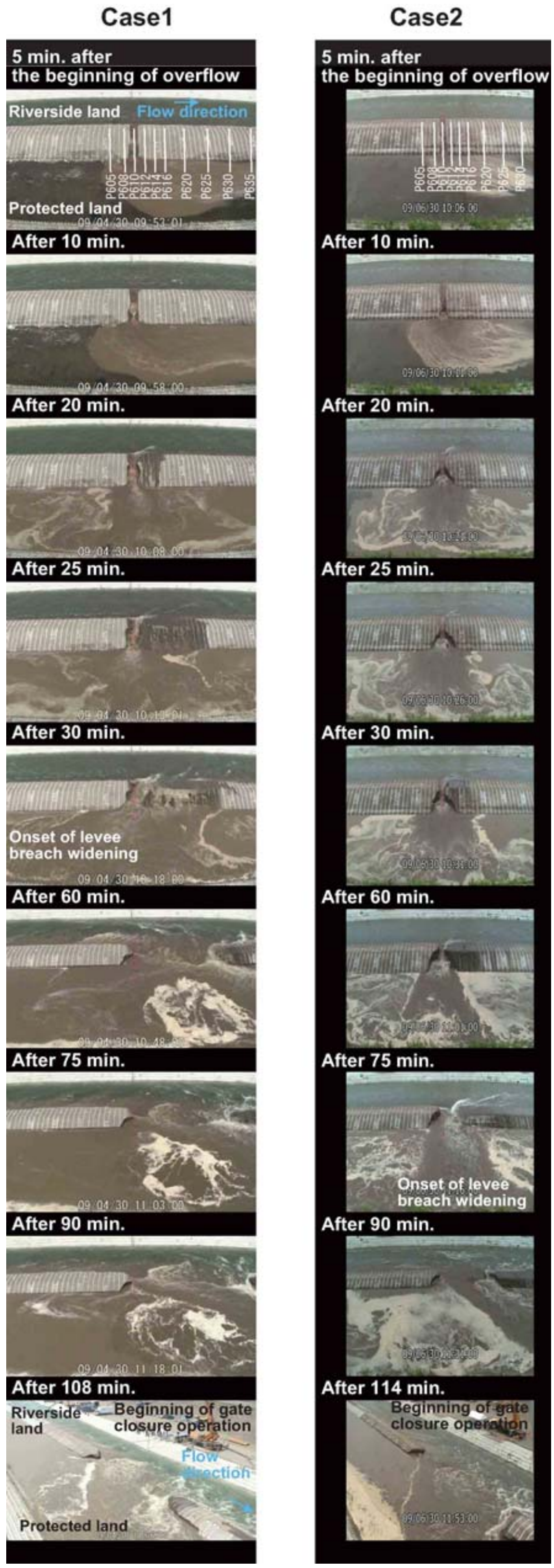


Fig. 5. Experiment conditions

of the breached sections for estimation of the overflow discharge. As mentioned above, a continuous flow rate can be calculated by multiplying the flow velocity by the cross-sectional area of flow when measuring the flow rate using an electric wave-type flow-meter. However, since changes in cross sections and other details cannot be measured during the period of water flow, comparison with the results of flow observation using ADCP was made. As the flow rates measured using the two methods simultaneously were almost identical, it was considered possible to adopt the flow rates estimated using an electric wave-type flowmeter.

Next, Figure 8 shows the overflow discharge values calculated from the difference in the flow rates measured upstream and downstream of the levee breach sections shown in Figure 7. Although the estimated values varied due to sharp water level fluctuations, those calculated from the observed values are shown without correction here. It can be seen that overflow discharge tended to increase dramatically from the time when significant levee breach widening was observed, as shown in the above-mentioned video images of the experiment conditions and in the water level observation results.

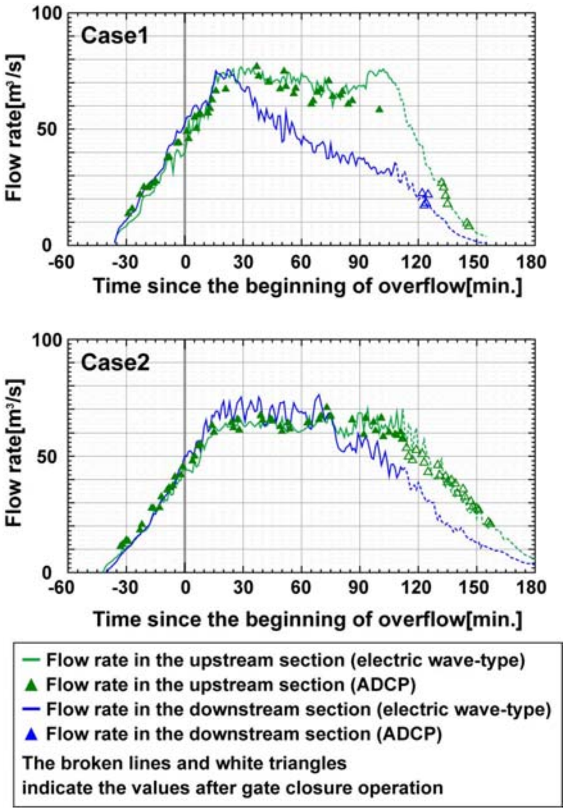


Fig. 7. Flow rates upstream and downstream of the levee breach section

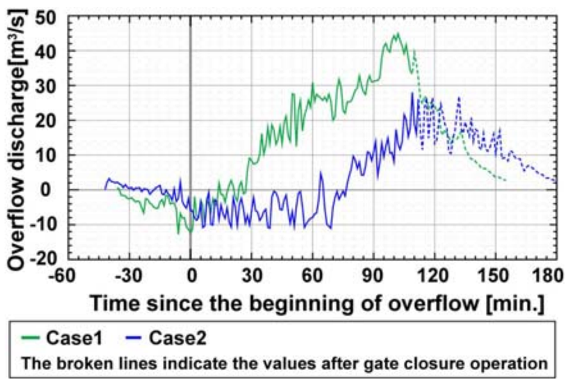


Fig. 8. Estimated overflow discharge

4. EXPERIMENT RESULTS (LEVEE BREACH PROCESS)

The experiment showed large differences in the mechanisms of levee breach progress between the time from the beginning of overflow to the onset of levee breach widening and the subsequent period. Accordingly, it was considered necessary to divide the levee breach process into a first stage (from the beginning of overflow to the onset of levee breach widening) and a second stage (after the onset of widening). The method adopted by the authors in past studies was used to summarize the progress of breaching together with the history of breaching protected land based on the measurements of the acceleration sensor placed protected land and the history of crest widening as obtained from video images.

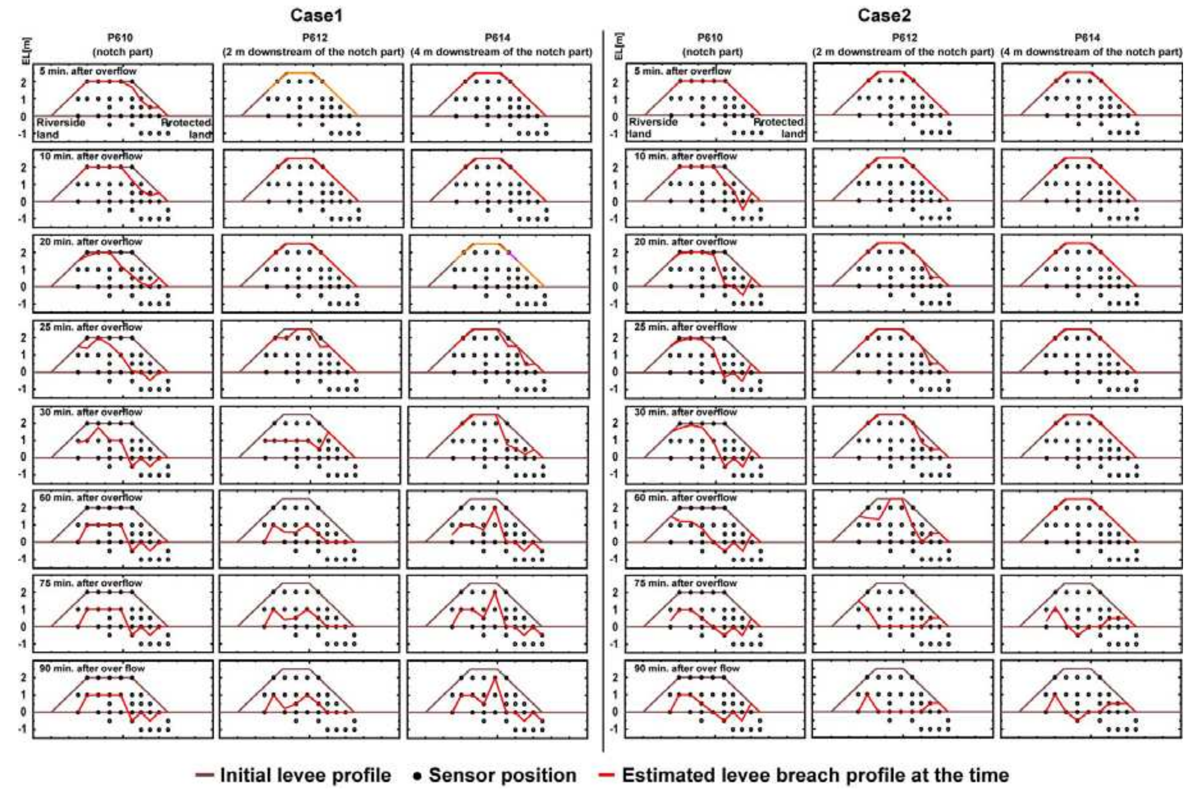


Fig. 9. Estimation of the levee breach process using acceleration sensor records

4.1 Progress of the first stage of breach

Figure 9 shows an example of the progress of levee breach in the section around the notch part as estimated from the records of the acceleration sensor.

In Case 1, erosion was observed at the top and on the surface of the back slope at P610 (the section of the notch part) until 25 minutes after the beginning of overflow. It can be seen that the crest was also eroded at an almost uniform rate. At P612 (the section around the notch part), no significant erosion was observed even after 25 minutes. The majority of the section then collapsed 30 minutes after the beginning of overflow, followed by levee breach widening.

In Case 2, erosion was observed at the top and surface of the back slope from the beginning of overflow at P610 (the section of the notch part). The rate of crest erosion was lower and the profile was steeper than in Case 1. While the crest was completely eroded 60 minutes after the beginning of overflow, the collapse of the majority of the section did not occur until after 75 minutes when levee breach widening began.

Comparison of Cases 1 and 2 indicated that the beginning of levee breach widening depended on whether the majority of the levee section had collapsed or not, regardless of soil type. This was the same as the widening process of levee breach by front overflow presented by the authors last year. The time required from the beginning of overflow to the onset of levee breach widening also differed because the material used in Case 2 had a higher fine-grain content and was more viscous than that used in Case 1, as in the past case. From the above results, it is considered possible to use the outcome of the two-dimensional experiment (front overflow) at least from the beginning of overflow to the onset of levee breach widening.

4.2 Progress of the second stage of breach

Figure 10 shows the time of levee breach as found from the records of a sensor placed on the longitudinal survey line at the center of the levee crest, along with levee crown widths measured at intervals of five minutes from video images to monitor collapse protected land. This was represented by setting the reference height of the channel bed to 0 m and plotting the sensor height and time of discharge.

As mentioned before, the levee crown widths increased toward the downstream side after the majority of the levee section had collapsed in both Cases 1 and 2. Collapse protected land occurred first at the top and spread downstream, followed by widening at the bottom of the levee in Case 1. However, widening occurred simultaneously from the top to the bottom of the levee at a rate similar to that of the crest widening seen in Case 2.

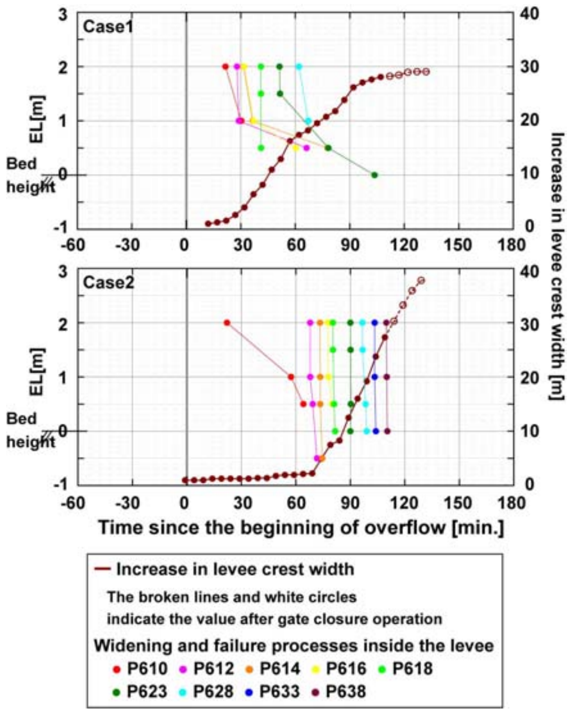


Fig. 10. Levee breach widening process

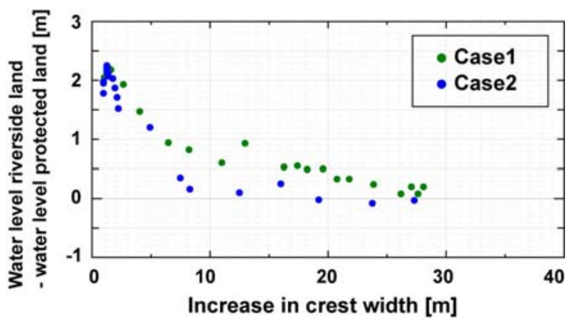


Fig. 11. Increase in levee crown width and differences in water levels between parts riverside and protected land

4.3 Differences in the levee breach widening process depending on the soil properties of the levee body

While the type of soil was assumed to be the only difference between Cases 1 and 2, there was also a difference in water level fluctuations inside and riverside land after the beginning of levee breach widening as shown in Figure 6. It is therefore not possible to compare the results of the second stage of levee breach simply by differences in soil type.

Figure 11 shows the relationship between the increase in the levee crown width and water level differences inside and riverside land in the section of the notch part. The results for up to around 10 m in levee breach width show that widening of the crest progressed and the difference in water levels was maintained, while the difference decreased gradually in both Cases 1 and 2. It can therefore be said that the difference in levee breach widening was due to the soil types of the levees until this stage. Up to the breach width of 10 m shown in Figure 10, levee breach widening seemed to progress in Case 1 with repeated widening of the levee bot-

tom following the widening of the top to a certain degree. It was therefore considered that the reduced rate of levee breach widening 60 minutes after the beginning of overflow was caused partially by reduced erosion of the levee bottom due to the absence of a difference in water levels between the areas inside and riverside land. Conversely, levee breach widening progressed while the top and bottom of the levee were collapsing at the same time in Case 2. The above results revealed differences in the levee breach widening process depending on the type of soil used, although this was only seen in the early stages of widening.
Widening progressed after the levee breach width reached 10 cm even though there was almost no difference in water levels in both Cases 1 and 2. In Case 2 in particular, widening continued without a decrease in its rate of progress. While this was thought to be due to erosion and collapse caused by the impact of flowing water on the levee body rather than levee breach by overflow, further studies on this phenomenon will be necessary.

5. CONCLUSION

In this study, a full-scale levee breach experiment involving lateral overflow was conducted with focus on differences in the type of soil used for the levee body. The findings of the study are as follows:

1. First stage of levee breach (from the beginning of overflow to the onset of levee breach widening)
After overflow from the levee, levee breach widening did not occur until after the majority of the levee section had collapsed. This was the same result as that seen in the levee breach experiment involving front overflow (in which the river flow was not taken into account), and the overflow conditions were also similar. The difference in the time taken from the beginning of overflow to the onset of levee breach was thought to be due to the soil types used. As with past cases, the time required until levee breach widening was longer when the fine-grain content was higher. Since the process between overflow and levee breach widening was the same as that in the past two-dimensional experiment, it is possible to use the results previously obtained. It was also considered that, even if overflow occurred, extremely serious damage (e.g., sudden increases in levee breach width and overflow discharge) was unlikely unless the majority of the levee section collapsed.
2. Second stage of levee breach (from the onset of levee breach widening)
The levee breach widening process progressed with repeated widening of the levee bottom following the widening of the top to a certain degree in the levee material with a high gravel content (Case 1). However, it was found that the top and bottom of the levee collapsed and that widening occurred simultaneously in the case of levee material with a high fine-grain content (Case 2).

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