CALCULATION METHOD OF INUNDATION DISCHARGE HYDROGRAPH FROM THE TEMPORAL CHANGES IN WATER SURFACE PROFILE DUE TO LEVEE BREACH

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ABSTRACT

For predicting discharge hydrograph and progress of inundation flow caused by the levee breach, it is important to evaluate inundation discharge precisely. In this study, utilizing that the change in hydraulic and geometrical conditions during the flood appear in the temporal changes in water surface profiles, we developed a calculation model to estimate inundation discharge hydrograph using unsteady two-dimensional flow equations and the temporal change in water surface profiles including effects of the levee breach. To validate the model, we carried out field experiments of levee breach of a channel constructed in the Joganji River. Compared with the experimental results, the simulated inundation discharges showed acceptable accuracy. Finally, several issues were raised during appllying this method to actual rivers.

Keywords: levee breach, inundation discharge hydrograph, field experiment, numerical calculation, temporal change in water surface profile

1. INTRODUCTION

The plan-scale floods happen frequently, and the levee-breach tends to be problem in Japan in recent years. The levee-breach occurs, the flood flow goes into landside and catastrophic damage is caused to a lot of human, social properties. It is necessary to estimate the inundation discharge that considers effective measures to the inundation according to the levee-breach. The inundation discharge is a boundary condition when the inundation analysis is done, and the accuracy of the inundation analysis is tightly related with the accuracy of the boundary condition. Therefore, it is important to estimate inundation discharge accurately and to make the progress of the flood flow in landside predictable to minimize damage by the levee-breach.

Homma’s formula (1962) has been used as a conventional method to calculate the inundation discharge. However, this method is not capable evaluating the phenomenon of lateral overflow, since it is front overflow formula. PWRI (Public Works Research Institute) proposed a method corrected from the Homma's formula which considers the inflow angle to the levee-breach point and bed slope by the hydraulic model experiment that reproduces the characteristic of lateral overflow (1996).

The changes in hydraulic and geometrical conditions of river channel during the flood can be reflected by the temporal changes in water surface profiles. Fukuoka (2004, 2005, 2005b, 2006) suggested a two dimensional flow analysis method using measured changes of water surface profiles to estimate the river discharge and verified its effectiveness. Meanwhile, field experiments of levee-breach were carried out in the Joganji River.

Based on the results from the experiments, the following three aspects are presented in the paper. Firstly, a calculation method for the inundation discharge hydrograph is developed, which uses the changes of water surface profiles which reflects effects of levee breach, and is validated through the comparison between the simulated and observed discharges. Secondly, the applicability of this method in the actual river systems is examined. Thirdly, the conventional method is applied in the experiment, and its accuracy is examined.

2. FIELD EXPERIMENTS OF LEVEE BREACH IN THE JOGANJI RIVER

In 2005 and 2006, the field experiments were carried out for simulating the levee-breach in the Joganji River (2006b). In this paper, 2006 experiment is mainly examined. The experimental channels (11.1-km point, 120-m-long, 6-m-wide, side slope 1:1) were made by digging sand bar in the river. Figure 1 shows the planform of the experimental waterway and Figure 2 shows the photograph of the experimental way and inundated water after levee-breach. Inundated waterway was set in W13 point at flow attack point. Inflow discharge was changed by adjusting inlet width of main waterway in upstream end, where the sand and

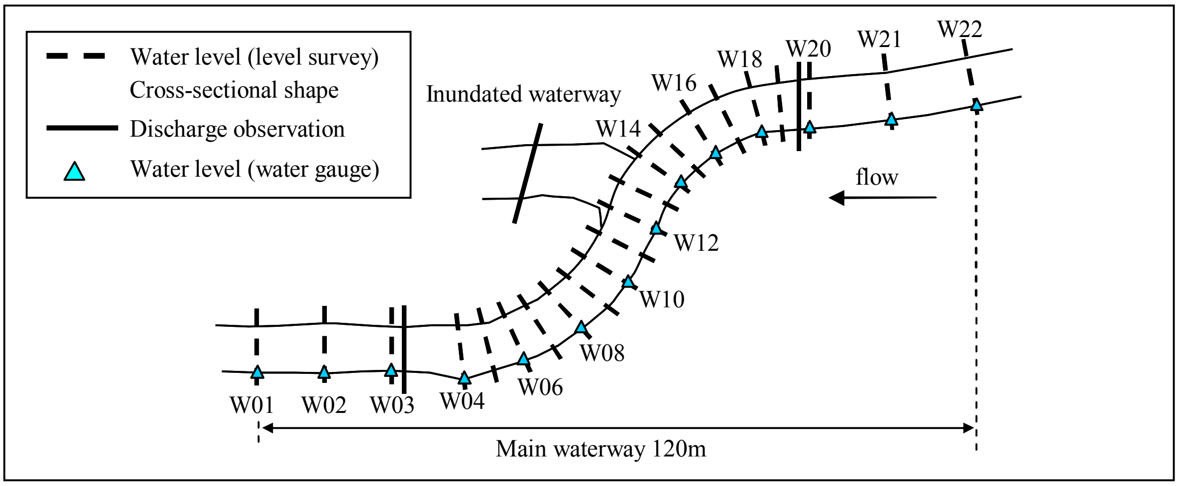

Figure 1. Planform of the experimental waterway

Figure 2. Photograph of the experimental way and inundated water after levee-breach

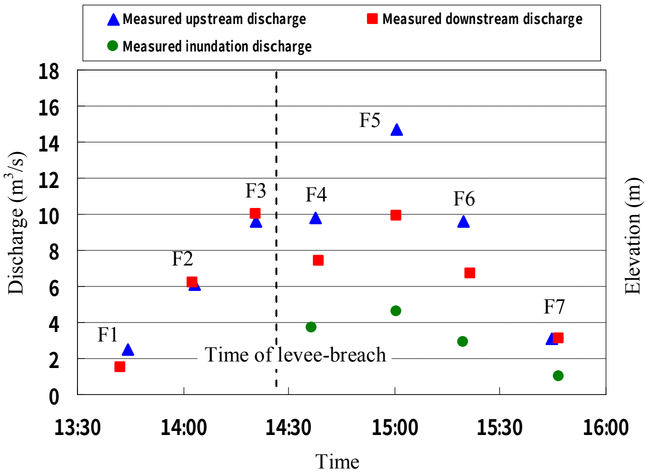

Figure 3. Temporal change in discharge in the experiment

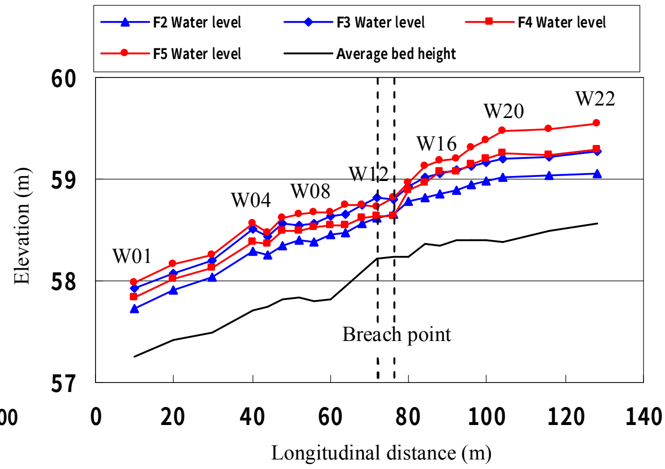

Figure 4. Bed height and F2 to F5 water surface profiles

gravel were moved by heavy equipment. Firstly, a flow discharge same as the peak discharge in the levee-breach experiment was released into the experimental channel, and the stable river bed was then made according to the peak discharge in the experiments. Secondly, the unsteady flow was released into experimental channel and the levee breached before the peak discharge was reached. The items, such as water level, discharge, shapes of channel and grain-size distribution of bed materials were measured. And the temporal changes in water surface profiles were observed in detail. Discharge was observed at three cross-sections: upstream and downstream from the breach point and the inundated waterway.

Results of the experiments

Figure 3 shows the temporal change in the experimental discharges. The peak discharge of the experiment is 14.7m^3/s, the inundation discharge is 4.6m^3/s. Figure 4 shows the longitudinal average bed height and F2 to F5 water surface profiles. Comparison between before and after levee-breach, the water surface slope is growing in levee-breach point neighbourhood because of discharge of main waterway flowed out to the inundated waterway. From results of the experiment, it is found that the change in the river conditions caused by levee-breach is clearly reflected by the temporal changes in water surface profiles.

3. METHOD OF ANALYSIS

Analytical outline

The levee-breach phenomenon has changed the main channel condition complexly because of changes in flow regime before and after the levee-breach, the variation of river bed and transportation of the earth and sand in breach point. However, the changes in the river conditions caused by levee-breach can be clearly reflected by the temporal changes in water surface profiles.

The accuracy of the observed temporal variation of river water surface profiles is higher than that of the observed discharges. Fukuoka (2004, 2006) calculates accurately discharge hydrograph using a two dimensional flow analysis method together with measured

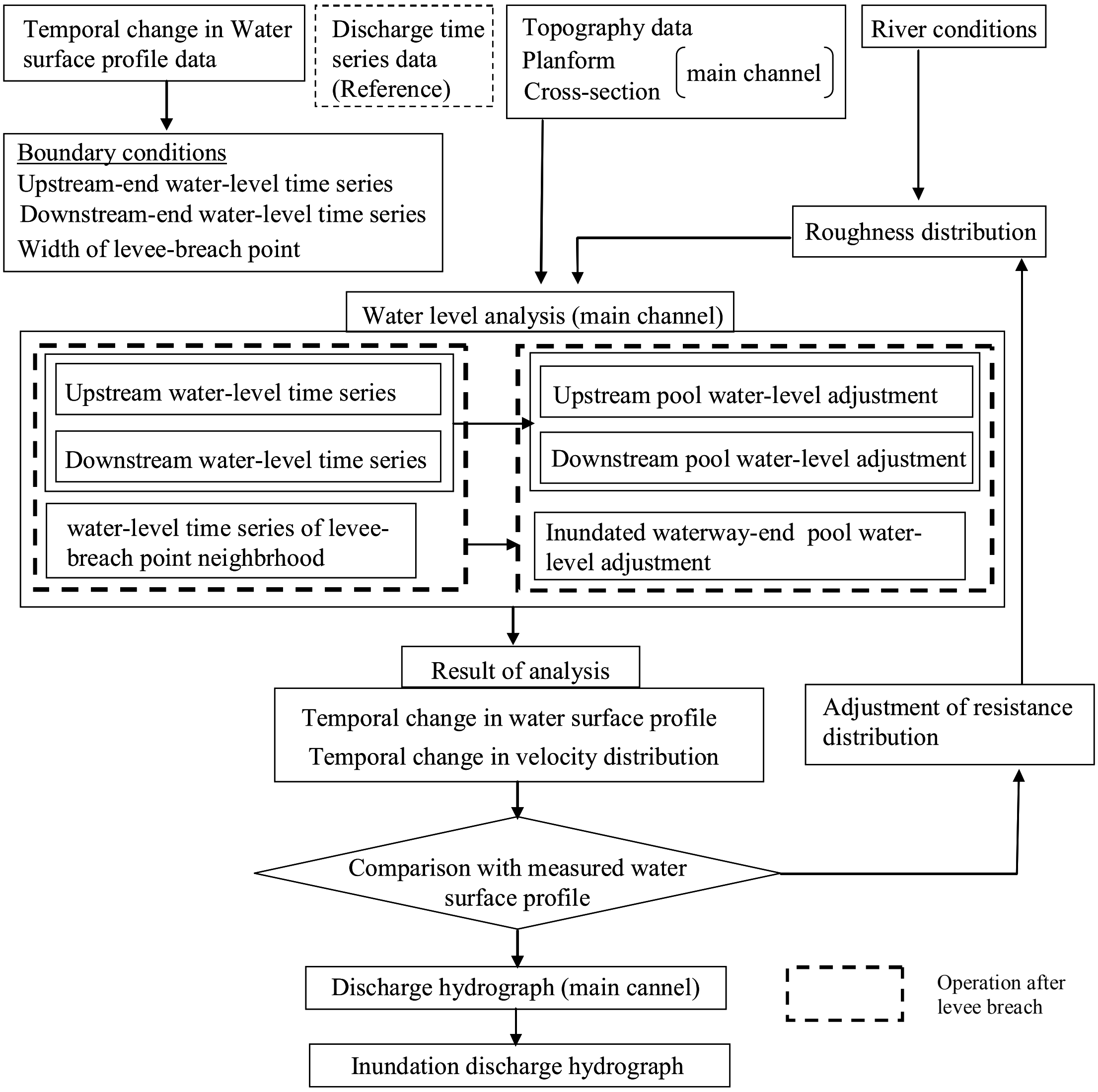

Figure 5. Flowchart of the analysis.

changes of water surface profiles. From this logic, this analytical method can apply the calculation of inundation discharge hydrograph from the temporal change in the water surface profiles in main channel which reflects the effects of levee-breach. This method yields the inundation discharge hydrograph without using overflow weir formulas.

Analysis method

The analysis method was developed by Fukuoka and Watanabe (2004). The governing equations are two dimensional shallow water equation and continuity equation based on general coordinate system. Figure 5 shows the flowchart of the analysis. Before levee-breach occured, ponds and weirs were installed hypothetically in the computation at the upstream and downstream end in main channel, and weirs in upstream and downstream were used to adjust the water levels of ponds. From the comparison between the measured and calculated water-level profiles, the spatial distribution of roughness coefficients is adjusted so that the calculated water surface profiles can represent measured profiles. After the levee-breach occured, inundation discharge hydrograph is determined by adjusting a weir in downstream

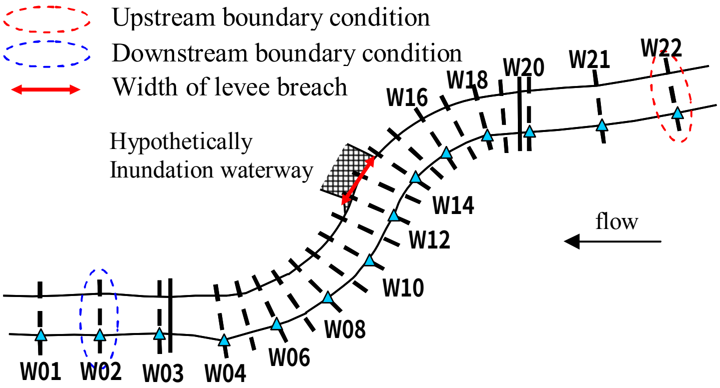

Figure 6. Condition for analysis

Table 1. Main channel's Manning roughness coefficient

Area	Roughness coefficient
W01～W03	0.018
W03～W06	0.040
W06～W11	0.018
W11～W17	0.040
W17～W23	0.018

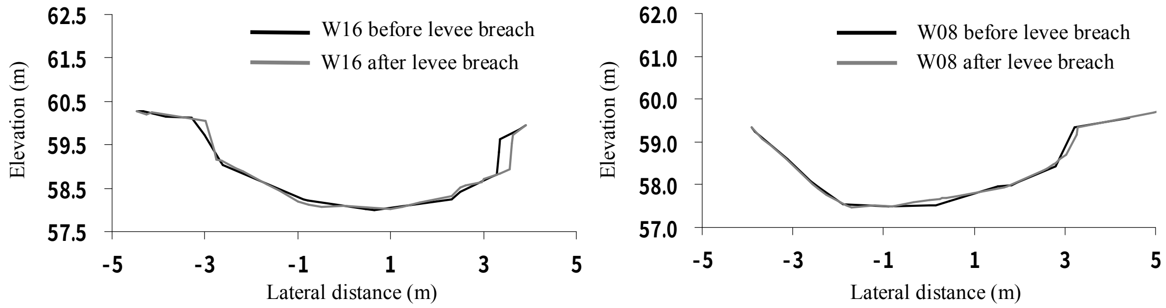

Figure 7. Cross-sectional shape of breach point neighborhood

end of inundated waterway to represent temporal changes in water surface profiles in main channel under the influence of levee breach.

4. LEVEE BREACH EXPERIMENTATION AND CONSIDERATION ON THE RESULTS OF ANALYSIS

Conditions for analysis

Figure 6 shows the condition for analysis. The experiment was carried out for 3-hours from 13:00 to 16:00 October 18, 2006. The same time was used in the analysis. The analytical reach is 120-meter-long from W01 to W22 point. Water levels were measured every 2 seconds using the pressure type water gauges placed at an 8-meter interval. Simultaneously, water levels were also measured according to level surveying every 20-minutes at a 4-meter interval. The boundary conditions in upstream side and downstream side are W22 and W02 points respectively. Water levels of four (W08, W10, W12, and W14) are used as considerable influence part of levee-breach point neighborhood. The width of breach point in a hypothetically inundated waterway uses the width after the experiment ends. The spatial distribution of roughness coefficients used for the analysis is shown in Table 1. The value of 0.040 is used in the section of W03-W06 and W11-W17 in meandering part. 0.018 is used in the section of W01-W03, W06-W11, and W17-W23 in straight part. In the meandering part, a large roughness coefficient is used because big power exerted from the wall when the stream line is bent by the curvature of the waterway. Figure 7 shows the cross-sectional shape of breach point neighbourhood. The analysis is treated as a fixed bed by using the measured

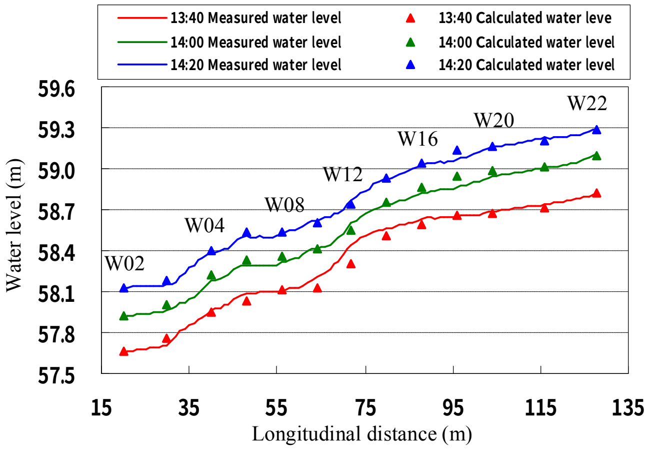

Figure 8(a). Measured and calculated water-level profile (rising-discharge phase)

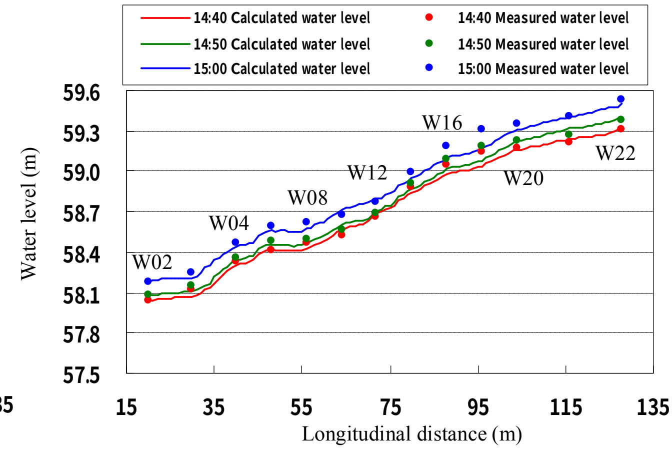

Figure 8(b). Measured and calculated water-level profile (Immediately after levee breach)

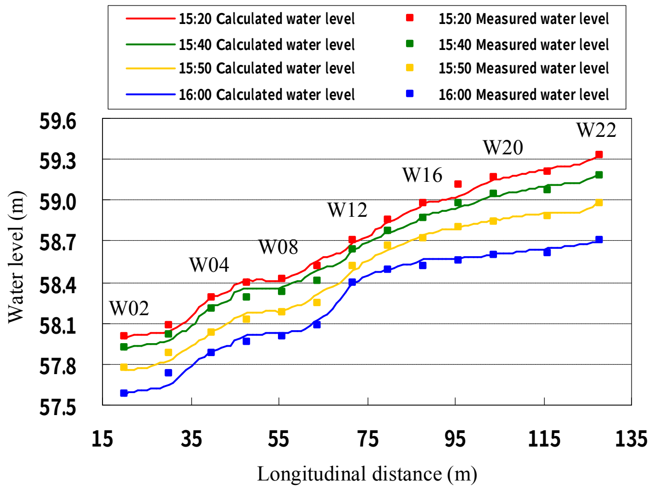

Figure 8(c). Measured and calculated water-level profile (Falling-discharge phase)

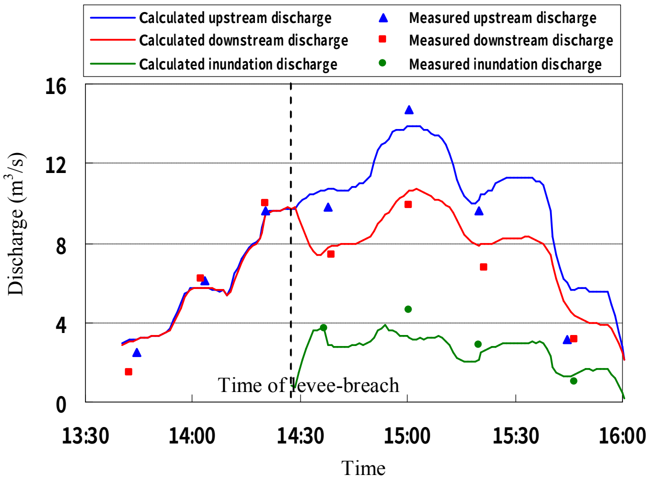

Figure 9. Temporal change in measured and calculated discharge hydrographs

results after the experiment ends because the variation of river bed is small without the breach point neighborhood. The computational grid consisteds of 120 divisions vertically and 10 division laterally. While for the hypothetical inundated way, the grid consists of 10 divisions vertically and 10 division laterally.

Consideration on the results of analysis

Figure 8 (a)-(c) shows the measured and calculated longitudinal left-bank water level profiles in the rising-discharge phase, immediately after levee breach, and the falling-discharge phase, respectively. It is found that the calculated water levels are generally in a good match with the observed values. In the meander part, calculated water levels are relatively low reproduction. In immediately after levee breach, the difference between calculated and measured water levels is growing in meander part, and the difference is remarkable as the discharge scale is growing.

In the meander part, it is a strong three dimensional flow-field, and it is difficult to reproduce the flow enough in the two dimensional shallow water equation to assume the hydrostatic pressure distribution because the pressure distribution is different from the hydrostatic pressure distribution

Figure 9 shows the comparison between measured and calculated discharge hydrographs. Compared with the rising-discharge phase, the accuracy is relatively low near the peak discharge during falling-discharge phase because the difference between measured and calculated water surface profiles caused the difference of discharge in the meander part.

From the above examination, it was shown that this method can evaluate well inundation discharge.

5. APPLICATION OF THIS METHODOLOGY TO ACTUAL RIVERS

From the field experiment and the analysis, the inundation discharge was evaluated by using observed temporal change in water surface profiles. However, in actual rivers, water level gauges are only set at an interval about several kilometres. Therefore, it is difficult to measure the temporal changes in water surface profiles accurately. This chapter describes the examination of this analytical method concerning the application method to the river.

Evaluation of inundation discharge from difference of upstream and downstream sides in main channel

The influence of levee-breach appears in not only the breach point neighborhood but also the channel overall. Therefore, the inundation discharge is appreciable by the separated analysis of temporal change in water surface profiles on the upstream side and the downstream side in main channel. And discharge hydrograph is estimated as the difference of calculated upstream and downstream discharge in main channel.

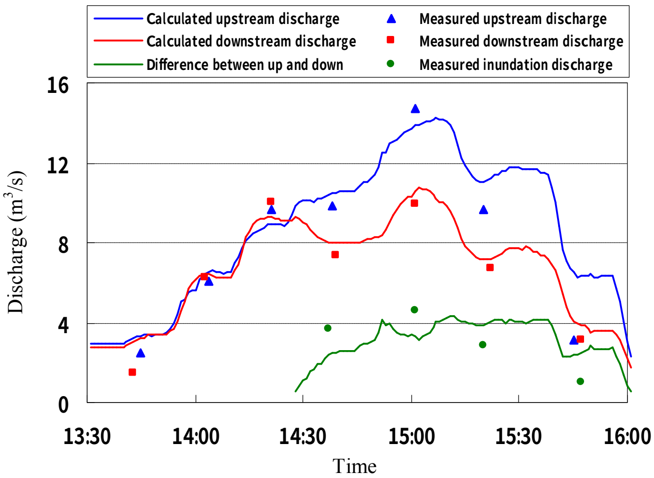

Figure 10. Difference between upstream and downstream sides calculated discharge hydrographs

The analysis method is the same as that used by Fukuoka and Watanabe (2004). Two dimensional analysis was carried out that reproduced the observed temporal change in water surface profiles in each section. W08 and W02 point are boundary conditions in upstream side, W22 and W20 point are boundary conditions in downstream side. The same Roughness coefficient is used as shown in Table 1.

Figure 10 shows the inundation discharge hydrograph calculated as the difference between upstream and downstream sides. The difference of inundation discharge separately calculated at upstream and downstream sides can reproduced measured discharge in main channel as well as the analytical result shown in Figure 9.

It was shown to be able to evaluate the inundation discharge hydrograph with a good accuracy by the separated analysis on the upstream and the downstream sides in main channel where the levee-breach point was set.

6. EVALUATION OF THE CONVENTIONAL CALCULATION METHOD OF INUNDATION DISCHARGE HYDROGRAPH

The Homma's over weir formula has been used to estimate the inundation discharge hydrograph in the locale. The river condition changes temporally in levee-breach phenomenon. The breach section shape and the water level of the breach point neighborhood are necessary to the application the formula. So it is impossible to obtain information with high accuracy especially near the breach point. Moreover, it is necessary to verify whether it is good to apply the weir formula to the levee-breach with a different river condition. In this chapter, the problem when the conventional method for calculating inundation discharge is applied to the field experiment, and its accuracy is examined.

Conventional calculation method of inundation discharge hydrograph

Homma's front overflow formula calculating quantity of overflow from weir is written by Eq. (1), (2) as condition of overflow

Complete overflow $$Q_0 = 0.35 h_1 B \sqrt{2 g h_1} \quad (1)$$

Submerged overflow $$Q_0 = 0.91 h_2 B \sqrt{2 g (h_1 - h_2)} \quad (2)$$

In which h_1 and h_2 is water level, Q_0 is quantity of overflow, B is width of breach point, g is gravitational acceleration

The PWRI (Public Works Research Institute) proposes calculation method of inundation discharge (written by Eq (3), (4), (5)) that corrects Homma's formula. This method considers the inflow angle to the levee-breach point and bed slope by the hydraulic model experiment in order to reproduces the characteristic of lateral overflow.

When bed slope is $I > 1/1580$ then

$$Q / Q_0 = (0.14 + 0.19 \times \log_{10}(1/I)) \times \cos(48 - 15 \times \log_{10}(1/I)) \quad (3)$$

When bed slope is $1/1580 \geq I > 1/33600$ then

$$Q / Q_0 = (0.14 + 0.19 \times \log_{10}(1/I)) \quad (4)$$

When bed slope is $1/33600 \geq I$ then

$$Q / Q_0 = 1 \quad (5)$$

In which Q is inundation discharge, Q_0 is Homma's quantity of overflow, I is bed slope.

Result and consideration of application

Figure 11 shows the comparison between measured total inundated volume and calculated one by the overflow weir formula. Horizontal axis shows the measured total inundated volume and longitudinal axis shows the calculated total inundated volume by Homma's formula, PWRI method, and this method from water surface profiles. The reason to use not inundation discharge (m^3/s) but total inundated volume (m^3) is that total inundated volumes are essentially important for the inundation phenomena. The calculated total inundated volume is calculated by time integrating the calculated discharge from Homma's formula, PWRI method, and this method from water surface profiles by using hydraulic and geometrical value at each observation time. And the measured total inundated volume is calculated in similar way. The calculated total inundated volume obtained by this method expresses the measured total inundated volume accurately. Moreover, the calculated total inundated value from the Homma's formula in 2006 experiment seems to be a result of explaining the observation value. But, it should be thought a coincidence in this result. The temporal change in water surface profiles and width of breach point neighborhood is necessary to evaluate the inundation discharge by using Homma's formula and the PWRI method. These values were observed in the experiment, and it was possible to use it to calculate. However, in a actual flood, it is almost impossible to obtain these values with good accuracy.

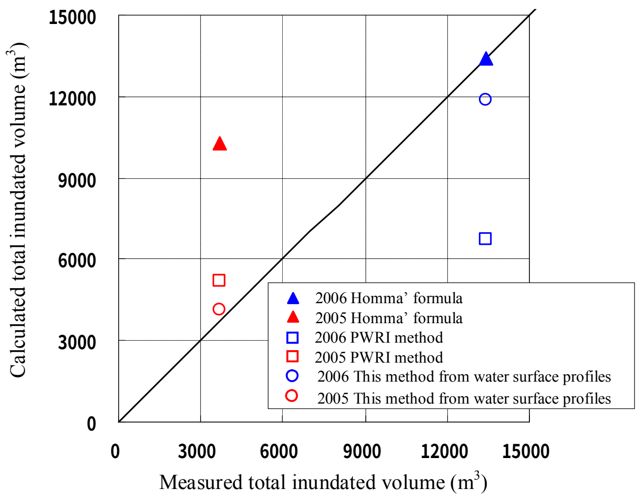

Figure 11. Comparison between measured and overflow weir formula

From this examination, it is found that this method to calculated inundation discharge from temporal change in water surface profiles is corrected physically and holds high reliability compared with conventional method using width and water levels in breach point that measurement is difficult. However, Homma's formula and PWRI method are useful for the estimation simply.

7. CONCLUSIONS

The authors carried out the levee-breach experiment to develop a calculation model to estimate inundation discharge hydrograph accurately and examined its validity. Secondly, the application method to the river of this analysis method was examined. Thirdly, the conventional method to calculate inundation discharge was applied to the experiment, and the applicability and the problem were examined. The conclusions in this research are presented below.

(1) Calculation method of inundation discharge hydrograph and results of analysis

Inundation discharge hydrograph was calculated by using temporal change in water surface profiles that reflects effects of levee breach and two dimensional flow analysis. Comparison with experimental results, it was showed that this method can evaluate inundation discharge precisely.

(2) Application of this methodology to actual rivers

It was shown to be able to evaluate the inundation discharge hydrograph as the difference of discharge between upstream and downstream sides of the levee-breach point in main channel with a good accuracy.

(3) Evaluation of the conventional calculation method of inundation discharge hydrograph

The conventional method using the overflow weir formula was applied to the levee breach experiment, and the problem was shown. It was shown that this method to calculate inundation discharge from temporal change in water surface profiles were useful.

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