Laboratory Investigation On Levee Breach And Risk On Floodplain Of Alluvial Fan River

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***Abstract*— In an alluvial fan, levee breach causes serious disaster due to inundation and sediment deposition on a floodplain. The phenomenon appears not only at levee but also from river to floodplain, and thus physical experiments are difficult while a numerical approach has not been well developed. In this study, the attempted to conduct small-scale laboratory experiments for an area including river, levee and floodplain by using coarse sand with Steep River bed slopes and got good results. As a river in an alluvial plain is often exposed to aggradation or degradation, the study focused on the effect of the relative river bed height to the floodplain, and investigated how the bed height of an alluvial fan river has influences on the risk of flood disasters in the floodplain. As the result, the higher bed level brings more rapid propagation of levee breach and longer widening with more sediment deposition in the floodplain from the river bed as well as the levee section. And, it suggests that the higher bed is exposed degradation to bring the more inundation and increase the risk of another breach of the levee in the upstream reach due to erosion of the foot of the levee. Concurrently conducted numerical study under the same condition, and the results of both approaches were in conformity. Thus presently developed techniques of small-scale laboratory experiments on levee breach are expected to bring more information about various aspects of related disasters associated with the numerical approaches.**

Keywords—Levee breach; disaster risk; floodplain; sediment deposition; laboratory experiment

I. INTRODUCTION

Now a day, levee breach disaster is one of the common natural hazards all over the world. And, particularly in Japan, most of the levee breach disasters occurred by rainfall due to typhoons and torrential rain. The Japan islands are on the route of typhoons in July-October, and Bay-u front are active there in June-July, which brings a day or a few day's rainfall event. The Japan islands are narrow and higher mountains from the backbone, and thus the watersheds are small and rivers are short and steep. These bring rapid runoff process. For Example, in 2000, massive rainfall attacked Nagoya metropolitan area, and the city perfectly lost the functions. In 2004, 10 typhoons hit the Japan islands and heavy rainfall due to front activities caused to levee breaches at many rivers to bring catastrophic disasters, when more than 200 peoples were killed [1]. In recent years, frequent rain has increased the risk of an overflow levee breach in small and a medium-sized river. The safety of the levee section is important to minimize the flood damage.

The failure of the levee causes huge damage to the agricultural production, residents, roads and other infrastructures in the floodplain. High river bed is risky because of the flood reaches the dangerous level in the small amount of discharge. The risk of higher bed level comes not only from the levee breach at smaller discharge, but from the more violent phenomena because of the larger amount of sediment outflow to the flood plain by breach, and it facilitates to the rapid breach expansion. Mechanism of levee breaches with the hydraulic phenomenon due to overflow breach is complex and not so clear, yet some parts are unknown.

There have been only few research works of this phenomenon except for some experimental studies conducted by Fujita and Tamura, 1987; Fujita, Muramoto, and Tamura, 1987; Islam, Okubo, and Muramoto, 1994; Shimada, Watanabe, Yokoyama, and Tsuji, 2009; Shimada, Hirai, and Tsuji, 2010 [2-6]. In those studies, they investigated levee breach expansion process and floodplain sedimentation, but did not consider on the river bed height relative to floodplain and the subsequent phenomena appearing in the river bed and floodplain. Recently, Islam and Tsujimoto, 2012 conducted a numerical study; they investigated breach evolution process and the risk of flood disasters in the low floodplain [7]. For further investigation, small-scale laboratory experiments have been carried out using coarse sand with steep river bed slope of an alluvial fan river, to recognize the disaster risk in the floodplain by analyzing the levee breach phenomena and topographic changes in the river, levee and floodplain.

II. Experimental set-up and Measurements Procedure

The experimental setup for the runs with conditions to be maintained for the different bed height of an alluvial fan river and measurements procedure are describes in this section. The experiments are performed (20 m long, 2.2 m wide and 1.0 m deep) in a flume, which is located in the Hydraulic Engineering Laboratory of Nagoya University. Using wood and coarse sand, the working section (6 m long and 2.2 m wide) is prepared, which is shown in Fig. 3.c. Levee slope is 1:2 for both sides, and height is 0.15 m from the floodplain. The river, levee and floodplain are used the same sizes of bed material, because of the floodplain have been formed by flooding sediment, and the levee have been made by piling up the sediment dredged from the river bed. Relative height of river bed to floodplain is set as follows: Run 1 (low river bed) z_b=-5 cm, Run 2 (river bed and floodplain at the same level) z_b=0 cm and Run 3 (high river bed) z_b=5 cm, respectively. Fig. 2 (a-b) is a schematic representation of the experiment setup, including the top view and the side view, respectively. In experiments, the inflow discharges (a) is supplied initially into an upstream inlet tank of the river channel from an underground water reservoir by a circulating pump. The fixed bed is made of wood (A, D) and the moving bed (B, C, E) is prepared by coarse sand are used to construct levee and floodplain. An initial notch (H) is prepared before starting the experiment, which is 2.5 m apart from the upstream. A 2 cm height of the wooden board is used as the downstream wall (e) in the floodplain, to protect the movable floodplain and maintain inundation depth into the floodplain. A 5 cm drainage channel (G) is provided at the downstream of the floodplain. The river inflow and outflow discharge are rectified (b) by using a steel wire, and the inflow water is passed through the river (F) over a rectangular weir (g). In order to keep the river water depth roughly to the uniform flow depth, a wooden weir (sill) (c) is installed at the downstream of the river channel. Two wave meters (f) (CHT6-30 made by KENEK Co., and CHT6-40 made by KENEK Co.) are put in front of the rectangular and triangular weir (d), to collect upstream and downstream overflow water depth, respectively. A video camera (GZ-HM350-B manufactured by JVC) is placed with moving carriage on top of the levee breach section to record the video footage of breach expansion and overflow by the breach, during experiment. Levee breach expansion processes as well as topographic changes in the river, levee and floodplain are taken by using a digital still camera (OptioS1manufactured by PENTAX). The floodplain topography and longitudinal length of the breach are surveyed by using an actuators (KMB-150A length 1.60 m and A30 length 1.0 m made by THK) along with laser sensor (IL-600 is made by KEYENCE), which is placed lateral (Fig. 2.a) and longitudinal (Fig. 2.b) directions over the working area.

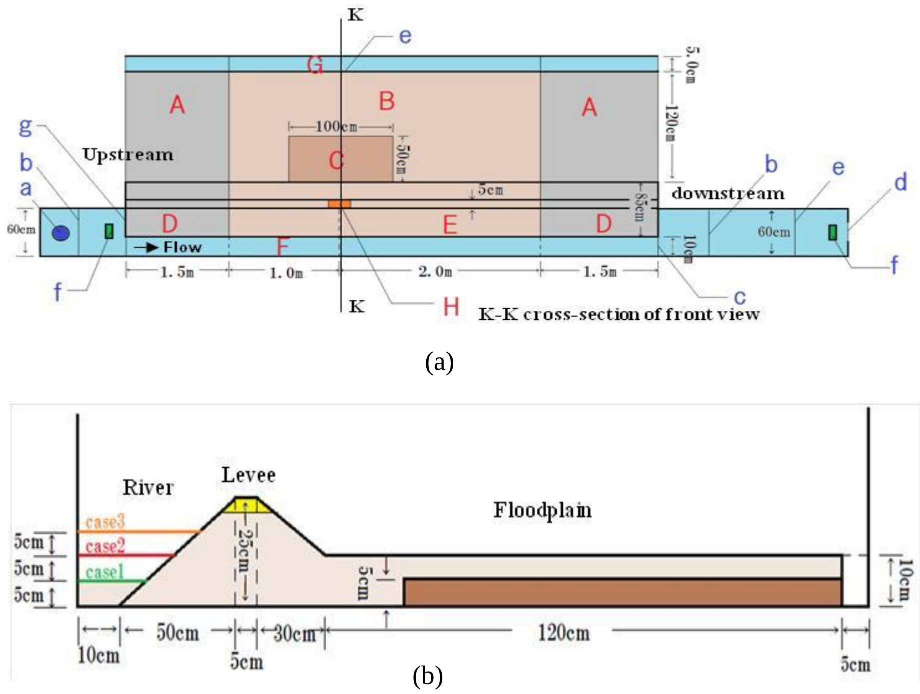

Fig. 1 Experimental setup: (a) top view; (b) side view**.**

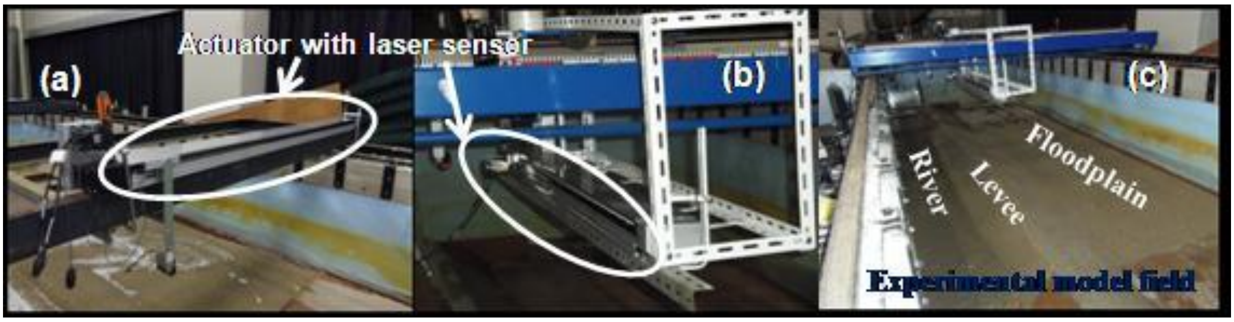

Fig. 2 Electronic actuator with computer aided laser sensor (a) lateral and (b) longitudinal direction; (c) experimental model field.

The tractive force in the river is higher than the critical tractive force and thus the bed is movable, this condition is satisfied for the every run. The critical tractive force is examined by using Iwagaki, 1956 equations [8]. The experimental conditions are compared with among the runs in Table 1, where the hydraulic parameters at the breaching section, which is measured before breaching.

Table 1 Experimental condition for all runs

Parameters	Run 1	Run 2	Run 3
Inflow Q ($m^3\ hr^{-1}$)	32.22	31.36	31.28
River bed slope ($m\ m^{-1}$)	1/500	1/500	1/500
River flow depth h_0 (m)	0.16	0.11	0.08
Mean velocity U ($m\ s^{-1}$)	0.16	0.19	0.23
Bed material size d_{50} (mm)	1.00	1.00	1.00
Shields number τ_*	0.20	0.13	0.10
Froude number F_r	0.12	0.19	0.26
Sand Reynolds number R_{e*}	57	47	40

At first, a notch (10×5 cm) is cut to provide the initial breach opening for the overflow experiment. To make a stable levee using coarser sand as the levee material, we analyzed the degree of compaction, and found it is reached nearly 100%. The wave meter reading is set at initial condition (zero) by filling the inlet and outlet tank with water. Then, inflow discharge is allowed to enter gently in the river section and raised the river flow depth up to notch opening by putting a downstream sill properly. The inflow and outflow water discharges is estimated by using the equation of Itaya and Tejima, 1951 for rectangular weir [9], and Kurokawa and Fuchizawa, 1942 for triangular weir [10], respectively. During experiment, the longitudinal breach widening with time is measured. After that, when the bed is become dried, the river section and the floodplain elevation are measured for each run using computer aided laser sensors, which is attached with the electronic actuator. The x-axis is the horizontal direction with y=0 at the top of the levee crest, which is 2.20 m apart from the upstream end; and the final breach expansion is measured in the test area. The bed level changes in the river channel and in the levee, are measured along 32 longitudinal transects with 3 cm intervals, start at the center of the river channel (x=0) towards the floodplain. The floodplain topographic changes are measured along 64 laterals transects with 5 cm intervals are pointed from the left side of the floodplain with y=0 towards the right side where the floodplain deposition is occurred and z start from the initial position of the floodplain. Finally, flow velocity vector is analyzed by large-scale PIV software, which is developed by Fujita, Mustc, and Kruger, 1998 [11].

III. Experimental Results and Discussion

The main purpose of this study is to investigate the disaster risk in the floodplain, utilizing the bed height of an alluvial fan river is discussed in this section, which would be realized by analyzing the process of levee breach and the topographic changes in the river, levee and floodplain. For the elevation differences in the river to floodplain, the flooding flow and inundation in the floodplain are varied. The flow capacity of the river is reduced with the increased of the bed height. Fig. 3 depicts the river flow and the overflow to the floodplain by the breach for Run 1, Run 2 and Run 3, respectively. In this experiments, nearly the same inflow discharges is provided for the Runs 1 to 3. Therefore, the initial overflow depth is elevated in the higher river bed level (3 cm) than the lower ones (1 cm), it means the larger amount of discharge is passed by the breach which will cause the high risk of flood disasters in the floodplain; this point is considered in our study.

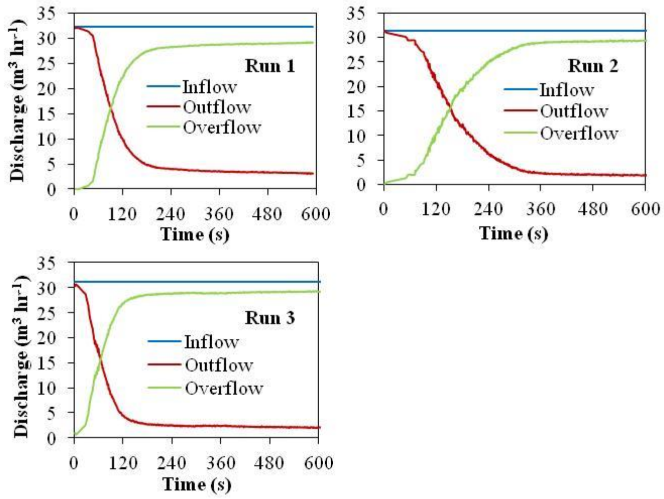

Fig. 3 River flow and flood flow by the breach.

A. Levee Breaching Process

- *Low River Bed as Compared to Floodplain Level*

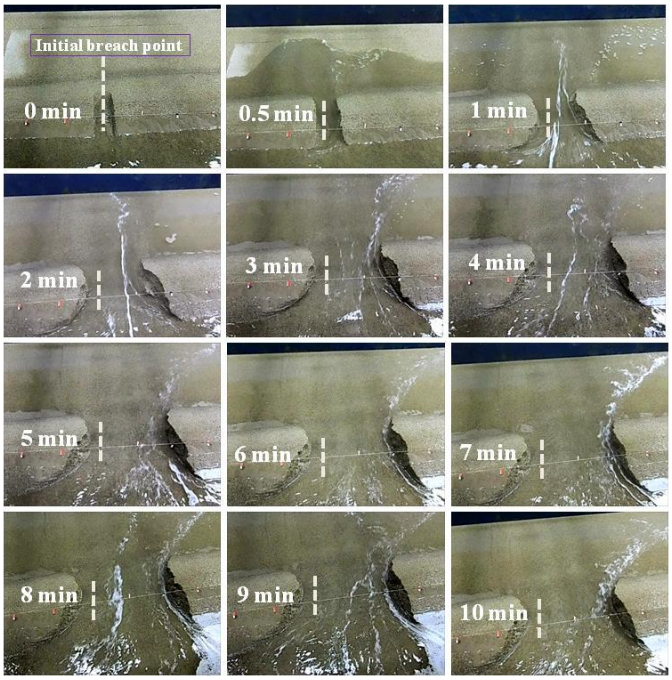

Photo. 1 Levee breaching process and bed topographic changes with time due to overflow levee breach (Run1).

- *River bed and Floodplain at the Same Level*

For the Run 2, almost same nature of the erosion process appears initially in the levee as compared to Run 1, which is shown in different snapshots at photo 2. Subsequently, the erosion process comes forward to the heel (inside edge of levee base at river side) of the levee section, and the levee material is washed out, and it deposited on the floodplain. Then, the horizontal widening process starts because of the levee section is lost totally, but the rate is slower than the Run 1. The river flow behavior is the same as Run

Levee breaching processes and the bed topographic changes in the river, levee and floodplain with time for the Run 1 are shown in Photo 1, and the flow velocity vector analyzed by LSPIV is shown in Fig. 4. After the beginning of overflow, the initial flow passes over the levee crest along with erosion on it near the floodplain, and then the overflow water is spread over the floodplain with eroded material from the breach section. Levee material is washed out continuously by the flow, and it deposited on the floodplain. The erosion of the breach section is increased in vertically, and then horizontal widening process starts by the collapse of the levee. It is also observed that, even if overflow is occurred, sudden increase in levee breach width and overflow discharge is unlikely unless the majority of the levee section is lost by vertical erosion. The river flow vector is initially concentrated to the floodplain, and then it attacks to the downstream of the levee section with the progress of the breach (Fig. 4), and floodplain flow tends to be mainly in the same direction.

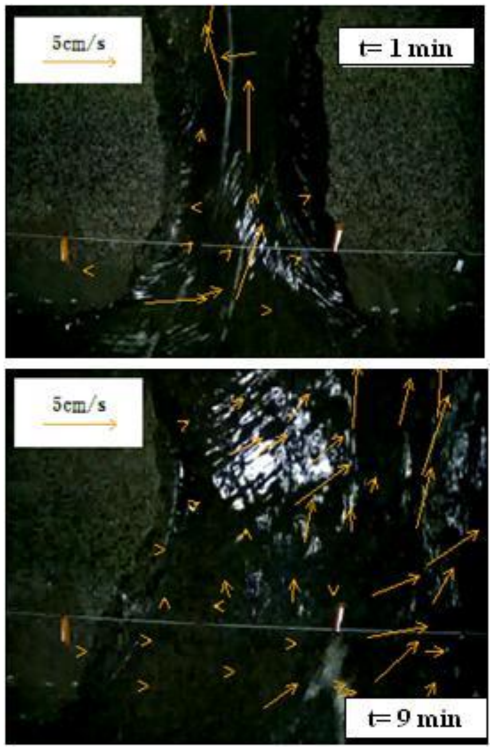

Fig. 4 Flow velocity vector analyzed by LSPIV technique (Run1)

1, but the inundation flow tendency is straight with the downstream of the floodplain at early stage, and then changed the flow direction with widening of the levee.

The longitudinal levee breach propagation along the river with time (Run 2) is depicted in Fig. 5. In the early stage of overflow, the levee breach is progress towards both in the vertical, and in the horizontal direction along the downstream of the levee. Then, the sudden breach widening process is occurred in the longitudinal direction of the levee. After that, the breach widening process is slow, not only in the horizontal but also vertical direction.

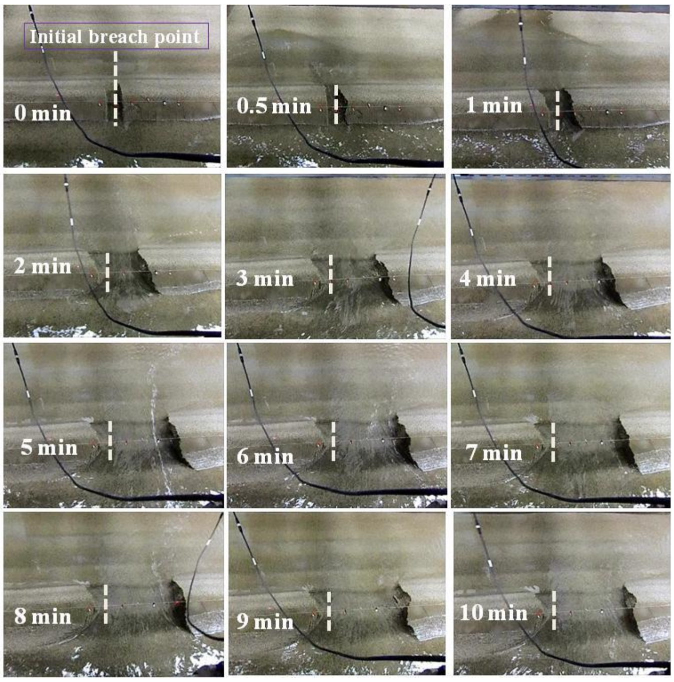

Photo 2. Levee breaching process and bed topographic changes with time due to overflow levee breach (Run2).

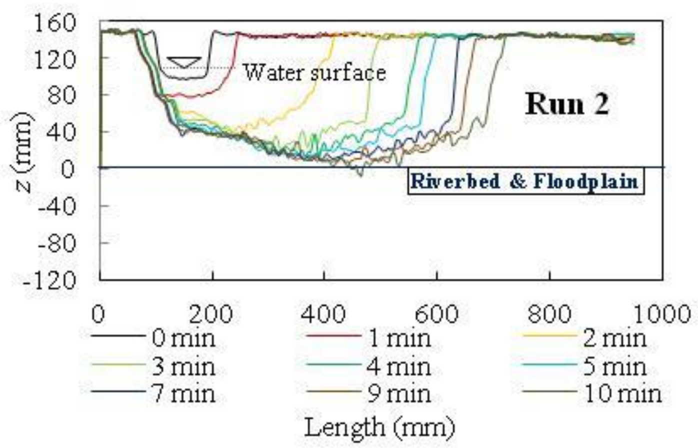

Fig. 5 Breach evolution processes with time along the longitudinal direction of river (Run2).

- *High River Bed as Compared to Floodplain Level*

Levee breaching processes and the bed topographic changes in the river, levee and floodplain with time for Run 3 are shown in Photo 1, and the flow velocity vector analyzed by LSPIV is shown in Fig. 6. Higher river bed means the decrease of the water flow area, and the river conveyance capacity is reduced, but the inflow discharges is almost same as previous Run 1 and Run 2. So, overflow depth is more as compared with other two runs, it causes rapid flow to the floodplain by breach, and it has more influence of the breach widening and consequences as the larger amount of sediment deposited to the floodplain.

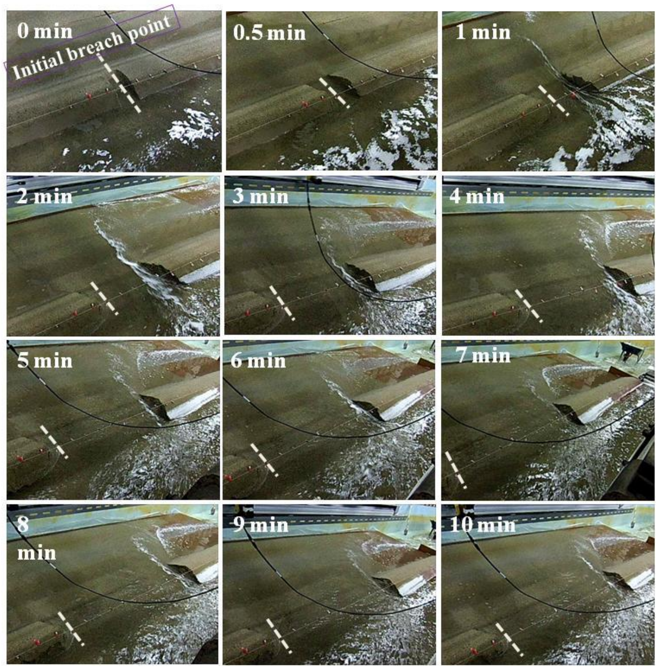

Photo 3 Levee breaching process and bed topographic changes with time due to overflow levee breach (Run3).

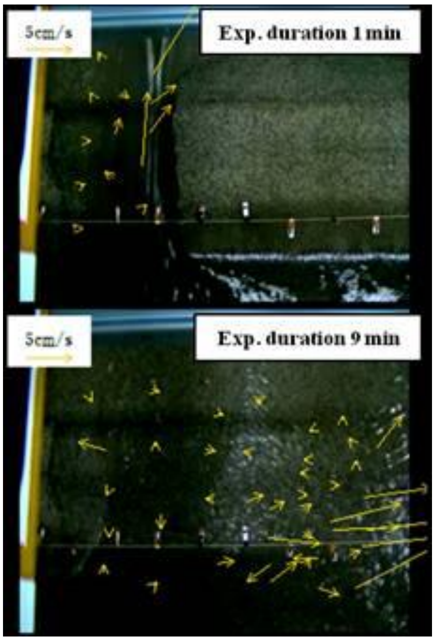

Fig. 6 Flow velocity vector analyzed by LSPIV technique (Run3).

Though the initial nature of the erosion is the same as Run 1 and Run 2, but the process is very quick, due to the large amount of inflow and the level difference between the river bed and floodplain. The levee breach widening process starts in the horizontal direction with the higher rate than the other two runs. At starting of the overflow, the flow velocity vector is concentrated from the river to the floodplain, and at the levee section. Then, the attacking flow is mainly migrated to the downstream of the levee, and finally; it is concentrated to the breaching section (Fig. 6). Higher bed level is more dangerous because of river bed deformation appears, and bed material is eroded due to the sediment outflow by the breach. The breach evolution processes of the levee with time along the river (Run 3) are shown in Fig. 7. At the beginning of overflow, the nature of the erosion process is almost same as the Run 2. However, the horizontal breach widening is rapid, and the vertical erosion process is slow as compared to the Run 1 and Run 2. The total length of the breaches is double than the Run 1 and Run 2.

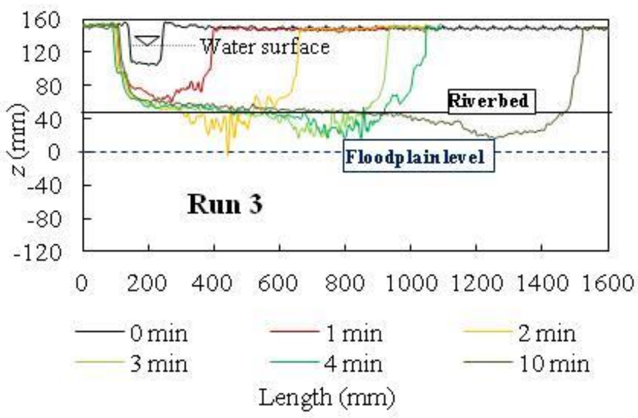

Fig. 7 Breach evolution processes with time along the longitudinal direction of river (Run3).

- *Difference in Levee Breach by River Bed Height Relative to Floodplain Level*

In Fig. 8 shows the comparisons of the final length of the breach widening at different experimental runs. The horizontal length of the widening is less in the Run 1 and Run 2 than in Run 3, but the vertical erosion is more in the Run 1 as well as in Run 2. The horizontal widening is longer; it means the more amount of inundation flow passes to the floodplain along with sediment outflow by the breach. It can be concluded that, the higher river bed has the high risk of flood disasters in the floodplain. The comparative analyses among the different experimental runs are summarized in Table 2. The natures of the erosion process are varied with the height changes of the river bed. In the Run 3, the duration of the vertical erosion and the transition of the breach widening are shorter; however, the final breaching is longer. It is noted that, rapid erosion with the horizontal widening process appears in the Run 3.

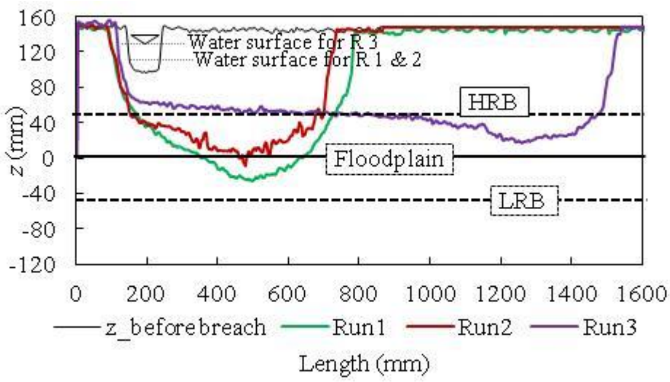

Fig. 8 Comparisons of the final length of breaching (t=10 min) at different height of river bed as compared to floodplain level.

Table 2 Comparative summary among the different experimental runs

Exp. Run	Erosion start at	Nature of the erosion	Duration of erosion before widening (Sec)	Transition of breach widening (vertical to horizontal) (Sec)	Final length of widening (m)
1	Levee crest at FP side	Vertical erosion & material washed out from levee	9 to 22	23	0.70
2	Levee crest at FP side	Vertical erosion with progress to river side & material washed out from levee	8 to 21	22	0.65
3	Levee crest at FP side	Rapid vertical erosion & material washed out from levee & river bed	7 to 17	18	1.41

B. Phenomena in River and Floodplain

Fig. 9 (a-b) depicts the final bed topographic pattern in the river channel; levee and floodplain at 10 minutes after the overflow breach for the Run 1, Run 2 and Run 3, the positions of the run are in a top, middle and below, respectively.

In the Run 1, the more vertical erosion is observed in the levee section. Due to vertical erosion in the levee section as well as near the levee heel, a thalweg is formed along the flow direction from the river to the floodplain. Deposition pattern in the floodplain is smooth, because of coarse bed material, and it indicated that the flow is passes to the right-side direction in the floodplain. However, in the Run 2, a little vertical erosion is observed in the levee section. The deposition pattern in the floodplain is exposed that the flow is moved all over the floodplain and had a little tendency to the right-side in the floodplain. Floodplain deposition thickness is observed high towards the both sides of the flow direction. In the Run 3, the less vertical erosion is observed in the downstream side of the levee along with erosion in the river bed. The early breach levee section is deposited by the eroded material from the levee section and the river bed. The sedimentation thickness in the floodplain is higher than the Run 1 and Run 2.

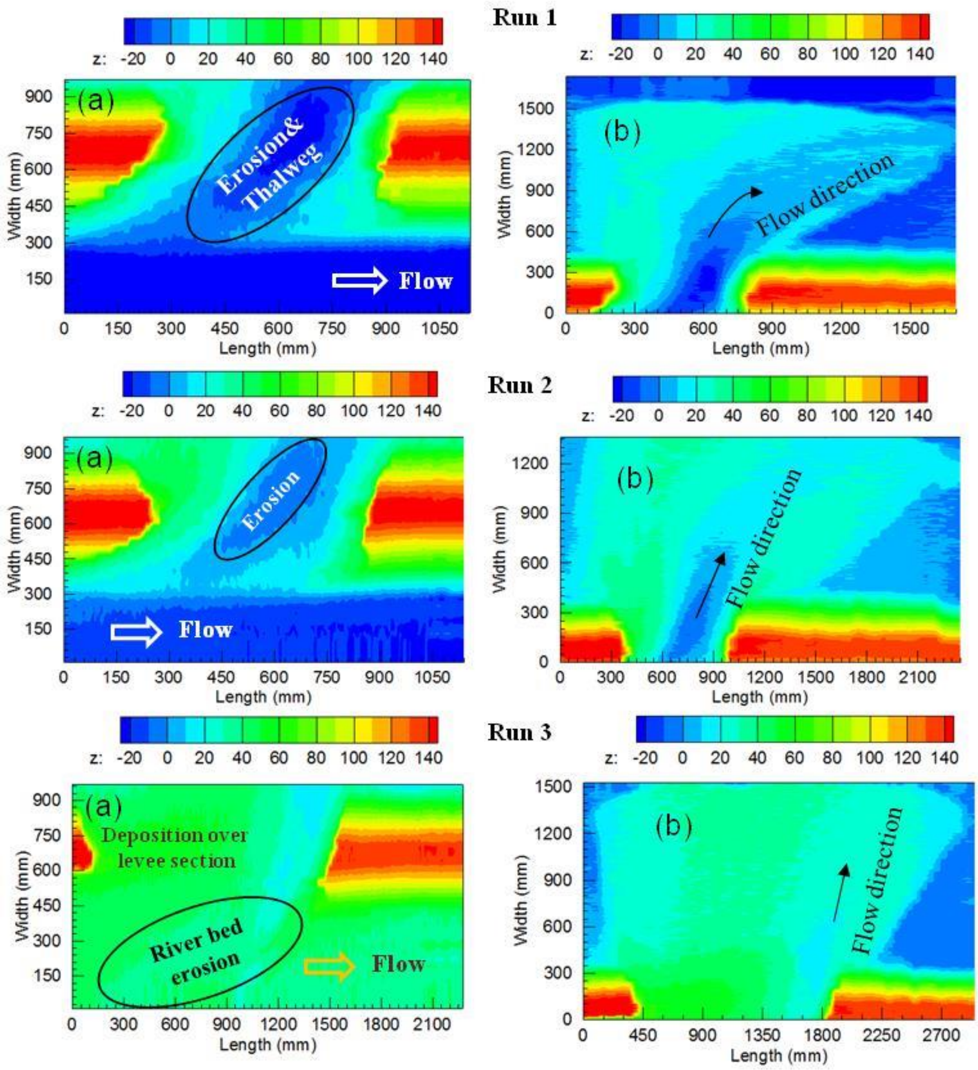

Fig. 9 Comparisons of final bed topographic changes in the river, levee and floodplain for the Run 1 (top), Run 2 (middle), and Run 3 (below) at same duration (t=10 min).

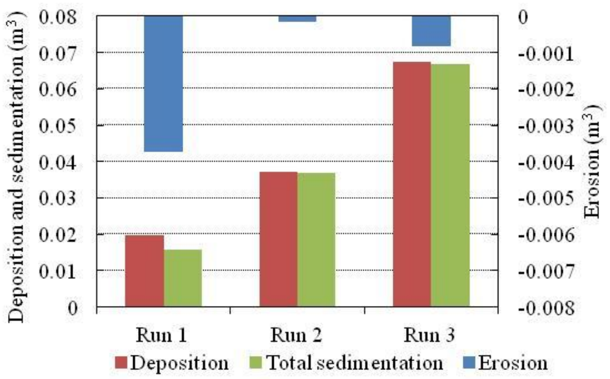

Fig. 10 Comparisons of the volume of the floodplain sedimentation at different relative height of the river bed and floodplain.

Comparisons of the volume of the floodplain sedimentation at different river bed height are depicted in the Fig. 10. The erosion is more, and the deposition is less at the low river bed (Run 1) as compare to the high river bed (Run 3) level. The floodplain sedimentation is increased with increased to the river bed level. It also shows that the higher river bed has the high risk of flood disasters in the floodplain with the larger amount of sedimentation in the floodplain.

C. River Bed Changes Accompanying Levee Breach

The comparisons of the changes in the river bed at the different relative height of river bed to floodplain are shown in the Fig. 11. The higher rate of changes is observed in the Run 3, as compared to the Run 1 and Run 2. The river bed material is eroded, and it is deposited to the floodplain by the breach as well as in the upstream of the levee breaching point. Levee breaches with the high river bed has the problem, not only in the rapid flow with the larger amount of sediment outflow to the floodplain by breach but also has the remarkable differences in river bed variation, which brings further risk of another breach of the levee in the upstream reach of the river.

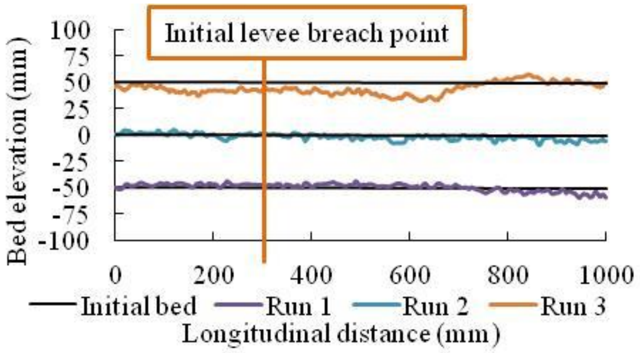

Fig. 11 Comparisons of the river bed variations (t=10 min) at different river bed conditions.

IV. COMPARISONS OF EXPERIMENTS WITH NUMERICAL

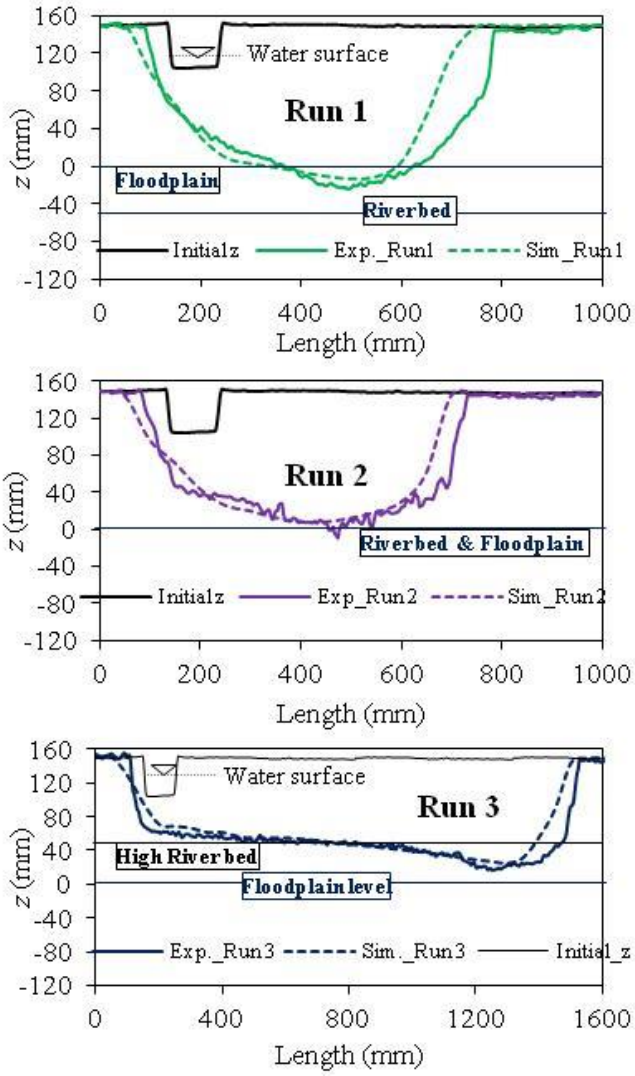

Fig. 12 Comparisons of longitudinal length of breaching (t=10 min) at different height of river bed as compared to floodplain level using experiments and simulation.

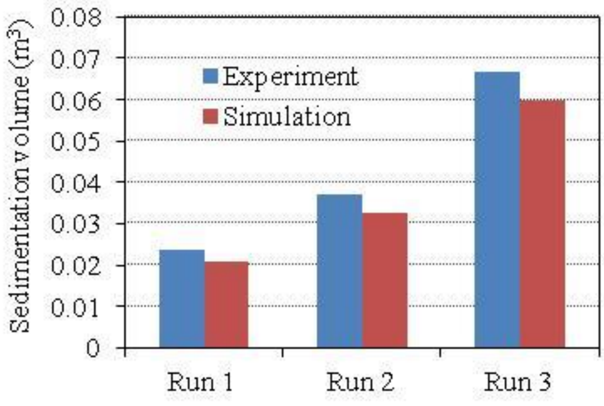

Fig. 13 Comparisons of the volume of the floodplain sedimentation at different runs both in the experiments and simulation.

In this study, an analysis were concurrently conducted using 2D RIC-Nays simulation scheme (http://i-ric.org/nays/ja/sitemap.html), to investigate the conformity of the experimental results in a same scale setting and conditions [12]. There had some difficulties in measurements during work in the laboratory and thus if the both approaches have sufficient conformity, these can be complimentarily employed. A good agreement between the experiments and numerical were found. Hence, these two approaches provided more information to understand the levee breach and flood disaster in the floodplain with relative height of river bed to floodplain. Some of them are presented in the Figs. 12 and 13. Fig. 12 shows the longitudinal breach length along the river in experiments and simulation for different height of river bed, and Fig. 13 depicts the comparisons of the volume of the floodplain sedimentation both in experiments and simulation.

V. CONCLUSIONS

This study was conducted in order to understand levee breaching process and the topographic changes in the river, levee and floodplain, and consequently the risk of flood disasters in the floodplain. As a river in alluvial fan is often exposed to aggradation or degradation, the effect of the relative bed height to the floodplain on levee breach and successive phenomena in river and floodplain were found. The research result demonstrates that the higher river bed not only influences the process of levee breaching and floodplain deposition, but also has clear differences in river bed variation. The conclusions are summarized below:

1. At early stage of overflow, water is passed through the breach to the floodplain with vertical erosion of the levee, and the longitudinal breach-widening is progressed after the majority of the levee section is eroded. The widening of breach brings serious disaster in the floodplain.

2. Levee breach is quickly expanded to the downstream and the propagation of inundation migrates on this side.

3. Higher river bed is exposed to levee breach with higher overflow depth and thus the widening rate of levee breach is more rapid and inundation with more sediment volume to the floodplain not only from levee but also from river bed as compared to the lower and the same river bed height.

4. Comparing with numerical simulation conducted under the same condition with the experiments, fair conformity between them is recognized, and the success of the present small-scale experiments promise the further progress of research on levee breach and its risk.

5. Furthermore, the large-scale numerical simulation we already conducted, we can recognize the fact that the higher river bed has the higher risk of flood disasters in the floodplain.

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