STUDY ON LEVEE BREACH AND SUCCESSIVE DISASTERS IN LOW-LAND THROUGH NUMERICAL AND EXPERIMENTAL APPROACHES

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STUDY ON LEVEE BREACH AND SUCCESSIVE DISASTERS IN LOW-LAND THROUGH NUMERICAL AND EXPERIMENTAL APPROACHES

Study on Levee Breach and Successive Disasters in Low-land through Numerical and Experimental Approaches

A dissertation submitted in partial fulfillment of the requirements for the degree of
DOCTOR OF ENGINEERING

by

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July, 2012

Dedicated to

My wife **Engr. Shahnaj Pervin**

STATEMENT BY AUTHOR

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Date

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SYNOPSIS

Bangladesh experiences levee breach flood more or less every year in different magnitudes due to the geographical position and obscured natural phenomenon. The country is the part of the most dynamic hydrology in the worlds and the biggest active delta system. The topography, location and outfall of the three great rivers appearance are the yearly hydrologic cycle in this country. Too much and/or little water in a cycle is the annual phenomenon. Regular monsoon event is the flood; the depth and duration of inundation are the deciding factors, whether it affecting beneficially or adversely. Extreme events of flood badly affect the development, economy, poverty and almost every sector. In flood management, Bangladesh has taken many structural and non-structural measures. One of the main constructional measures is to build an earthen levee for flood protection has been old history of Bangladesh because of their cheapest construction cost and availability of materials. A levee may be defined as an embankment aligned generally parallel to the river channel and designed to protect the area behind it from being flooded by high flow through the river. Failure of levees always creates risky situation on the floodplain inhabitants who are living inside the boundary of the levee. So, the construction of safe levee is very essential to protect lives and properties from the breach. There have many causes of levee failure and some of the main causes recorded in the available literature are overtopping, seepage, piping, river migration, and improper design and construction. The inadequacy of levee construction that is below specified standards and the poor maintenance of the levee have been considered common in Bangladesh.

Almost every year, during the rainy seasons due to excess load of flooding water and huge sediment, which are settled over the river bed; the river conveyance capacity has been reduced, and an overbank flow occurs that cause severe damage to an agricultural production, roads and other infrastructures on the floodplain. To minimize flood disaster effect, sediment dredging from the river bed is important. Due to lack of proper dredging facilities, Bangladeshi river bed is increasing, and it is susceptible to overbank flow through the levee by the breach and inundation in the low-land floodplain. High river bed is risky because of flood reaches the dangerous level although the discharge is small. 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 the breach, and it facilitates to the breach expansion. Geographical location of Bangladesh and insufficiency in the study, make it difficult to avoid levee breach and disaster in the floodplain. Thus, the present research has a scope to analyze the disaster risk in the floodplain due to the levee breach. Both numerical and experimental investigations are carried out to understand the levee breaching phenomena and the effects of disaster in the floodplain.

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 simulation approach has not been well developed. RIC-Nays, a two-dimensional (2D) model for flood flow and morphology are utilized in this study upon confirmation through the experimental works in this research and another numerical study. As for simulation scheme, schematic model area is considered with main channel, levee and floodplain, and they are roughly composed of the same sediment characteristics because the floodplains are formed by flooding sediment, the levees are made by piling up the sediment dredged from the river bed. Therefore, these three components are treated simultaneously in the simulation model. The main channel, levee, floodplain, and the flow parameters are selected in conformity with the study field of Sirajganj district and Jamuna River in Bangladesh. Levee breach is considered to initiate in the middle of the levee with crest opening. Based on the calculated results, inundation of water and sediment in the floodplain and evolution process of the levee breach are investigated; utilizing with the inflow discharges, the opening sizes in vertical and longitudinal scales, and the relative height of the river bed to floodplain.

In this study, small-scale laboratory experiments for an area including river, levee and floodplain are conducted by using sand with river bed slopes and got good results. As a river in an alluvial plain is often exposed to aggradation or degradation, this 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. The same scenario numerical investigations have been conducted concurrently 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.

Flood disaster is caused by the levee breach is one of the common natural hazards all over the worlds. Thus, the disaster comparisons are carried out between two countries, which have topographic and hydrological differences. The channel and flow parameters are selected in conformity with the typical model fields of Bangladesh and Japan. According to the simulation results, evolution process of the levee breach and inundation of water and sedimentation in the floodplain are investigated, and it showed that the levee breach with steeper river bed slope using coarser bed materials has the high risk of flood disasters in the floodplain.

In floodplain have the different land use pattern, and the disaster effects are not equal all over the floodplain. Therefore, the research is necessary and the attempted is made to analyze the disaster effects on the floodplain utilizing with the 2D numerical schemes. For simulation, five types of schematic model flood plains are chosen, and the river channel and flow parameters are selected as the concern study area of Bangladesh. The flow pattern and the process of sedimentation over the floodplain as well as the levee breaches for each model flood plains are analyzed to find out the disaster effects on the floodplain.

Furthermore, comparing the results among the large-scale numerical simulation with small-scale laboratory experiments and same condition simulation analyses, fair conformities between them are recognized, and the success of the present research promises the future progress of research on levee breach and its risk on low-land floodplain.

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LIST OF NOTATIONS

Symbol	Description	Dimension
h	depth of flow	m
t	time	s
u	depth-averaged velocity components in x- direction	m/s
v	depth-averaged velocity components in y- direction	m/s
x	component of the Cartesian coordinate in streamwise direction	-
y	component of the Cartesian coordinate in transverse direction	-
g	acceleration due to gravity g = 9.81 m/s^2	m/s^2
H	water surface elevation	m
D_x,D_y	diffusion terms in x and y directions, respectively	-
C_d	bed friction coefficient	-
K_v	permeability factor	-
u_*	shear velocity	m/s
z	component of the Cartesian coordinate in vertical direction from initial bed	-
q_b	bedload transport rate in the depth-averaged velocity direction	m^2/s
s_g	specific gravity of sediment	-
d	sediment diameter	m
I_e	Energy slope	-
V	total velocity of flow	m/s
n_m	Manning's roughness coefficient	$s/m^{1/3}$

V_b	total flow velocity at bottom	m/s
z_b	bed elevation	m
V_n	sediment movement velocity component in *n*- direction	m/s
V_s	sediment movement velocity component in *s*- direction	m/s
u_{bn}	near-bed velocity in *n*- direction	m/s
u_{bs}	near-bed velocity in *s*- direction	m/s
N_*	coefficient to describe the intensity of secondary flow	-
r_s	radius of curvature of a streamline	m
s	streamline direction	-
w_f	settling velocity of sediment	m/s
q_{su}	rate of entrainment of suspended sediment	m/s
c_b	reference concentration at $z = 0.05h$	-
c	local concentration of suspended sediment	-
C	depth-averaged concentration	-
K_c	coefficient in Eq. (3.55)	-
B_*	parameter in Eq. (3.56)	-
a'	$a' = B^* / \tau_* - 1/\eta_0$ = parameter in Eq. (3.56)	-
r	normalized hydrodynamic force	-
r'	fluctuation component of r	-
q_x	bedload transport rate per unit width in *x*- direction	m^2/s
q_y	bedload transport rate per unit width in *y*- direction	m^2/s
k	turbulence kinetic energy	m^2/s^2
L_b	length of levee breach	m
h_c	levee crest height from top of levee	m
L	length of computational channel reach	m
Y	total width of channel including river, levee and floodplain	m
S_L	levee slope	-
S	river bed slope	-
h_L	height of levee from floodplain	m
Q	water flow rate (discharge)	m^3/s
d_m	mean sediment size	mm
dzb	deviation of bed elevation	m

h_0	river water depth	m
U	mean velocity	m/s
Fr	Froude number	-
Re_*	sand reynolds number	-

Greek Symbols

τ_x, τ_y	x and y components of resistance to flow	N/m^2
ρ	density of water	kg/m^3
ν_t	eddy viscosity	m^2/s
τ_{bx}	x- component of bottom-friction	N/m^2
τ_{by}	y- component of bottom-friction	N/m^2
τ_{vx}	x- component of vegetation drag	N/m^2
τ_{vy}	y- component of vegetation drag	N/m^2
κ	Von Karman constant $\kappa = 0.4$	-
ε	dissipation rate of the turbulence kinetic energy	m^2/s^3
ξ	streamwise component of general coordinate	-
η	transverse component of general coordinate	-
θ	angle between x- and ξ–axis	-
τ_*	dimensionless shear stress on the bed/shields number	-
τ_{*c}	dimensionless critical shear stress	-
γ	angle between x- and s-axis	-
γ_g	adjustment co-efficient for slope gravitational effect	-
$\tilde{u}_b^{\xi}, \tilde{u}_b^{\eta}$	velocity components at the bottom in ξ and η directions	-
μ_s	static friction coefficient of bed materials	-
μ_k	kinetic friction coefficient of bed materials	-
ϕ	angle between the sediment movement direction and streamline	-
β_v	parabolic function for velocity distribution $\beta_v = 3(1-\sigma_v)(3-\sigma_v)$	-
σ_v	$\sigma_v = \dfrac{3}{\phi_0 \kappa + 1}$	-

ϕ_0	velocity coefficient (= V/u_*)	-
δ	angle between main stream direction and flow near bed	-
θ_s	angle of mainstream direction with *x*-axis	-
β	angle of sediment transport direction with *x*-axis	-
β_s	$\beta_s = w_f h / \varepsilon_s$ = parameter in Eq. (53)	-
ς	z/h	-
ε_s	sediment diffusivity	m^2/s
α_*	coefficient in Eq. (3.55)	-
ρ_s	density of sediment	kg/m^3
Ω	parameter in Eq. (3.55)	-
ζ	dummy variable = $= r' / \sqrt{2}\,\sigma$	-
η_0	coefficient in Eq. (3.56)	-
σ^2	variance of hydrodynamic force	-
Δ	roughness height in rippled bed	m
Δ_g	submerged specific gravity of sediment $\Delta_g = (\rho_s - \rho)/\rho$	-
ν	kinematic viscosity	m^2/s
λ	porosity of bed materials	-
Δt	time step	s
τ_w	wall shear stress	N/m^2

CHAPTER 1

Introduction

1.1 Background

The densely populated Bangladesh is located in the south Asian sub-continent. The country is mostly flat with only a few hills in the southeast and the northeast parts. Generally ground slopes of the country extend from the north to the south and the elevation ranging from 60 meters to one meter above Mean Sea Level (MSL) at the boundary at Tatulia (north) and at the coastal areas in the south. The geographical positions of Bangladesh have been described in an **Appendix A**.

The river system of Bangladesh is one of the most extensive in the world. The Brahmaputra River, locally known as the Jamuna River, is a braided river channel. More than 80% of annual precipitations occur in five months of monsoon season. The river water starts rising in March/April due to snow melt in the Himalayas and reach a peak in June. It rises again and reaches the highest peak in the late July to mid-August. Mean annual peak discharges of nearly 69,000 m^3/s (Delft Hydraulics and DHI, 1996) with a maximum of about 100,000 m^3/s (recording during severe flooding in 1998, daily discharge's data recorded at Bahadurabad) and mean annual amount of sediment transport is found up to 200×10^6 tons, the third highest yearly sediment load in the world (Schumm and Winkley, 1994). Minimum flow in the river generally occurs at the end of February or beginning of March. The Maximum range of water level variation in the Jamuna River at Bahadurabad is up to 8 m. In **Fig. 1.1**, a typical hydrograph of the Jamuna has been added here, where huge variation of water discharges as well as water levels can be recognized. The detailed description of the Jamuna River has been shown in an **Appendix B**.

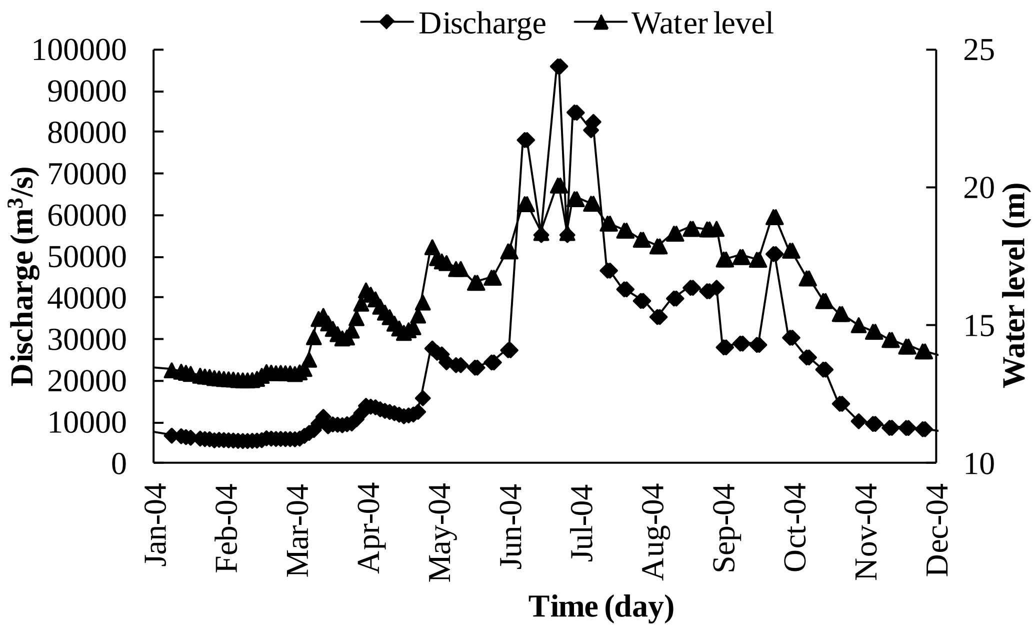


Fig. 1.1 Hydrograph of the Jamuna River at Bahadurabad (Year 2004)

Bangladesh is the lowest riparian country in basins of three world-class great rivers: the Ganges, the Brahmaputra and the Meghna (**Fig. 1.2**), combined total catchment areas of which is about 1.7 million km^2 extending over Bhutan, China, India and Nepal, flow through Bangladesh into Bay of Bengal. Only 7% of this huge catchment area lies in Bangladesh and 93% outside the country. The annual flow volume of the rivers is about 1200 billion m^3, and 80% of this flow passes during June to September, to the sea, which if impounded on our flood plain would have about 9 meters deep standing water. Over the years, due to the sedimentation on the river bed and lack of proper dredging facilities, the Bangladeshi rivers conveyance capacity has been reduced. Moreover, at some river reaches, we have localized congestions due to the river aggradation and man-made interventions over time that impeding drainage adding to the flood recession like that occurred in 1998, 2004, 2007 and so on. Bangladesh has also a single coast line, concave in shape, which causes a higher sea level by wind during the monsoon period. Due to the unique land topography, river system and rainfall pattern, flood occurs in Bangladesh almost every year and devastating ones in every 5 to the 10-year interval (BWDB, 2007). The Ganges and the Brahmaputra join at Aricha-Goalundo and the lower river course is known as the Padma River. The Meghna joins with the Padma near Chandpur, and the flow into Bay of Bengal is called as the (Lower) Meghna River (BWDB, 2010). Every year during the monsoon season, heavy rainfall around Assam and snow melt in the Himalayas cause flooding of settlements and agricultural areas. The flooding and its causes have been explained in an **Appendix C**.

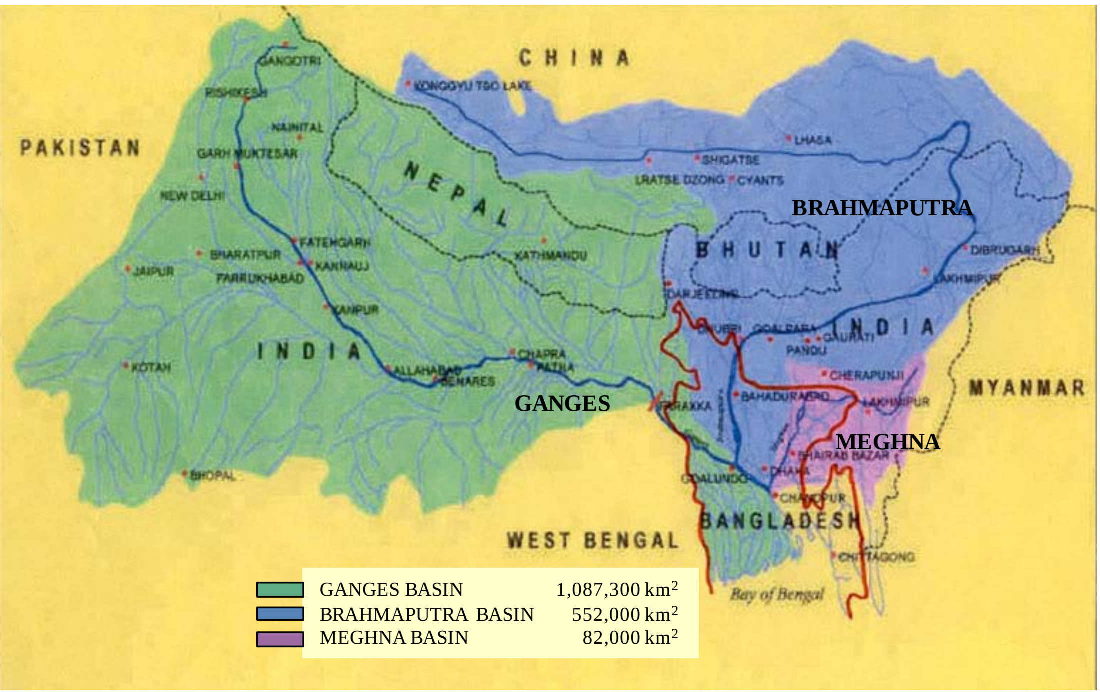


Fig. 1.2 The Brahmaputra, Ganges and Meghna River basin

The average flood discharges of the three main rivers (namely the Ganges, the Brahmaputra, and the Meghna) individually are within the range 14,000 to 100,000 m^3/s (Sarker *et al.,* 2003). The mean annual rainfall within Bangladesh varies from 1250 mm to 5700 mm (Tingsanchali *et al.*, 2005). During the rainy seasons (June to September), nearly a trillion cubic meter of water laden with about two billion tons of silt passes through the main rivers, it is come from upstream catchment in India, Nepal, Bhutan and China. These sediments settle over the river beds, flood plains and low-lying areas during the inundation and the recession of flood water. As a result, river channels and their distributaries are silted up with sediments composed of fine sands and silts causing drainage congestion and overbank flow resulting in levee failure (Islam *et al.,* 1994a and Islam *et al*., 1994b).

This study has been tentatively focused on Jamuna River Right Bank Levee (JRRBL) breach during the flood in 2007 and an adjacent floodplain in Sirajganj district. The details of this district along with levee breach information have been described in an **Appendix D**.

In flood management, Bangladesh has taken many structural and non-structural measures. The river training works in Bangladesh have been discussed in details in an **Appendix E**. The construction of an earthen levee for flood control is the history of Bangladesh, which is the main countermeasure to protect the city from the flood. In an **Appendix F**, describes the levee design criteria and parameters, which are pre-requirements to construct a safe levee in Bangladesh. Also, there are some explanations of the different causes of levee failure along with some remedies to control the unexpected failure.

The construction of flood levee has an established practice for protecting crops and other properties in Bangladesh against flood damage. There have been many causes of levee failure and some of the main causes of levee failure recorded in the available literature are overtopping, seepage, piping, river migration, and improper design and construction. The inadequacy of levee sections, construction that is below specified standards and the poor maintenance of the levee has been considered common in Bangladesh (MPO, 1985 and UNDP, 1988). In other cases, properly designed sections had not been maintained, at the time of construction due to rights of way and acquisition problems or because of the subsequent deterioration, settlement, and weathering of earth works and they're not being topped up or resection under a proper preventive maintenance schedule. The DND (Dhaka-Narayanganj-Demra) levee was threatened by failure due to overtopping during the flood of 1988. Many of the levee projects have been jeopardized because of faulty construction methods and bad design, and they have been the causes of most of the levee failures during periods of severe flooding (Safiullah, 1988). An investigation have been carried out by Islam (1991) found that only ten breaches in eight embankments caused sediment deposition more than 16 million m^3 over the floodplain, it damage to an agricultural crops of about 667 km^2. In most cases, the average depth (from the crest to the bottom) of the levee breach reached equal to the height (from the crest to the base) of the levee.

According to those data, the levee top widths ranged from 2.0 to 5.0 m. Most of the river side (r/s) and land side (c/s) slopes of the levee ranged from 1:1 to 1:1.3, and they are steeper than those recommended by slope criteria of the Bangladesh Water Development Board and Local Government and Engineering Bureau. In addition, the practical condition of Bangladesh most of the levees cross section are not uniform due to lack of proper maintenance and ignorance by the local people and/or respective authorities. During construction, existing volume of earth work was not maintained as the design manner which always less than design value, this is another illegal point based on the reality. According to the field study, the causes of failure of the ten embankment sections have been classified into three broad categories:

i) In five cases, failure was attributable to improper construction.

ii) In three cases, failure could be attributed to piping failure caused by holes and burrows made by rats, insects, and other burrowing animals. It means failure occurred due to lack of maintenance.

iii) In two cases, failure could be attributed to erosion of embankment materials due to river migration.

The analysis of embankment failure and the conclusions suggested that suitable levee code for proper design, construction, and maintenance and so on should be followed to avoid and mitigate flood disasters caused by levee breaches. Such a code, if followed properly, should provide safe and economic levees in the country that minimize damage to the floodplain inhabitants (Islam, 1991).

1.2 Previous Researches

Some studies on levee breaching have been done since long. Fujita and Tamura (1987) investigated enlargement of breaches in the flood levee on alluvial plains and find out the hydraulic characteristics and the mechanism that operate during enlargement of a breach. Fujita *et al.*, (1987) conducted on the inflow of river water and sediment due to levee breach; they investigated breach expansion process using different sizes of levee. Islam *et al.*, (1994a) examined embankment failure and sedimentation over the floodplain in Bangladesh: field investigation and basic experiment; they carried on field investigation and conducted a physical model study, to find out the process of floodplain sedimentation due to river embankment failure. Aureli and Mignosa (2003) described the comparisons between experimental and numerical results of 2D flows due to levee-breaching; mainly, they focus on flow phenomena on the breaching section. Tsujimoto *et al.*, (2006) studied levee breach process of a river by overflow erosion; they conducted numerical approach for the evolution process of levee using unlike relative height of floodplain to river bed. Shimada *et al.*, (2010) observed levee breach experiment by overflow at the Chiyoda experimental channel; they observed the process of levee widening with time using different sizes of levee materials.

1.3 Need to Present Research

In spite of these studies mentioned above, most of the previous research works have been focused on levee breach expansion process and some of them are only investigated sedimentation process in the floodplain. A lot of numerical simulations of inundation process following to levee breach has been conducted to make flood hazard maps for almost all rivers with large to meddle scales basins in Japan. In such simulations, levee breach widths and their widening process are very roughly postulated to be proportional to river channel width and visually gathered empirical data. But, they did not consider so much about subsequent phenomena appearing in the river bed and in the floodplain as well as topographic changes over the floodplain during levee breach.

As the description in the aforementioned section, Bangladeshi rivers carry a huge amount of water and sediment load from upstream catchment areas, and day by day rivers conveyance capacity have been reduced due to continuous sedimentation on river bed as because of lack of necessary dredging from river bed. During the rainy seasons due to excess load of flooding water; an overbank flow occur that cause severe damage to an agricultural production, roads and other infrastructures in the country side floodplain with inundation and sedimentation. Especially, floodplain residents are suffering with flood disaster, which are living inside the boundary of the levee. To minimize flood disasters effect, sediment dredging from the river bed is important. Due to lack of proper dredging facilities, Bangladeshi river bed level is increasing and it is susceptible to overflow through levee by the breach and flooding in the low-land floodplain. High river bed is risky because of flood reaches the dangerous level although the discharge is small. 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 the breach expansion. Geographical position of Bangladesh and insufficiency in the study, make it difficult to avoid levee breach and disaster suffering to the inhabitant’s in the floodplain. Therefore, the present research is necessary to recognize the effects of flood disasters in the low-land and to analyze the risk during the levee breach. In order to save huge amount of money, lives, agriculture and ecology, it is most important to carry out the research on investigation of the levee breach processes and flood flow dynamics, and the morphological changes in the river, levee and floodplain.

In this research, the attempted have been taken to recognize the levee breach phenomena and the successive disasters in low-land using a numerical simulation scheme and as well as small-scale laboratory experiments.

1.4 Objectives and Approach

In view of the problems mentioned in the preceding sections, the present research is mainly aimed to improve understandings of the levee breaching process and flood disasters risk in low floodplains during influent flow through the breach. Some precise objectives have been fixed to reach the target of this research. However, the specific objectives of the present study can be summarized as follows:

- Characteristics of levee breaching and topographic changes around there including river bed, levee body and floodplain surface with considering the effect of inflow discharges, duration, initial breach length and different river bed height using numerical approaches

- Levee breach and the risk of flood disaster in the floodplain as particular reference to the relative height of river bed to floodplain considered with various bed material effects using small-scale laboratory experiments;

- Understanding of levee breach mechanism using both of small-scale experiments and numerical analyses with same scenario as experiments;

- Comparisons of levee breach disasters between Japan and Bangladesh; and

- Understand the characteristics of flood disaster in floodplain using various landscapes.

Both of numerical analyses and laboratory experiments have been conducted to explore the levee breach phenomena and topographic changes in the river, levee and floodplain. As there has been many cases to be dealt with because of many aspects of levee breaching and successive disasters in the floodplain, at first conducted two dimensional (2D) numerical analyses to recognize the levee breach characteristics using different inflow discharges, duration, and various initial breach opening of the levee and the relative height of river bed to floodplain. Then, to clarify the phenomena conducted small-scale experiments in the laboratory using the relative height of river bed to floodplain with considering the effect of two different bed materials. Further, to understand the mechanism of breaching as well as the risk of flood disasters in the floodplain, examined the small-scale laboratory experiments by using same scenario simulation analyses. After conducted a small-scale laboratory investigation and numerical analysis, an additional investigation has been carried out using a large-scale numerical approaches to compare the effect of flood disasters between Japan and

Bangladesh utilizing these two countries basic characteristics of the river and floodplain. Finally, to recognize the phenomena on the floodplain due to levee breach used some typical landscape on the floodplain considering the view points of model field of Sirajganj district in Bangladesh and analyzed the characteristics of disasters effect on the floodplain.

1.5 Dissertation Framework and Outline

The contents described in this dissertation are the sequential explanations of different phases of the present research. This dissertation is composed of seven chapters in total from introduction in Chapter 1 through the conclusion in Chapter 7, as described below:

In Chapter 1, briefly introduces the present research including the motivation for this study, objective, and approaches to achieve the defined goals. Some basic information on this research such as River system in Bangladesh, existing river training methods as well as flood management approaches in Bangladesh, causes of flooding, and flood protection by using a levee with its causes of failure have been discussed in an Appendices and link-up with this chapter.

In Chapter 2, describes a numerical approach to levee breach and disasters in low land for utilizing the effect of inflow discharges, initial breach lengths and depth in the levee, and level difference between the river bed and floodplain. The result of the simulations shows reasonably good agreement with the results of another numerical (NHSED2D) study. It is found that different inflow; initial breach length and river bed level has strong influences on levee breaching and floodplain phenomena. This chapter has been published as technical papers in the *International Journal of Civil Engineering* (Islam and Tsujimoto, 2012b), in the *International Conference on Geotechnique, Construction Materials and Environment* (Islam and Tsujimoto, 2011a), and in the *International Journal of GEOMAT* (Islam and Tsujimoto, 2011b).

In this study, the levee breach phenomena and the topographic changes in the river, levee and floodplain has been investigated using small-scale laboratory experiments.

Chapter 3 deals of levee breach and inundation in floodplain with sediment deposition. This chapter focuses on levee breaching phenomena, and flood disasters risk in the low floodplain for different relative height of river bed to floodplain by using different bed materials. It is found that the higher bed level has the high risk of flood disasters in the floodplain. The works described in this chapter has been published as technical papers in *Advances in River Engineering, JSCE*, (Tsujimoto, *et al.*, 2012) and in the *International Review of Civil Engineering* (Islam *et al.*, 2012).

In Chapter 4, the experiences from the laboratory observations, same scenario numerical simulation has been conducted to understand the characteristics and mechanism of the levee breaching and phenomena in the river, levee and floodplain. Both analyses gave more clarification on levee breach understanding considering the effect of the relative river bed height and different bed materials.

Levee breach and flood disaster phenomena in the floodplain are not uniform all over the worlds. Particularly, in Japan and Bangladesh, both these two countries have unlike land topography and river system, so the levee breaching effect would be different. In Chapter 5, gave a description on flood disaster comparisons between Bangladesh and Japan in a same simulation scheme. This chapter has been published as technical paper in the *Procedia Engineering, Science Direct, Elsevier Publisher* (Islam and Tsujimoto, 2012a).

In Chapter 6, discussion has been made on the characteristics of levee breach disasters depending on landscape on floodplain. Basically, in the floodplain has different land use pattern, and the effects are not equal all over the floodplain during the flood. The five typical model floodplains have been considered to understand the flow pattern and the process of sedimentation in the floodplain as well as an analyzed the disaster effect for individual floodplain and compare among them.

Finally, the overall conclusions of this research have been drawn and suggested some recommendations for further researches relating to this topic are depicted in this chapter 7. Concluding remarks are also made at the end of each chapter based on the results obtained in different phases of the research within the framework of the objectives.

The framework of the research phases presented in this dissertation with the relationship between them is delineated with a figure (**Fig. 1.3**).

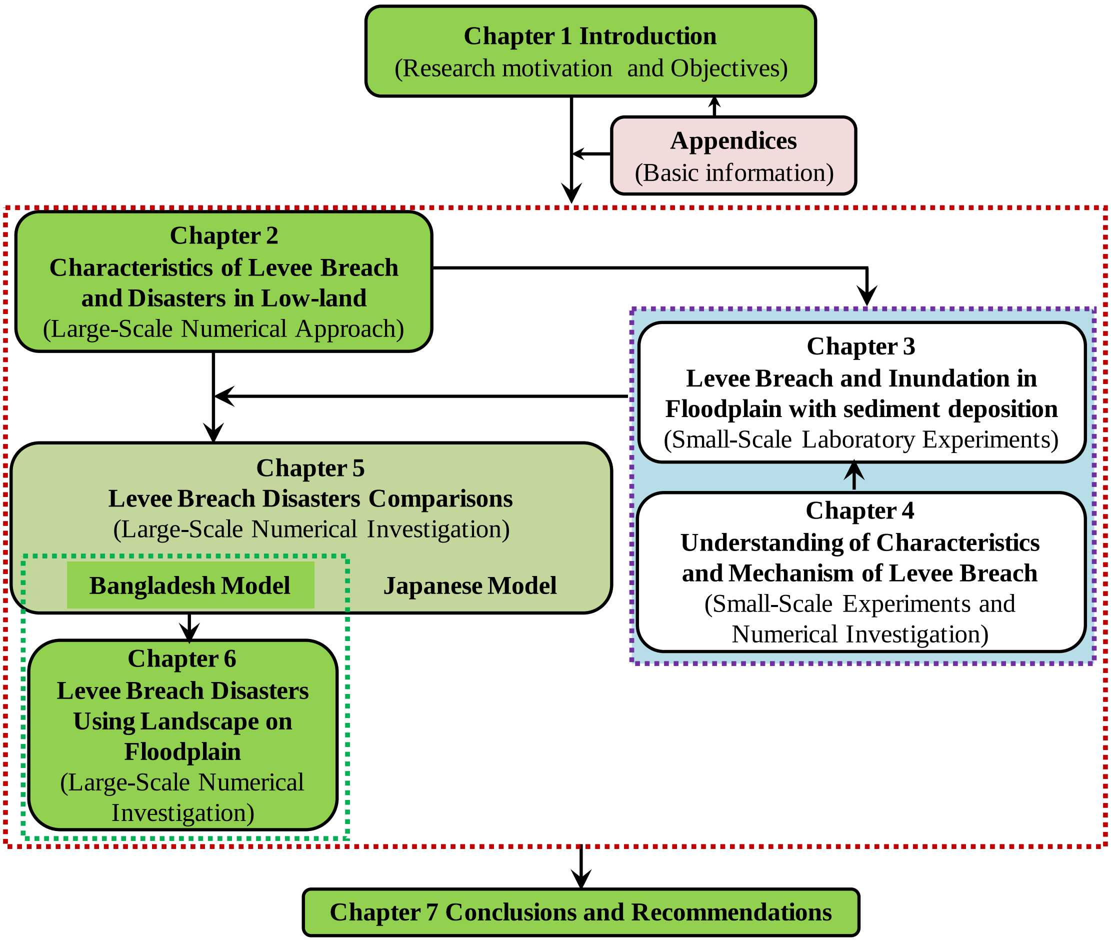


Fig. 1.3 Graphical representation of the dissertation framework

CHAPTER 2

Numerical Approach to Characteristics of Levee Breach and Disasters in Low-Land

Summary

During flood seasons, a large amount of water flows through Bangladeshi river, and it causes earthen levee failure, and huge damage occurs in the inhabitants inside the levees. Thus, it is important to recognize the process of inundation, and attempts have been taken to do through numerical simulation. As for simulation scheme, schematic model area is considered to consist of main channel, levee and floodplain, and all of them are composed of sediment having roughly same characteristics because the flood plain is formed by flooding sediment, the levees are made by piling up the sediment dredged from the river bed. Therefore, these three components are treated simultaneously in the simulation model. The main channel, levee, floodplain and flow parameters are selected in conformity with the study field of Sirajganj district and the Jamuna River in Bangladesh. And an excellent solver included in RIC-Nay package, a two-dimensional numerical model for flood flow and morphology is utilized in this study upon confirmation with another simulation study. Based on the calculated results, inundation of water and sediment in the floodplain and evolution process of the levee breach are investigated. Levee breach is considered to initiate in the middle of the levee with crest opening. The change the inflow discharges, the opening size in vertical and longitudinal scales, and the relative river bed height to the floodplain.

2.1 General

Levee breach flood disaster is one of the common natural hazards in Bangladesh. Flooding, levee breach and sedimentation over floodplain have become alarming problems that have severe and adverse effect on the national economy of Bangladesh. On an average, the area inundated every year is about 26,000 km^2, which is nearly 18% of the total country area (Ahmed *et al.,* 1992). High rate of discharge through Bangladeshi rivers is produced by the geographical position of Bangladesh and the river system. Also, the rainfall patterns and flat land topography of Bangladesh are susceptible to flood. Levee breached during the rainy seasons due to excess load of the flooding water. The failure of levee not only increases the siltation in the river beds and the flood plains, but also it causes huge damage to an agricultural production, residents, roads and other infrastructures in the floodplain. Because of geographical position of Bangladesh, it is difficult to avoid levee breach disaster and suffering of the inhabitants in the floodplain. In order to save lots of lives, a huge amount of money, crops of agriculture and valuable ecosystem, it is the most important to carry out levee breach disasters over the alluvial floodplain during the flood for the vulnerable area of Sirajganj district in Bangladesh. This kind of study is rare in the available literatures except for few numerical, field investigation and experimental studies, which have been discussed in the preceding chapter.

Computational simulation can make comprehensive analysis on the levee breach flooding and its impacts on the entire flood plains. In this chapter, the attempted have been made to recognize the process of levee breach and disasters effect in the floodplain after levee breach using a numerical simulation approaches for different discharges with time, initial breach opening lengths and depths, and the various river bed height to the floodplain.

This research is mainly aimed to improve the understanding of the characteristics of flood disasters in low floodplain during the overflow levee breach. The specific objectives of the present research can be summarized as follows:

- To investigate the characteristics of the levee breach utilizing with the effect of flow dynamics and the process of sedimentation in low-land for specific discharge with time, various inflow discharges and initial breach lengths, and various height of river bed to floodplain;

- Investigate the evolution process of the levee with time.

2.2 Numerical Model

A free software package for fluvial hydraulic analysis named RIC-Nays includes an excellent two dimensional (2D) numerical model for flood flow and morphology simulation, developed by the foundation of Hokkaido River Disasters Prevention Center, Japan (http://i-ric.org/nays/ja/sitmap.html) is utilized in this study.

2.2.1 Hydrodynamic Equations

The system of equations governing the flow consists of the continuity and horizontal momentum equations. According to the manuals of RIC-Nays, derivation process and explanations of the basic equations for not only flow analysis but also sediment transport are introduced below.

Assuming that the vertical component of velocity is negligible and that the pressure is hydrostatic, the two-dimensional equations, using a Cartesian coordinate system (*x*, *y*), can be given as follows:

Continuity equation:

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \tag{2.1}$$

Momentum equations:

$$\frac{\partial (hu)}{\partial t} + \frac{\partial (hu^2)}{\partial x} + \frac{\partial (huv)}{\partial y} = -hg\frac{\partial H}{\partial x} - \frac{\tau_x}{\rho} + D_x \tag{2.2}$$

$$\frac{\partial (hv)}{\partial t} + \frac{\partial (huv)}{\partial x} + \frac{\partial (hv^2)}{\partial y} = -hg\frac{\partial H}{\partial y} - \frac{\tau_y}{\rho} + D_y \tag{2.3}$$

With:

Shear stresses

$$\frac{\tau_x}{\rho} = \frac{\tau_{bx} + \tau_{vx}}{\rho} = \left(C_d + K_v h\right) u \sqrt{u^2 + v^2} \ , \frac{\tau_y}{\rho} = \frac{\tau_{by} + \tau_{vy}}{\rho} = \left(C_d + K_v h\right) v \sqrt{u^2 + v^2} \quad (2.4)$$

Diffusion terms

$$D_x = \frac{\partial}{\partial x}\left[\nu_t \frac{\partial (hu)}{\partial x}\right] + \frac{\partial}{\partial y}\left[\nu_t \frac{\partial (hu)}{\partial y}\right] \quad (2.5)$$

$$D_y = \frac{\partial}{\partial x}\left[\nu_t \frac{\partial (hv)}{\partial x}\right] + \frac{\partial}{\partial y}\left[\nu_t \frac{\partial (hv)}{\partial y}\right] \quad (2.6)$$

where h is depth of flow; H is water stage; u, v are depth-averaged velocity components in x and y directions, respectively; τ_x, τ_y are x and y components of resistance to flow, respectively; τ_{bx}, τ_{by} are x and y components of bottom-friction, respectively with C_d is bed friction coefficient; τ_{vx}, τ_{vy} are x and y components of vegetation drags, respectively, where $K_v = 1/2\, C_{dv} N_a d_v$ with C_{dv} is drag coefficient of vegetation, N_a vegetation density, and d_v is mean diameter of arbors; ρ is density of water; and ν_t is eddy viscosity. For considering turbulence in the flow phenomena, both zero- and two-equation turbulence models are available in the calculation framework. One of them is parabolic eddy viscosity model, $\nu_t = \kappa u_* z\left(1 - \frac{z}{h}\right)$; it is integrated over flow depth to get the depth-averaged one, $\nu_t = \frac{\kappa}{6} u_* h$; where u_* is bed shear velocity $= \sqrt{\frac{\tau_x^2 + \tau_y^2}{\rho}}$, and κ is Von Karman's constant (= 0.4). It is utilized in the present calculation; other available models are mixing length and k-ε turbulence models.

Transformation of flow equations from Cartesian coordinates (x,y) to General coordinates (ξ, η) system is as follows:

$$\frac{\partial}{\partial x} = \frac{\partial \xi}{\partial x}\frac{\partial}{\partial \xi} + \frac{\partial \eta}{\partial x}\frac{\partial}{\partial \eta}, \quad \frac{\partial}{\partial y} = \frac{\partial \xi}{\partial y}\frac{\partial}{\partial \xi} + \frac{\partial \eta}{\partial y}\frac{\partial}{\partial \eta}$$

or,

$$\begin{pmatrix} \dfrac{\partial}{\partial x} \\ \dfrac{\partial}{\partial y} \end{pmatrix} = \begin{pmatrix} \xi_x & \eta_x \\ \xi_y & \eta_y \end{pmatrix} \begin{pmatrix} \dfrac{\partial}{\partial \xi} \\ \dfrac{\partial}{\partial \eta} \end{pmatrix} \tag{2.7}$$

where,

$$\xi_x = \frac{\partial \xi}{\partial x},\ \xi_y = \frac{\partial \xi}{\partial y},\ \eta_x = \frac{\partial \eta}{\partial x},\ \eta_y = \frac{\partial \eta}{\partial y}$$

In the same manner,

$$\frac{\partial}{\partial \xi} = \frac{\partial x}{\partial \xi}\frac{\partial}{\partial x} + \frac{\partial y}{\partial \xi}\frac{\partial}{\partial y},\ \frac{\partial}{\partial \eta} = \frac{\partial x}{\partial \eta}\frac{\partial}{\partial x} + \frac{\partial y}{\partial \eta}\frac{\partial}{\partial y}$$

or,

$$\begin{pmatrix} \dfrac{\partial}{\partial \xi} \\ \dfrac{\partial}{\partial \eta} \end{pmatrix} = \begin{pmatrix} x_\xi & y_\xi \\ x_\eta & y_\eta \end{pmatrix} \begin{pmatrix} \dfrac{\partial}{\partial x} \\ \dfrac{\partial}{\partial y} \end{pmatrix} \tag{2.8}$$

Where,

$$x_\xi = \frac{\partial x}{\partial \xi},\ x_\eta = \frac{\partial x}{\partial \eta},\ y_\xi = \frac{\partial y}{\partial \xi},\ y_\eta = \frac{\partial y}{\partial \eta}$$

Therefore,

$$\begin{pmatrix} \dfrac{\partial}{\partial \xi} \\ \dfrac{\partial}{\partial \eta} \end{pmatrix} = \frac{1}{\xi_x\eta_y - \xi_y\eta_x} \begin{pmatrix} \eta_y & -\eta_x \\ -\xi_y & \xi_x \end{pmatrix} \begin{pmatrix} \dfrac{\partial}{\partial x} \\ \dfrac{\partial}{\partial y} \end{pmatrix} = \begin{pmatrix} x_\xi & y_\xi \\ x_\eta & y_\eta \end{pmatrix} \begin{pmatrix} \dfrac{\partial}{\partial x} \\ \dfrac{\partial}{\partial y} \end{pmatrix} \tag{2.9}$$

With:

$$J = \xi_x\eta_y - \xi_y\eta_x,\ \frac{1}{J}\begin{pmatrix} \eta_y & -\eta_x \\ -\xi_y & \xi_x \end{pmatrix} = \begin{pmatrix} x_\xi & y_\xi \\ x_\eta & y_\eta \end{pmatrix} \tag{2.10}$$

$$x_\xi = \frac{1}{J}\eta_y,\ y_\xi = -\frac{1}{J}\eta_x,\ x_\eta = -\frac{1}{J}\xi_y,\ y_\eta = \frac{1}{J}\xi_x$$

or,

$$\eta_y = Jx_\xi,\ \ \eta_x = -Jy_\xi,\ \ \xi_y = -Jx_\eta,\ \ \xi_x = Jy_\eta$$

$$J = \xi_x\eta_y - \xi_y\eta_x = J^2\left(x_\xi y_\eta - x_\eta y_\xi\right)$$

$$J = \frac{1}{\left(x_\xi y_\eta - x_\eta y_\xi\right)} \tag{2.11}$$

Contravariant components of flow velocity in (ξ, η) coordinates are defined as u^ξ and u^η (**Fig. 2.1**) by

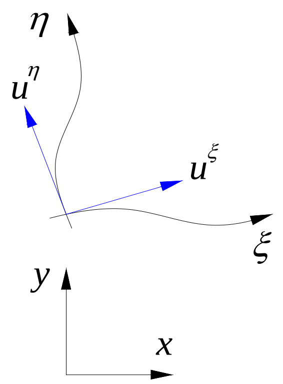


Fig. 2.1 Moving boundary-fitted coordinate system with contra variant components of velocity

$$u^\xi = \xi_x u + \xi_y v \tag{2.12}$$

$$u^\eta = \eta_x u + \eta_y v \tag{2.13}$$

or,

$$\begin{pmatrix} u^\xi \\ u^\eta \end{pmatrix} = \begin{pmatrix} \xi_x & \xi_y \\ \eta_x & \eta_y \end{pmatrix}\begin{pmatrix} u \\ v \end{pmatrix} \tag{2.14}$$

$$\begin{pmatrix} u \\ v \end{pmatrix} = \frac{1}{J}\begin{pmatrix} \eta_y & -\xi_y \\ -\eta_x & \xi_x \end{pmatrix}\begin{pmatrix} u^\xi \\ v^\eta \end{pmatrix} \tag{2.15}$$

Therefore, 2D flow equations are:

$$\frac{\partial}{\partial t}\left(\frac{h}{J}\right)+\frac{\partial}{\partial \xi}\left(\frac{hu^{\xi}}{J}\right)+\frac{\partial}{\partial \eta}\left(\frac{hu^{\eta}}{J}\right)=0 \tag{2.16}$$

$$\frac{\partial u^{\xi}}{\partial t}+u^{\xi}\frac{\partial u^{\xi}}{\partial \xi}+u^{\eta}\frac{\partial u^{\xi}}{\partial \eta}+\alpha_1 u^{\xi}u^{\xi}+\alpha_2 u^{\xi}u^{\eta}+\alpha_3 u^{\eta}u^{\eta}=-g\left[\left(\xi_x^2+\xi_y^2\right)\frac{\partial H}{\partial \xi}+\left(\xi_x\eta_x+\xi_y\eta_y\right)\frac{\partial H}{\partial \eta}\right]$$
$$-\frac{C_d u^{\xi}}{hJ}\sqrt{\left(\eta_y u^{\xi}-\xi_y u^{\eta}\right)^2+\left(-\eta_x u^{\xi}+\xi_x u^{\eta}\right)^2}+D^{\xi} \tag{2.17}$$

$$\frac{\partial u^{\eta}}{\partial t}+u^{\xi}\frac{\partial u^{\eta}}{\partial \xi}+u^{\eta}\frac{\partial u^{\eta}}{\partial \eta}+\alpha_4 u^{\xi}u^{\xi}+\alpha_5 u^{\xi}u^{\eta}+\alpha_6 u^{\eta}u^{\eta}=-g\left[\left(\eta_x\xi_x+\eta_y\xi_y\right)\frac{\partial H}{\partial \xi}+\left(\eta_x^2+\eta_y^2\right)\frac{\partial H}{\partial \eta}\right]$$
$$-\frac{C_d u^{\eta}}{hJ}\sqrt{\left(\eta_y u^{\xi}-\xi_y u^{\eta}\right)^2+\left(-\eta_x u^{\xi}+\xi_x u^{\eta}\right)^2}+D^{\eta} \tag{2.18}$$

In which,

$$\alpha_1=\xi_x\frac{\partial^2 x}{\partial \xi^2}+\xi_y\frac{\partial^2 y}{\partial \xi^2},\ \alpha_2=2\left(\xi_x\frac{\partial^2 x}{\partial \xi\partial \eta}+\xi_y\frac{\partial^2 y}{\partial \xi\partial \eta}\right),\ \alpha_3=\xi_x\frac{\partial^2 x}{\partial \eta^2}+\xi_y\frac{\partial^2 y}{\partial \eta^2} \tag{2.19}$$

$$\alpha_4=\eta_x\frac{\partial^2 x}{\partial \xi^2}+\eta_y\frac{\partial^2 y}{\partial \xi^2},\ \alpha_5=2\left(\eta_x\frac{\partial^2 x}{\partial \xi\partial \eta}+\eta_y\frac{\partial^2 y}{\partial \xi\partial \eta}\right),\ \alpha_6=\eta_x\frac{\partial^2 x}{\partial \eta^2}+\eta_y\frac{\partial^2 y}{\partial \eta^2} \tag{2.20}$$

$$D^{\xi}=\left(\xi_x\frac{\partial}{\partial \xi}+\eta_x\frac{\partial}{\partial \eta}\right)\left[\nu_t\left(\xi_x\frac{\partial u^{\xi}}{\partial \xi}+\eta_x\frac{\partial u^{\xi}}{\partial \eta}\right)\right]+\left(\xi_y\frac{\partial}{\partial \xi}+\eta_y\frac{\partial}{\partial \eta}\right)\left[\nu_t\left(\xi_y\frac{\partial u^{\xi}}{\partial \xi}+\eta_y\frac{\partial u^{\xi}}{\partial \eta}\right)\right] \tag{2.21}$$

$$D^{\eta}=\left(\xi_x\frac{\partial}{\partial \xi}+\eta_x\frac{\partial}{\partial \eta}\right)\left[\nu_t\left(\xi_x\frac{\partial u^{\eta}}{\partial \xi}+\eta_x\frac{\partial u^{\eta}}{\partial \eta}\right)\right]+\left(\xi_y\frac{\partial}{\partial \xi}+\eta_y\frac{\partial}{\partial \eta}\right)\left[\nu_t\left(\xi_y\frac{\partial u^{\eta}}{\partial \xi}+\eta_y\frac{\partial u^{\eta}}{\partial \eta}\right)\right] \tag{2.22}$$

Generally, ξ and η are non-dimensional values and can be expressed in the computational domain as,

$$0\le\xi\le 1,\ \ 0\le\eta\le 1 \tag{2.23}$$

Therefore, the dimensions of ξ_x, ξ_y, η_x, and η_y are [1/Length], and the dimensions of u^{ξ} and u^{η} are [1/Time]. The directions of u^{ξ} and u^{η} are ξ and η, respectively; but their magnitudes are not in velocity-unit. In order to describe them in velocity dimensions, transformation is needed using local computational grid sizes. Defining the actual local grid-sizes as $\Delta\tilde{\xi}$ and $\Delta\tilde{\eta}$, the ratio with the computational grid-sizes, $\Delta\xi$ and $\Delta\eta$ are as follows:

$$\frac{\Delta\xi}{\Delta\tilde{\xi}} = \xi_r,\quad \frac{\Delta\eta}{\Delta\tilde{\eta}} = \eta_r \tag{2.24}$$

Using these relationships, ξ_x, ξ_y, η_x, and η_y can be described as follows:

$$\xi_x = \frac{\partial\xi}{\partial x} = \xi_r \frac{\partial\tilde{\xi}}{\partial x} = \xi_r\,\tilde{\xi}_x,\quad \xi_y = \frac{\partial\xi}{\partial y} = \xi_r \frac{\partial\tilde{\xi}}{\partial y} = \xi_r\,\tilde{\xi}_y \tag{2.25}$$

$$\eta_x = \frac{\partial\eta}{\partial x} = \eta_r \frac{\partial\tilde{\eta}}{\partial x} = \eta_r\,\tilde{\eta}_x,\quad \eta_y = \frac{\partial\eta}{\partial y} = \eta_r \frac{\partial\tilde{\eta}}{\partial y} = \eta_r\,\tilde{\eta}_y \tag{2.26}$$

The physical contravariant velocity components in velocity-unit, $\tilde{u}^{\xi}$ and $\tilde{u}^{\eta}$ can be written as follows.

$$\tilde{u}^{\xi} = \tilde{\xi}_x u + \tilde{\xi}_y v = \frac{u^{\xi}}{\xi_r},\quad \tilde{u}^{\eta} = \tilde{\eta}_x u + \tilde{\eta}_y v = \frac{u^{\eta}}{\eta_r} \tag{2.27}$$

The assumptions made to simplify the momentum diffusion terms are (i) second order derivatives with metric coefficients are negligible, and (ii) grids are treated quasi co-orthogonal locally. Thus, the diffusion terms are described as follows:

$$D^{\xi} \cong \frac{\partial}{\partial\xi}\left(\nu_t \xi_r^2 \frac{\partial u^{\xi}}{\partial\xi}\right) + \frac{\partial}{\partial\eta}\left(\nu_t \eta_r^2 \frac{\partial u^{\xi}}{\partial\eta}\right) \tag{2.28}$$

$$D^{\eta} \cong \frac{\partial}{\partial\xi}\left(\nu_t \xi_r^2 \frac{\partial u^{\eta}}{\partial\xi}\right) + \frac{\partial}{\partial\eta}\left(\nu_t \eta_r^2 \frac{\partial u^{\eta}}{\partial\eta}\right) \tag{2.29}$$

In which the following relationships were used:

$$\xi_x^2 + \xi_y^2 = \xi_r^2\left(\tilde{\xi}_x^2 + \tilde{\xi}_y^2\right) = \xi_r^2\left(\sin^2\theta + \cos^2\theta\right) = \xi_r^2$$

$$\xi_x\eta_x + \xi_y\eta_y = \xi_r\eta_r\left(\tilde{\xi}_x\,\tilde{\eta}_x + \tilde{\xi}_y\,\tilde{\eta}_y\right) = \xi_r\eta_r\left(-\cos\theta\sin\theta + \cos\theta\sin\theta\right) = 0$$

$$\eta_x^2 + \eta_y^2 = \eta_r^2\left(\tilde{\eta}_x^{\,2} + \tilde{\eta}_y^{\,2}\right) = \eta_r^2\left(\sin^2\theta + \cos^2\theta\right) = \eta_r^2$$

$$J = \xi_x\eta_y - \xi_y\eta_x = \xi_r\eta_r\left(\tilde{\xi}_x\,\tilde{\eta}_y - \tilde{\xi}_y\,\tilde{\eta}_x\right) = \xi_r\eta_r\left(\sin^2\theta + \cos^2\theta\right) = \xi_r\eta_r$$

where θ is an angle between x- and ξ- or , y- and η- axes.

2.2.2 Sediment Transport Equations

Morphological computation involves a combination of flow fields, sediment transports, and bed evolution associated with the levee breach. After resolving the flow fields, the sediment transport fields are computed from the expressions of both bed load and suspended load separately. Finally, the changes in the bed topography due to total load are determined.

The bedload in the depth-averaged velocity direction q_b can be calculated by the following Ashida and Michiue (1972) formula,

$$q_b = 17\tau_*^{3/2}\left(1 - \frac{\tau_{*c}}{\tau_*}\right)\left[1 - \sqrt{\frac{\tau_{*c}}{\tau_*}}\right]\sqrt{(s_g - 1)gd^3} \qquad (2.30)$$

in which τ_{*c} is dimensionless critical shear stress; conditions for checking critical tractive force, which has been examined by Iwagaki's (1956) equations as follows:

$$\begin{aligned}
&671.0 \le R_{e^*} && ;\tau_c^{\,*} = 0.05 \\
&162.7 \le R_{e^*} \le 671.0 && ;\tau_c^{\,*} = 0.00849 R_{e^*}^{\,3/11} \\
&54.2 \le R_{e^*} \le 162.7 && ;\tau_c^{\,*} = 0.034 \\
&2.14 \le R_{e^*} \le 54.2 && ;\tau_c^{\,*} = 0.195 R_{e^*}^{\,-7/16} \\
&R_{e^*} \le 2.14 && ;\tau_c^{\,*} = 0.14
\end{aligned} \qquad (2.31)$$

τ_* is dimensionless total bed shear stress acts on the channel bed $= \dfrac{hI_e}{(s_g - 1)d}$, with I_e is energy slope, s_g is specific gravity; d is sediment diameter. When Manning's formula is applied for I_e, τ_* becomes as follows,

$$\tau_* = \frac{C_d V^2}{(s_g - 1)gd} = \frac{n_m^2 V^2}{(s_g - 1)dh^{1/3}} \tag{2.32}$$

In which n_m is Manning's roughness coefficient; g is acceleration due to gravity; V is total velocity, which can be defined as, $V = \sqrt{u^2 + v^2}$.

One of the important factors for the computation of bedload transport fields is the effect of gravity on the sand particles in the transverse slope of the bed surface (**Fig. 2.2**).

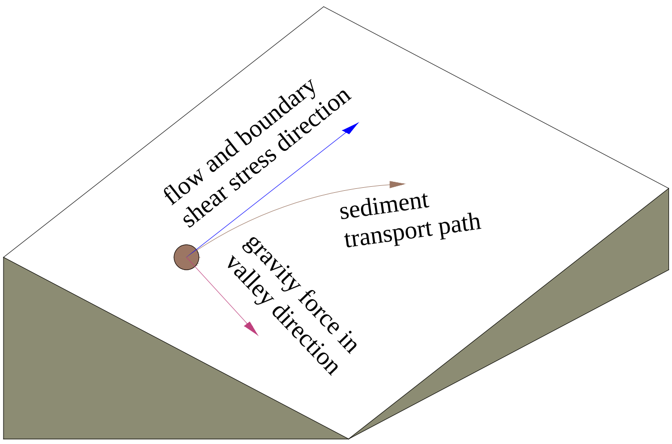


Fig. 2.2 Gravity effect on sediment particles

Watanabe *et al.* (1990) proposed the following equation considering the gravitational effect in streamline and transverse directions,

$$\tilde{q}^{\xi} = q_b \left[\frac{\tilde{u}_b^{\xi}}{V_b} - \gamma_g \left(\frac{\partial z_b}{\partial \tilde{\xi}} + \cos\theta \frac{\partial z_b}{\partial \tilde{\eta}} \right) \right] \tag{2.33}$$

$$\tilde{q}^{\eta} = q_b \left[\frac{\tilde{u}_b^{\eta}}{V_b} - \gamma_g \left(\frac{\partial z_b}{\partial \tilde{\eta}} + \cos\theta \frac{\partial z_b}{\partial \tilde{\xi}} \right) \right] \qquad \backslash \tag{2.34}$$

In which $\tilde{u}_b^{\xi}$ and $\tilde{u}_b^{\eta}$ are velocity components at the bottom in ξ and η directions; V_b is total velocity at the bottom; z_b is bed elevation; and γ_g is an adjustment coefficient for slope gravitational effect. Hasegawa (1983) proposed the following formula for this coefficient,

$$\gamma_g = \sqrt{\frac{\tau_{*c}}{\mu_s \mu_k \tau_*}} \tag{2.35}$$

Thus, he derived a simple equation for the angle between the sediment movement direction and streamline as follows,

$$\tan\phi = \frac{V_n}{V_s} = \frac{u_{bn}}{u_{bs}} - \sqrt{\frac{\tau_{*c}}{\mu_s \mu_k \tau_*}} \frac{\partial z_b}{\partial n} \tag{2.36}$$

where V_s and V_n are sediment movement velocity components in *s* and *n* directions (*s*, streamline direction of the depth-averaged flow; *n*, transverse direction perpendicular to streamline), respectively; μ_s and μ_k are static and kinetic friction coefficients of bed materials, respectively with μ_s μ_k = 0.5; u_{bs} and u_{bn} are near-bed velocities in *s*- and *n*- directions, respectively. The first term of the right-hand side of Eq. 2.35 is the direction of flow velocity near the bed, and the second term expresses the effect of gravity on sand particles on the transverse slope of the bed surface. If the bed cross-section is transversely flat, the second term disappears, and the directions of the sediment movement and flow near the bed coincide with each other.

Now, the near-bed stream wise velocity can be estimated as,

$$u_{bs} = \beta_v V \tag{2.37}$$

where u_{bs} is simply related to the depth-averaged flow velocity, β_v is assumed as a parabolic function by Engelund (1974) for velocity profile in depth direction and proposed as, $\beta_v = 3(1-\sigma_v)(3-\sigma_v)$, where $\sigma_v = \dfrac{3}{\phi_0 \kappa + 1}$, with ϕ_0 = velocity coefficient (=V/u_*). However, in curved flow, secondary flow (spiral flow in transverse direction) induced by the centrifugal force acting on the curved streamline is developed, and q_n driven by the secondary flow is produced (**Fig. 2.3**), which is very important factor to predict river bed topography in curved flow.

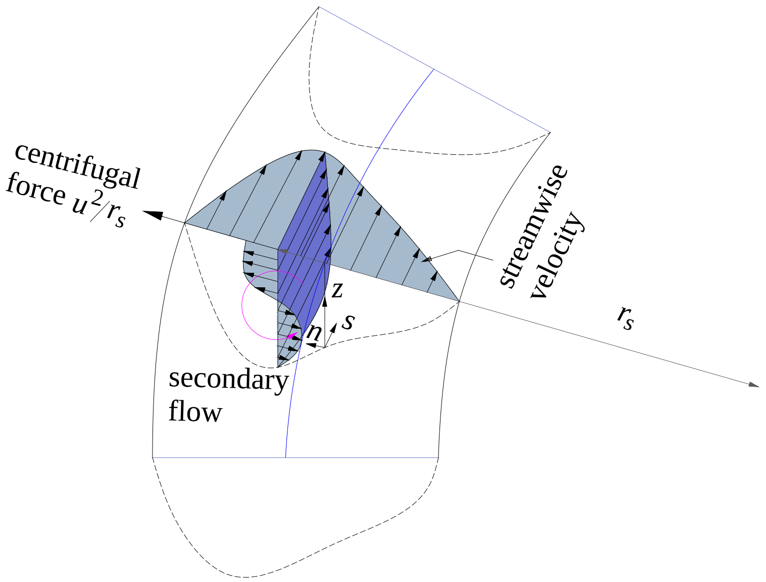


Fig. 2.3 Secondary flow

Accordingly, it has been taken into account as,

$$u_{bn} = -u_{bs} N_* \frac{h}{r_s} \tag{2.38}$$

where, N_* is a co-efficient to describe the intensity of secondary flow in a curved streamline; and r_s is a radius of curvature of the streamline. Investigations of the value of N_* have been performed by many researchers, e.g., Ikeda (1974), Engelund (1974), Rozovskii (1961), and Zimmerman (1977). N^* = 7.0 is adopted in the calculation as proposed by Engelund (1974). Angle between near-bed velocity vector and s-axis, δ

can be defined as, $\tan\delta = \dfrac{u_{bn}}{u_{bs}} = -N_* \dfrac{h}{r_s}$, and angle between *x*- and *s*-axis, θ_s can be written as, $\tan\theta_s = \dfrac{v}{u}$. Finally, the angle between sediment movement direction and the *x*-axis, β can be known from, $\beta = \phi + \theta_s$ (**Fig. 2.4**).

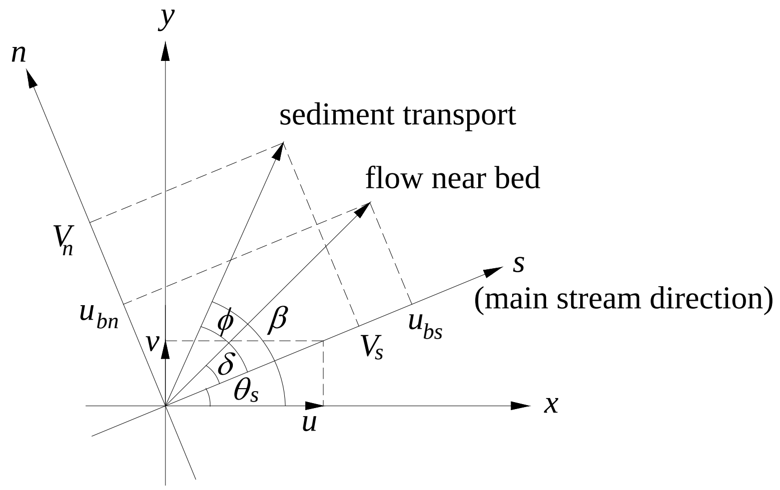


Fig. 2.4 Angles of flow and sediment transport direction

From Equations (2.36) and (2.37), V_b in Equations (2.32) and (2.33) can be expressed as,

$$V_b = \sqrt{u_{bs}^2 + u_{bn}^2} \approx u_{bs} \tag{2.39}$$

It is because the order of u_{bn} is one order smaller than that of u_{bs}. $\tilde{u}_b^{\xi}$ and $\tilde{u}_b^{\eta}$ can be obtained from the following equations:

$$\tilde{u}_b^{\xi} = \frac{\partial \tilde{\xi}}{\partial s} u_{bs} + \frac{\partial \tilde{\xi}}{\partial n} u_{bn} = \left(\frac{\partial x}{\partial s}\frac{\partial \tilde{\xi}}{\partial x} + \frac{\partial y}{\partial s}\frac{\partial \tilde{\xi}}{\partial y} \right) u_{bs} + \left(\frac{\partial x}{\partial n}\frac{\partial \tilde{\xi}}{\partial x} + \frac{\partial y}{\partial n}\frac{\partial \tilde{\xi}}{\partial y} \right) u_{bn}$$

$$= \left(\cos\theta_s\, \tilde{\xi}_x + \sin\theta_s\, \tilde{\xi}_y \right) u_{bs} + \left(-\sin\theta_s\, \tilde{\xi}_x + \cos\theta_s\, \tilde{\xi}_y \right) u_{bn}$$

$$= \frac{1}{\xi_r} \{ \left(\cos\theta_s \xi_x + \sin\theta_s \xi_y \right) u_{bs} + \left(-\sin\theta_s \xi_x + \cos\theta_s \xi_y \right) u_{bn} \tag{2.40}$$

$$\tilde{u}_b^{\eta} = \frac{\partial \tilde{\eta}}{\partial s} u_{bs} + \frac{\partial \tilde{\eta}}{\partial n} u_{bn} = \left(\frac{\partial x}{\partial s}\frac{\partial \tilde{\eta}}{\partial x} + \frac{\partial y}{\partial s}\frac{\partial \tilde{\eta}}{\partial y} \right) u_{bs} + \left(\frac{\partial x}{\partial n}\frac{\partial \tilde{\eta}}{\partial x} + \frac{\partial y}{\partial n}\frac{\partial \tilde{\eta}}{\partial y} \right) u_{bn}$$

$$= \left(\cos\theta_s \, \tilde{\eta}_x + \sin\theta_s \, \tilde{\eta}_y \right) u_{bs} + \left(-\sin\theta_s \, \tilde{\eta}_x + \cos\theta_s \, \tilde{\eta}_y \right) u_{bn}$$

$$= \frac{1}{\eta_r} \left\{ \left(\cos\theta_s \eta_x + \sin\theta_s \eta_y \right) u_{bs} + \left(-\sin\theta_s \eta_x + \cos\theta_s \eta_y \right) u_{bn} \right\} \tag{2.41}$$

In which the following relations are used:

$$\frac{\partial x}{\partial n} = -\frac{v}{V} = -\sin\theta_s, \quad \frac{\partial y}{\partial n} = -\frac{u}{V} = \cos\theta_s \tag{2.42}$$

$$\frac{\partial x}{\partial s} = \frac{u}{V} = \cos\theta_s, \quad \frac{\partial y}{\partial s} = \frac{v}{V} = \sin\theta_s \tag{2.43}$$

The curvature of the streamline, $1/r_s$ is determined by the angle θ_s between the streamline in the mainstream direction and *x*-axis in Cartesian coordinates, as shown in **Fig. 2.5** below.

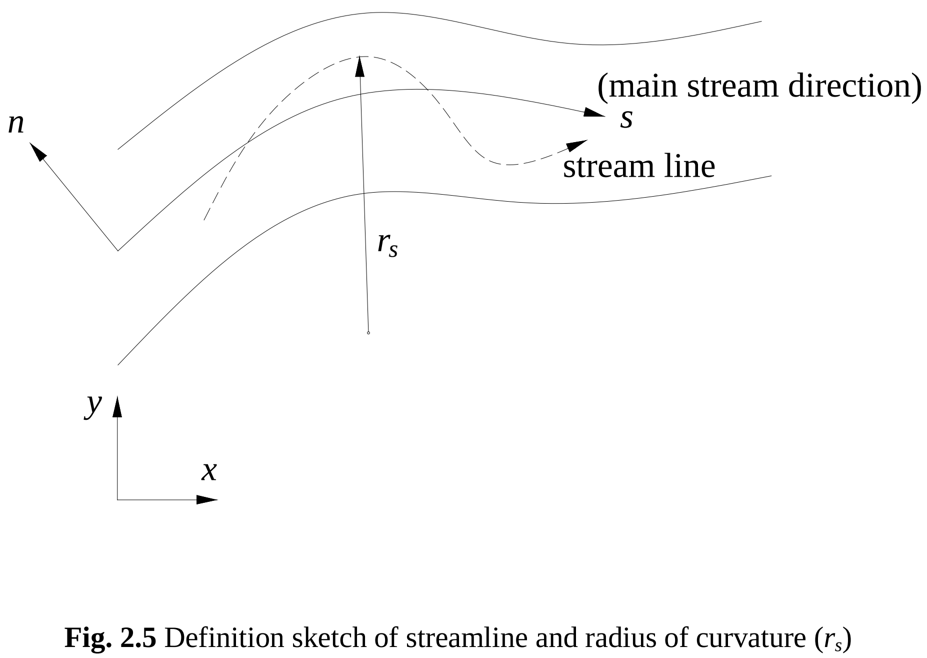


Fig. 2.5 Definition sketch of streamline and radius of curvature (r_s)

$$\frac{1}{r_s} = \frac{\partial \theta_s}{\partial s} \tag{2.44}$$

$$\theta_s = \tan^{-1}\left(\frac{v}{u}\right) \tag{2.45}$$

$$\frac{1}{r_s} = \frac{\partial}{\partial s}\left[\tan^{-1}(T)\right] = \frac{\partial}{\partial T}\left[\tan^{-1}(T)\right]\frac{\partial T}{\partial s} = \frac{1}{1+T^2}\frac{\partial T}{\partial s} \tag{2.46}$$

In which, $T = \dfrac{v}{u}$, and $\dfrac{1}{1+T^2} = \dfrac{1}{1+\left(v/u\right)^2} = \dfrac{u^2}{u^2+v^2} = \dfrac{u^2}{V^2}$

$$\frac{\partial T}{\partial s} = \frac{\partial}{\partial s}\left(\frac{v}{u}\right) = \frac{u\dfrac{\partial v}{\partial s} - v\dfrac{\partial u}{\partial s}}{u^2} \tag{2.47}$$

$$\frac{\partial}{\partial s} = \frac{\partial x}{\partial s}\frac{\partial}{\partial x} + \frac{\partial y}{\partial s}\frac{\partial}{\partial y} = \frac{u}{V}\frac{\partial}{\partial x} + \frac{v}{V}\frac{\partial}{\partial y} = \frac{u}{V}\left(\xi_x\frac{\partial}{\partial \xi} + \eta_x\frac{\partial}{\partial \eta}\right) + \frac{v}{V}\left(\xi_y\frac{\partial}{\partial \xi} + \eta_y\frac{\partial}{\partial \eta}\right) \tag{2.48}$$

According to Eq. 2.47, the curvature of streamline, $1/r_s$, in the moving boundary-fitted coordinate system is given by

$$\frac{1}{r_s} = \frac{1}{V^3}\left[u^2\left(\xi_x\frac{\partial v}{\partial \xi} + \eta_x\frac{\partial v}{\partial \eta}\right) + uv\left(\xi_y\frac{\partial v}{\partial \xi} + \eta_y\frac{\partial v}{\partial \eta}\right) - uv\left(\xi_x\frac{\partial u}{\partial \xi} + \eta_x\frac{\partial u}{\partial \eta}\right) - v^2\left(\xi_y\frac{\partial u}{\partial \xi} + \eta_y\frac{\partial u}{\partial \eta}\right)\right] \tag{2.49}$$

In considering suspended load transport, an exponential distribution of concentration is assumed in the vertical direction, and sediment transport expression is used to derive the local equilibrium concentration fields, which is employed to find the spatial distribution of sediment concentration utilizing the depth-averaged advection-diffusion equation. The two-dimensional equation for suspended load transports can be expressed as,

$$\frac{\partial}{\partial t}\left(\frac{Ch}{J}\right) + \frac{\partial}{\partial \xi}\left(\frac{Cu^{\xi}h}{J}\right) + \frac{\partial}{\partial \eta}\left(\frac{Cu^{\eta}h}{J}\right) = \frac{q_{su}}{J} - \frac{w_f c_b}{J} \tag{2.50}$$

For steady, uniform flow condition, this equation can be rewritten as,

$$\frac{\partial}{\partial t}(Ch)+\frac{\partial}{\partial x}(Cuh)+\frac{\partial}{\partial y}(Cvh)=q_{su}-w_f c_b \tag{2.51}$$

With

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=0 \qquad \text{: Advection phase} \tag{2.52}$$

And

$$\frac{\partial C}{\partial t}=\left(q_{su}-w_f c_b\right)/h \qquad \text{: Non-advection phase} \tag{2.53}$$

In which C is the depth-averaged volumetric concentration of suspended sediment, c_b is the reference concentration (here reference level is at b = 0.05h from the bed), q_{su} is the rate of entrainment of suspended sediment from unit area of bed surface, w_f = the fall velocity of sediment. Exponential distribution of suspended sediment is assumed in the model, which can be written as,

$$C=c_b\exp(-\beta_s\varsigma) \tag{2.54}$$

With $\beta_s=w_f h/\varepsilon_s$, $\varsigma=z/h$, where ε_s = the depth-averaged diffusion coefficient of sediment = $\kappa u_* h/6$. Integrating Eq. 2.53, the depth-averaged concentration then can be derived as,

$$C=\frac{1}{h}\int_0^1 c\,d\varsigma=\frac{c_b}{\beta_s}\left(1-\exp(-\beta_s)\right) \tag{2.55}$$

According to Itakura and Kishi (1980), the pick-up rate q_{su} can be estimated from the following expression:

$$q_{su}=K_c\left(\alpha_*\frac{\rho_s-\rho}{\rho_s}\frac{gd}{u_*}\Omega-w_f\right) \tag{2.56}$$

With $$\Omega = \frac{\tau_*}{B_*} \frac{\int_{a'}^{\infty} \zeta \frac{1}{\sqrt{\pi}} \exp\left(-\zeta^2\right) d\zeta}{\int_{a'}^{\infty} \frac{1}{\sqrt{\pi}} \exp\left(-\zeta^2\right) d\zeta} + \frac{\tau_*}{B_* \eta_0} - 1 \tag{2.57}$$

where $a' = B^* / \tau_* - 1/\eta_0$; in which $B_* = 0.143$ and $\eta_0 = \sqrt{2}\sigma = 0.5$ could be adopted in the model. A value of $\alpha_* = 0.14$ was determined by an examination of the data reported by Kishi *et al.* (1966), and a value of K_c = 0.008 is determined so as to fit many data for c_b. Also $\zeta = r' / \sqrt{2}\sigma =$ a dummy variable in the equation, where r' is fluctuating component of r and r is normalized hydrodynamic force, and σ^2 is variance of hydrodynamic force. For the fall velocity of suspended load, the following Rubey's (1933) equation is used:

$$\frac{w_f}{\sqrt{\Delta_g g d}} = \sqrt{\frac{2}{3} + \frac{36\nu^2}{\Delta_g g d^3}} - \sqrt{\frac{36\nu^2}{\Delta_g g d^3}} \tag{2.58}$$

where ν is kinematic viscosity = 0.01 cm^2/s, Δ_g = submerged specific gravity of sediment = 1.65, d = sediment size (cm).

Two-dimensional sediment continuity equation, when only bedload contributes the change in bed level, can be expressed as,

$$\frac{\partial z_b}{\partial t} + \frac{1}{1-\lambda}\left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y}\right] = 0 \tag{2.59}$$

where q_x and q_y are bedload transport rates per unit width in x and y directions, respectively; and λ is porosity of bed materials. It has been depicted in the following figure (**Fig. 2.6**),

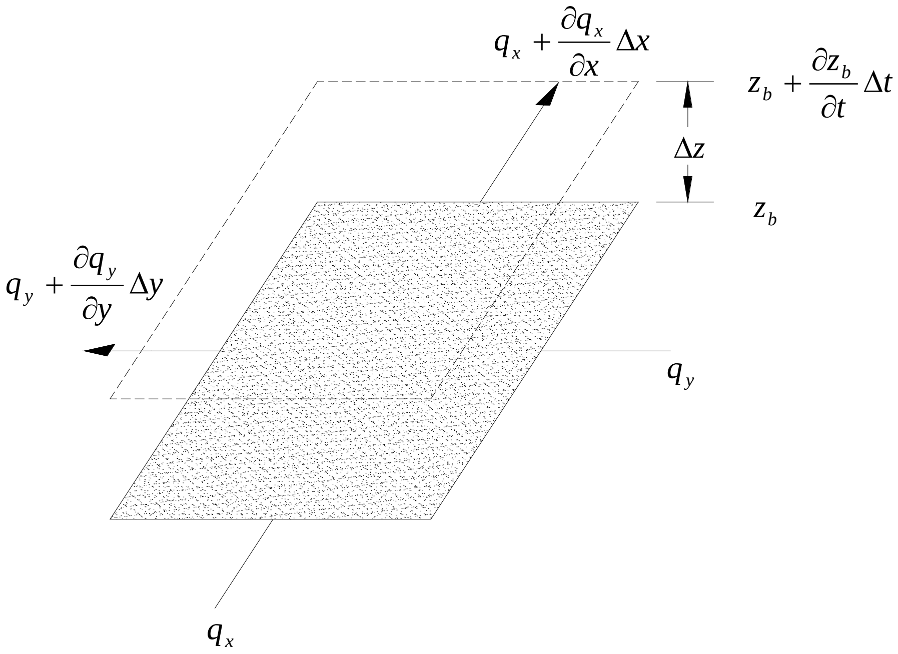


Fig. 2.6 Description of bedload transport and bed evolution

As both bedload and suspended load transports occur in alluvial rivers with fine sand, finally the bed deformation is determined using two-dimensional sediment continuity equation, can be written as,

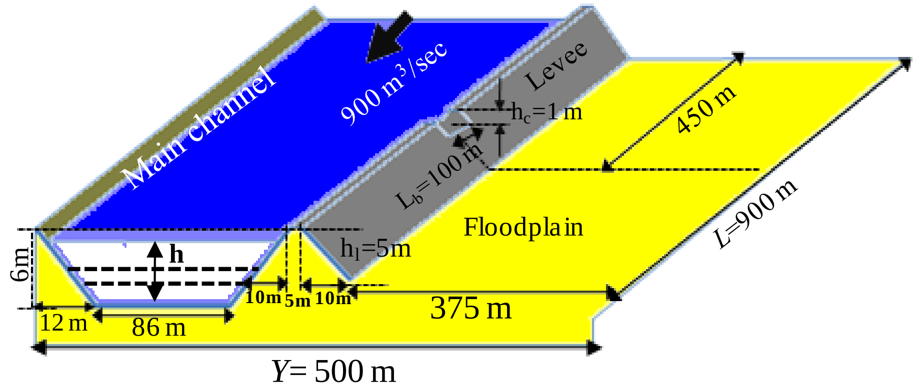
$$\frac{\partial z_b}{\partial t} + \frac{1}{1-\lambda}\left[\left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y}\right) + \left(q_{su} - w_f c_b\right)\right] = 0 \tag{2.60}$$

Upwind differential scheme for advection term is utilized; also CIP (Yabe and Ishikawa 1990) method is available to apply.

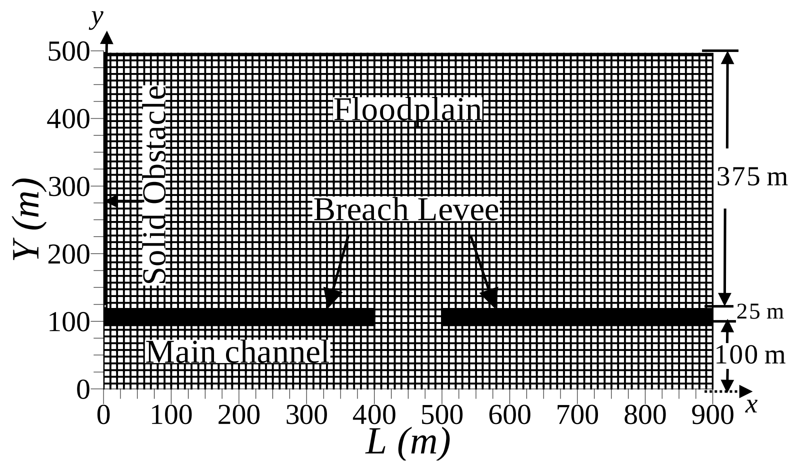
2.3 Numerical Approach

2.3.1 Model Setup

As for the simulation scheme, the river channel, levee, floodplain and flow parameters are selected in correspondence with the typical field of Sirajganj district and Jamuna River in Bangladesh. Schematic model area is spatially limited to in a part of actual field, which represents only 1/5500 of actual horizontal extent. For the first case of simulation, computation reach is 900 m long (L) and 500 m wide (Y) (river channel=100 m, levee=25 m and floodplain=375 m) with a bed slope of river channel is 7.5 cm/km. **Fig. 2.7 (a, b)** depicts one of the model fields for simulation, which approximates the levee breach area of the JRRBE, Khokshabari and model layout with computational domain (square cells with Δx=5 m and Δy=5 m) of river channel, breach levee and floodplain, respectively. Levee slope is assumed as S_l= 1:2 on both land side and river side and levee height is taken as h_L=5 m from the floodplain and 6 m from the river bed. Idealized flow and sediment parameters are considered in the computation. For the first case of simulation, inflow discharges in the river channel before the breach, 900 m^3/s (Q) is considered with the peak flow of Jamuna River in flooding season, and the median size of sediment is chosen as d_m= 0.10 mm for the whole domain. Overflow starts from the hypothetical notch on top of the levee as a trigger of the breach where the initial breach is 100 m long (L_b) and crest height is 4 m (h_c) from the floodplain. Though the river discharge has a hydrograph in general, uniform discharge corresponding to the peak is assumed here. Solid boundary wall is imposed on the left side of the floodplain to protect the direct flow into the floodplain.



(a)



(b)

Fig. 2.7 (a) schematic sketch of simulated model: (b) Plan view of the modeled area with river channel, breach levee and floodplain.

2.3.2 Procedure

The details of the model equations are described in the preceding section. Equations are solved for the unknown nodal values by an iterative process. First, the flow field is computed utilizing initial and boundary conditions; the sediment transport field is then computed to evaluate the rates of sedimentation, and followed by bed topography changes. In considering suspended sediment, an exponential profile of concentration is assumed to know the planar distribution of depth-averaged concentration and the 2D advection-diffusion equations are solved. Finally, the bed deformation is determined using the 2D sediment continuity equation. A computational time step is used of 0.002 second is set, and the model runs are continued for the duration of 60 minutes, when the variables are considerably reduced. By numerical calculation, the flow behavior and the process of sedimentation around the breach and in the floodplain can be described with morphological changes, and can be realized spatial characteristics of the phenomena as well as temporal evolution of the levee breach. **Fig. 2.8** depicts the outline of the simulation steps for computation.

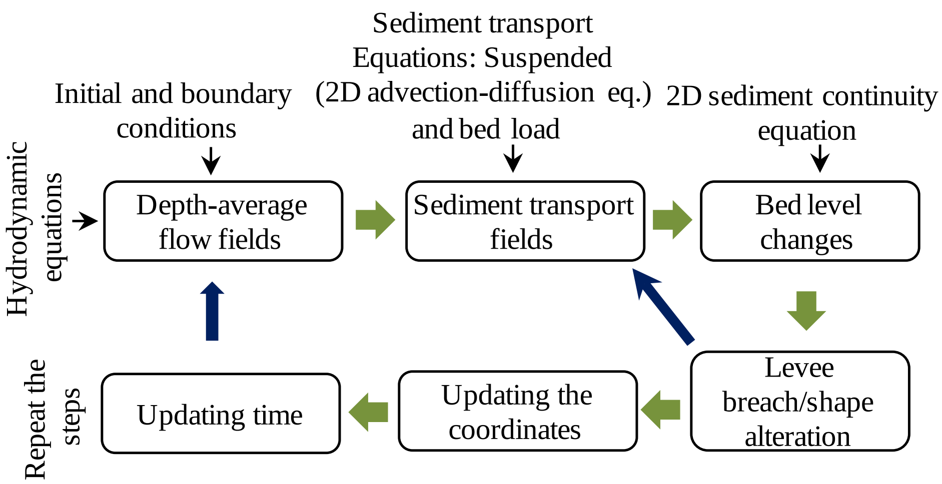


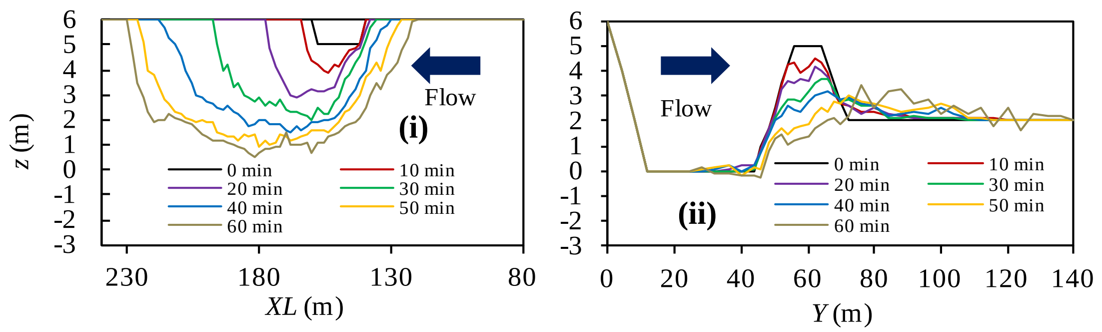
Fig. 2.8 Outline of model computation steps.

2.4 Model Validation

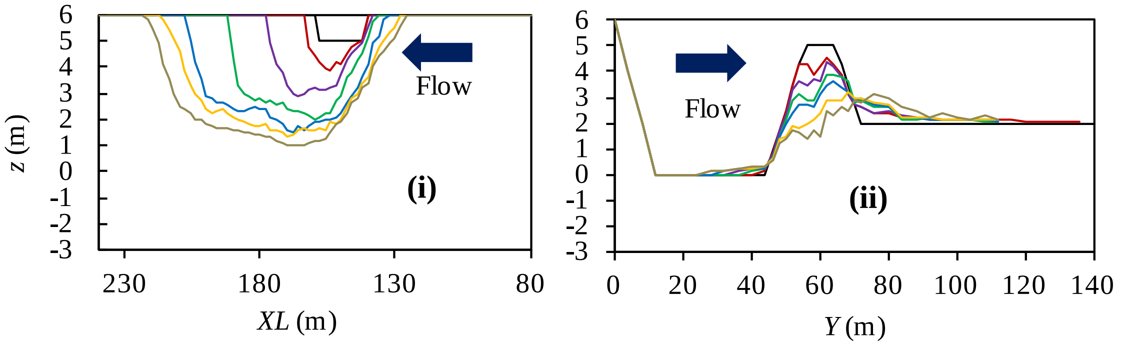
The present model is verified with the NHSED2D model study by Tsujimoto *at el.* (2006). Both NHSED2D and RIC-Nays models are based on 2D horizontal flow model and coupling with the bed-load transport and morphological change, where the area for simulation includes river, flood levee and floodplain. Using NHSED2D model, levee breach process of a river by overflow erosion have been investigated. The framework of this model was developed by Nagoya University Hydraulic Laboratory (Goto et al., 2001). The following sets were used in this study: Computation reach is 300 m long and floodplain is 300 m x 225 m, river bed slope=1/3690, levee slope=1:2, channel bottom, B=32 m, levee height 6 m, material of levee and floodplain, d=0.375 mm, river discharge before breach, Q=750 m^3/s, initial crest opening 1 m, initial breach length, L_b=20 m and duration, t=55 min. The simulation results have been discussed with an example on actual levee breach

(Kariyata river and Ikarashi river levee breach 2004) and showing inundation using simulation in the Shinkawa river basin for Tokai heavy rainfall in 2000.

Fig. 2.9 depicts the comparison between NHSED2D and RIC-Nays model simulation results with a same scale. Both temporal growth of breaching and the loss of levee cross section of NHSED2D model are well reproduced with RIC-Nays numerical scheme at short duration, though some discrepancies are present in the long run of the breach evolution process. So, it can be concluded that the present study model is capable for levee breach simulation.



(a) NHSED2D Model results: (i) Growth of breaching section at y= 62 m (front view)
(ii) Loss of levee cross-section at x = 170 m (side view)



(b) RIC-Nays Model results: (i) Growth of breaching section at y = 62 m (front view)
(ii) Loss of levee cross-section at x = 170 m (side view)

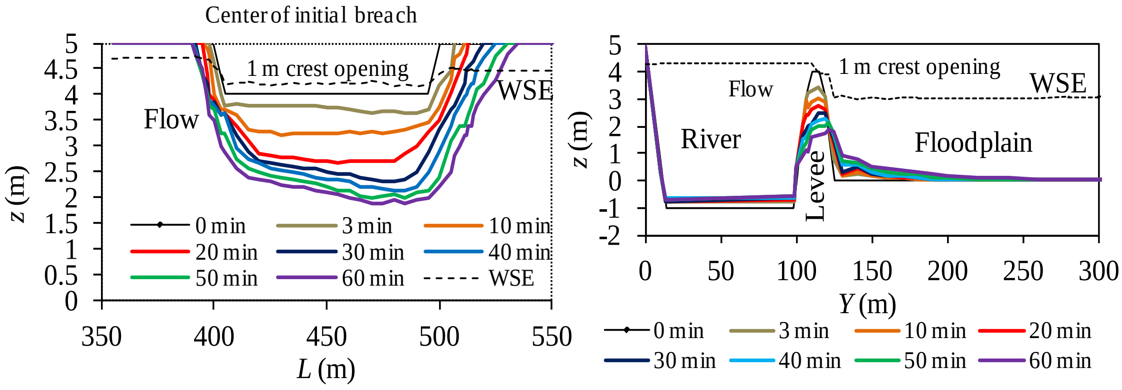
Fig. 2.9 Comparison of NHSED2D and RIC-Nays model simulation results

2.5 Results and Discussion

Selected results of the flow-fields, deviation of bed elevations and breach propagation are presented in this section to understand the levee breach disasters in low-land using typical model study field.

2.5.1 Evolution Process with Time

In Bangladesh, floodplain was formed by flooding, and the levee was constructed by dredging from the river bed materials. Normally, the river bed is lower than the floodplain level in spite of the large amount of sediment transport due to elaborate efforts of dredging. Therefore, these three components are treated simultaneously in the simulation model. The evolution process of a levee is carried out for the river inflow discharge of 900 m^3/s with duration of 60 minutes provided an initial crest opening of 100 m long and 1 m deep from the top of the levee crest and floodplain slope as S=10 cm/km is taken into consideration are shown in **Fig. 2.10 (a, b)**. The breach evolution is expressed as the temporal growth of breaching section (front view at y=115 m) and temporal loss of levee cross section (side view at L=475 m). Obviously, the breaching section for higher duration is higher, and it results that the large amount of discharge causes serious inundation in the floodplain. In addition, not only the inundation but also sediment deposition in the floodplain is more than lower duration, which causes another aspect of a flood disaster inside the boundary of the levee. Furthermore, initial levee breaching increased with time as well as sediment deposition thickness and volume is also increased, which also showed during field investigation in Bangladesh (Islam, *et al.,* 1994a). The relationships between the horizontal breach widening and vertical erosion are shown in **Fig. 2.11** for the inflow discharge of 900 m^3/s and initial breach is 100 m long and 1 m deep from the top of the levee. Both of the horizontal widening and vertical erosion are measured considering with the maximum expansion of the levee for respective time steps. Initially the breach is expanded rapidly both in horizontal and vertical direction then the rate is reduced with time.



(a) (b)

Fig. 2.10 Evolution process of levee reach with time: (a) temporal growth of breaching section (front view at y=115 m); (b) temporal loss of levee cross section (side view at L=475 m).

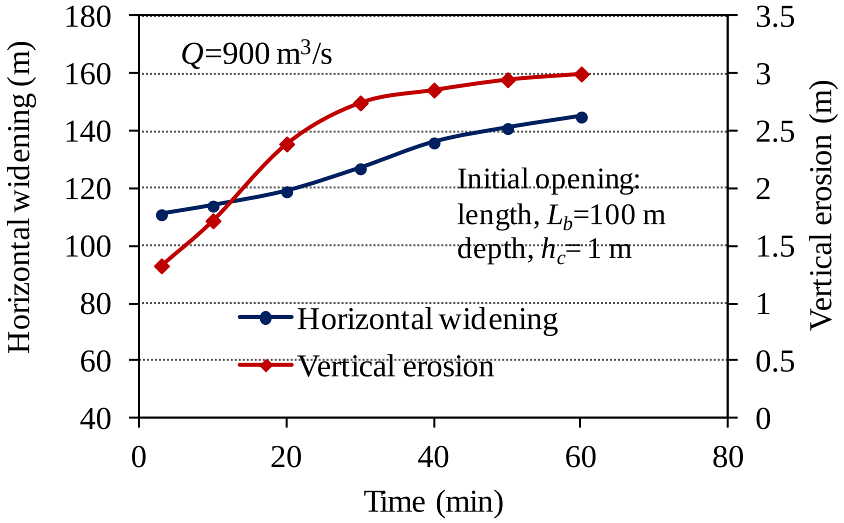


Fig. 2.11 Relationships between horizontal widening and vertical erosion of the levee with time for inflow discharge of 900 m^3/s.

The flood flow and morphological changes have been observed over the floodplain for the duration of 60 minutes is shown in **Fig. 2.12,** also the inundation on the floodplain and the river flow rates with time are presented in **Fig. 2.13** for the same inflow discharges. For simulation analyses, some distance of the run-up reach is necessary in the upstream of the river channel to avoid an unexpected degradation in the river bed. For the time being, this kind of setting was not considered in this study. Due to this reason, during the analyses of simulation results for investigation of the process of inundation and sedimentation on the floodplain by the breach small amount of deposition appear near the upstream of the channel as because of lack of run-up reach setting with the existing domain. Though, this study not only concern about river bed changes phenomena but also levee evolution process as well as inundation and sedimentation process on floodplain. Although some deposition occurs at the upstream on the river bed, but the calculated result demonstrates effective analyses of the characteristics of levee breach and disaster in low-land. Initially, river water depth investigated high, and it is decreased with time in the main channel because of the river water is diverted to the floodplain by the breach. Floodplain inundation depth increased up to definite duration. It can be concluded that after certain period of time at any specific discharges, inundation depth is not increased in the floodplain, although duration increased. The sediment deposition thickness decreased gradually towards the downstream of the floodplain with increased the distance from the location of the breach.

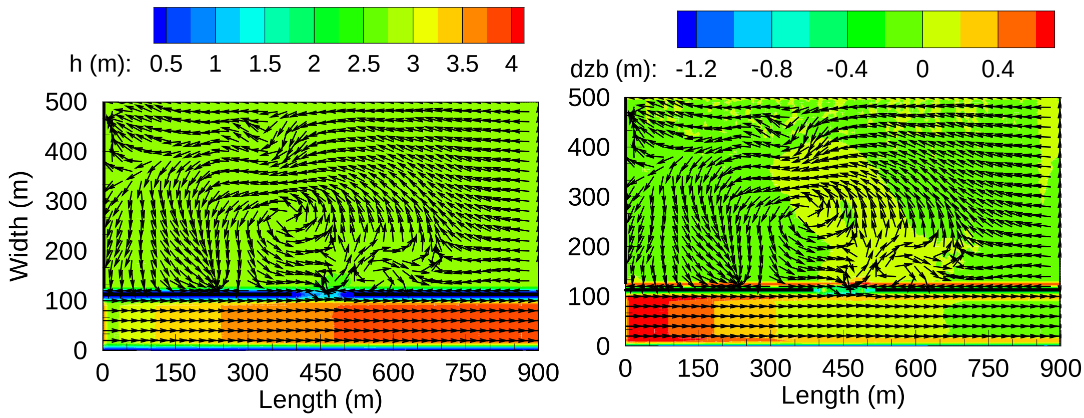


Fig. 2.12 Spatial characteristics of flow and morphological changes at levee breach (t=60 min); contours indicate the water depth (h) and deviation of bed elevation (dzb).

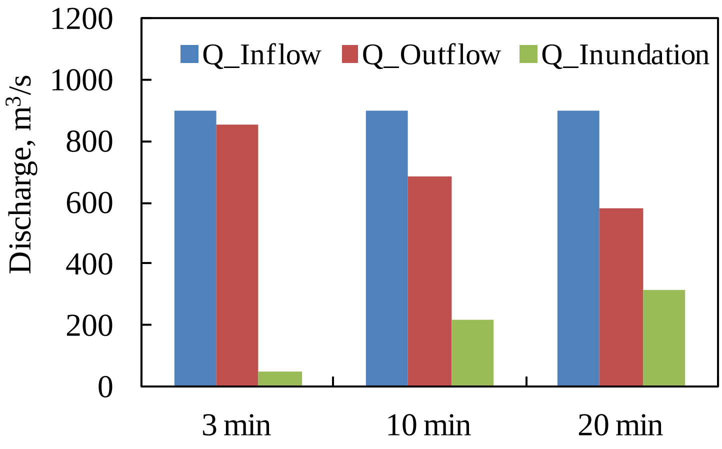


Fig. 2.13 Discharge into the river and floodplain with time

Fig. 2.14 depicts the transverse distribution of velocity components *u* and sedimentation profile along the main channel and floodplain at *L*=475 m on breach with time. Overtopping water passes from the river to the floodplain by the breach initially at high-flow velocity and the velocity is reduced with time because of the elevation difference in the levee crest to floodplain. River water flows to the downstream into the main channel, and some portion of water is diverted to the floodplain by the breach levee. It is clearly seen that the transverse distribution of velocity components *u* is observed high at short duration near the breach inside the river, top of the levee and as well as in the floodplain adjacent to the breach. So, it is concluded that along the flow direction, velocity is high, and it is decreased with time. Furthermore, velocity distribution pattern is not same in the floodplain due to the vortex form in the floodplain. Sediment deposition is occurred near the breach and along the flow direction in the floodplain. Depth of sedimentation increased with time, it is clearly observed at *L*=475 m.

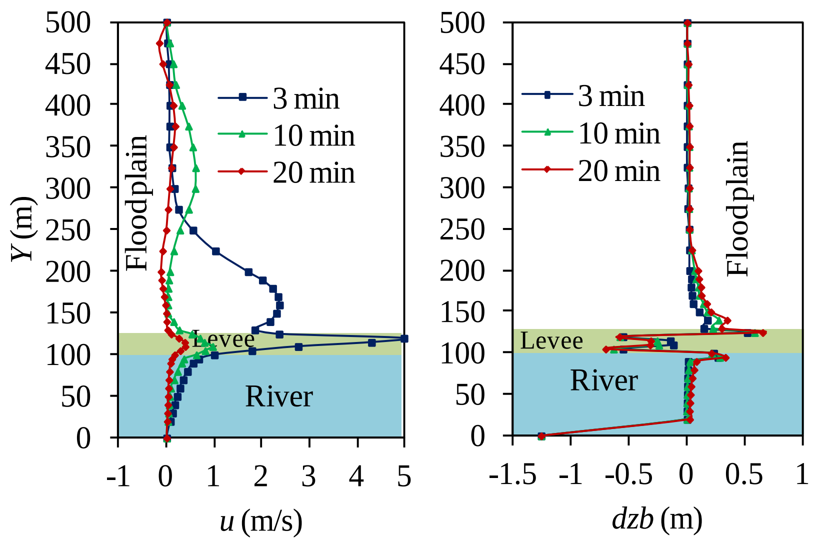


Fig. 2.14 Transverse distribution of velocity (u) and sedimentation (dzb) profile at L=475 m on breach with time where h_c= 4 m from floodplain.

In **Fig. 2.15**, shows the comparisons of the flow and sedimentation pattern over the floodplain where the effect of the floodplain slopes are taken into consideration. The slope criterion (10 cm/km) is taken from an actual field condition. Due to sloping floodplain, the mass transfer rate is observed high from the river to the floodplain by the breach. Velocity of flow in the floodplain is changed rapidly with sloping ground, and the sediment deposition rate is slightly more is observed in the sloping floodplain near the breach.

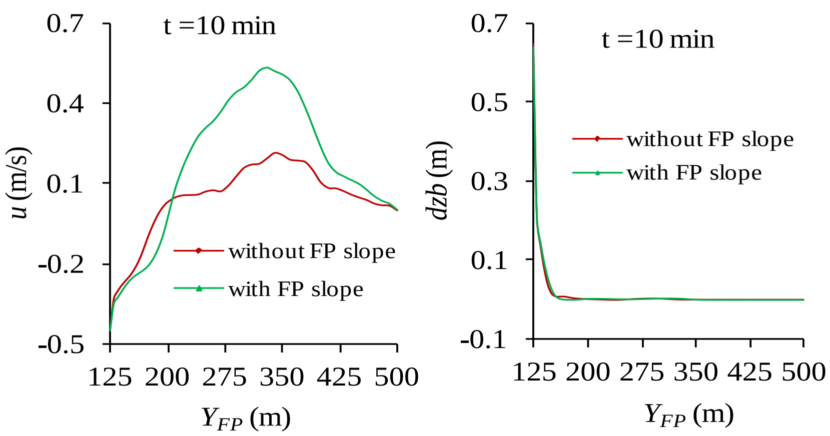


Fig. 2.15 Comparison of transverse velocity and sedimentation profile in the floodplain at L=450 m on breach considering with and without floodplain slope where h_c=4 m from Floodplain

2.5.2 Effect of Inflow Discharges

In this section, the levee breach widening is compared with the different inflow discharges. **Figs. 2.16, 2.17** and **2.10** (previous section) shows the calculated results demonstrated by the temporal development of the breach for the different inflow discharges of 800, 850 and 900 m^3/s, respectively. From the calculated results, both in the growth of breaching section and the loss of levee cross section for higher discharges are higher, and it results that the larger amount of discharge causes more inundation in the floodplain. Not only, inundation but also sediment deposition rate in the floodplain is more as compared to lower discharges.

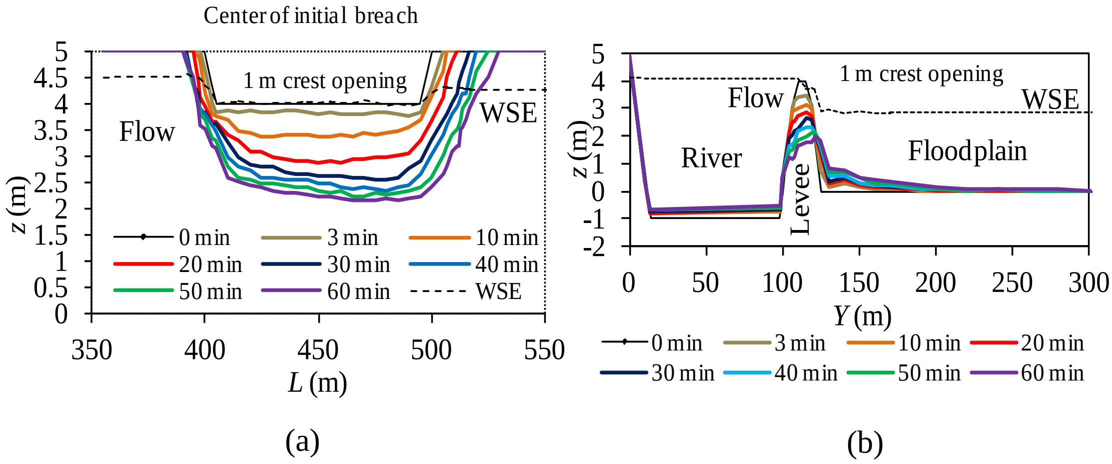


Fig. 2.16 Evolution process of levee reach with time for Q=800 m^3/s: (a) temporal growth of breaching section (front view at y=115 m); (b) temporal loss of levee cross section (side view at L=475 m).

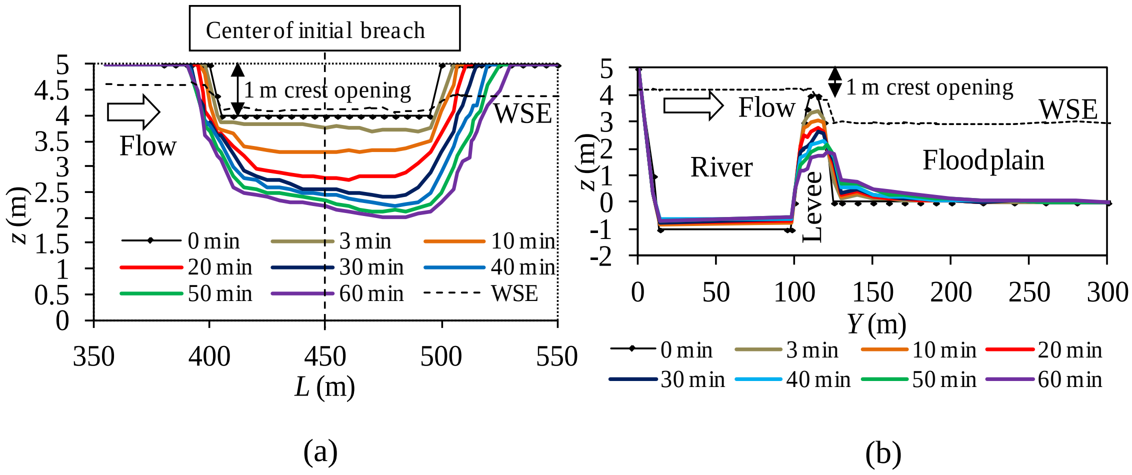


Fig. 2.17 Evolution process of levee reach with time for Q=850 m^3/s: (a) temporal growth of breaching section (front view at y=115 m); (b) temporal loss of levee cross section (side view at L=475 m).

Fig. 2.18 depicts the comparisons of the relationships between the horizontal and vertical breaching with time for the different inflow discharges of 800, 850 and 900 m^3/s, respectively. Both of the horizontal widening and vertical erosion are measured considering with the maximum expansion of the levee for respective time steps. Larger inflow discharge exposes longer breach expansion in horizontal and vertical direction as well as more inundation and sediment outflow by the breach to the floodplain.

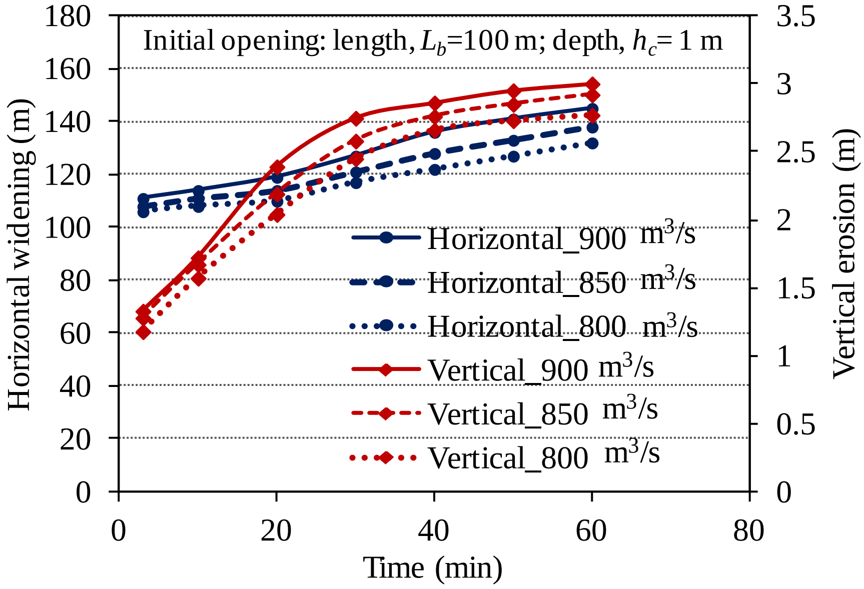


Fig. 2.18 Relationships between horizontal widening and vertical erosion of the levee with time for different inflow discharges.

Inundation and sedimentation pattern over the floodplain at different inflow discharges are shown in **Fig. 2.19**. The discharge dependent inundation and sedimentation process are observed over the floodplain for 60 minutes each with an inflow discharge of 800, 850 and 900 m^3/s, respectively. Floodplain inundation depth is increased with the inflow discharges in the main channel. Larger area of floodplain sedimentation is observed with higher inflow discharges. Near the breach, velocity is observed high at any inflow discharges, and then it is decreased due to the river water passes through the levee crest with the gradient difference from the crest to the floodplain. Sediment deposition area is increased with the increased of inflow discharges, and depth is gradually decreased in the downstream of the floodplain along the flow direction.

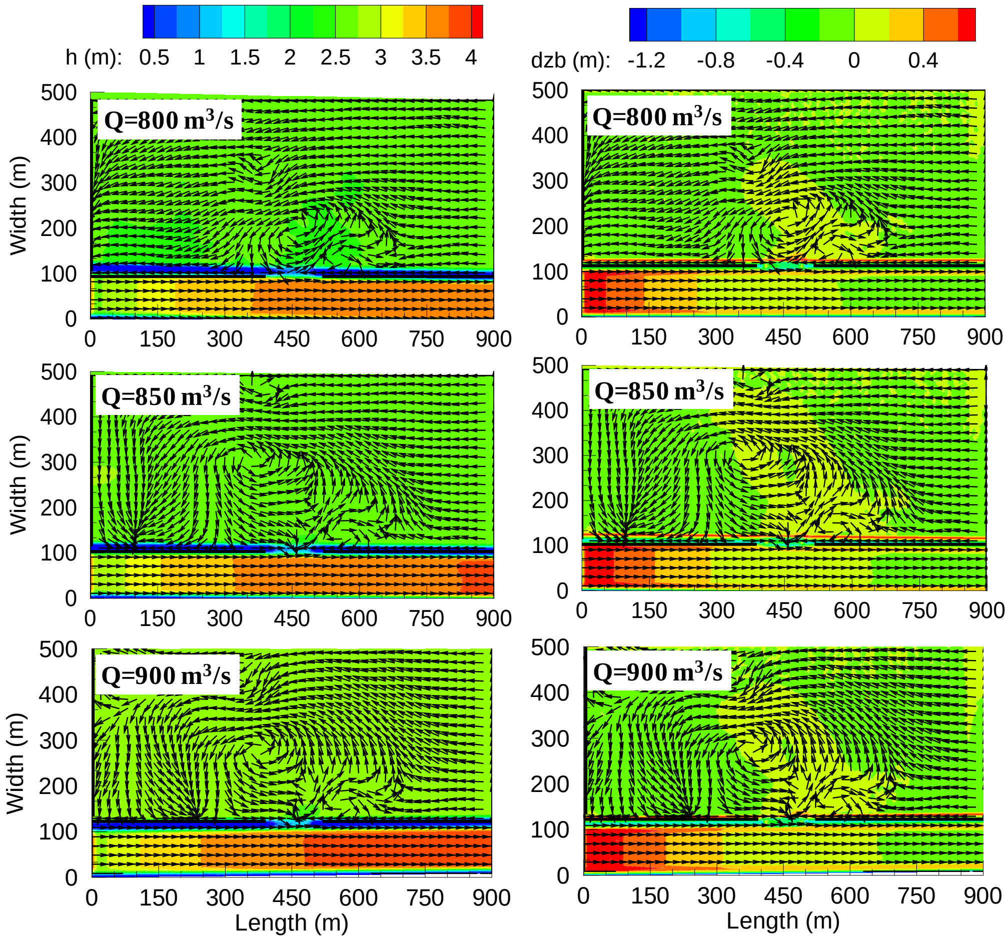


Fig. 2.19 Simulated flow field in the vicinity of the river, breach levee and floodplain where h_c=4 m from floodplain; contours indicate the water depth (*h*) and deviation of bed elevation (*dzb*) at 800, 850 and 900 m^3/s discharges (top to bottom), respectively.

The floodplain inundation and river flow with three different river inflow discharges are presented in **Fig. 2.20** and each of same duration is 60 minutes. Larger amount of water is passed by the breach to the floodplain with higher inflow discharges, which brings more inundation on the floodplain.

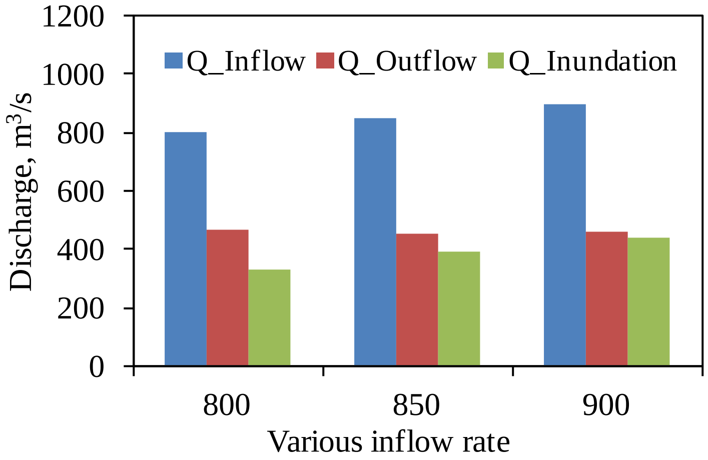


Fig. 2.20 The River flow and inundation on floodplain with different inflow discharges

Comparisons of the floodplain sedimentation due to levee breach for different inflow discharges are depicted in **Fig. 2.21** for the duration of 60 minutes. Higher inflow discharges has been carried out higher volume of sedimentation on the floodplain.

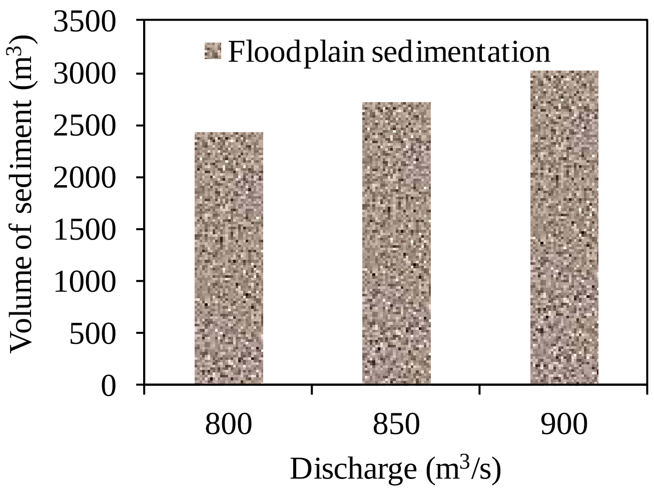


Fig. 2.21 Comparisons of sedimentation on floodplain for different inflow discharges

2.5.3 Effect of Initial Breach Lengths in the levee

Levee breach is considered to initiate in the middle of the levee with the crest opening of h_c=4 m from the floodplain and 1 m from top of the levee. **Fig. 2.22** shows the sketch of the three different initial breach length of the levee as narrow to wide, which are considered as 100 m, 200 m and 300 m, respectively.

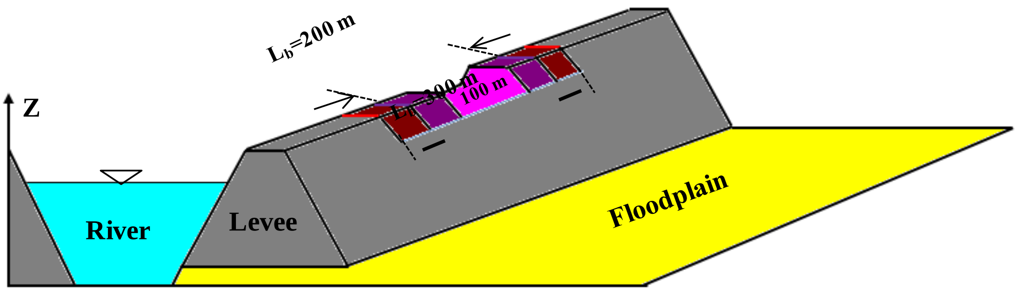


Fig. 2.22 Defining sketch of initial breach opening of the levee

In this section, the levee breach widening is compared with the three different initial breach opening. **Figs. 2.10** (previous section)**, 2.23** and **2.24** shows the calculated results demonstrated by the temporal development of the breach with same discharges is 900 m^3/s for the three different initial breach length of 100 m, 200 m and 300 m, respectively. Based on the calculated results, the growth of breaching section and loss of levee cross section are rapid with narrow opening as compared to wider initial breach length. Though the breach widening is less with wider initial opening, it results that the larger amount of inundation flow passes by the breach to the floodplain with more area of sedimentation because of wider initial breach length.

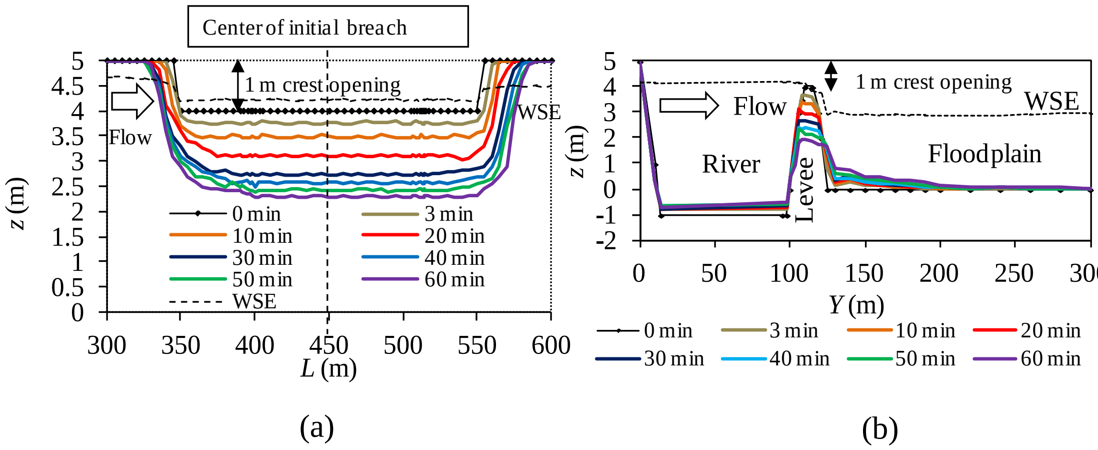


Fig. 2.23 Evolution process of levee reach with time for L_b=200 m: (a) temporal growth of breaching section (front view at *y*=115 m); (b) temporal loss of levee cross section (side view at *L*=475 m).

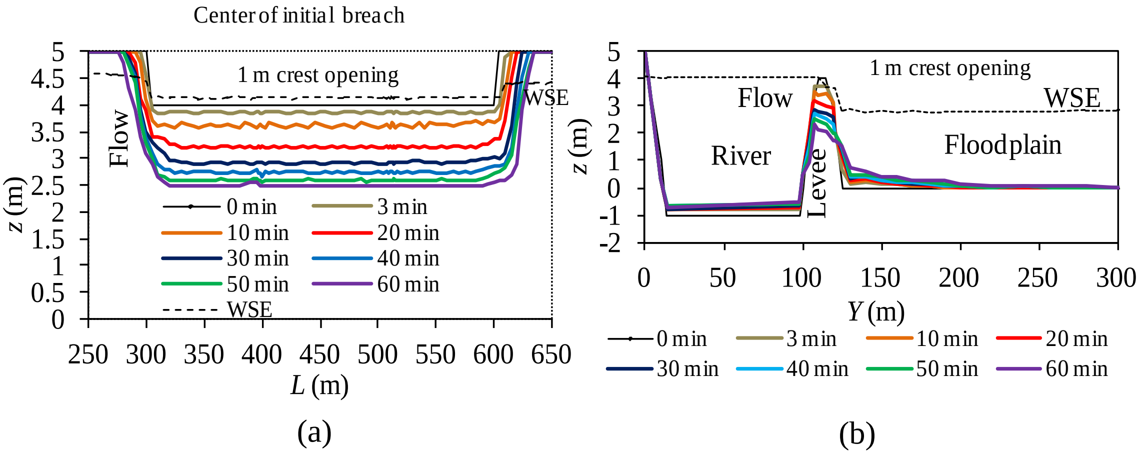


Fig. 2.24 Evolution process of levee reach with time for L_b=300 m: (a) temporal growth of breaching section (front view at y=115 m); (b) temporal loss of levee cross section (side view at L=475 m).

Fig. 2.25 depict the comparisons of the relationship between the horizontal and vertical breaching with time for the three different initial breach length of the levees are 100 m, 200 m and 300 m, respectively and each of same inflow discharges of 900 m^3/s and initial crest depth of 1 m from the top of the levee. Both of the horizontal widening and vertical erosion are measured considering with the maximum expansion of the levee for respective time steps. Narrow initial opening exposes rapid vertical erosion than wider one.

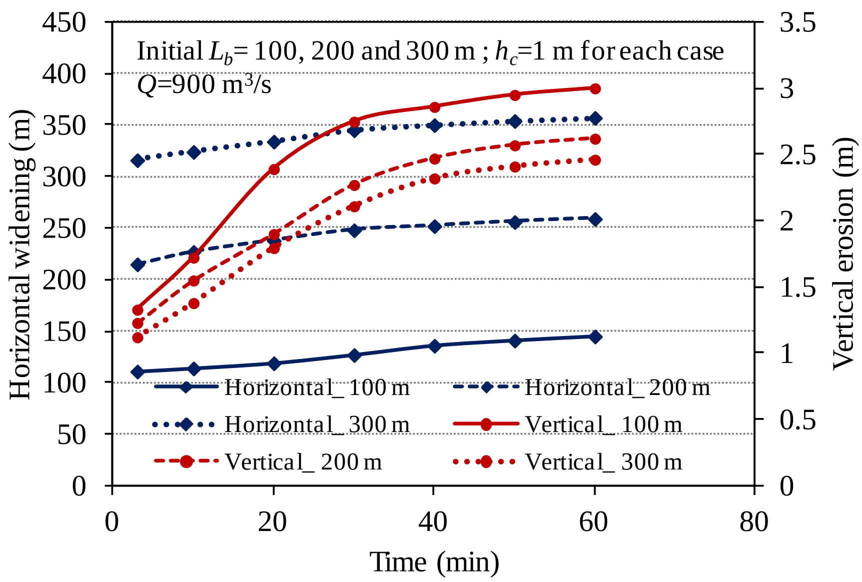


Fig. 2.25 Relationships between the horizontal widening and vertical erosion of the levee with time for different initial breach length in the levee

The inundation and the sedimentation process over the floodplain are investigated with three different initial length of the breaches are 100 m, 200 m and 300 m, and each of 60 minutes duration and same inflow discharges of 900 m^3/s, which are shown in **Fig. 2.26**. Floodplain inundation depth is increased with the larger breaches than the smaller one. Sediment depth and deposition area is more, when the levee breach overflow is happened with larger initial length of the breach. Near breach velocity is observed high with narrow opening and it reduced with time as well as increases the length of the initial opening of the levee. Sediment deposition took place over the floodplain along the flow direction.

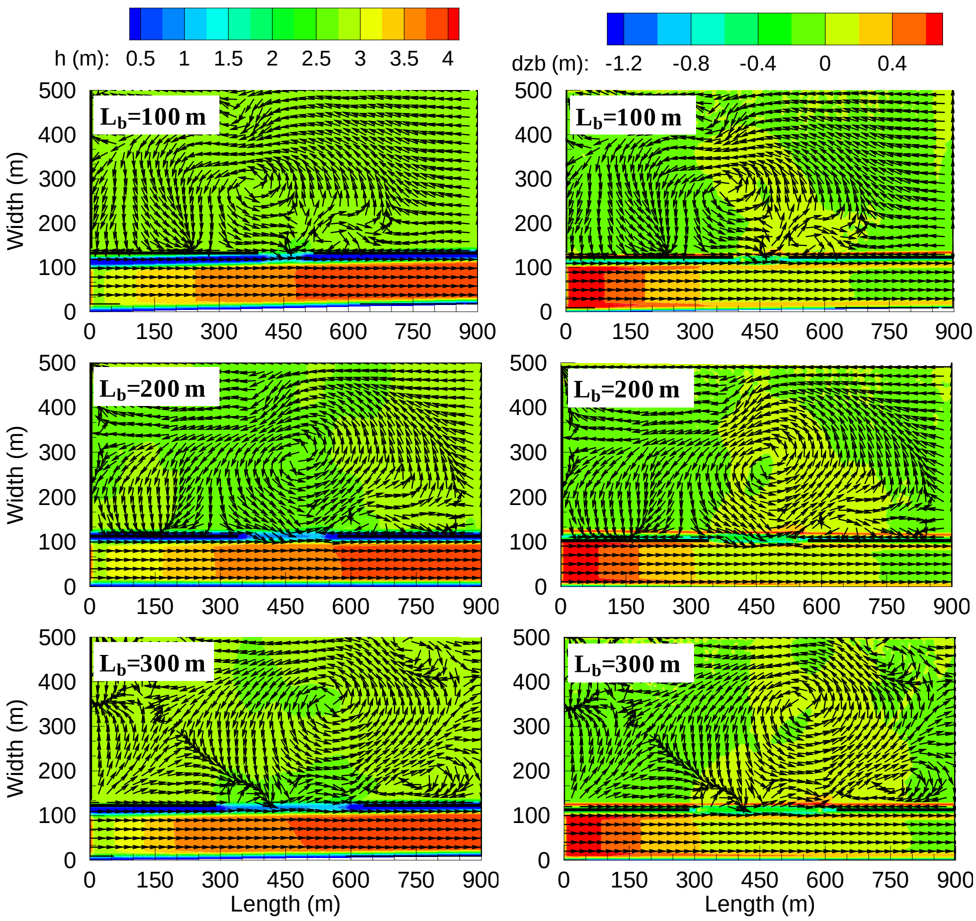


Fig. 2.26 Simulated flow field in the vicinity of the river, breach levee and floodplain where h_c=4 m from floodplain; contours indicate the water depth (h) and deviation of bed elevation (*dzb)* at 100, 200 and 300 m breach length (top to bottom), respectively.

The river flow and the floodplain inundation with various initial length of the breach opening are presented in **Fig. 2.27**. More inundation discharge is passed by the breach to the floodplain with larger breach opening.

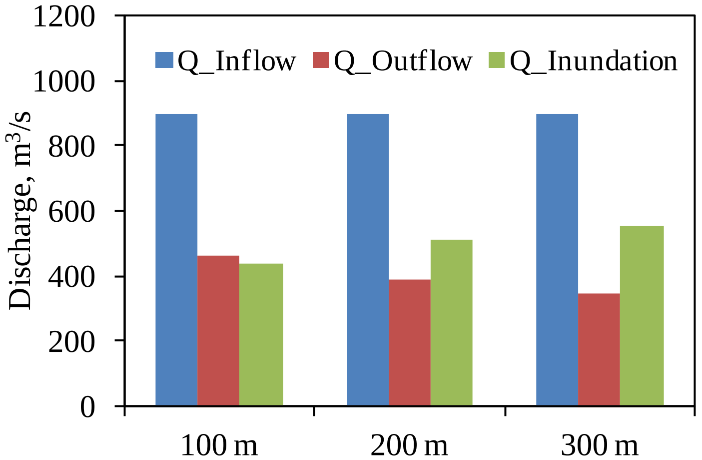


Fig. 2.27 The river flow and the floodplain flow with various length of initial breach opening.

The comparisons of the floodplain sedimentation due to levee breach for the three different initial breach lengths are depicted in **Fig. 2.28** with same duration of 60 minutes. Higher sedimentation volume on the floodplain is observed with wider initial breaches of the levee as compared to the narrow initial opening.

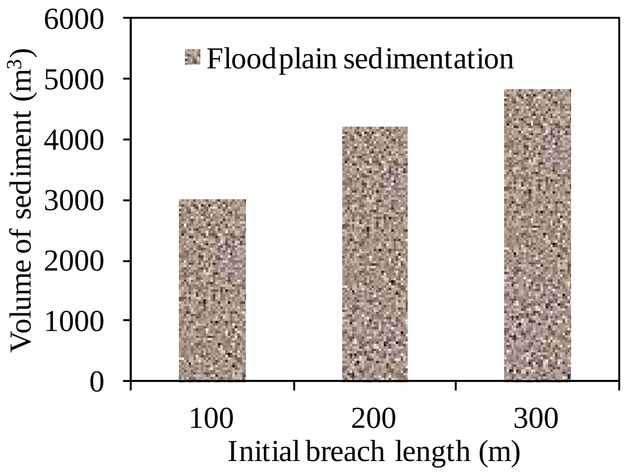


Fig. 2.28 Comparisons of sedimentation on floodplain for different initial breach length of the levee

2.5.4 Effect of Level Difference between River Bed and Floodplain

A river in a fluvial fan often flow the highest crest, and the river bed is higher than the floodplain. This type of river requires higher levees, and it has the high risk of disaster on levee breach during the flood.

At present situation of Bangladesh, although the water and sediment load is same from upstream catchment, but the levee breach risk are increases due to the raising of the river bed level by gradual sediment deposition on the river bed. Considering the above criteria, the flow dynamics and sedimentation process are compared with the different relative height of river bed in order to recognize how the river bed height are influences on the levee breach as well as disaster risk in the floodplain. **Fig. 2.29** depicts definition sketch for three different relative height of river bed, which are higher river bed (HRB) at 1 m as compare to floodplain, river bed and floodplain at the same level and lower river bed (LRB) at 1 m as compare to floodplain level.

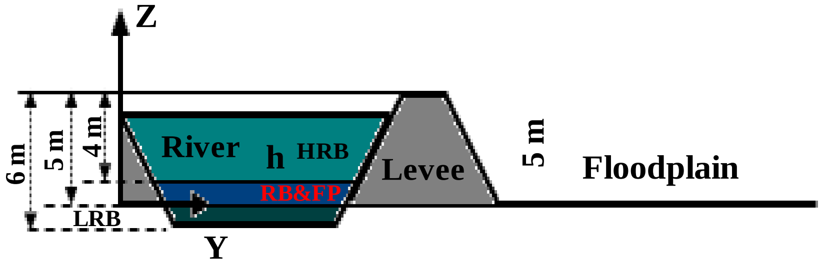


Fig. 2.29 Defining sketch for different river bed levels.

The flow dynamics and the morphological changes at three different river bed levels over the floodplain are investigated, which are carried out for 15 minutes and provided an initial breach opening length of 100 m and deep is 1 m from the top of the levee, and the river inflow discharges of 900, 800 and 700 m^3/s for the low, same and high river bed levels, respectively, as shown in **Fig. 2.30 (a-c)**. To maintain the same water surface elevation (WSE) over the crest; river inflow discharges are varied. The flood water is diverted rapidly by the breach to the floodplain at higher river bed height. It causes more inundation and sedimentation in the floodplain by the breach as well as rapid growth of the levee breaches which causes severe damage to the inhabitant in the floodplain.

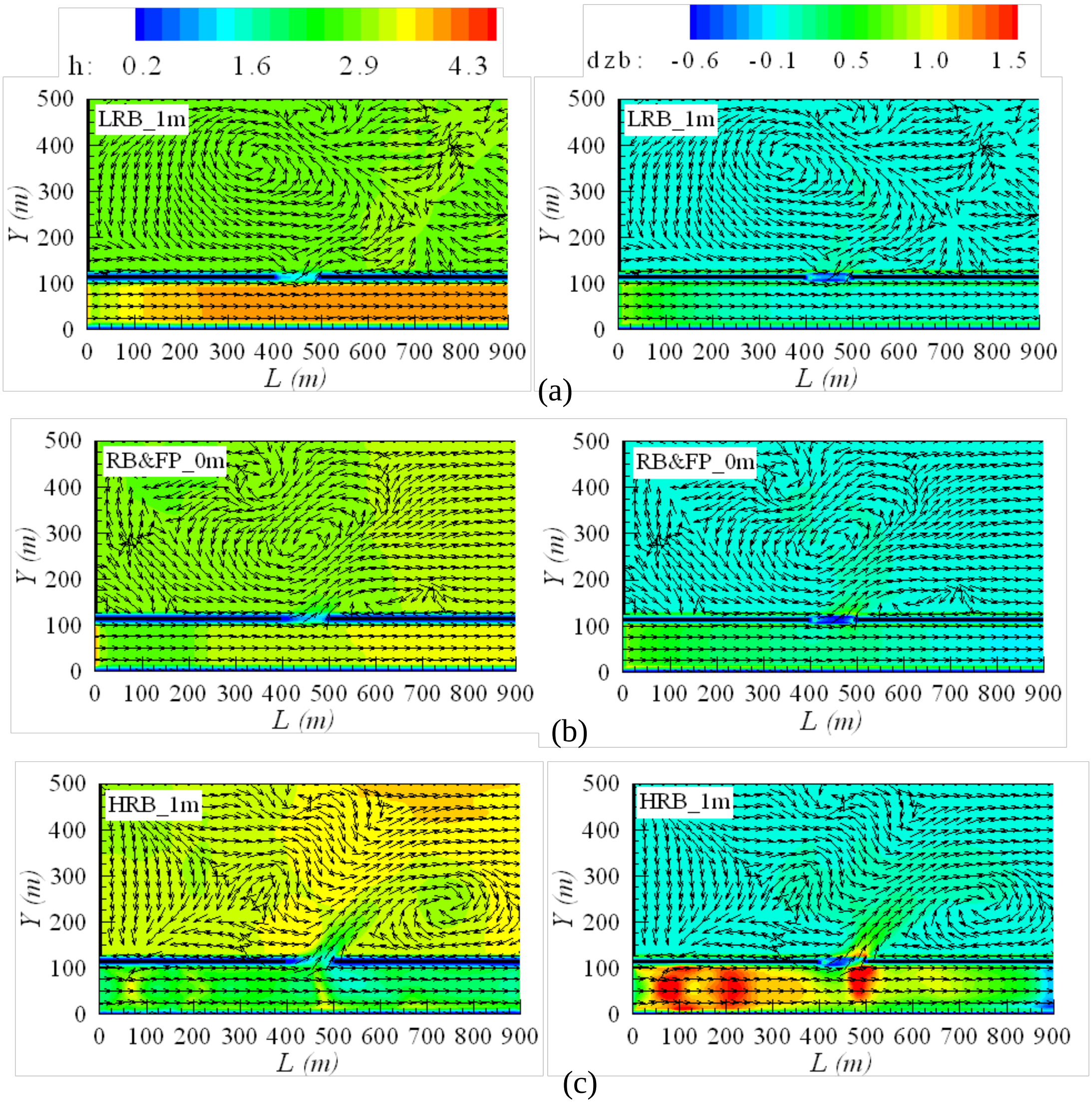


Fig. 2.30 Spatial characteristics of flow and morphological changes at levee breach with various river bed level changes as compared with floodplain level (*t*=15 min): (a) LRB_1 m; (b) RB and FP at same level; and (c) HRB_1 m, where h_c=4 m from floodplain; contours indicate the water depth (*h*) and deviation of bed elevation (*dzb*).

In **Fig. 2.31,** depicts the calculated results of transverse distribution of velocities components *u* and sedimentation profile after 15 minutes across the main channel and floodplain at *L*=475 m on the breach with the different relative height of river bed to floodplain. Near the breach, flow velocity and sedimentation are observed high at higher river bed level than the lower and the same bed height relative to the floodplain, and it is decreased with the increased of distances from the breach location. Obviously, it can be concluded that the higher river bed has more influences on the flood flow, process of inundation and sedimentation in the floodplain as well as it causes the high risk of disasters during the breach.

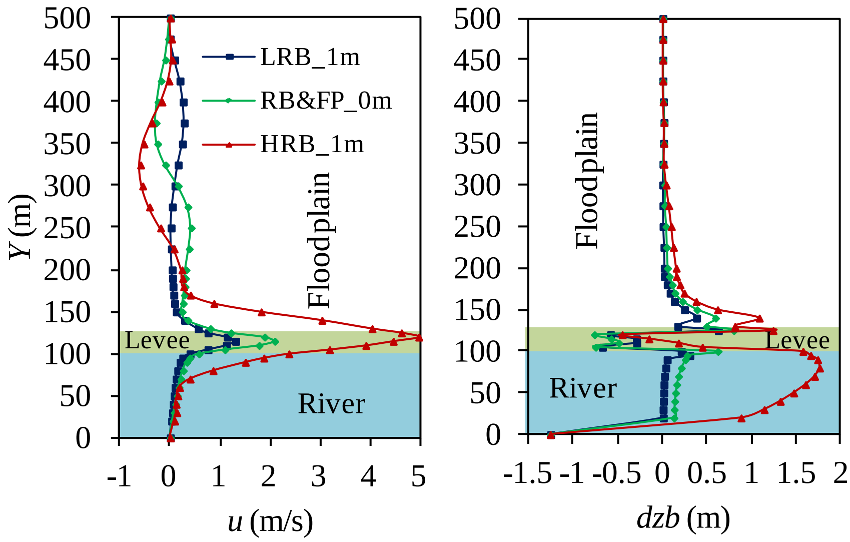


Fig. 2.31 Transverse distribution of velocity (u) and sedimentation (dzb) profile after 15 minutes at L=475 m on breach with various river bed levels where h_c=4 m from floodplain

In this section, the evolution process of the levee breach is compared with the different relative height of the river bed to floodplain. **Fig. 2.32 (a-b)** shows the calculated results by the present simulation demonstrated by the temporal development of the breach. According to the calculated results, both in the growth of breaching section and the loss of levee cross section for higher river bed is higher, and it results that the larger amount of discharge causes serious inundation in the floodplain. Not only, inundation but also sediment deposition rate in the floodplain is more as compared to the lower and the same river bed levels. So, the higher river bed has the high risk of flood disasters and consequences as more damages on the floodplain.

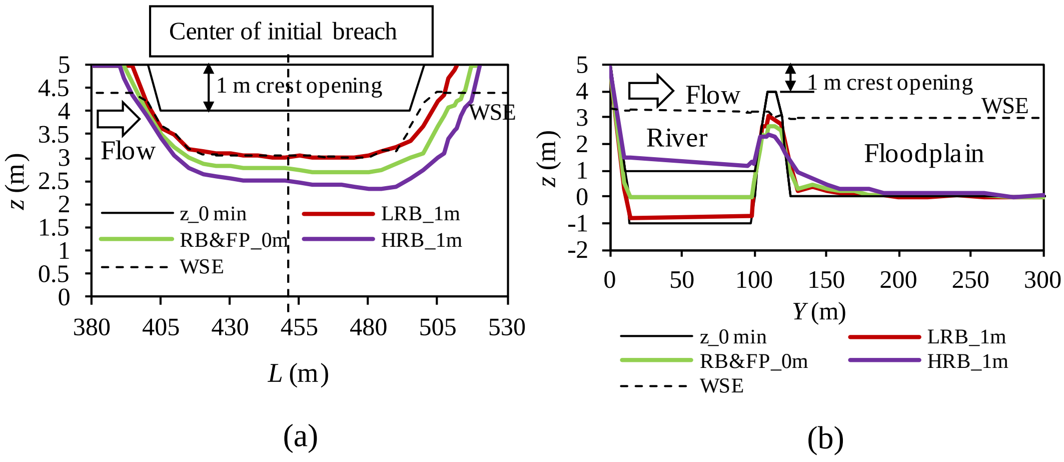


Fig. 2.32 Evolution process of levee reach due to different river bed levels: (a) temporal growth of breaching section (front view at *y*=115 m); (b) temporal loss of levee cross section (side view at *L*=475 m).

The relationships between horizontal widening and vertical erosion for different river bed height are shown in **Fig. 2.33.** In both direction breaches are expanded with the increased of the river bed height.

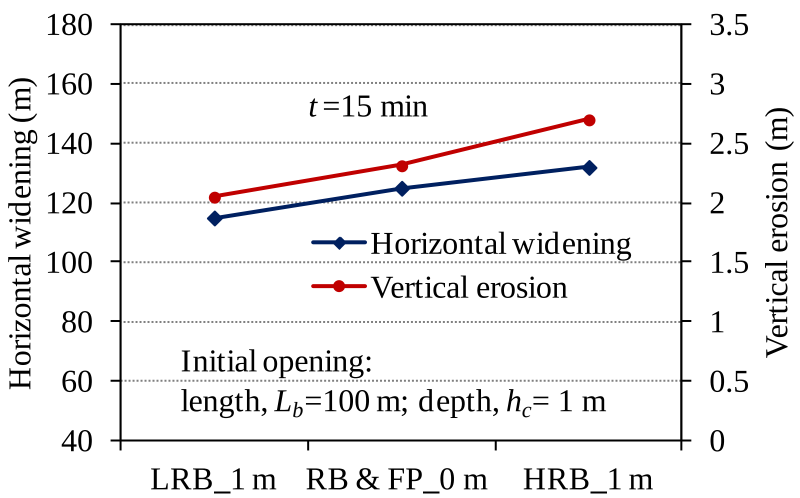


Fig. 2.33 Relationships between horizontal widening and vertical erosion of the levee with different relative height of river bed to floodplain.

In **Fig. 2.34**, depicts the river bed variation of different relative height of river bed to floodplain. Larger bed deformation is observed using higher river bed level, and bed materials are eroded and deposited on the floodplain by the breach, not only floodplain deposition but also it deposited to the downstream of the river bed which has another problem for the flow through the river in the future.

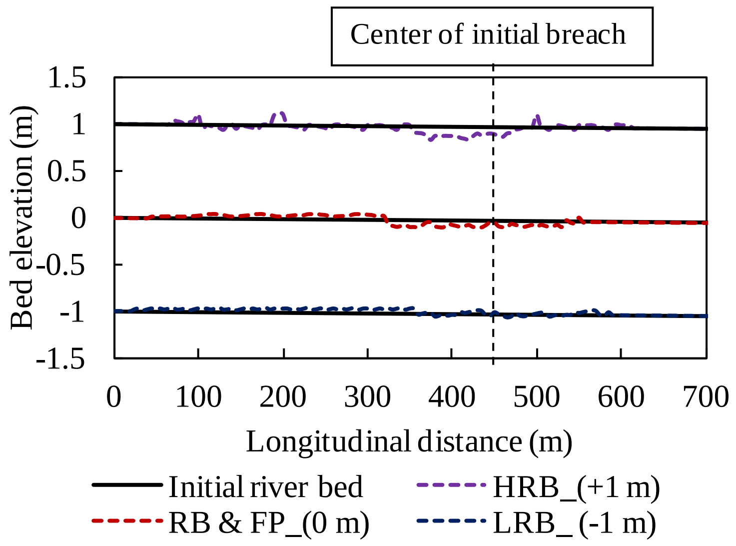


Fig. 2.34 River bed variation comparisons with respect to the relative height of river bed to floodplain.

2.6 Conclusions

This study has been conducted in order to understand the characteristics of the levee breach and consequences as disaster effect in the low-land utilizing with the different aspects of analyses by numerically. Based on the results, some unexpected deposition occurs at the upstream on the river bed (described in the preceding section 2.5.1); though it appears the calculated results demonstrate effective analyses of the characteristics of levee breach and disaster in low-land. The main conclusions in this chapter are drawn are as follows:

- Floodplain inundation depth is increased with time as well as increases of the inflow discharges and the initial breach length in the levee.

- During overflow, the breach widening is rapid at higher river bed with time. However, floodplain inundation depth, thickness and volume of sedimentation as well as damages to the floodplain residents are increased.

- Near the breach, velocity is observed high both in the river and in the floodplain at short duration, and with higher river bed condition compared to floodplain level. Velocity is reduced with increases the initial breach length in the levee.

- Sediment deposition is occurred near the breach, and it decrease in the flow direction in the floodplain. Deposition depth increased with time.

- For the breach evolution, both in temporal growth of breaching section and the loss of levee cross section is increased with time, and the rate is quick in the higher river bed height.

Finally, the case with the higher river bed suggests the possibility of levee breach with smaller discharge. It can be demonstrated that the inundation and deposition in this case are much in spite of smaller flood discharge to bring the smaller overflow water diverted into the floodplain. The research results showed that higher river bed has high risk of flood disasters in the floodplain.

In order to get more clarification about the process of inundation, evolution process of levee and sedimentation in the floodplain further laboratory experiments are necessary, which has been discussed in the next chapter.

CHAPTER 3

Laboratory Experiment of Levee Breach and Inundation in Floodplain with Sediment Deposition

Summery

Levee breach causes severe flood damage as well as floodplain inhabitant's suffering, and particularly in Bangladesh, such disasters occurs every year during the monsoon. In order to understand disasters consequent to levee breach, it is important to clarify the phenomena appearing not only around the breach opening but also over the floodplain and along the river bed, and it is attempted by using small-scale laboratory experiments. Con-currently carried out the numerical study under the same conditions as the experiments, and this two approaches may provide us more information to understand the levee breach and the successive disaster. In this study, a particular reference of the difference of relative river bed height to the floodplain levels is set on levee breach by overflow and phenomena appearing on a floodplain. A levee model is built in a laboratory experimental flume using sand with proper compaction. An initial condition for the overflow breach is provided with a partial crest opening. For every run, changes are made on the river bed height and the river bed slope. According to the results, the higher river bed level brings more rapid propagation of levee breach and widening with more sediment deposition on the floodplain area, even though the discharge provided into the river is smaller. And, it suggests that river bed degradation in the upstream of the levee breach point may cause further risk of the levee breach during the flood.

3.1General

Most of the river courses in Bangladesh are of alluvial nature; especially the Jamuna is one of the largest rivers in the world. It carries huge upstream catchment water and fine-grained non-cohesive sediment load along with heavy rainfalls during monsoon seasons, and it also has increased the risk of overflow levee breach and suffers floodplain inhabitants. Unique land topography, river system and rainfall pattern, flood occurs in Bangladesh almost every year and devastating ones at 5 to 10-years intervals. Bangladeshi river beds are aggraded very quickly due to continuous sedimentation, so that changes in the river bed level can be observed during one's lifetime. Another problem is damming of the river, which reduces the power of water flow downstream from the dam, and the sediments carried by the river start to settle down faster on the riverbed; causing the river beds aggradation and in turn reducing the water carrying capacity of the river (Khalequzzaman, 1994; Shalash, 1982), consequences as to overflow their banks and an overtopping of flow causes levee breach. **Fig. 3.1** shows the river bed aggradation of the Jamuna River in Bangladesh, and two images are compared between the year of 2000 and 2010.

High river bed is risky because flood level reaches the dangerous level although the discharge is small. 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 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 on this phenomenon, and those studies have been investigated levee breach expansion process as well as floodplain sedimentation process but did not consider on the river bed height relative to floodplain, and the phenomena appearing in the river bed and in the floodplain.

For further investigation, small-scale laboratory experiments have been carry out using sand to recognize the phenomena appearing in the leave and topographic changes in the river, levee and floodplain with particular reference to the relative height of river bed to floodplain.

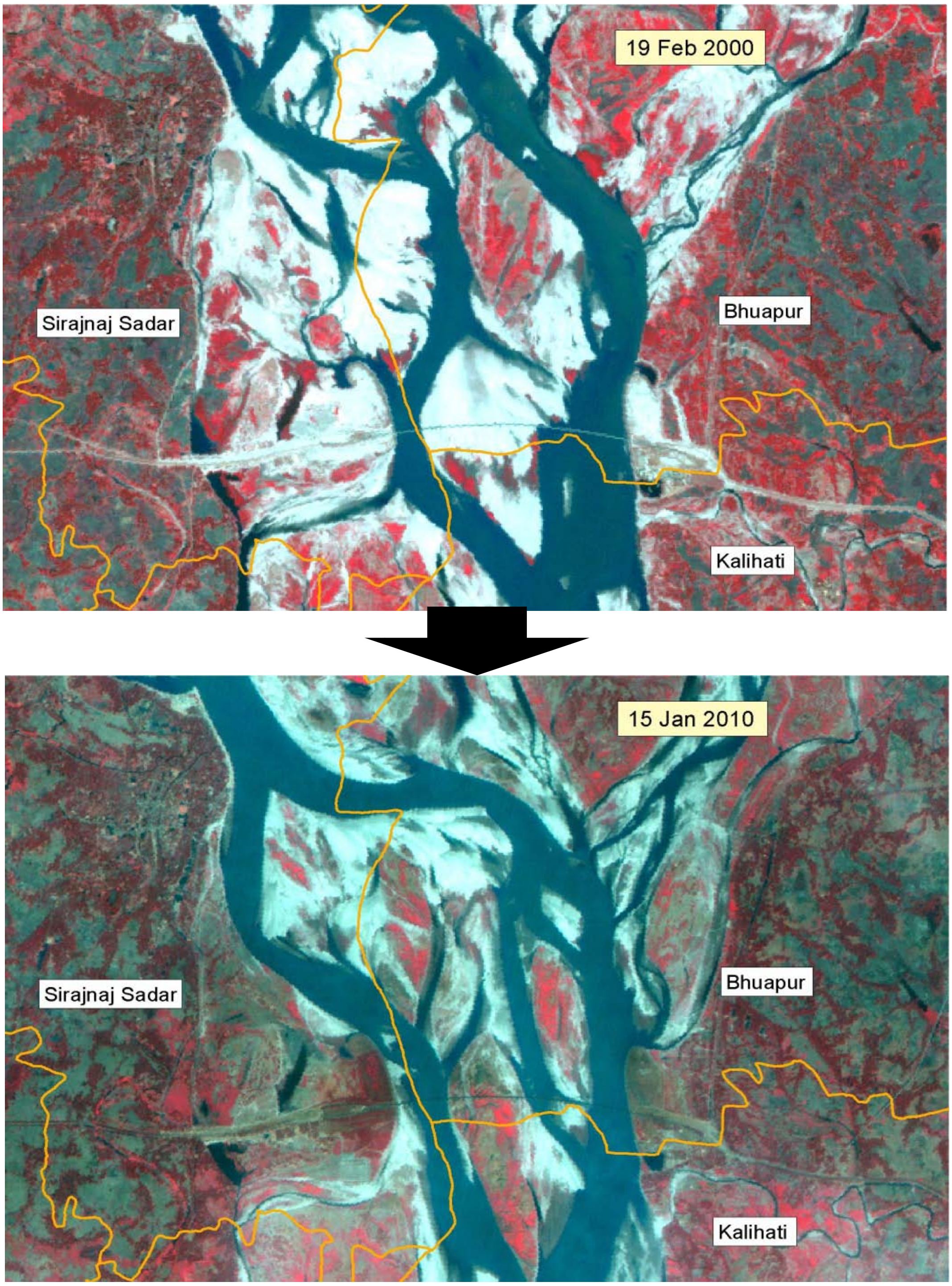
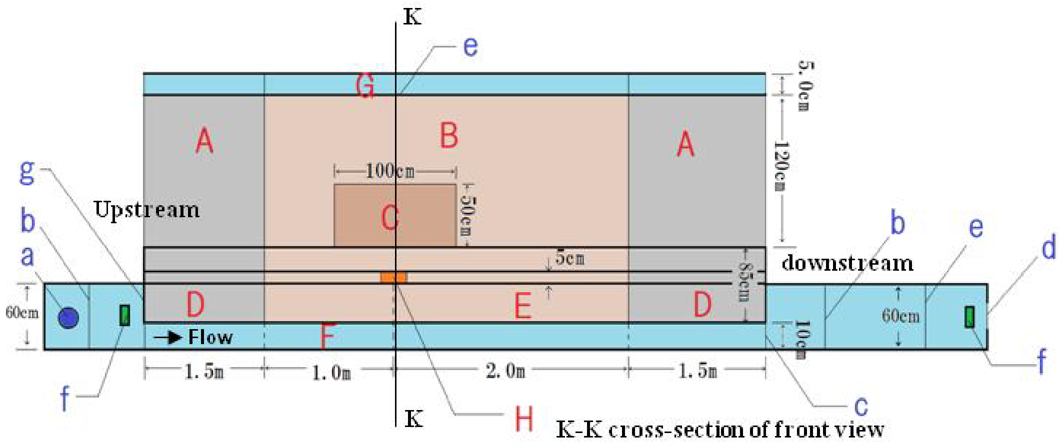


Fig. 3.1 Images of the Jamuna River in Bangladesh, showing the river bed aggradation between the year of 2000 (top) and 2010 (below). (Source: CEGIS, Dhaka, Bangladesh)

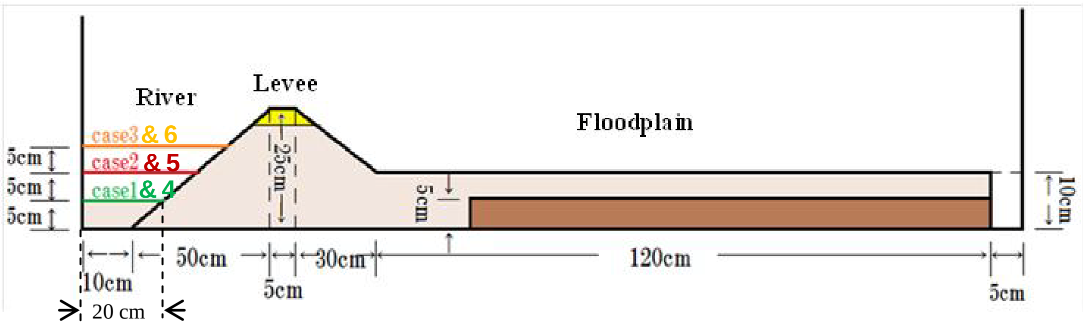
3.2 Flume Experiment

3.2.1 Experimental Set-up

This section describes the laboratory preparation for the runs with experimental conditions to be maintained for different river bed height, and operational procedures to fulfill the aforementioned objectives. The experiments are performed in a 20 m long, 2.2 m wide and 1.0 m deep concrete flume is equipped in the Hydraulic Engineering Laboratory of Nagoya University. The experimental models are made of wood and sand, which are 6 m long and 2.2 m wide (including river channel, levee, floodplain, and drainage channel). The river bed slopes are assumed 1/500 and 1/1000 for coarse and fine sand, respectively. The levee slope is 1:2 for both sides, and levee height is 0.15 m from the floodplain level. Same material (fine sand: d_{50}=0.13 mm and coarse sand: d_m=1.00 mm) are used in the river bed, levee body and floodplain. Relative height of river bed and floodplain is set as follows: Run 1 and Run 4 (low river bed) z_b=-5 cm, Run 2 and Run 5 (river bed and floodplain at the same level) z_b=0 cm and Run 3 and Run 6 (high river bed) z_b=5 cm, respectively. **Fig. 3.2 (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 sand are used to construct levee and floodplain. Initial breaching point is set at 2.5 m apart from upstream, and a notch (H) is prepared before starting the experiment. A downstream wall (e) of the floodplain is made of 2 cm height of the wooden board from the floodplain, and this wall is used to protect the movable floodplain, and as well as it maintained 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. A wave meter (f) (CHT6-30 made by KENEK Co.) is put in front of a rectangular weir to collect the crest over flow water depth, and in the same way another wave meter (CHT6-40 made by KENEK Co.) is set near the downstream side triangular weir (d) (**Fig. 3.3.d**). During experiment, 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. Levee breach expansion processes as well as topographic changes in the river, levee and floodplain are memorized by using a digital still camera (OptioS1manufactured by PENTAX). Two types of actuators (KMB-150A length 1.60 m & A30 length 1.0 m made by THK) along with laser sensor (IL-600 is made by KEYENCE) is placed lateral **(Fig. 3.3.a)** and longitudinal **(Fig. 3.3.b)** directions over the working area to survey floodplain topography and longitudinal length of the levee breach.



(a)



(b)

Fig. 3.2 Experimental setup: (a) plan view; (b) side view**.**

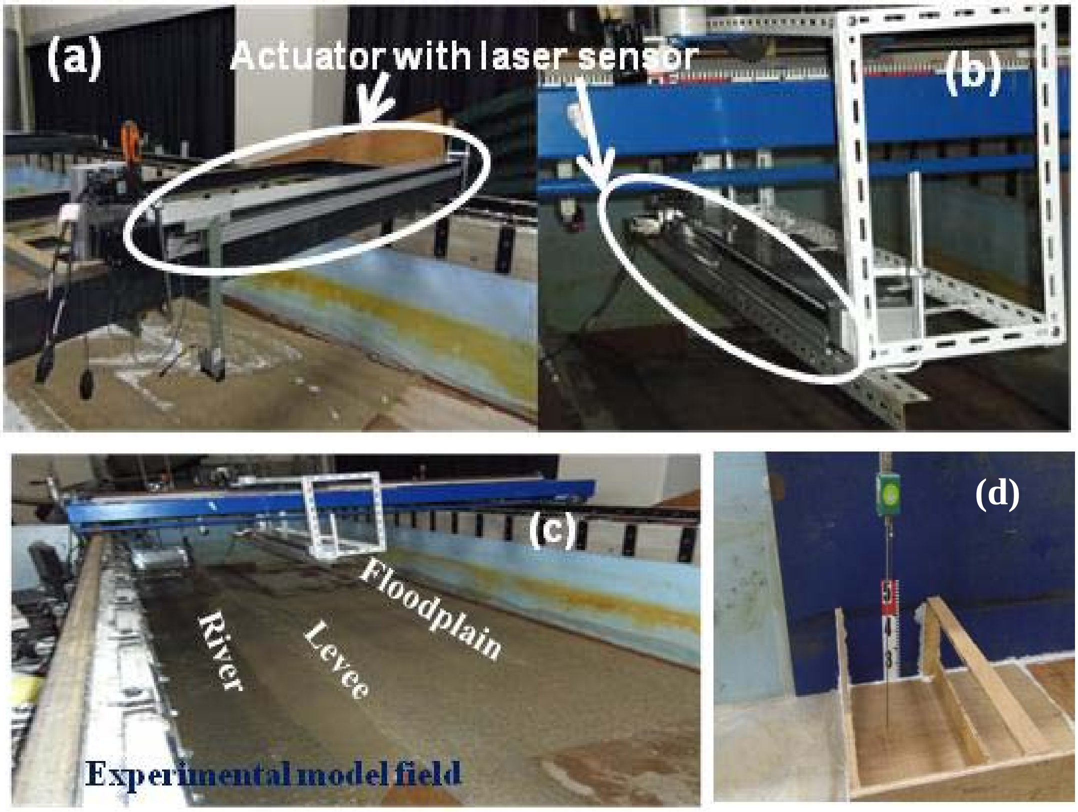
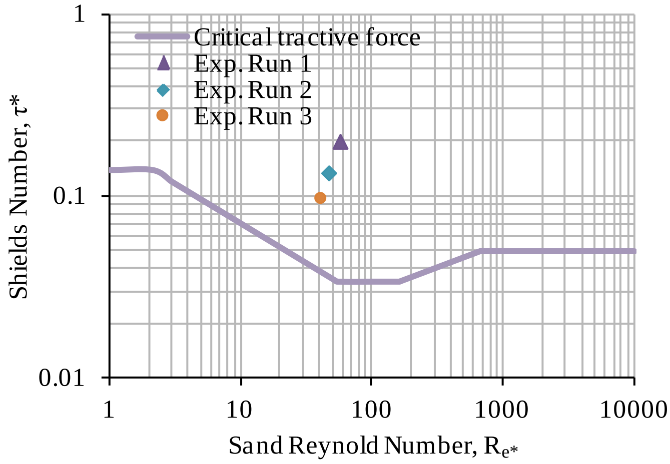


Fig. 3.3 Electronic actuator with computer aided laser sensor: (a) lateral and (b) longitudinal direction; (c) experimental model field; (d) a wave meter setting.

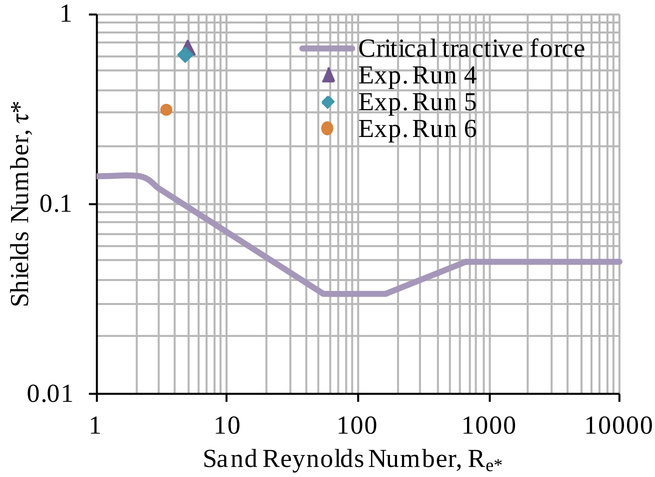
Fig. 3.4 Soil tamping equipment

3.2.2 Experimental Condition

In every run, the tractive force in the river is higher than the critical tractive force and thus the bed is movable. The critical tractive force is examined by using Iwagaki's (1956) equation (Chapter 2, equation 2.31). The movable bed conditions are compared among the experimental Runs 1 to 3 and Runs 4 to 6 as shown in **Fig. 3.5**.



(a)



(b)

Fig. 3.5 Movable bed conditions: (a) Runs 1 to 3; (b) Runs 4 to 6.

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 3.1

EXPERIMENTAL CONDITION FOR ALL RUNS

Parameters	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
River bed height to floodplain (cm)	-5	0	+5	-5	0	+5
Inflow Q (l/s)	8.95	8.71	8.69	9.49	8.85	4.93
River flow depth h_0 (cm)	16	11	8	16	11	6
Mean velocity U (cm/s)	15.54	19.31	22.63	18.08	22.13	21.91
Bed material size d_{50} (mm)	1.00	1.00	1.00	0.13	0.13	0.13
Shields number τ_*	0.20	0.13	0.10	0.67	0.62	0.31
Froude number F_r	0.12	0.19	0.26	0.14	0.21	0.29
Sand Reynolds number R_{e*}	57	47	40	4.88	4.66	3.31

3.2.3 Measurement Procedure

During the levee preparation, put the sand at the different layers and compact it by using tamping equipment (**Fig. 3.4**), particularly using coarse sand. Before starting the experiment, the working section of the flume is prepared as shown in **Fig. 3.3.c**, and then a notch (10×5 cm) is cut to provide the initial breach opening for the overflow experiment. Soil sample is collected from this notch section of the levee and analyzed the degree of compaction; we found it is reached nearly 100%. Then, the inlet and outlet tank is filled with water, and the wave meter reading is set at initial condition (zero). 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 early placed wave meter data are taken to estimate the inflow and outflow water discharge by using the equation of Itaya and Tejima (1951) for rectangular weir, and Kurokawa and Fuchizawa (1942) for triangular weir, respectively.

The equations are as follows:

The overflow discharge rate is:

$$Q_{in} - Q_{out} = Q_{overflow} \tag{3.1}$$

where Q_{in}: inflow discharge (m^3/s), Q_{out}: outflow discharge (m^3/s) , $Q_{overflow}$: overflow discharge (m^3/s).

The inflow discharge rate (Itaya and Tejima, 1951) is:

$$Q = Cbh^{3/2} \tag{3.2}$$

where $$C = 1.785 + \frac{0.00295}{h} + 0.237\frac{h}{D} - 0.428\sqrt{\frac{(B-b)h}{BD}} + 0.034\sqrt{\frac{B}{D}} \tag{3.3}$$

Q: inflow discharge (m^3/s); b: width of weir crest (m); h: over flow water depth (m); C: const.; B: width of river (m); D: height of the weir crest from the river bed (m).

Application conditions,

$0.5\text{m} \le B \le 6.3\text{m}, \quad 0.15\text{m} \le b \le 5\text{m}, \quad 0.15\text{m} \le D \le 3.5\text{m}, \quad bD/B^2 \ge 0.06,$
$0.03\text{m} \le h \le 0.45\sqrt{b}\text{m}$

The outflow discharge rate (Kurokawa and Fuchizawa, 1942) is:

$$Q = Ch^{5/2} \tag{3.4}$$

where $$C = 1.354 + \frac{0.004}{h} + (0.14 + \frac{0.2}{\sqrt{D}})(\frac{h}{B} - 0.09)^2 \tag{3.5}$$

Application conditions,

$0.5\text{m} \leqq B \leqq 1.2\text{m}, \quad 0.1\text{m} \leqq D \leqq 0.75\text{m}, \quad 0.07\text{m} \leqq h \leqq 0.26\text{m}$

The reference formula for estimating outflow discharge rate, which is given by Tomson (JIS K0094) as:

$$Q = 1.404h^{5/2} \tag{3.6}$$

This equation is mostly used for industrial purposes and suitable for triangular weir (shape is 90^0).

The electronic actuator with laser sensor is fixed with a moving carriage on the working area that is travels over the steel frame on both sides of the flume. During experiment, the longitudinal breach widening with time is measured. The river section and the floodplain are drained, and the bed is dried; the elevation of the bed is measured using computer-aided laser sensors for each run. The *x*-axis is the longitudinal 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. This software is developed by Fujita *et al.,* (1998). The sketch of the collection of a video file and the analyzing procedure of an overflow velocity vector with a flowchart by using PIV software are shown in **Figs. 3.6** and **3.7**, which are as follows:

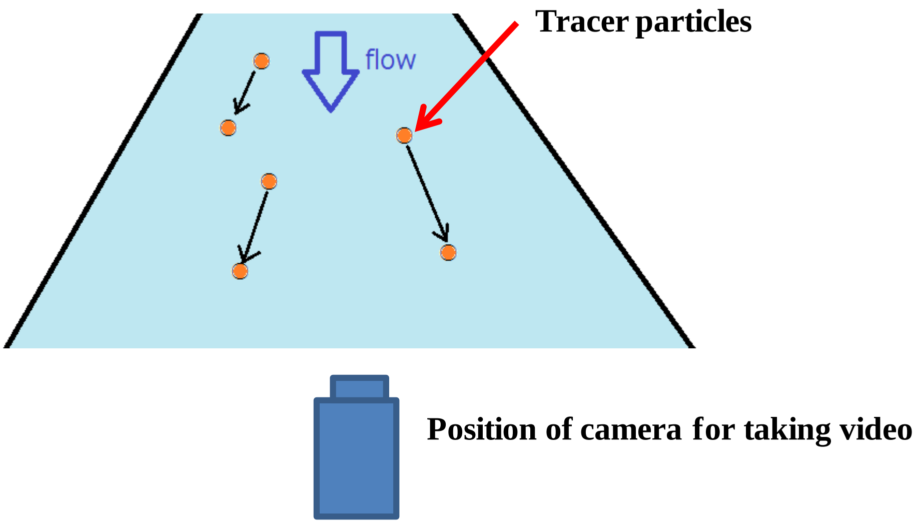


Fig. 3.6 Schematics diagram of the collection of a video file.

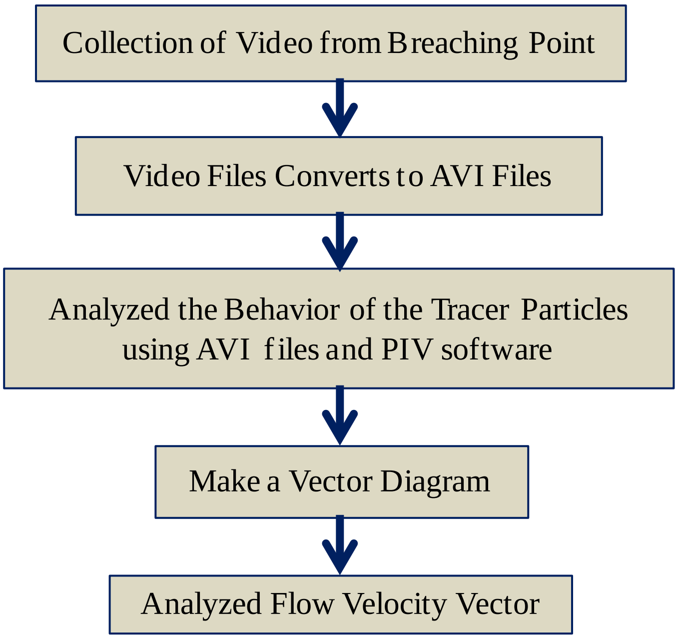
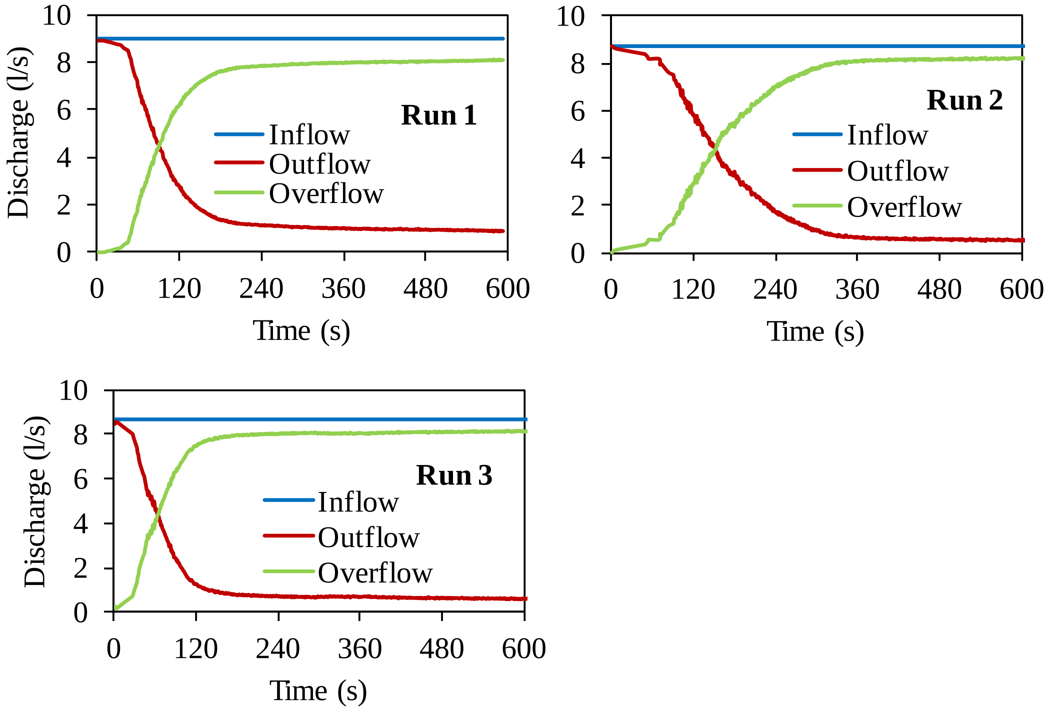


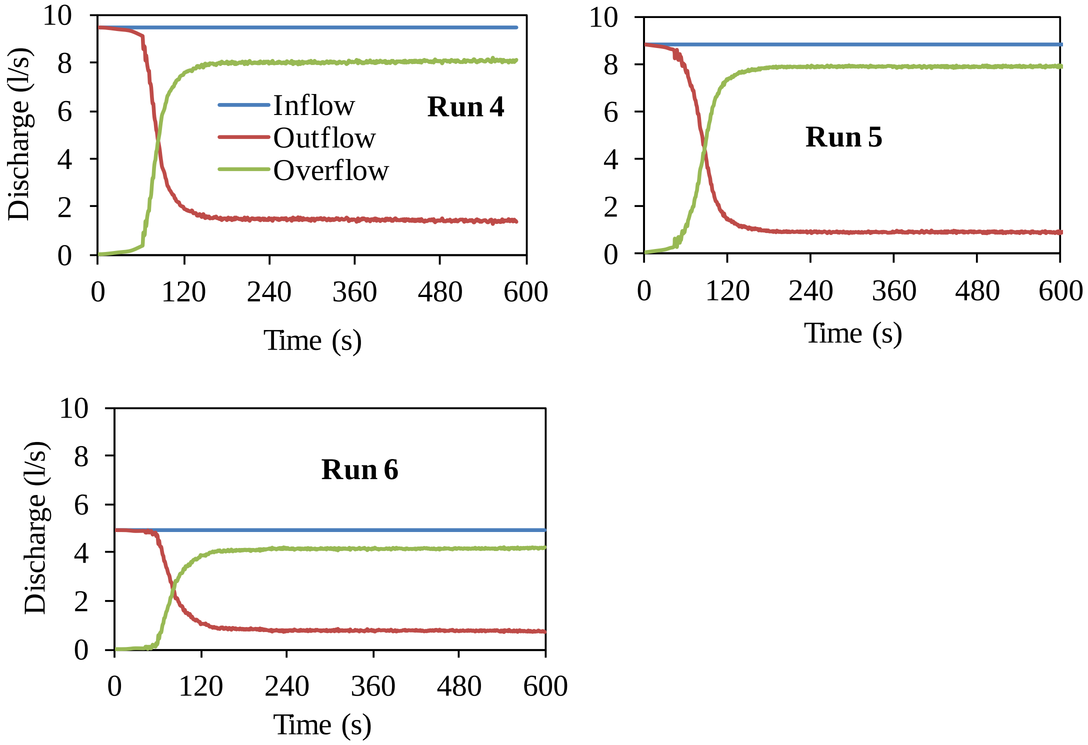
Fig. 3.7 A flow-chart to analyzed velocity vector using PIV software.

3.3 Experimental Results and Discussion

The main purpose of this study is to investigate the process of levee breaching and the topographic changes in the river, levee and floodplain with relative height of river bed to floodplain are discussed in this section, which would be realized how the river bed height has influences on the risk of flood disasters in floodplain. For the elevation differences in the river and floodplain, the flooding flow and inundation in the floodplain are varied. The flow capacity of the river is reduced with the increased of the river bed height. **Fig. 3.8 (a-b)** depicts the river flow and the overflow to the floodplain by the breach. The inflow discharges is provided nearly the same for the Runs 1 to 3 (**Fig. 3.8.a**). 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. Whereas, for the Runs 4 to 6 (**Fig. 3.8.b**), the inflow discharges is reduced with increased the river bed height, it means the small amount of discharge is capable of an overflow levee breach; these two points are considered in this study.



(a) Runs 1 to 3



(b) Runs 4 to 6

Fig. 3.8 River flow and inundation flow on floodplain by the breach: (a) Runs 1 to 3; (b) Runs 4 to 6.

3.3.1 Levee Breaching Process

In this study, two sets of experiments and each of three runs were conducted. Coarse bed material with steep river bed slope and fine material with mild slope were considered for the first and second set, respectively. To understand the levee breaching process, compared among the Runs 1, 2 and 3; and the Runs 4, 5 and 6 for the low, same and high river bed level, relatively.

3.3.1.1 Low River Bed as Compared to Floodplain Level

Levee breaching processes and the bed topographic changes in the river, levee and floodplain with time for the Run 1 are shown in **Photo 3.1**, and the flow velocity vector analyzed by LSPIV is shown in **Fig. 3.9**.

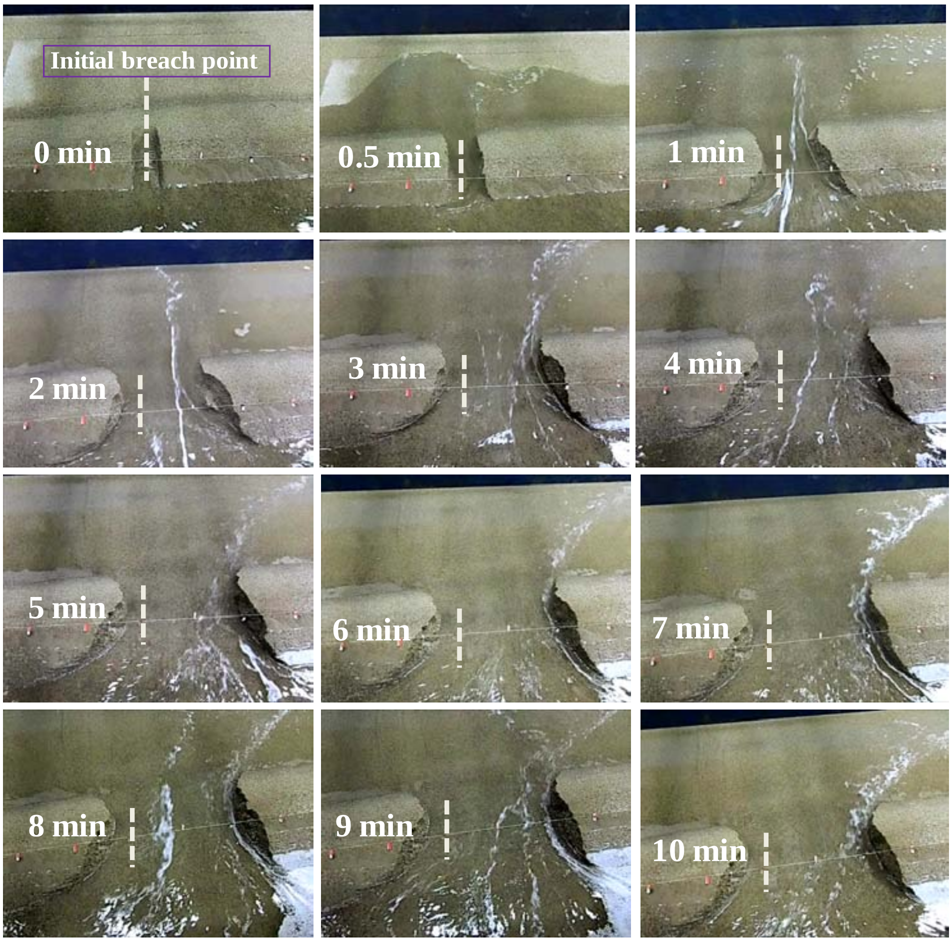


Photo 3.1 Levee breaching process and bed topographic changes with time due to overflow levee breach (Run 1).

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. 3.9**) and floodplain flow tends to be mainly in the same direction.

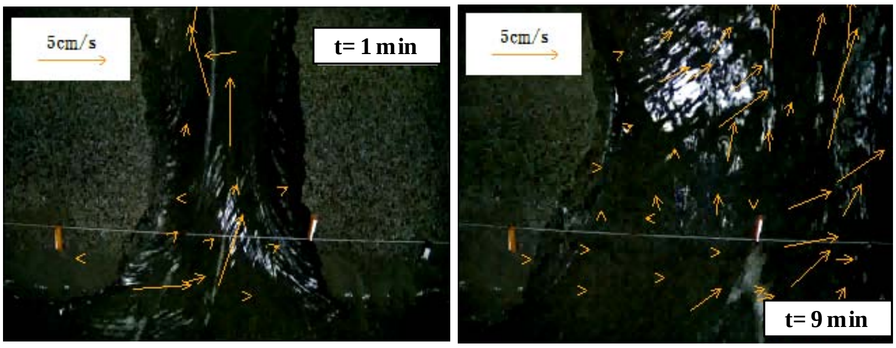


Fig.3.9 Flow velocity vector analyzed by LSPIV technique (Run1)

Levee breaching processes and the bed topographic changes in the river, levee and floodplain with time for the Run 4 are shown in **Photo 3.2**. In this case, very beginning of overflow, the initial flow passes straight with the downstream of the floodplain, and then the erosion process starts in the floodplain near the levee toe (outside edge of levee base at the floodplain side). A turbulent motion appears at the levee toe with huge erosion, and the overflow water is spread over the floodplain. Then, the erosion process comes forward to the center of the levee with vertical erosion in the levee section, and the horizontal widening process starts by the collapse of the levee. The river flow is mainly concentrated form the river to the floodplain and the levee breach widening process is progress to the downstream side of the levee, and the floodplain flow is migrated on that direction.

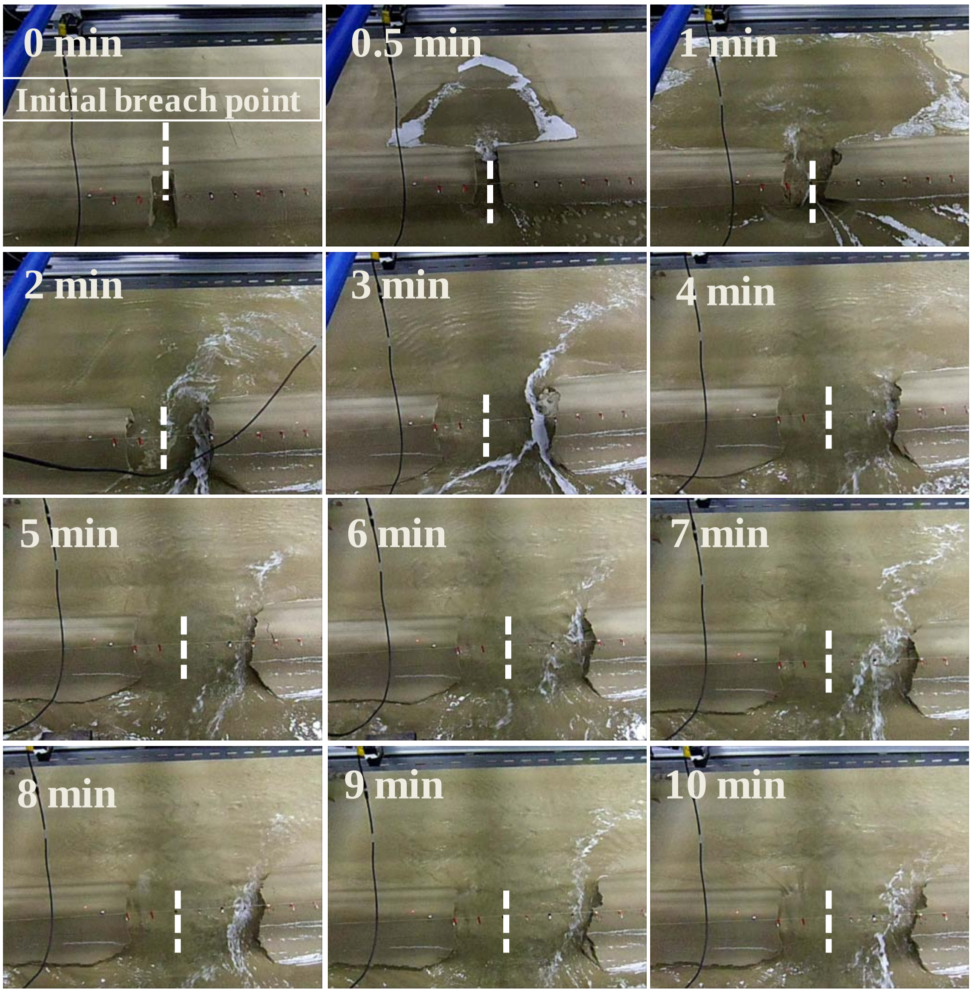


Photo 3.2 Levee breaching process and bed topographic changes with time due to overflow levee breach (Run 4).

Fig. 3.10 shows the longitudinal levee breach propagation along the river with time (Run4). 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 sudden breach widening process is occurred in the longitudinal direction. After that, the breach widening process is slow, not only in the horizontal but also vertical direction.

For finer bed material and low river bed condition, the relationships between the horizontal breach widening and vertical erosion with time (*t*=10 min) are shown in **Fig. 3.11** for the inflow discharges of 9.49 l/s and initial opening is 10 cm long and 5 cm deep from the top of the levee. In both directions, breaching is measured choosing with the maximum expansion of the levee for respective time steps. At early stage of overflow, the expansion process is progresses both in the horizontal and vertical direction, then the huge vertical erosion is occurred. After that the horizontal breach widening is continued at slow rate and vertical erosion is reduced with time.

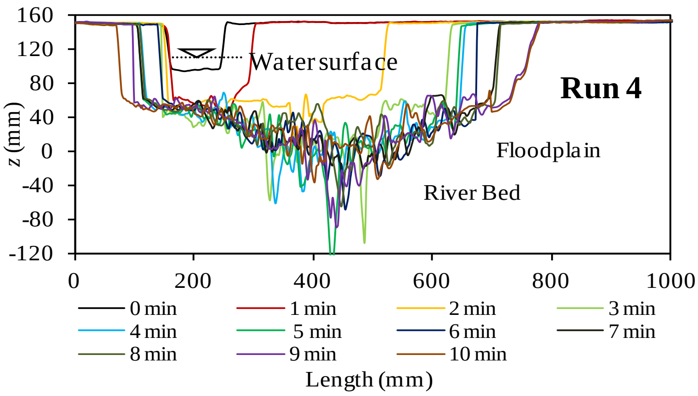


Fig. 3.10 Breach evolution processes with time along the longitudinal direction of the river (Run 4).

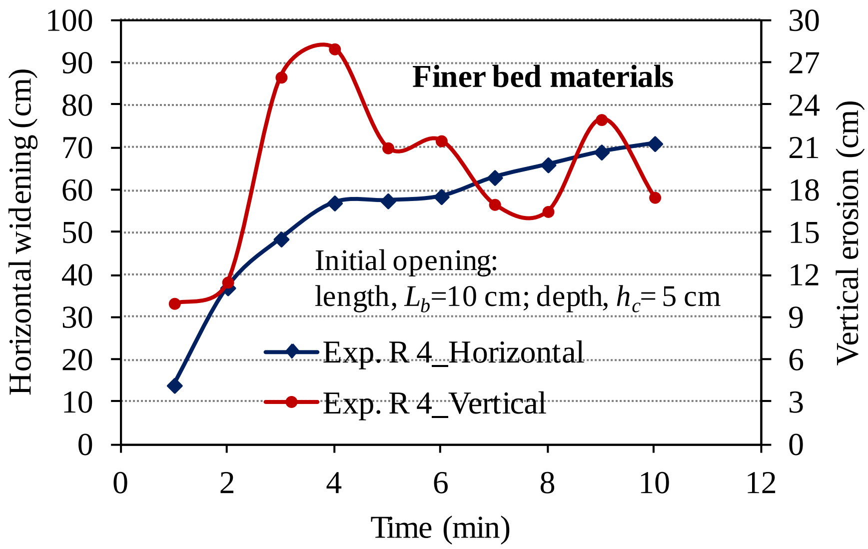


Fig. 3.11 Relationships between horizontal widening and vertical erosion of the levee with time for experimental Run 4

3.3.1.2 River Bed and Floodplain at the Same Level

Levee breaching processes and the bed topographic changes in the river, levee and floodplain with time for Run 2 are shown in **Photo 3.3**. Almost same nature of the erosion process appears initially in the levee as compared to Run 1. Subsequently, the erosion process comes forward to the heel (inside edge of levee base at river side) of the levee section, and levee material is washed out, and it deposited on the floodplain. Then, the horizontal widening process started 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 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.

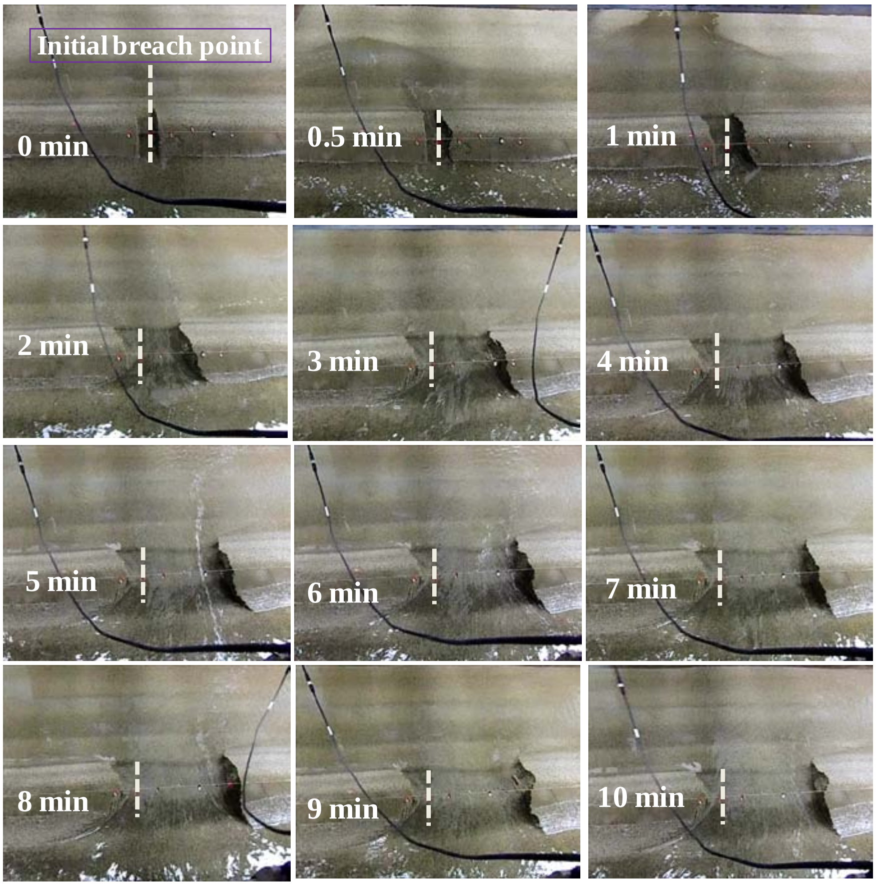


Photo 3.3 Levee breaching process and bed topographic changes with time due to overflow levee breach (Run 2).

In **Photo 3.4**, shows the levee breach widening processes and the bed topographic changes with time for Run 5. The different nature of the erosion process appears in the levee as compare to Run 4. The erosion process starts between the levee toe and the center of the levee, and at the same time the levee section is eroded vertically. Suddenly, the erosion process dominates in the levee section with huge vertical erosion of the levee material, and a turbulent motion appears there. Finally, the horizontal breach widening process starts by loss of the levee section. During the breach widening, the erosion process comes forward to the heel (inside edge of levee base at river side) of the levee as well as in the river bed. The river bed material is eroded, and it is deposited on the floodplain with overflow by the breach. The overflow behavior and the nature of the breach widening are almost same as Run 4 but the inundation flow tendency in the floodplain is nearly straight, and it passes all over the floodplain.

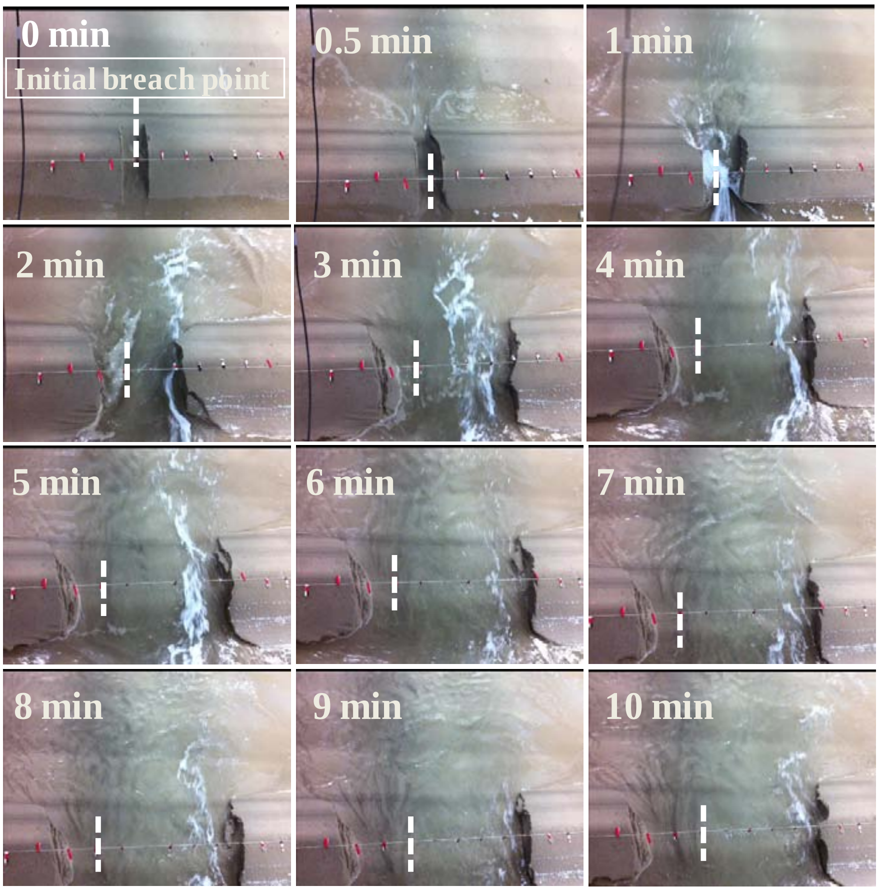


Photo 3.4 Levee breaching process and bed topographic changes with time due to overflow levee breach (Run 5).

Fig. 3.12 shows the longitudinal levee breach propagation along the river with time (Run 2). 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. After that, the breach widening process is slow, not only in the horizontal but also vertical direction.

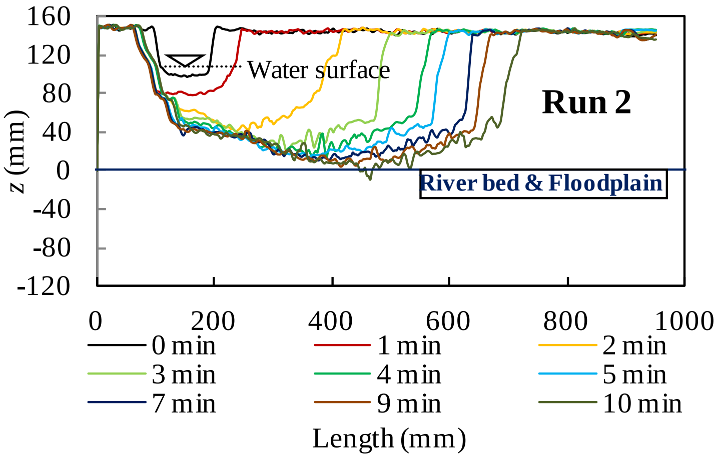


Fig. 3.12 Breach evolution processes with time along the longitudinal direction of the river (Run 2).

In **Fig. 3.13**, shows the longitudinal breach evolution process with time along the river (Run 5). At shorter duration, no horizontal erosion but remarkable vertical erosion are observed, and then the levee breach widening process is same as Run 4. The longer of the breach widening is observed than Run 4 it causes the larger amount of sediment outflow to the floodplain by the breach.

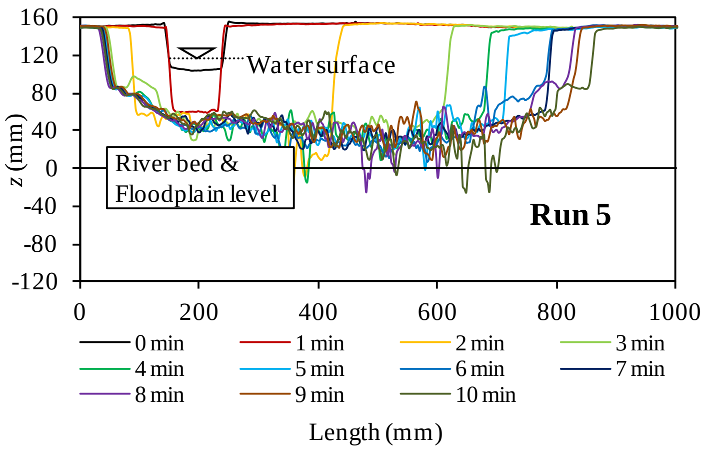


Fig. 3.13 Breach evolution processes with time along the longitudinal direction of the river (Run 5).

The relationships between the horizontal breach widening and vertical erosion with time are shown in **Fig. 3.14**, which is represents the same bed height of the river to floodplain and almost same inflow discharges but the changes of bed materials are coarse and fine for the experimental Runs 2 and 5, respectively. Both in the vertical and horizontal direction, the breach are measured choosing the maximum expansion of the levee for respective time steps. Using finer bed material (Run 5) initially more rapid vertical erosion appears as compared to the coarser bed material (Run 2), and then the erosion is decreased with time, which is same as the coarser bed material but the fluctuation is observed using the finer bed material. Whereas, horizontal widening is rapid at shorter duration for finer material, then the expansion rate is same as the coarser bed material and the final length of widening is more with finer materials.

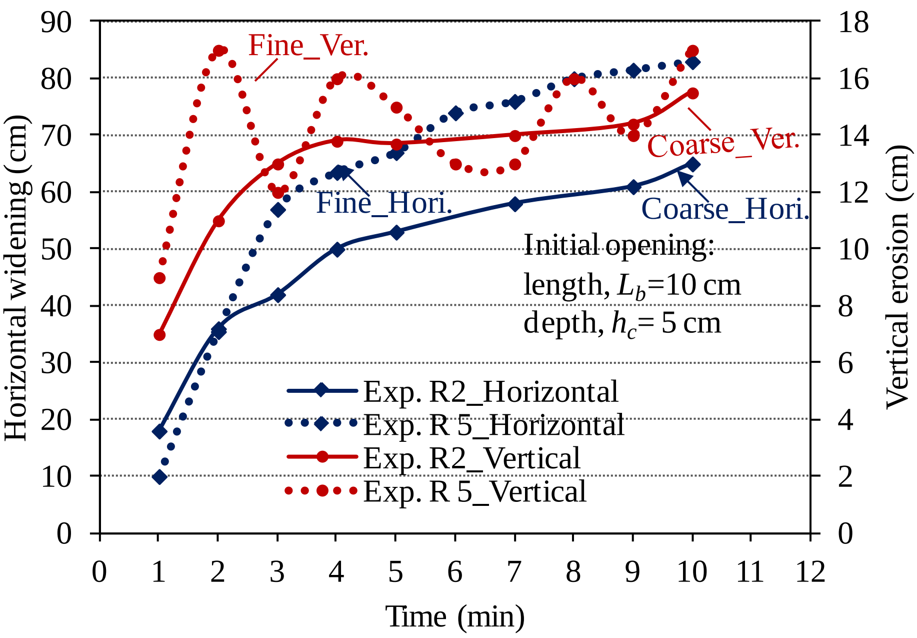


Fig. 3.14 Relationships between horizontal widening and vertical erosion of the levee with time for experiments: (a) Run 2; (b) Run 5

3.3.1.3 High River Bed as Compared to Floodplain Level

For Run 3, levee breaching processes and the bed topographic changes in the river, levee and floodplain with time are shown in **Photo 3.5**, and the flow velocity vector analyzed by LSPIV is shown in **Fig. 3.15**. 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.

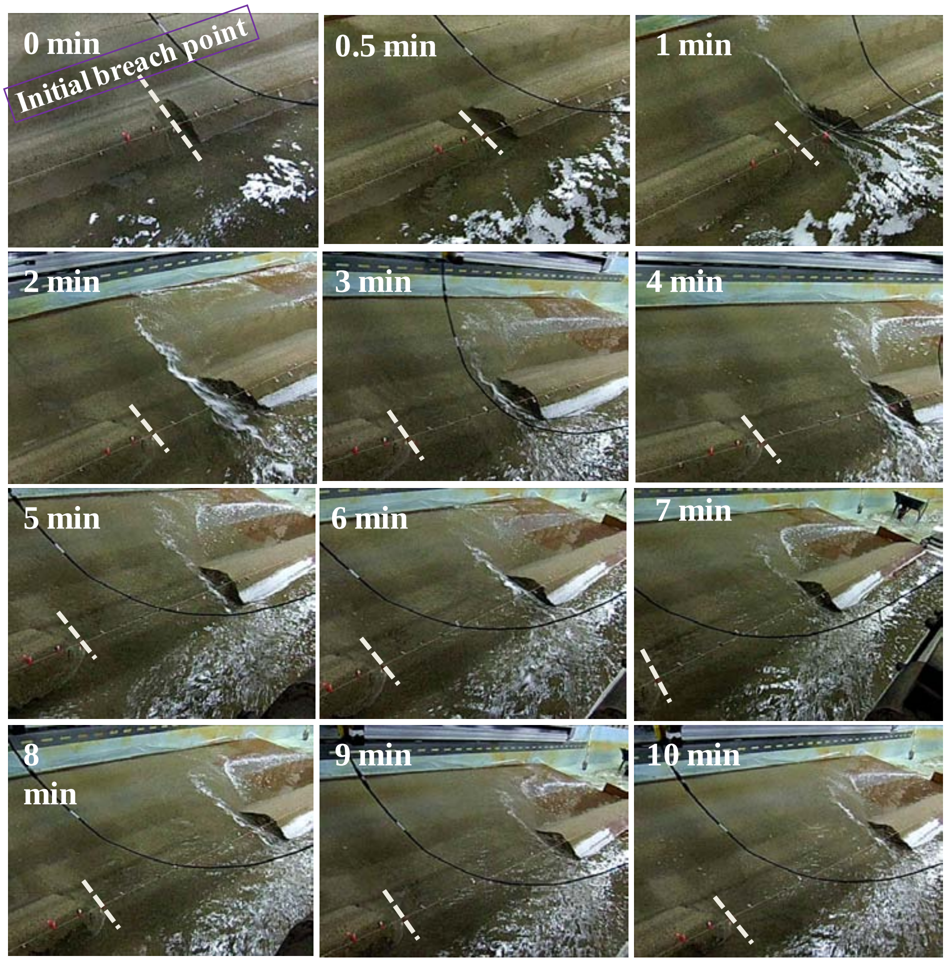


Photo 3.5 Levee breaching process and bed topographic changes with time due to overflow levee breach (Run 3).

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 very early stage, the river flow vector is concentrated towards the floodplain and 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. 3.15**). 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.

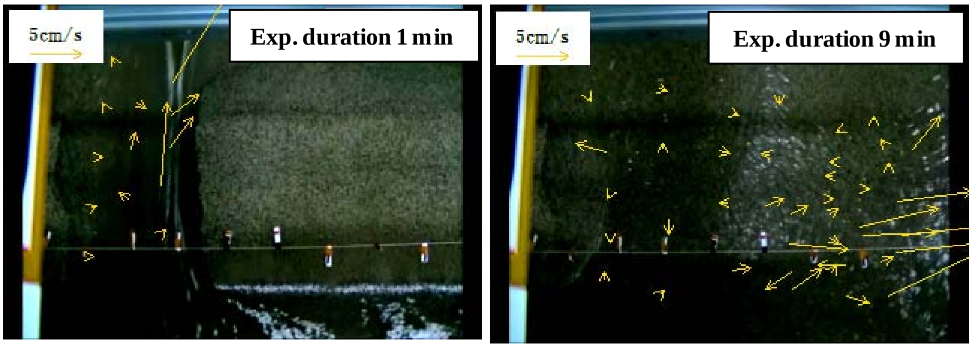


Fig.3.15 Flow velocity vector analyzed by LSPIV technique (Run3)

The levee breaching process and the bed topographic changes in the river, levee and floodplain with time are shown in **Photo 3.6** (Run 6). The inflow discharges through the river is smaller than Run 4 and Run 5, but the nature of the erosion process is rapid, though the erosion process starts at the levee toe as same as the Run 4. Because of the level difference between the river beds to floodplain, overflow water is quickly passed to the floodplain by the breach with huge vertical erosion in the levee section. And, in parallel the levee bottom is eroded, finally the levee widening process starts in the horizontal direction at the higher rate than the other two runs. The river flow is concentrated to the downstream of the levee and the early breach upstream section is deposited by the eroded material from the river bed and the levee section.

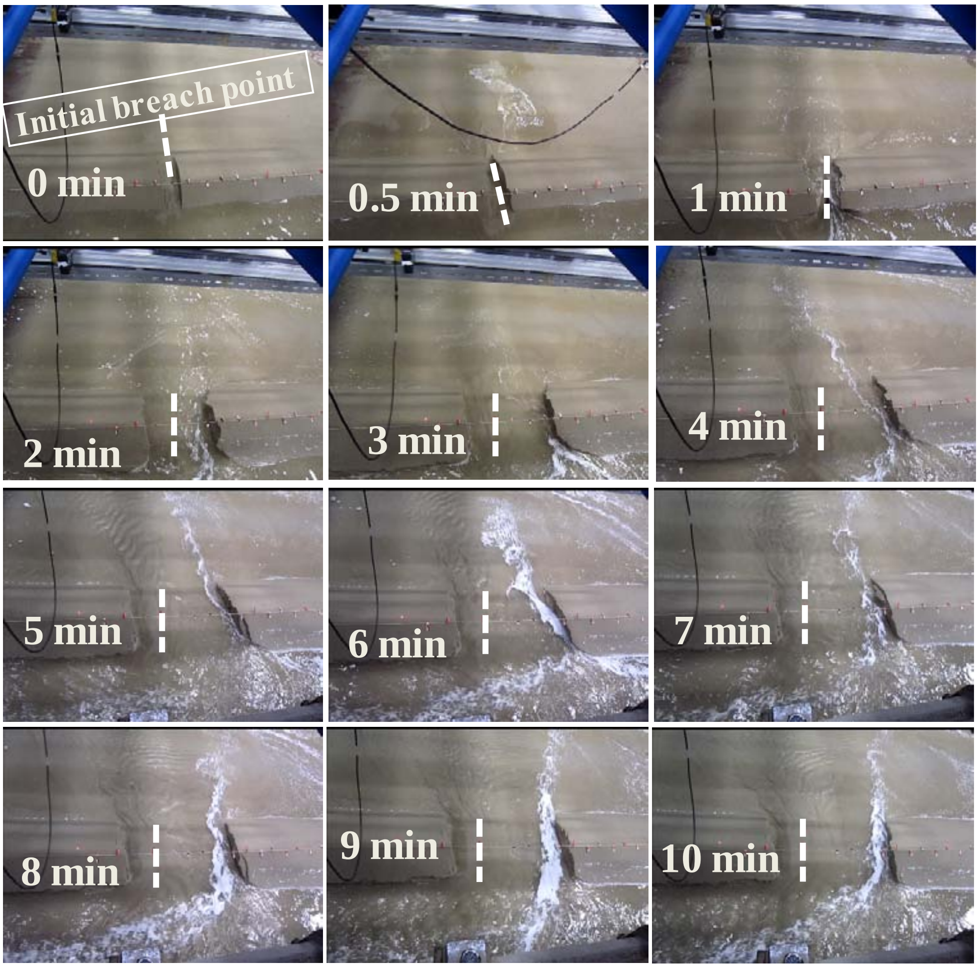


Photo 3.6 Levee breaching process and bed topographic changes with time due to overflow levee breach (Run 6).

The breach evolution processes of the levee with time along the river (Run 3) are shown in **Fig. 3.16**. 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.

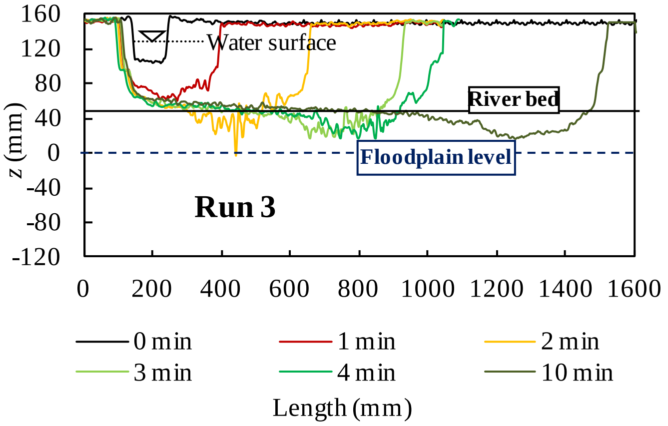


Fig. 3.16 Breach evolution processes with time along the longitudinal direction of the river (Run 3).

The breach evolution processes of levee with time along the river (Run 6) are shown in **Fig. 3.17**. At very early stage of overflow, the nature of the erosion is almost same as the Run 5. However, the horizontal breach widening process is rapid, and the vertical erosion process is slow as compared to the Run 4 and Run 5. The total length of the breaches is more than the Run 4 and near about same as the Run 5.

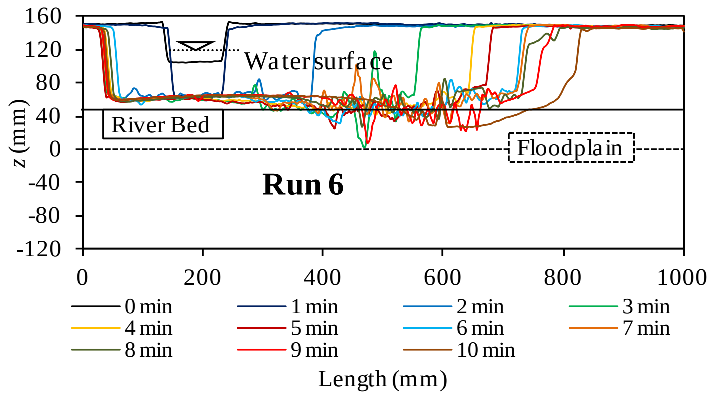


Fig. 3.17 Breach evolution processes with time along the longitudinal direction of the river (Run 6).

In **Fig. 3.18** shows the relationships between the horizontal breach widening and vertical erosion with time for higher river bed level using coarse and fine bed materials with two different discharges of 8.69 and 4.93 l/s for the experimental Runs 3 and 6, respectively. The breaching is compared with higher bed conditions but the discharge is not same; though the various inflow discharges is provided, the important observation is how the bed material effect on breaching with small amount of discharges. In both directions, breaching is measured choosing with the maximum expansion of the levee for respective time steps. For the Run 3, the more rapid horizontal widening and vertical erosion process appears at short duration, and then the vertical erosion is decreased but widening is progress with higher rate, due to lack of measuring capacity of the instrument in this analysis plotted data is not appear from 4 min to 9 min and it shows straight line. On the other hand for Run 6, the breaching is start at slow rate in the beginning of the overflow for both direction, and then vertical erosion is increased, after that it decreased with time. In Run 3, horizontal widening is longer than the Run 6 as because of coarser bed material and higher inflow discharges.

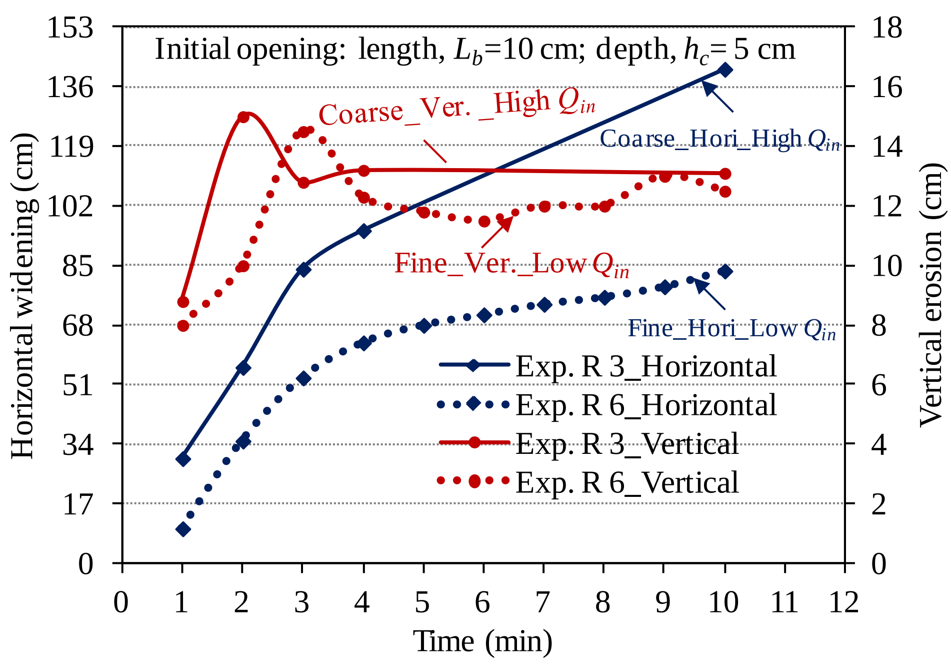


Fig. 3.18 Relationships between horizontal widening and vertical erosion of the levee with time for experiments: (a) Run 3; (b) Run 6

3.3.1.4 Differences in Levee Breach by River Bed Height Relative to Floodplain Level

Fig. 3.19 (a-b) 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 Runs 1, 4 and Runs 2, 5 than in Runs 3, 6 but the vertical erosion is more in the Runs 1, 4 as well as in Run 2, 5. 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 (Runs 3 and 6) has the high risk of flood disasters in the floodplain.

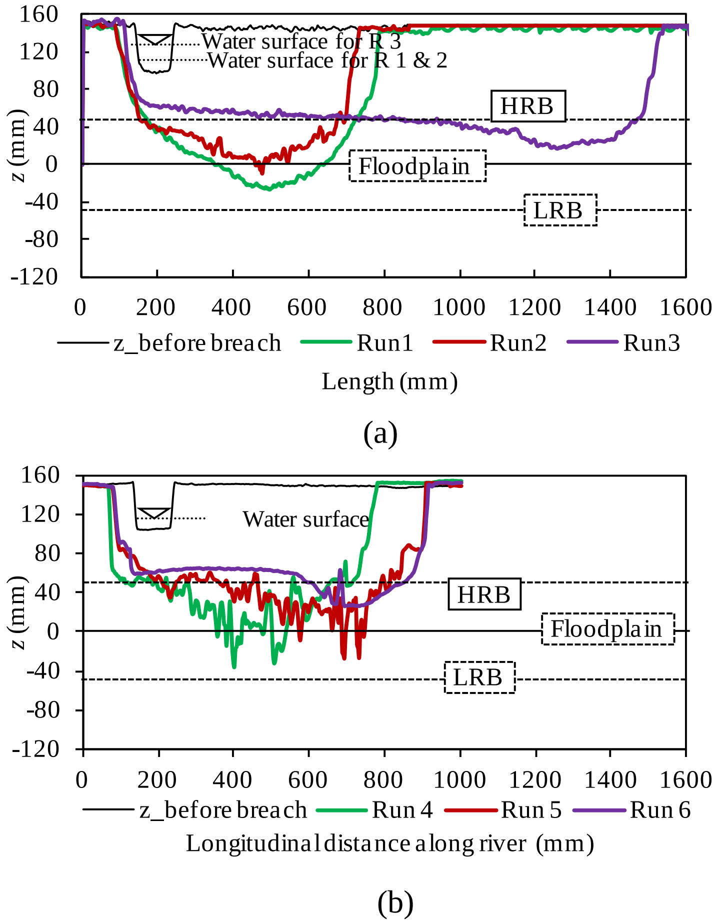


Fig. 3.19 Comparisons of the final length of breaching (t=10 min) at different height of river bed as compared to floodplain level: (a) Run 1 to Run 3; (b) Run 4 to Run 6.

The comparative analyses among the different experimental runs are summarized in **Table 3.2**. The natures of the erosion process are varied with the height changes of 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 vertical erosion with the horizontal widening process appears in the Run 3. Whereas, the duration of the vertical erosion before widening is shorter and the transition of the breach widening is earlier in the Run 4, but the final breaching is longer in the Run 6. It is exposed that, after the transition of breaching the horizontal widening process is rapid in the Run 6.

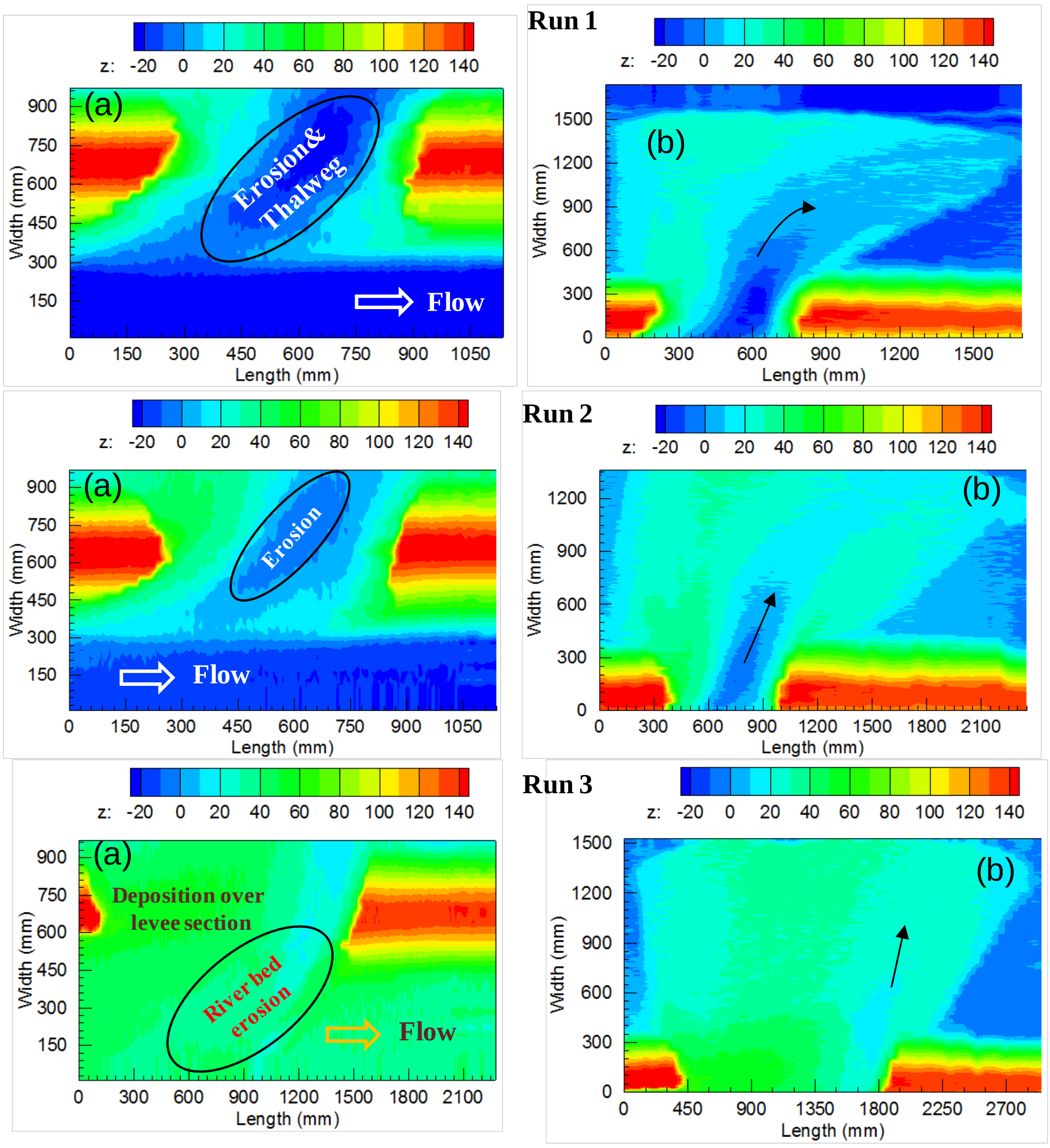
TABLE 3.2

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 (cm)
1	Levee crest at FP side	Vertical erosion & material washed out from levee	9 to 22	23	70
2	Levee crest at FP side	Vertical erosion with progress to river side & material washed out from levee	8 to 21	22	65
3	Levee crest at FP side	Rapid vertical erosion & material washed out from levee & river bed	7 to 17	18	141
4	Toe of levee	Huge vertical erosion with turbulent motion at levee toe & erosion from levee	22 to 38	39	71
5	Between levee toe & center	Huge vertical erosion with turbulent motion between levee toe and center of the levee as well as erosion in the levee heel and from the river bed	45 to 62	63	83
6	Toe of levee	Erosion at levee toe & rapidly progressed to the all levee section then concentrate at the center of the levee with turbulent motion & erosion from the river bed	35 to 63	64	83.5

3.3.2 Phenomena in River and Floodplain

Fig. 3.20 (a-b) depicts the final bed topographic pattern in the River, 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.



(a) River and levee section (b) Floodplain

Fig. 3.20 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).

In the Run 1, the more vertical erosion is observed in the levee section. Due to erosion in the levee 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 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.

Comparisons of the volume of the floodplain sedimentation at different river bed height are depicted in the **Fig. 3.21**. 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.

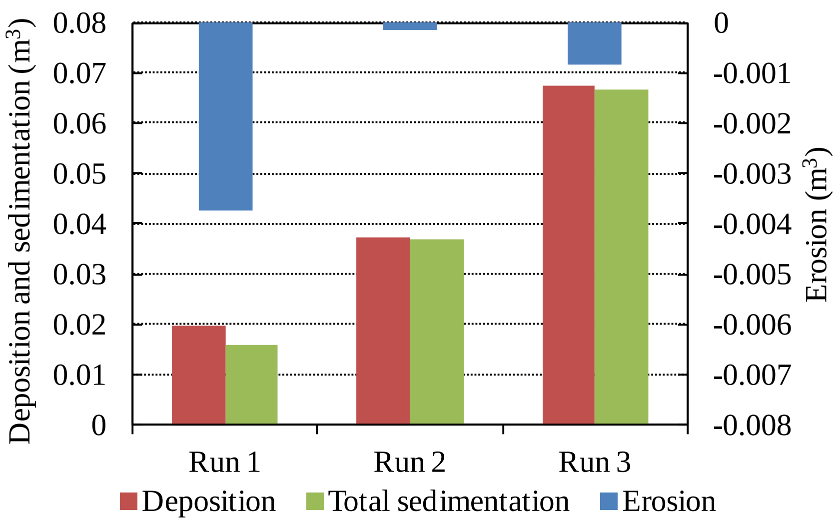
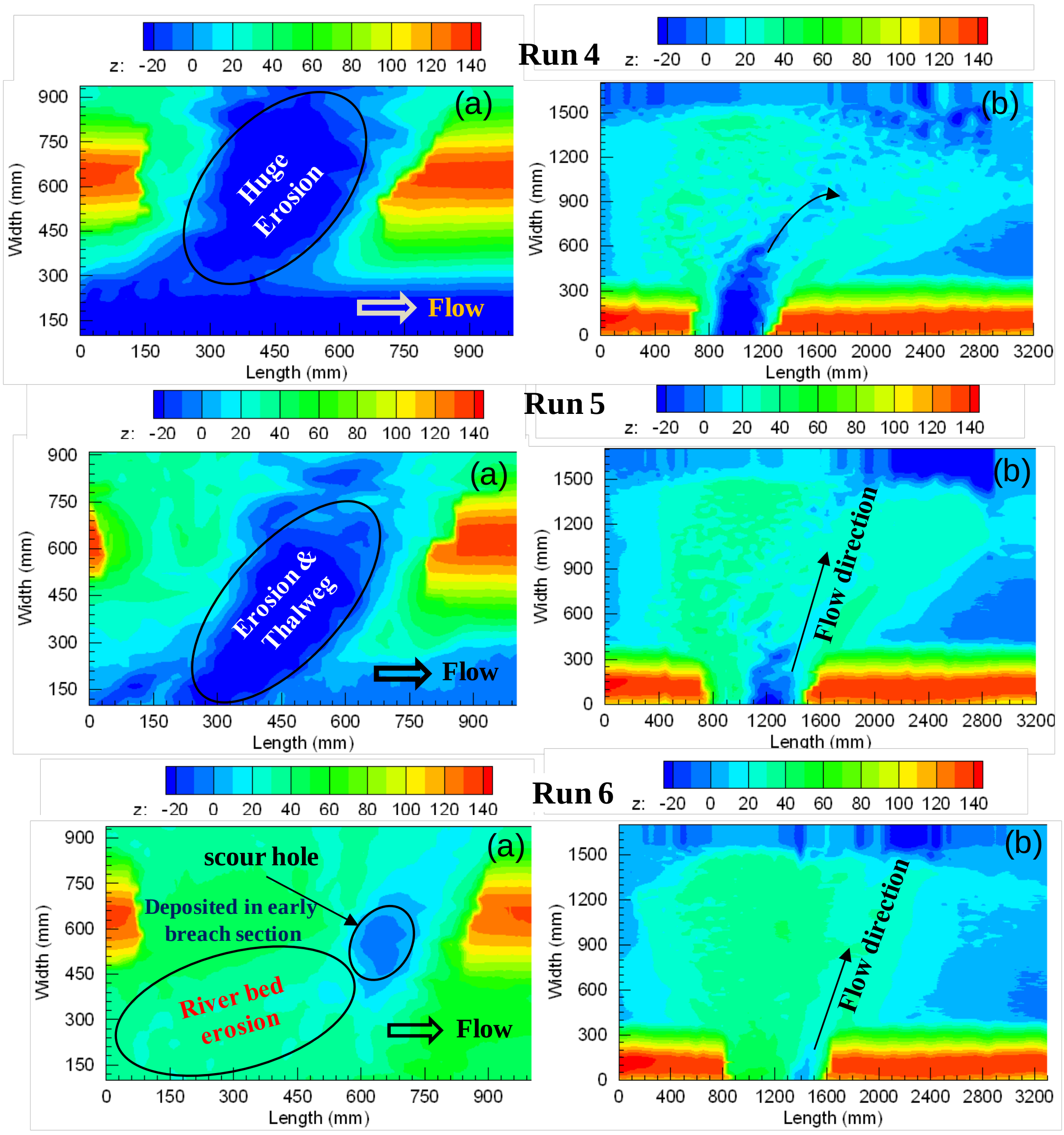


Fig. 3.21 Comparisons of the volume of the floodplain sedimentation at different relative height of river bed and floodplain (Run 1 to 3).

Fig. 3.22 (a-b) depicts the final bed topographic pattern in the River, levee and floodplain at 10 minutes after the overflow breach for the Run 4, Run 5 and Run 6, the positions of the run are in a top, middle and below, respectively.



(a) River and levee section (b) Floodplain

Fig. 3.22 Comparisons of final bed topographic changes in the river, levee and floodplain for the Run 4 (top), Run 5 (middle), and Run 6 (below) at same duration (t=10 min).

In the Run 4, the large vertical erosion is observed in the levee section with little erosion in the river bed. The ripples and dunes of various dimensions are observed in the floodplain because of the fine bed material. Deposition pattern in the floodplain is indicated that the flow is passes to the right-side direction in the floodplain. However, in the Run 5, due to the erosion from the river bed, a thalweg is formed inside the river near the levee along the overflow direction from river to the floodplain. 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. Whereas, in the Run 6; the less vertical erosion is observed in the downstream side of the levee along with erosion in the river bed. In this case also (as like Run 3), the early breach levee section is deposited by the eroded material from the levee section and the river bed; and the sedimentation thickness in the floodplain is higher than the Run 4 and Run 5.

Comparisons of the volume of the floodplain sedimentation at different river bed height are depicted in the **Fig. 3.23**. The erosion and the deposition is less at the low river bed (Run 4) as compare to the high river bed (Run 6) level. The sedimentation volume is more in the Runs 4 and 5 (finer bed material) as compared to Runs 1 and 2 (coarser bed material), though these runs are in the same conditions, because of huge vertical erosion appears in the levee section and it is deposited on the floodplain by breach for the Runs 4 and 5. The floodplain sedimentation is increased with the increased of river bed level. It also shows that the higher river bed (Runs 3 and 6) has the high risk of flood disasters in the floodplain with the larger amount of sedimentation in the floodplain.

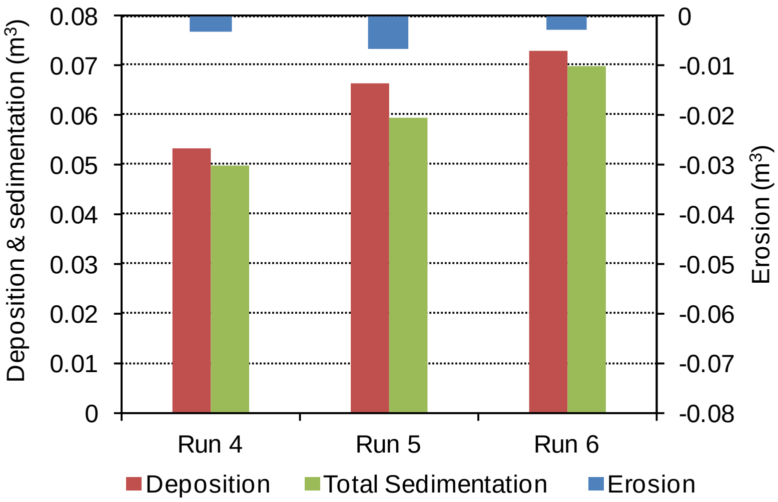


Fig. 3.23 Comparisons of the volume of the floodplain sedimentation at different relative height of river bed and floodplain (Run 4 to 6).

3.3.3 River Bed Changes Accompanying Levee Breach

The comparisons of the changes in the river bed at different relative height of river bed to floodplain are shown in the **Fig. 3.24**. For the coarser bed material (Runs 1 to 3), the higher rate of changes is observed in the Run 3, as compared to the Run 1 and Run 2. Whereas for the finer bed material (Runs 4 to 6); more deformation is seen in the Runs 5 and 6. The river bed material is eroded, and it is deposited on the floodplain by the breach as well as in the upstream of the early breach levee section. Levee breaches with the higher river bed level has the problem, not only in the rapid flow with the larger amount of sediment outflow to the floodplain by breach but also the river bed variation is remarkable, which brings further risk of the levee breach in the upstream reach of the river.

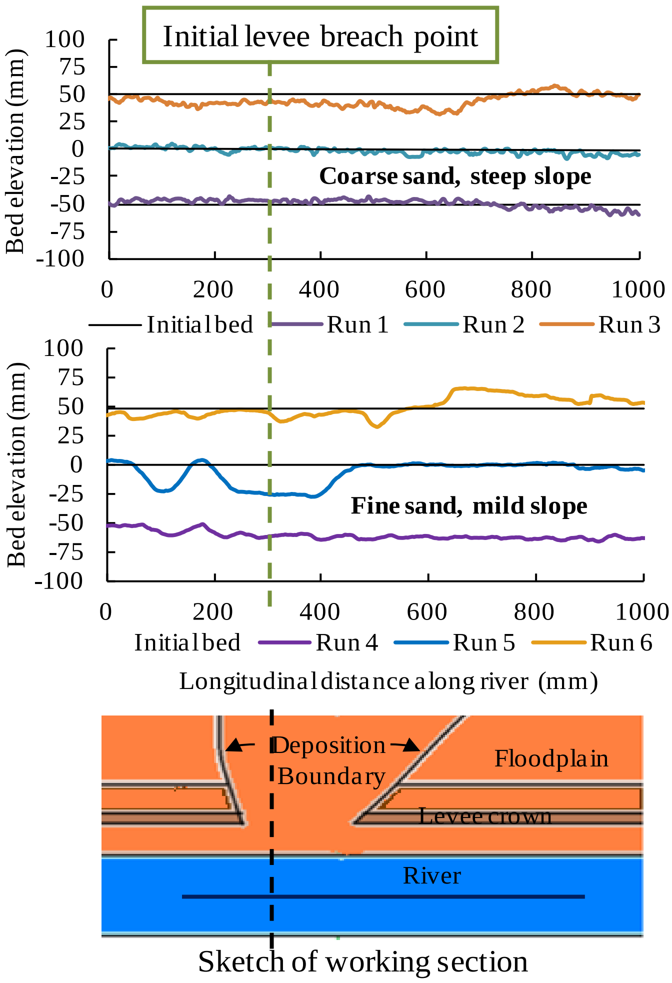


Fig. 3.24 Comparisons of the river bed variations (t=10 min) at different river bed conditions (Run 1 to 6).

3.3.4 Comparisons of Experiments with Numerical

In this study, using 2D RIC-Nays simulation scheme (http://i-ric.org/nays/ja/sitemap.html) concurrently conducted an analysis, to investigate the conformity of the experimental results in a same scale setting and conditions. There was some difficulties in measurements during work in the laboratory and thus if the both approaches have sufficient conformity, these can be complimentarily employed. The results showed a good agreement between the experiments and numerical. Hence, these two approaches provide more information to understand the levee breach and flood disaster in the floodplain with relative height of river bed to floodplain. Some of them have been presented in the **Fig. 3.25**; which is the longitudinal breach length along the river both in experiments and simulation for different height of river bed.

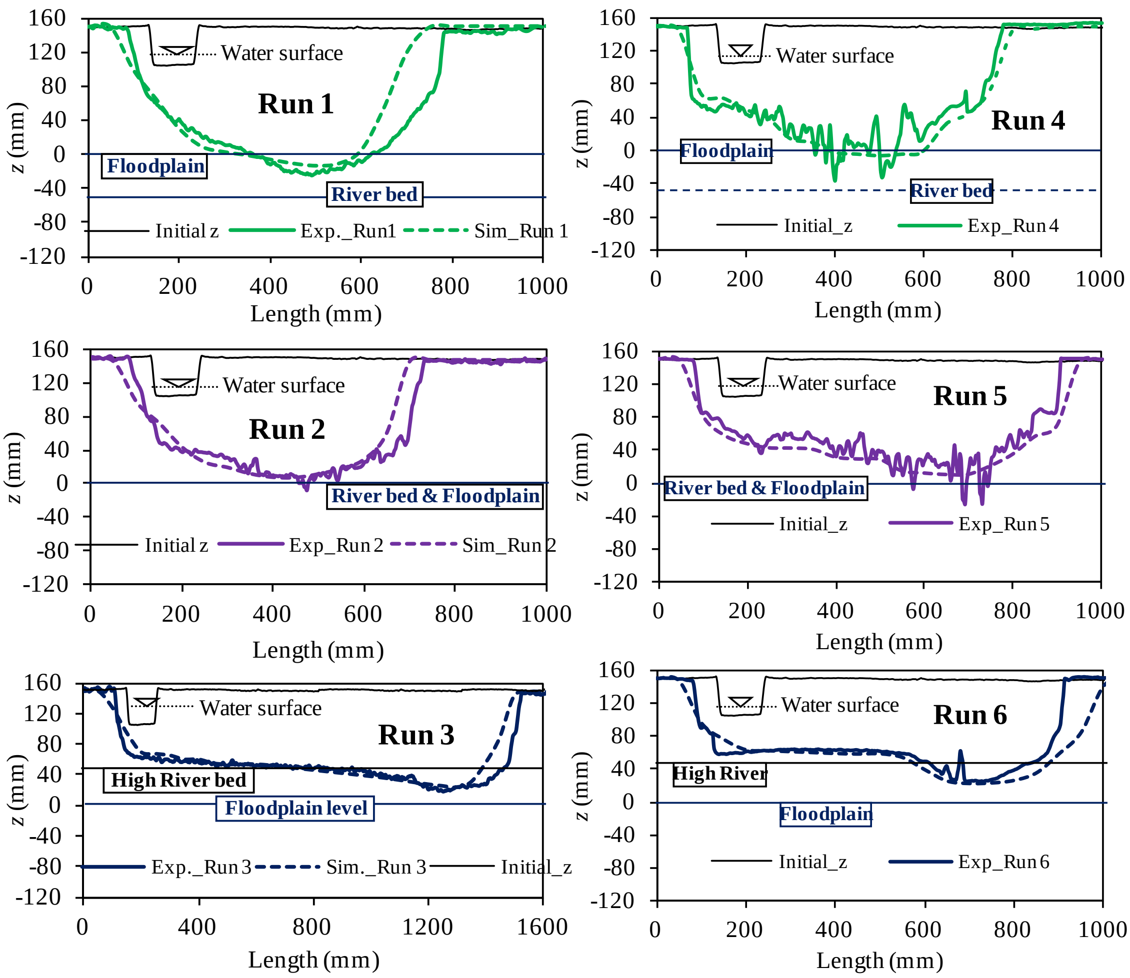


Fig. 3.25 Comparisons of longitudinal length of breaching (t=10 min) at different height of river bed as compared to floodplain level using experiments and simulation (Run 1 to 6).

3.5 Conclusions

This study has been conducted in order to understanding levee breach process and the topographic changes in the river, levee and floodplain and consequences as the risk of flood disasters in the floodplain with different relative height of river bed and floodplain. 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 main results on levee breaching characteristics can be summarized as:

- After the beginning of overflow, though the water is passed through a breach to the floodplain, the horizontal breach widening is not progressed until levee section is lost totally.
- Even if overflow is occurred, serious damage happens after the majority of the levee section is lost.
- Levee breach is quickly expanded to the downstream and the propagation of inundation migrates on this side.
- Higher river bed is exposed to levee breach with more overflow depth and/or smaller discharge with less overflow depth. Although the discharge is small, the breach widening rate is rapid and inundation with more sediment volume to the floodplain not only from levee but also from the river bed as compared to the lower and the same river bed height.
- Furthermore, the large scale numerical simulation have already been conducted, the fact is recognized that the higher river bed has the higher risk of flood disasters in the floodplain.

CHAPTER 4

Understanding of Characteristics and Mechanism of Levee Breach

Summery

Small-scale laboratory experiments and same scenario numerical analyses were conducted to understand the breaching phenomena appearing at the levee and consequences as the disasters risk in the floodplain using different height of river bed with various bed materials and river bed slopes. This study have been carried out considering the area including river, levee and floodplain, and got satisfactory results. These two approaches may provide more information to understand the levee breach and successive disaster in the floodplain. According to the experiments and simulation results, the higher bed level brings more rapid propagation of the levee breach and widening with more sediment deposition in the floodplain using coarse sand with steep river bed slopes as compared to the fine sand with mild slopes. River bed degradation in the upstream of the levee breach point may cause further risk of another levee breach there during the flood. Further investigation demonstrate that the levee breach with higher river bed using fine bed material has also the high risk not only more deposition on the floodplain but the river bed degradation is remarkable.

4.1 General

In recent years, the frequency of abnormal floods in Bangladesh has increased substantially, causing serious damage to lives and property. Mostly, the levee breach disaster occurs in Bangladesh due to huge upstream catchment water and sediment load. The heavy monsoon downpour and synchronization of flood-peaks of the major rivers are generally considered to be the main causes of the floods. Some underlying factors also deserve serious consideration as possible contributors to the recent floods: a possible increase in the watershed area due to seismic and neotectonic activities in the region, river bed aggradation due to siltation and damming of rivers, soil erosion due to unwise tilling practices, deforestation in the upstream region, and excessive development and population growth.

Particularly, Bangladeshi river beds are aggrades very quickly due to continuous sedimentation, that changes in the river bed level can be observed during one's lifetime. Another problem is damming of the river, which reduces the power of water flow downstream from the dam, and the sediments carried by the river start to settle down faster on the riverbed; causing the river beds aggradation and in turn reducing the water carrying capacity of the river (Khalequzzaman, 1994; Shalash, 1982), consequences as their banks an overflow, and the flow causes the levee breach. As for the example, due to the Farakka Barrage on the Ganges has already caused tremendous damage to the agri culture, navigation, environment, and hydrodynamic equilibrium in Bangladesh (Shahjahan, 1983, Siddiqui, 1983, Broadus *et al.,* 1986, Khalequzzaman, 1989).

The failure of the levee causes huge damage to an agricultural production, residents, roads and other infrastructures in the floodplain. Thus, the safety of the levee is important to minimize the flood damage. Mechanism of levee breaches with hydraulic phenomenon due to overflow breach is complex and not so clear, yet some parts are unknown. This kind of study is rare in the available literatures except for few experimental, numerical and field investigation have been conducted by Fujita *et al*., 1987a, b; Islam *et al*., 1994a; Aureli and Mignosa, 2003; Tsujimoto *et al.*, 2006; and Shimada *et al*., 2010. In those studies; they investigated levee breach expansion process as well as floodplain sedimentation process but did not consider on the river bed height relative to floodplain and the subsequent phenomena appearing in the river bed and in the 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. Levee breaching phenomena appears not only at levee but also from the river to floodplain, and thus physical experiments are difficult while a numerical approach has not been well developed. In this study, the attempt have been taken to conduct small-scale laboratory experiments and same condition numerical analyses using coarse and fine sand with steep and mild river bed slope, respectively. There had some difficulties in measurements during work in the laboratory and thus the numerical simulation is necessary for the conformity of this study. Therefore, the investigation have been carried out utilizing both approaches to understand the breaching phenomena on the levee, and to evaluate the disaster risk in the floodplain with different height of river bed to floodplain, various river bed materials and slopes.

4.2 Solution Approach

4.2.1 Experimental Set-up and Measurements Procedure

The experimental setup for the runs with conditions to be maintained for the different bed height using various river bed material and slopes, and measurements procedure have been described 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 sand (coarse and fine), the working section (6 m long and 2.2 m wide) is prepared. Levee slope is 1:2 for both sides, and height is 0.15 m from the floodplain. Same sizes of bed material in the river, levee and floodplain of d_{50}=1.00 mm (Runs 1 to 3) and 0.13 mm (Runs 4 to 6) are used, 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. The river bed slopes are considered as 1/500 (Runs 1 to 3) and 1/1000 (Runs 4 to 6). Relative height of river bed and floodplain is set as follows: Runs 1 and 4 (low river bed) z_b=-5 cm, Runs 2 and 5 (river bed and floodplain at the same level) z_b=0 cm, and Runs 3 and 6 (high river bed) z_b=5 cm, respectively. The details of the experimental setup with the top view, side view and the equipment settings have been discussed in the preceding chapter (Chapter 3). In every experimental run, the tractive force in the river is higher than the critical tractive force and thus the bed is movable. The critical tractive force is examined by using Iwagaki's (1956) equation (chapter 2, equation 2.31).

A notch is cut to provide an initial breach opening for the overflow experiment. Then, the inlet and outlet tank is filled with water, and the wave meter reading is set at an initial condition (zero). The inflow and outflow water discharge is estimated from the early placed wave meter reading by using the equation for rectangular (Itaya and Tejima, 1951) and triangular weir (Kurokawa and Fuchizawa, 1942), respectively. During experiment, the longitudinal breach widening with time is measured. After the experiments, when the bed is become dried, the bed topographic changes in the river, levee and floodplain are measured using computer aided laser sensor, which is attached with the electronic actuators. Finally, the flow velocity vector is analyzed by using large-scale PIV software, which is developed by Fujita *et al.,* (1998). The details of the measurement procedure have been discussed in the chapter 3.

The experimental conditions are compared with among the runs in **Table 4.1**, where the hydraulic parameters at the breaching section, which is measured before breaching. The same inflow discharges and bed materials have been used for the numerical analyses and corresponding river flow depth before breaching also shown in the below table.

TABLE 4.1

CONDITION FOR ALL RUNS (SAME DISCHARGES AND BED MATERIALS ARE USED IN NUMERICAL)

Parameters	Coarser bed material with steep river bed slope			Finer bed material with mild river bed slope		
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
River bed height to floodplain (cm)	-5	0	+5	-5	0	+5
Inflow Q (l/s) (Exp. & Numerical)	8.95	8.71	8.69	9.49	8.85	4.93
River d/s sill (cm) (Exp. & numerical)	13	8	3	13	8	3
River flow depth h_0 (cm) (Experiments)	16	11	8	16	11	6
River flow depth h_0 (cm) (Numerical)	16.3	11.5	8.2	16.5	11.6	6.1
Mean velocity U (cm/s)	15.54	19.31	22.63	18.08	22.13	21.91
Bed material size d_{50} (mm) (Exp. & Numerical)		1.00			0.13	
Shields number τ_*	0.20	0.13	0.10	0.67	0.62	0.31
Froude number F_r	0.12	0.19	0.26	0.14	0.21	0.29
Sand Reynolds number R_{e*}	57	47	40	4.88	4.66	3.31

4.2.2 Simulation Set-up and Procedure

The analyses have been made to observe the process appearing in the river, levee and floodplain in a same simulation scheme during the breach. Floodplain inundation with sediment and evolution process of the breach is studied with a numerical model. RIC-

Nays (http://i-ric.org/nays/ja/sitmap.html), a two-dimensional (2D) model for the flood flow and morphology is utilized in this study. As for the simulation scheme, the river channel, levee, floodplain and the flow parameters are selected in the conformity with the typical field data. Schematic model area is spatially limited to a part of the actual fields. For all cases of simulation, computation reach is 6.00 m long and 2.20 m wide (river channel, levee and floodplain) with a bed slope of river channel is 1/500 (Runs 1 to 3) and 1/1000 (Runs 4 to 6) for the coarse and fine bed materials, respectively. **Fig. 4.1** depicts one of the model fields for simulation. Levee slope is considered as S_l=1:2 on both country side and river side. The levee height is taken as h_l=15 cm from the floodplain and 20 cm (Runs 1 and 4), 15 cm (Runs 2 and 5) and 10 cm (Runs 3 and 6) from the river bed as represent the low, same and high river bed, respectively. Idealized flow and sediment parameters are considered in the computation. Overflow starts from the hypothetical notch on top of the levee as a trigger of the breach, where an initial breach is 10 cm long (L_b) and 5 cm (h_c) deep from the top of the levee. Though the river discharge has a hydrograph in general, non-uniform discharge is correspond to the peak is assumed here by putting the downstream sill in the river. The solid boundary wall is imposed on the left-side of the floodplain to protect the direct flow through the floodplain. The inflow discharges (Q) and the corresponding river flow depth before the breach, and the median sizes (d_m) of sediment are chosen, which are shown in **Table 4.1**.

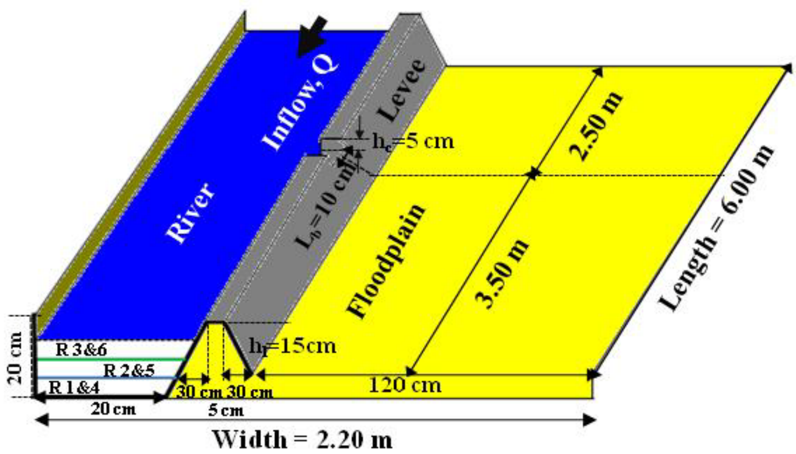


Fig. 4.1 Simulated schematic model fields.

The flow model is based on the depth-averaged shallow-water equations. The equations expressed in a general coordinate system are solved on the boundary-fitted structured grids using the finite-difference method. Bed-load is calculated by Ashida and Michiue (1972) equations; the effect of cross-gradient (Hasegawa, 1983) and the influence of secondary flow (Engelund, 1974) are taken into account. Finally, the bed deformation is determined using the 2D sediment continuity equation. Equations are solved for the unknown nodal values by an iterative process. The details of the model equations have been discussed in the preceding chapter (Chapter 3). First, the flow field is computed utilizing initial and boundary conditions; then the sediment transport field is computed, to evaluate the rate of sedimentation, and followed by the bed topography changes. **Fig. 4.2** depicts the outline of the simulation steps for computation. The number of cell in the longitudinal and lateral direction is 120 and 44, respectively. In this study, the computation time step is used to 0.002 second, and the model run is made in 10 minutes, when the temporal variations are considerably reduced. By numerical calculation, the breach propagation and the bed topography changes in the river, levee and floodplain can be described [**see Figs. 4.3** (Sim.R1, Sim.R2, Sim.R3) and **4.5** (Sim.R4, Sim.R5, Sim.R6)], which is realized spatial characteristics of the levee breaching as well as disaster risk in the floodplain during the flood.

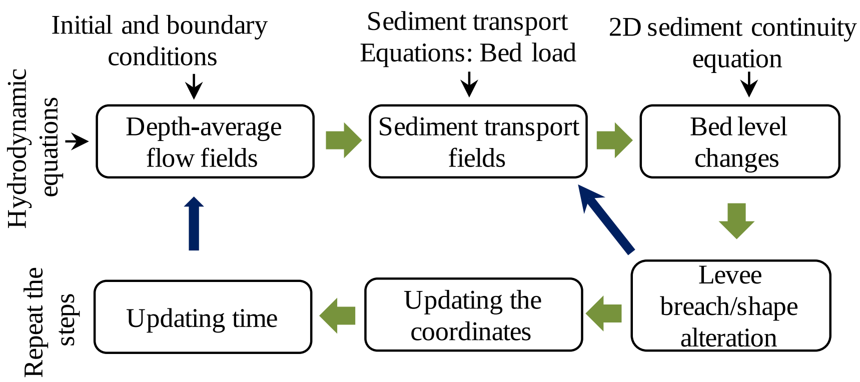


Fig. 4.2 Outline of model computation steps

4.3 Results and Discussion

The main purpose of this study is to understand the characteristics of levee breaching and disasters risk in the floodplain using different river bed height to floodplain with various river bed materials and slopes are discussed in this section by using small-scale laboratory experiments and same conditions numerical simulation. For the elevation differences in the river to floodplain, the flooding flow and inundation in the floodplain are varied. In this study, two sets of experiments and numerical analyses were conducted, and each had three runs. For the first set (Run 1 to 3), coarse bed materials with steep river bed slope were taken. The inflow discharges is provided nearly the same both in experiments and numerical throughout the all runs. The river flow capacity is reduced with the increased of the river bed height. Therefore, the initial overflow depth is lifted in case of the higher river bed level (3 cm for Run 3) than the lower ones (1 cm for Run 1).

However, the second sets of experiments (Runs 4 to 6) have been carried out using fine bed material with mild river bed slope. The inflow discharged is reduced with the increased of the river bed height. The river inflow is higher (9.49 l/s) in Run 4 and lower (4.93 l/s) in the Run 6. Though, the small amount of inflow discharges is provided in the Run 6, which is capable of an overflow levee breach.

Considering the above criteria, this research has been focused on the levee breaching phenomena and evaluates the disasters risk in the floodplain using both in experiments and numerical approaches. The inflow discharges and the corresponding river flow depth before the breach has been shown in **Table 4.1**.

4.3.1 Levee Breaching Process and Phenomena in River and Floodplain

4.3.1.1 Coarser bed materials and steep river bed slope

In Fig. 4.3 depicts the final bed topographic pattern in the river channel, levee and floodplain at 10 minutes after the overflow breach for both in the experiments (Exp.R1, Exp.R2 and Exp.R3) and simulation (Sim.R1, Sim.R2 and Sim.R3). The positions of the run are in a top, middle and below for the Run 1, Run 2 and Run 3, individually. Bed topographic pattern in river and levee section; and the floodplain are denoted by (a) and (b), respectively.

After the beginning of overflow, the initial flow passes over the levee crest along with erosion on it near the floodplain, and afterwards, the inundation water is spread over the floodplain with vertical erosion from the breach point. Then, the horizontal widening process starts by the collapse of the levee (Exp.R1). The more vertical erosion is observed on the levee section. Due to erosion in the levee 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 (Exp.R1, Sim.R1).

In the Run 2, almost same nature of the erosion process appears initially; 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, then the horizontal widening process starts, but the rate is slower than the Run 1 (Exp.R2). A little erosion is observed on 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 (Exp.R2, Sim.R2).

Whereas in the Run 3, 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 discharge, which provide high overflow depth and the level difference between the river bed to floodplain. The levee breach widening process starts in the horizontal direction with the higher rate than the other two runs (Exp.R3). The erosion is observed in the downstream side of the levee along with 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 more than the Run 1 and Run 2. Higher bed level is more dangerous because of river bed deformation appears, and bed material is eroded and deposited on the floodplain by the breach (Exp.R3, Sim.R3).

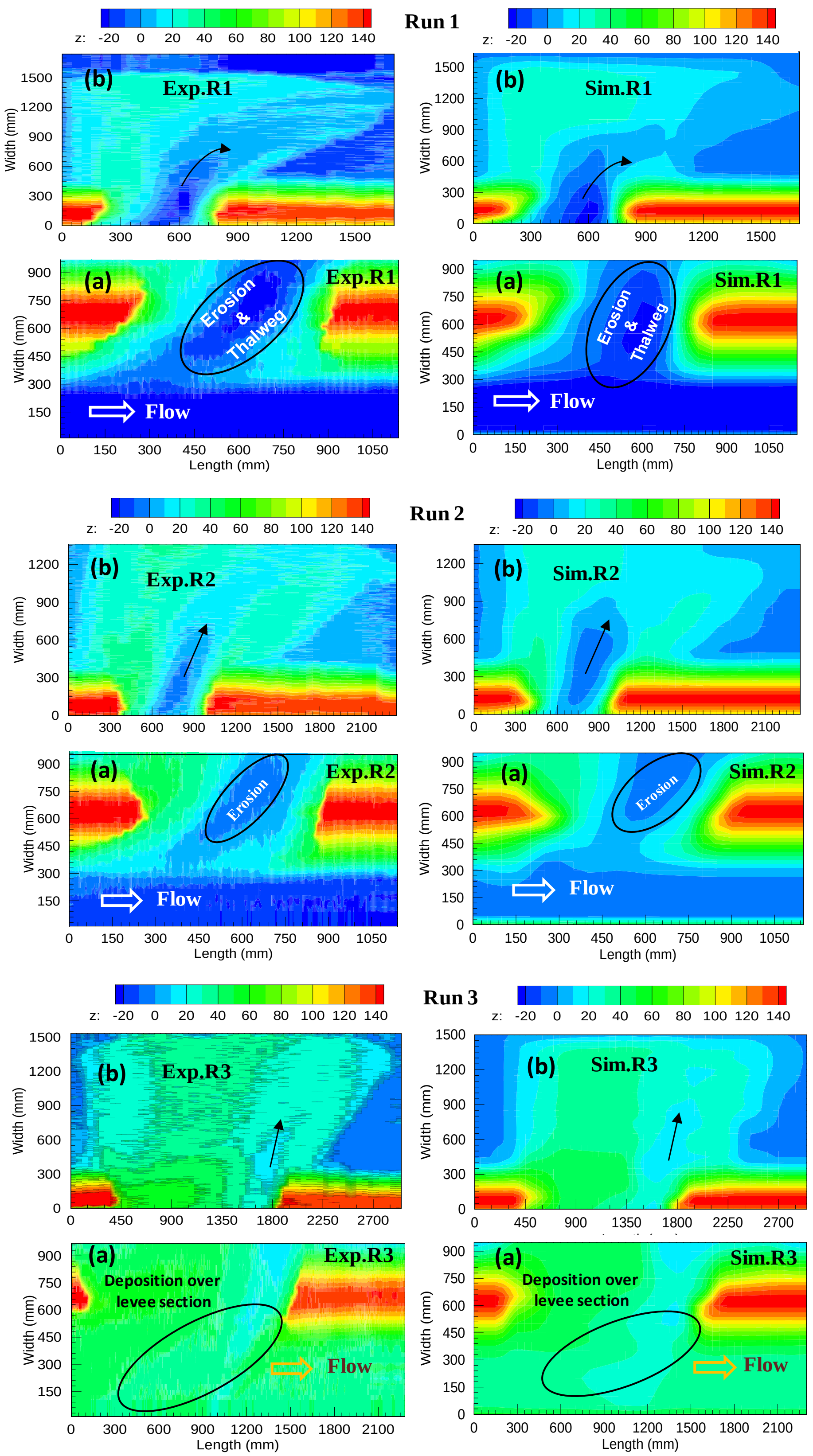


Fig. 4.3 Experiments (Exp.R1, Exp.R2 and Exp.R3) and simulation (Sim.R1, Sim.R2 and Sim.R3) results of bed topographic changes (t=10 min): (a) River channel and levee section; (b) Floodplain.

Fig. 4.4 (a-b) shows the longitudinal levee breach propagation along the river with time for the Run 2 and Run 3 both in experiments and simulation. 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 (Exp.R2, Sim.R2). For the Run 3 (Exp.R3 and Sim.R3), the nature of the early 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 2. The total length of the breaches is double than the Run 2.

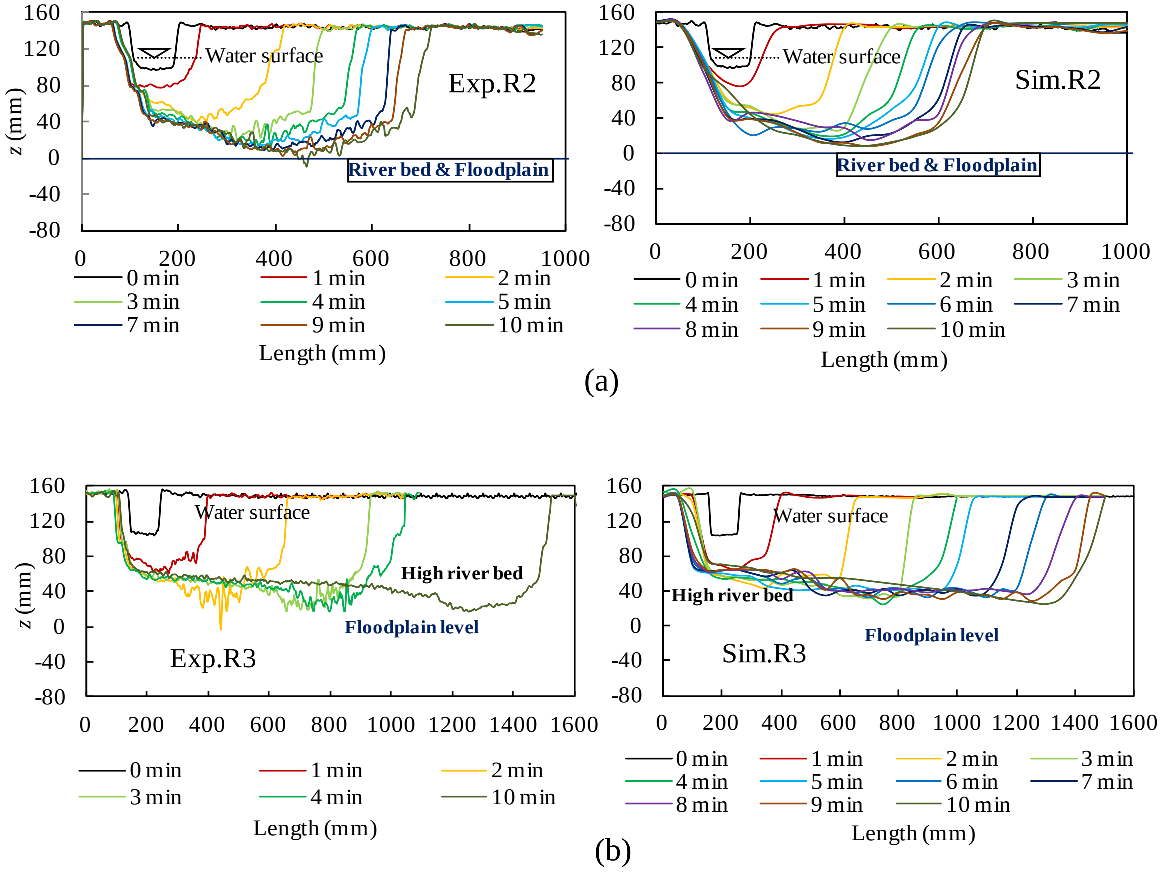


Fig. 4.4 Longitudinal breach evolution processes of levee with time both in experiment and simulation: (a) Run 2 (Exp.R2, Sim.R2); and (b) Run 3 (Exp.R3, Sim.R3).

4.3.1.2 Finer bed materials and steep river bed slope

The final bed topographic pattern in the river channel, levee and floodplain at 10 minutes after the overflow breach for both in the experiments (Exp.R4, Exp.R5 and Exp.R6) and simulation (Sim.R4, Sim.R5 and Sim.R6) are shown in the **Fig. 4.5**. The positions of the run are in a top, middle and below for the Run 4, Run 5 and Run 6, individually. Bed topographic pattern in river and levee section; and the floodplain are denoted by (a) and (b), respectively.

In the Run 4, the initial flow passes straight with the downstream of the floodplain, and then the erosion process starts in the floodplain near the levee toe (outside edge of levee base at the floodplain side). Afterwards, the erosion process comes forward to the centre of the levee with vertical erosion in the levee section, and the horizontal widening process starts by the collapse of the levee (Exp.R4). The large vertical erosion is observed in the levee section with little erosion in the river bed. The ripples and dunes of various dimensions are observed in the floodplain because of the fine bed material. Deposition pattern in the floodplain is indicated that the flow is passes to the right-side direction in the floodplain (Exp.R4 and Sim.R4).

However, in the Run 5, the different nature of the erosion process appears in the levee as compare to Run 4. The erosion process starts between the levee toe and the centre of the levee, and at the same time the levee section is eroded vertically. Suddenly, the erosion process dominates in the levee section with huge erosion of the levee material. Finally, the horizontal breach widening process starts by loss of the levee section. During the breach widening, the erosion process comes forward to the heel (inside edge of levee base at river side) of the levee as well as in the river bed (Exp.R5). Due to the erosion from the river bed, a thalweg is formed inside the river near the levee along the overflow direction. The river bed material is eroded, and it is deposited on the floodplain by the breach. 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 (Exp.R5 and Sim.R5).

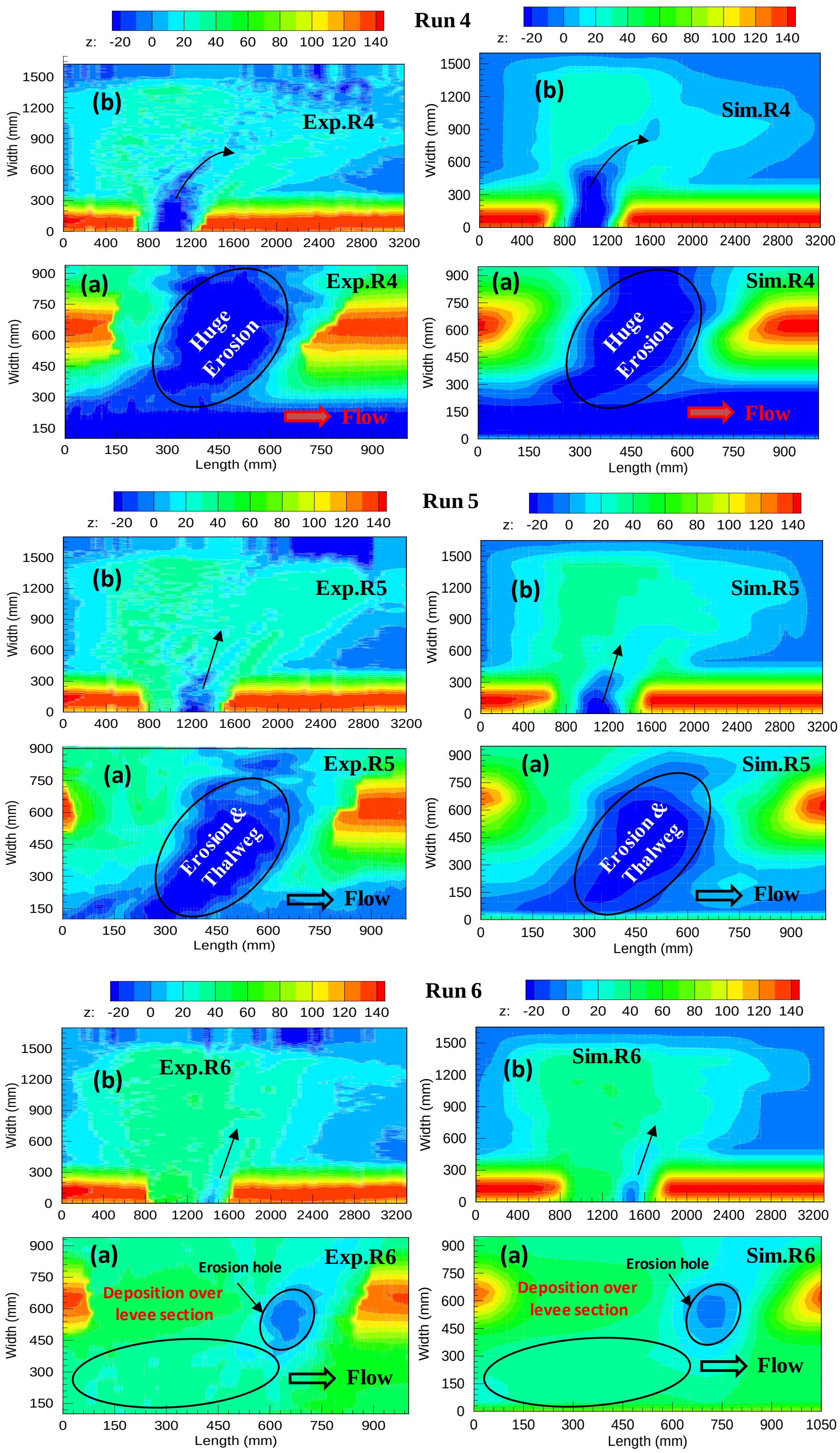


Fig. 4.5 Experiments (Exp.R4, Exp.R5 and Exp.R6) and simulation (Sim.R4, Sim.R5 and Sim.R6) results of bed topographic changes (t=10 min): (a) River channel and levee section; (b) Floodplain.

Whereas, in Run 6, the inflow discharges through the river is smaller than Run 4 and Run 5, but the nature of the initial erosion process is rapid, though the erosion process starts at the levee toe as same as the Run 4. Because of the level difference between the river bed and floodplain, overflow water is quickly passed to the floodplain by the breach with huge vertical erosion in the levee section. Finally, the levee widening process starts in the horizontal direction at the higher rate than the other two runs (Exp.R6). The less vertical erosion is observed in the downstream side of the levee along with erosion in the river bed. In this case also (as like Run 3), 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 4 and Run 5 (Exp.R6 and Sim.R6).

Fig. 4.6 (a, b and c) shows the longitudinal levee breach propagation along the river with time for the Run 4, Run 5 and Run 6 both in experiments and simulation. At short duration, the levee breach is progress towards both in the vertical, and in the horizontal direction along the downstream of the levee. Subsequently, the breach widening process is occurred in the longitudinal direction. After that, the breach widening process is slow, not only in the horizontal but also vertical direction (Exp.R4, Sim.R4). In the Run 5 (Exp.R5 and Sim.R5), initially no horizontal erosion is observed throughout the experiment, but the breach is progress towards both in vertical and horizontal direction in simulation. Then, the breach widening process is same both in experiments and simulation as like in the Run 4. For the Run 6 (Exp.R6 and Sim.R6), the nature of the erosion is nearly equivalent as the Run 5. Even though, the horizontal breach widening process is rapid, and the vertical erosion process is slow as compared to the Run 4 and Run 5. The total length of the breaches is more than the Run 1 and near about same as the Run 2.

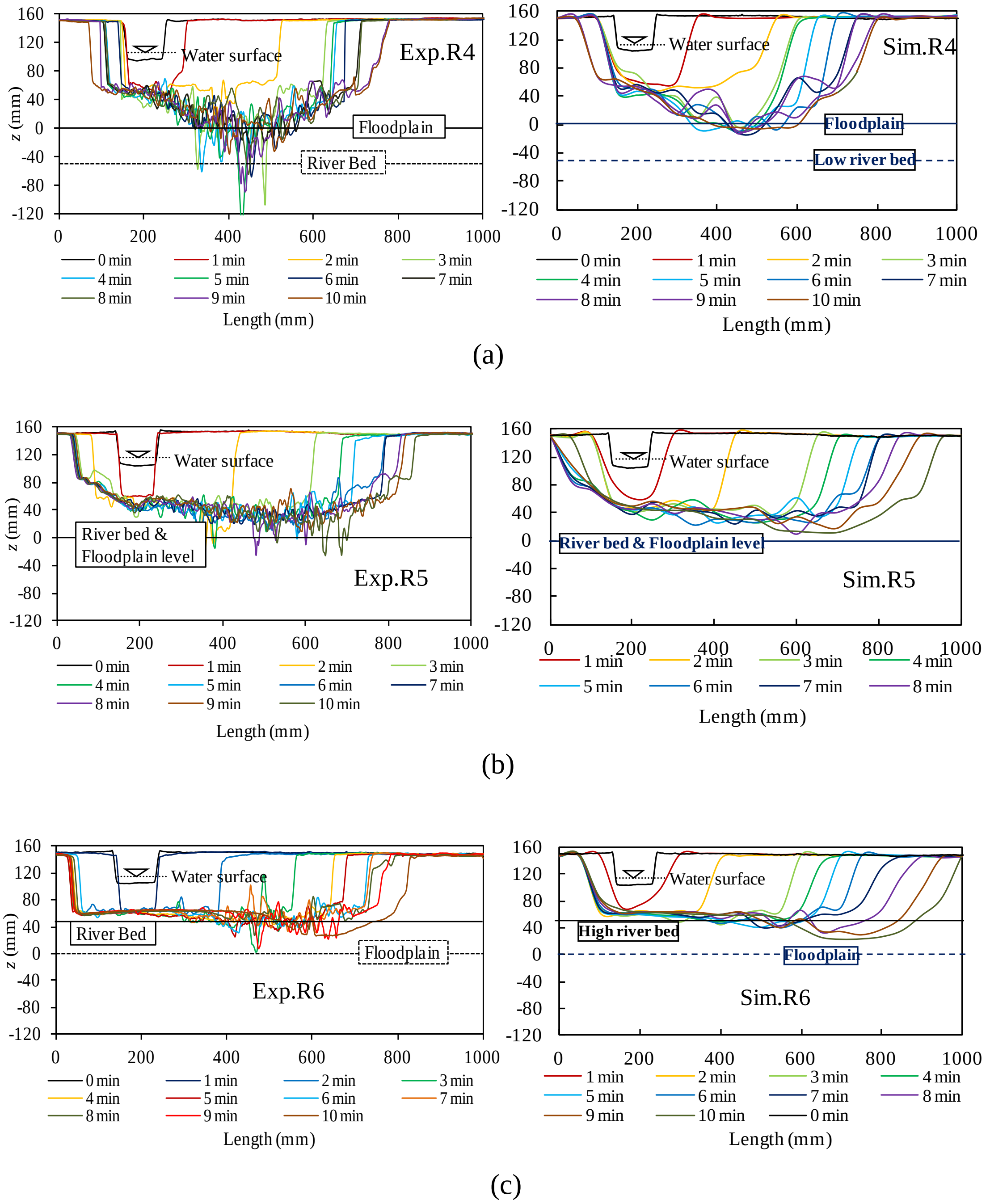


Fig. 4.6 Longitudinal breach evolution processes of levee with time both in experiment and simulation: (a) Run 4 (Exp.R4 & Sim.R4); (b) Run 5 (Exp.R5 & Sim.R5); and (c) Run 6 (Exp.R6 & Sim.R6).

Comparisons of the volume of the floodplain sedimentation at different river bed height are depicted in the **Fig. 4.7 (a-b)** for both in the experiment and simulation. The sedimentation is less at the low river bed (Run 1, Run 4) as compare to the high river bed (Run 3, Run 6) level. The floodplain sedimentation is increased with increased to the river bed level, and the rate is more in the finer bed material due to huge vertical erosion from the levee section and the river bed. It also shows that the higher river bed (Runs 3 and 6) with finer bed materials has the high risk of flood disasters in the floodplain considering with the sedimentation in the floodplain.

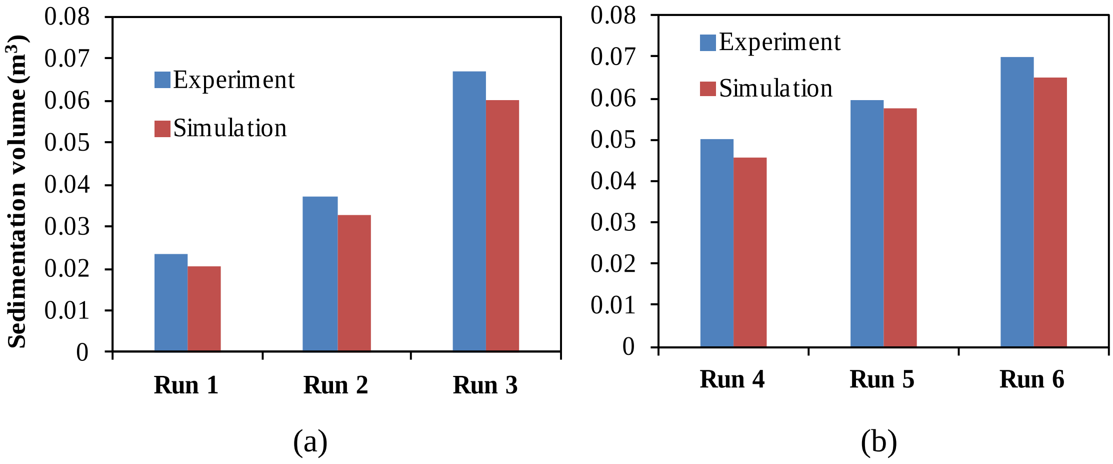
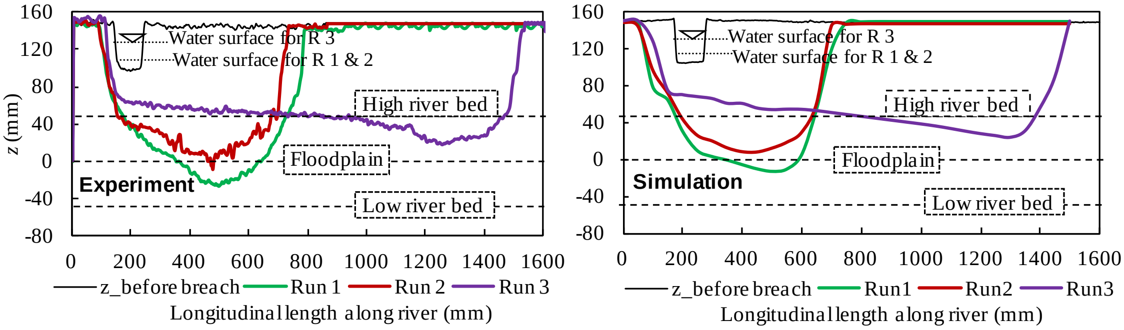


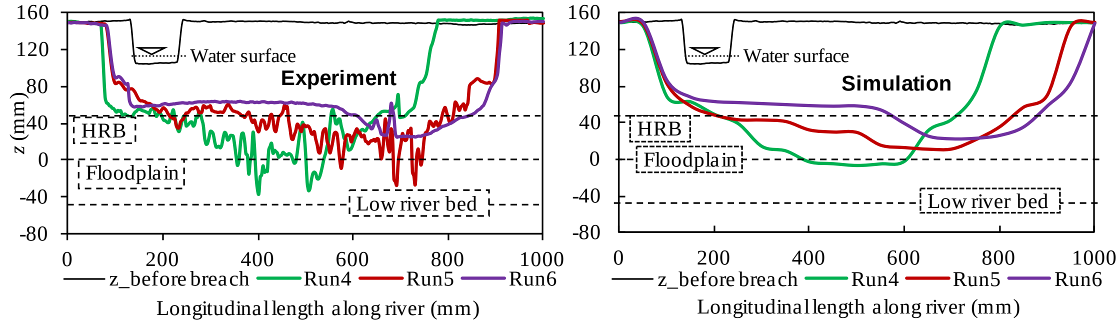
Fig. 4.7 Comparisons of the volume of the floodplain sedimentation both in experiments and simulation Runs 1 to 6: (a) Coarser bed material and steep river bed slope; (b) Finer bed material and mild river bed slope.

4.3.2 Differences in Levee Breach by River Bed Height Relative to Floodplain

The comparisons of the final length of the breach widening at different runs for both in experiments and simulation are shown in the **Fig. 4.8 (a-b)**. The horizontal lengths of the widening are less in the Run 1 and Run 2 than in Run 3, but the vertical erosion is more in the Run 1 and Run 2. However, the larger widening is seen in the Run 6 as compare to the Run 4 and Run 5 but the vertical erosion is more in the Run 4 and Run 5. In case of higher river bed with coarser material (Run 3), horizontal widening is almost double than the lower and same river bed conditions. It happens due to the high river inflow with more overflow depth, and possesses the less bonding effect between the coarser particles. 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 with coarser bed materials has the high risk of flood disasters in the floodplain.



(a)



(b)

Fig. 4.8 Comparisons of the final longitudinal lengths of breach along the river for experiments and simulation (t=10 minutes): (a) Runs 1 to 3; and (b) Runs 4 to 6.

4.3.3 River Bed Changes Accompanying Levee Breach

The river bed deformation comparisons at different relative heights of river bed to floodplain are depicted in **Fig. 4.9 (a-b)**. Both in experiments and simulation, for coarser bed material, the higher rates of changes are observed in the Run 3, as compared to the Run 1 and Run 2. Nevertheless, the overall deformation rate is more in the Run 5 and Run 6. Using finer bed material with the same and high river bed level are dangerous as because of more bed deformations are seen. 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 the breach but also the river bed variation is remarkable, which brings further risk of the levee breach in the upstream reach across the river. 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.

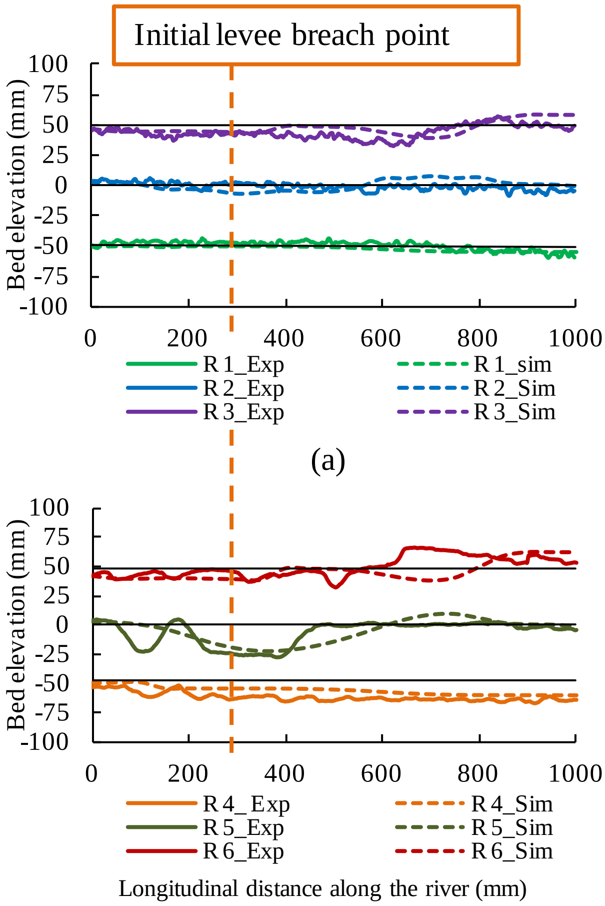
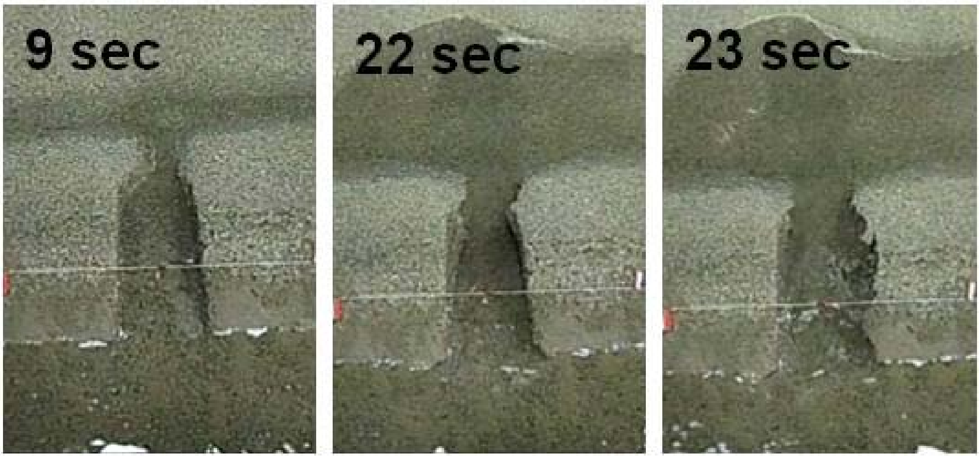


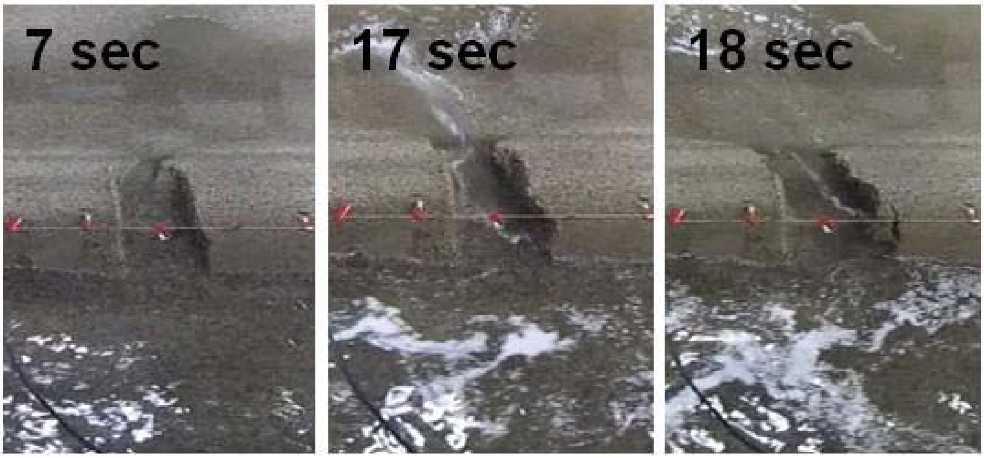
Fig. 4.9 Comparisons of river bed variations along the river for experiments and simulation: (a) Runs 1 to 3; and (b) Runs 4 to 6.

4.3.4 Understanding of levee breach mechanism

In this section, the river bed height and bed materials effects have been discussed to understand the breaching phenomena of the levee and disaster risk in the floodplain. **Fig. 4.10 (a-b)** shows the snapshot of breaching at different duration after overflow starts for the Run 1 and Run 3. In the Run 3, the duration of erosion before widening (7 to 17 second) and the transition of breach expansion (18 second) from vertical to horizontal direction are earlier than that of the Run 1. Both runs are same hydraulic condition, but only the changes of the river bed height. Due to higher bed level, flow is passed rapidly by the breach to the floodplain with high overflow head, which provides quick vertical erosion from levee section as well as the widening of the levee starts at shorter duration. The final horizontal breaching is longer in the Run 3.



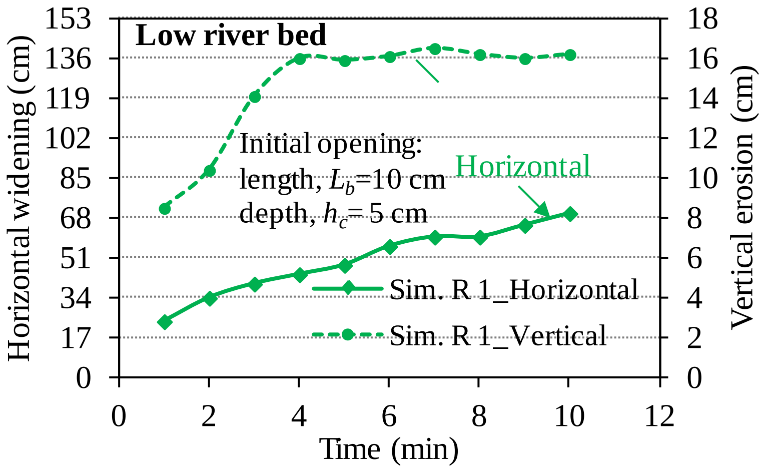
(a) Run 1 (Low river bed as compared to floodplain)



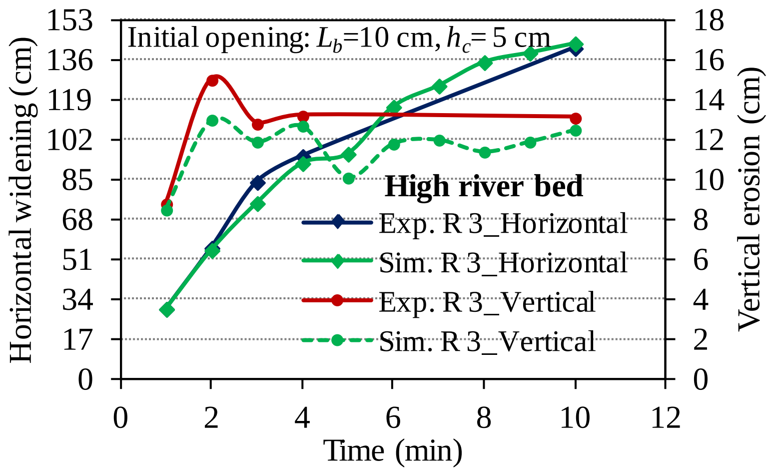
(b) Run 3 (High river bed as compared to floodplain)

Fig. 4.10 Snapshots with time steps for the effect of River bed height on breaching

In **Fig. 4.11** shows the relationships between the horizontal breach widening and vertical erosion with time (*t*=10 min) for low and high river bed level as compared to floodplain using coarser bed material as denoted in the Runs 1 and 3, respectively with an initial opening is provided as 10 cm long and 5 cm deep from the top of the levee. In both directions, breaching is measured choosing the maximum deformation of the levee with respective time steps. From the simulation results of the Run 1 shows that the vertical erosion is dominated at an early stage of breaching, then the erosion process become zero; but horizontal widening process is progressed with time at the same rate. In Run 3, for both in experiments and simulation analysis exposed that the vertical erosion and horizontal widening process appears rapidly at short duration, and then the vertical erosion is decreased but widening is progress with an increased rate. Horizontal widening is almost double in Run 3 than Run 1 as because of higher river bed elevation with almost same discharge (8.95 and 8.69 l/s for Runs 1 and 3) is provided although the river bed height is increased. It can be concluded that the higher river bed has the high risk of disaster on floodplain with larger breaching.



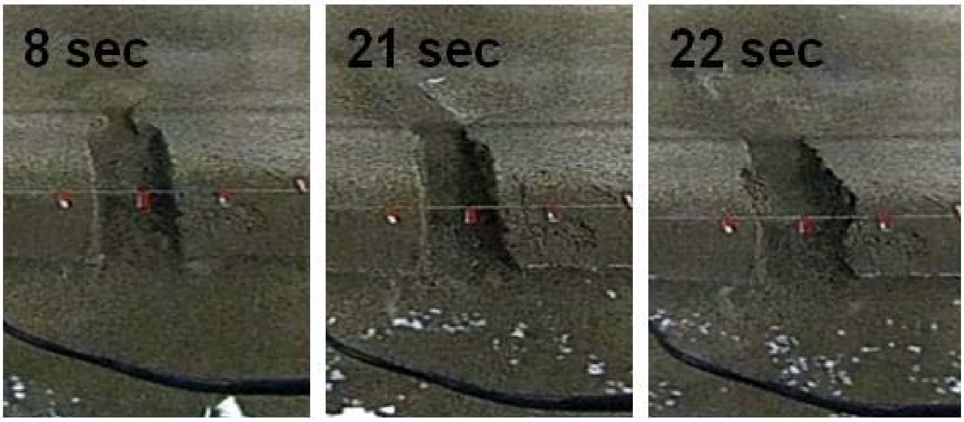
(a) Run 1



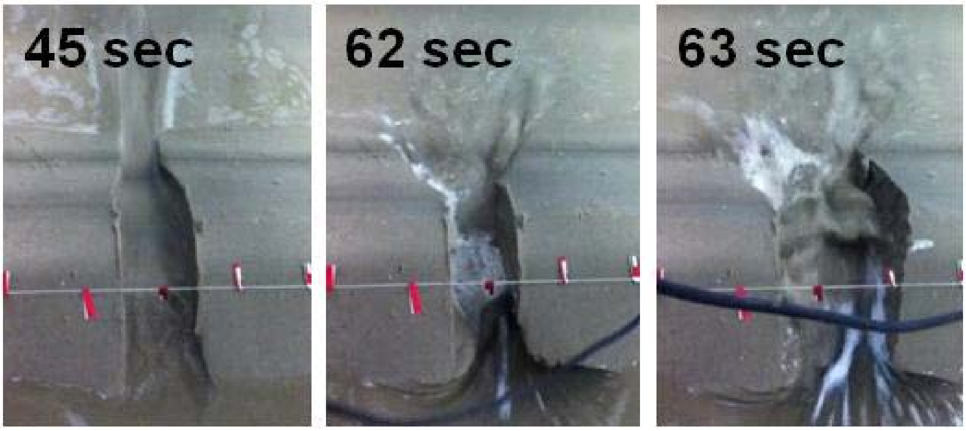
(b) Run 3

Fig. 4.11 Relationships between horizontal widening and vertical erosion of the levee with time for experiments and simulation: (a) Run 1; (b) Run 3.

Fig. 4.12 (a-b) shows the snapshot of breaching with time after overflow starts for Run 2 and Run 5. The comparisons have been made to clarify the effects of the different bed materials on levee breach phenomena. In the Run 2 (coarser bed material), the duration of erosion before widening (8 to 21 second) and the transition of breach expansion (22 second) from vertical to horizontal direction are observed in earlier than that of the Run 5 (finer bed material). Using the same hydraulic conditions, though the breach and the transition of widening are starts at shorter duration in the Run 2, but the final widening is longer in the Run 5. In the coarser material, breach is progressed only wash out the levee material. Whereas, using the finer bed materials, the huge vertical erosion appears from the levee section and in the river bed.



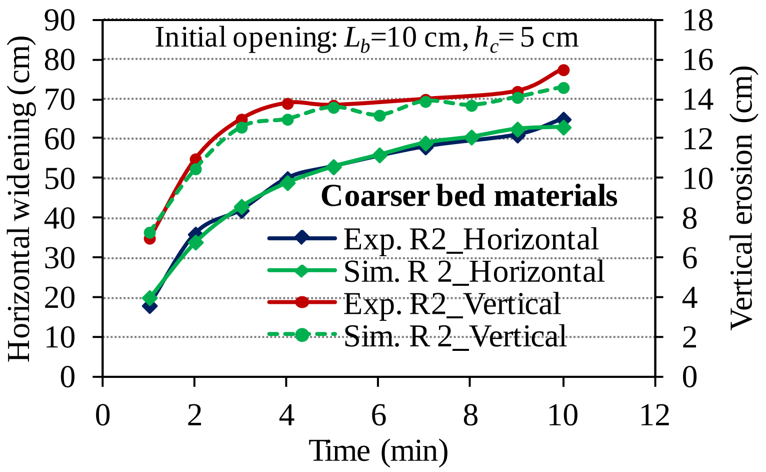
(a) Run 2 (Coarser bed material)



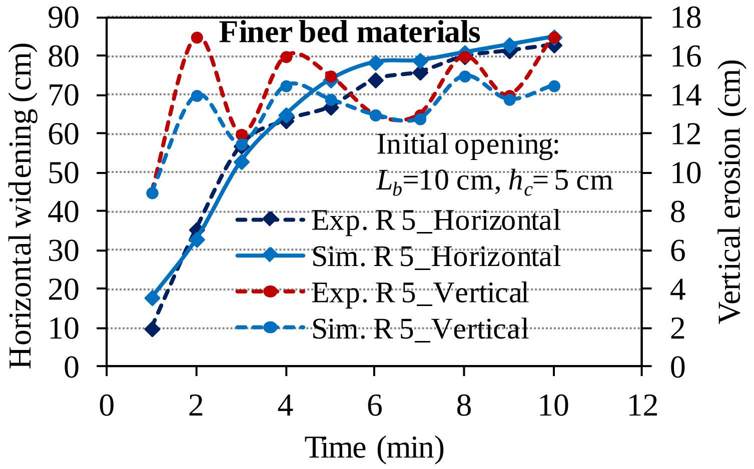
(b) Run 5 (Finer bed material)

Fig. 4.12 Snapshots with time steps for the effect of levee and bed materials on breaching

The relationships between the horizontal breach widening and vertical erosion with time are shown in **Fig. 4.13**, which is represents the same bed height of the river to floodplain using coarser and finer bed materials, and almost same discharges of 8.71 and 8.85 l/s for the experiments and simulation Runs 2 and 5, respectively. In Run 2, the breaching process is progressed both in the horizontal and vertical direction, then the rate is slow with time. Whereas in Run 5, more vertical erosion is progressed in the beginning of the breach, then the erosion is decreased and showing the fluctuation with time; but initially horizontal widening is increased rapidly, then it is decreased with time. Both in experiments and simulation analysis, the effect of bed materials exposed that the finer bed material has the higher risk not only vertical erosion but also horizontal widening of the levee as well as it brings more disaster on the floodplain



(a) Run 2



(b) Run 5

Fig. 4.13 Relationships between horizontal widening and vertical erosion of the levee with time for experiments and simulation: (a) Run 2; (b) Run 5.

For further clarification, the above discussions have been summarized in the **Table 4.2**.

TABLE 4.2

COMPARATIVE SUMMARY AMONG THE EFFECT OF RIVER BED HEIGHT & LEVEE AND BED MATERIALS

Parameters		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 (cm)	Sedimentation in floodplain (m^3)
River bed height	Low (Run 1)	Levee crest at FP side	Vertical erosion & material washed out from levee	9 to 22	23	70	0.016
	High (Run 1)	Levee crest at FP side	Rapid vertical erosion & material washed out from levee & river bed	7 to 17	18	141	0.067
Bed Material	Coarse (Run 2)	Levee crest at FP side	Vertical erosion with progress to river side & material washed out from levee	8 to 21	22	65	0.037
	Fine (Run 5)	Between levee toe & center	Huge vertical erosion with turbulent motion between levee toe and center of the levee as well as erosion in the levee heel and from the river bed	45 to 62	63	83	0.059

4.4 Conclusions

This study have been conducted using the different sets of experiments and same scenario numerical analyses, to understand the levee breach process and evaluates the disasters risk in the floodplain with considering the effect of river bed height, bed material sizes and river bed slopes. The research result showed that the higher river bed not only influences the effect of levee breaching and floodplain deposition, but also it has unlike characteristics in the river bed variation using different bed materials. The conclusion can be drawn as follows:

- Though have some discrepancies between experiments and same condition numerical analyses, both results showed reasonably good agreement.

- In coarser bed material, the erosion process starts mainly on the levee crest, and the breach is progress by the washout of levee material with flow; whereas to use finer bed material the different breach phenomena with huge vertical erosion in the levee along with more river bed deformation appears.

- In coarser bed material, higher river bed is exposed to levee breach with higher overflow depth and thus the widening rate of the 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 finer bed material as well as to the lower and the same river bed height.

- Using finer material, both in the same and the high river bed level, river bed deformation is remarkable and bed material is deposited not only in the floodplain but it revealed degradation on the upstream of the river bed to bring another risk of breach in the next flood.

- Furthermore, the levee breach with higher river bed is risky both in coarser and finer bed material, because of the rapid breach widening with more inundation and sediment outflow to the floodplain by the breach as compared to the lower river bed due to a difference to the level between river bed to floodplain.

CHAPTER 5

Levee Breach Disasters between Bangladesh and Japan

Summery

Flood disaster is caused by the levee breach due to high river flow and consequences as huge damage occurs in the inhabitants inside the levees. Thus, it is important to recognize the process of levee breaching and inundation; and the attempted have been taken to do through numerical simulation. As for simulation scheme, schematic model area is considered with main channel, levee and floodplain composed of same materials. The channel and flow parameters are selected in conformity with the typical model field of Bangladesh as well as Japan. And RIC-Nays, a two-dimensional numerical model for flood flow and morphology is utilized in this study upon confirmation through another numerical study. Based on the calculated results, evolution process of levee breach and inundation of water and sedimentation in the floodplain are investigated. Levee breach is considered to initiate in the middle of the levee with crest opening.

5.1 General

Bangladesh is extremely flat with low land relief with only a few hills in the southeast and the northeast part of the country. It has world’s three great river basins and their floodplain which is the Ganges, the Brahmaputra and the Meghna (GBM Basins) covering a combined total catchment area of about 1.7 million sq. km. extending over

Bhutan, China, India and Nepal, flow through Bangladesh. The watersheds are wide with longer river length consisting mild river slopes. Over the years, Bangladeshi river carries the huge amount of sediment from upstream catchment, and day by day the conveyance capacity of the river is reduced. Sediments settle over the river beds, flood plains and low-lying areas during the flood by the levee breach with the inundation and the recession of water. As a result, river channels and their distributaries are silted up with sediments composed of fine sands and silts causing drainage congestion and overbank flow resulting in river levee failure (Islam *et al.*, 1994a).

In Japan, about 49% of the population and 75% of real property are on flood plains, and flooding is currently one of the most serious natural hazards faced by the country. 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 few day's heavy rainfall event. The 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. In Japan, most of the levee breach flood disasters occurred by massive rainfall due to typhoons and torrential rain. For Example, the Tokai Flood in 2000, huge rainfall attacked Nagoya metropolitan area, and the city perfectly lost the functions, which caused 10 fatalities and 115 injuries. The Niigata-Fukushima Flood on 13 July 2004, 10 typhoons hitting the Japan islands and heavy rainfall due to front activities caused levee breaches at many rivers to bring catastrophic disasters, when more than 200 peoples were killed (Tsujimoto *et al*., 2006; Zhai *et al.*, 2006a).

Considering both this two countries characteristics, computational simulation can make comprehensive analysis on levee breach flooding and its impacts on the entire flood plains. Although has different river system and floodplain both in Bangladesh and Japan, to analyze the comparisons of the levee breach and successive disaster in the floodplain utilizing with the typical model fields including river, levee and flood plains. Levee breach causes huge damage to the floodplain infrastructure as well as live and properties. In order to save the amount of money, lives, agriculture and ecology, it is most important to carry out research on investigation of flood disasters over the floodplain during the levee breach. In this chapter, the attempted have been made to compare the process of inundation, sedimentation and breach evolution in the floodplain after levee breach using a numerical simulation scheme.

5.2 Solution Approach

RIC-Nays, a two dimensional (2D) model for flood flow and morphology, developed by the foundation of Hokkaido River Disasters Prevention Center, Japan is utilized in this study.

5.2.1 Model Setup

In this study, the process have been analyzed which appears in the river, levee and floodplain in a same simulation scheme during flood. This study is conducted two schematized model field for Bangladesh and Japan, which has same domain but the changes made on inflow discharges, sediment diameters and river bed slope. As for simulation schemes, the main channel, levee, floodplain and flow parameters are selected in conformity with the model field of these two countries. Schematic model area is spatially limited in a part of actual fields. For both case of simulation, computation reach is 1800 m long (L) and 1000 m wide (Y) (river channel=100 m, levee=30 m and floodplain=870 m). Both these two countries floodplains are considered as same characteristics, although have different topographic variation.

TABLE 5.1

FLOW AND MODEL FIELD PARAMETERS FOR TWO COUNTRIES

Parameters	Bangladesh Model	Japanese Model
Inflow discharge, Q (m^3/s)	750	1250
River bed slope, S (m/km)	0.075	3.69
Sediment diameter, d (mm)	0.1	0.375
Froude number, Fr	0.185	0.363
Shields number, τ_*	8.11	8.35
Sand Reynolds number, R_{e*}	11.45	84.38

Levee slope is considered as S_l= 1:2 on both country side and river side and levee height is taken as h_L=6 m from the floodplain and 8 m from the river bed. During high flow in a river, overflow starts from the hypothetical notch on top of the levee as a trigger of the breach where the initial breach is 50 m long (L_b) and crest height is 5 m (h_c) from the floodplain. Though the river discharge has a hydrograph in general, a uniform discharges corresponding to the peak is assumed here. Solid boundary is imposed on the left side of the floodplain. **Fig. 5.1** depicts one of the model fields for simulation.

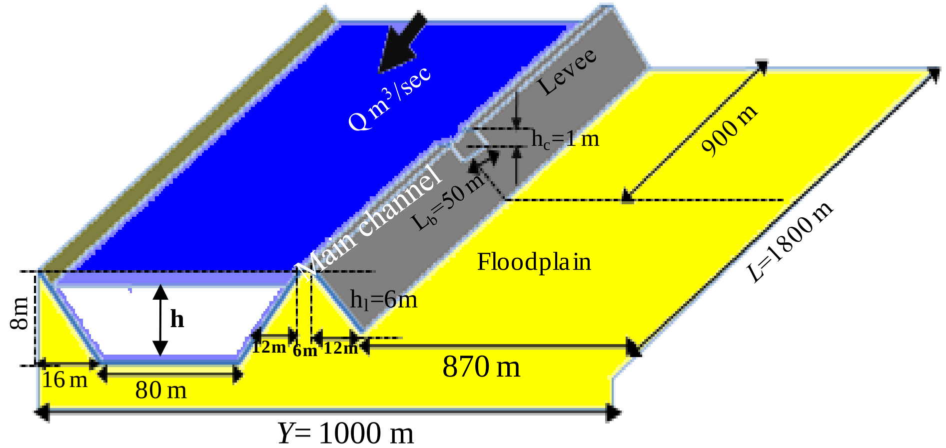


Fig. 5.1 Simulated model area showing river channel, breach levee and floodplain.

5.2.2 Procedure

The flow model is based on the depth-averaged shallow-water equations. The equations expressed in general coordinate system are solved on the boundary-fitted structured grids using the finite-difference method. Bed-load is calculated by Ashida and Michiue (1972) equation; the effect of cross-gradient and the influence of secondary flow, are taken into account. In considering suspended sediment, an exponential profile of concentration is assumed to know planar distribution of depth-averaged concentration and the 2D advection-diffusion equations are solved. Finally, the bed deformation is determined using the 2D sediment continuity equation. Equations are solved for the unknown nodal values by an iterative process. First the flow field is computed utilizing initial and boundary conditions; the sediment transport field is then computed, to evaluate sedimentation rates, and followed by bed topography changes. The details of the model equation have been described in the preceding chapter (Chapter 2). **Fig. 5.2** depicts the outline of the simulation steps for computation. The number of cell in longitudinal and transverse direction is 360 and 200, respectively. In this study, the computation time step is used as 0.002 second and the model runs are continued for 20 minutes, when the temporal variations of variables are considerably reduced. By numerical calculation, the flow behavior and the process of sedimentation around the breach and in the floodplain can be described with morphological changes (see **Fig. 5.3**), and it would be realized spatial characteristics of the phenomena as well as the propagation of the levee breach with time.

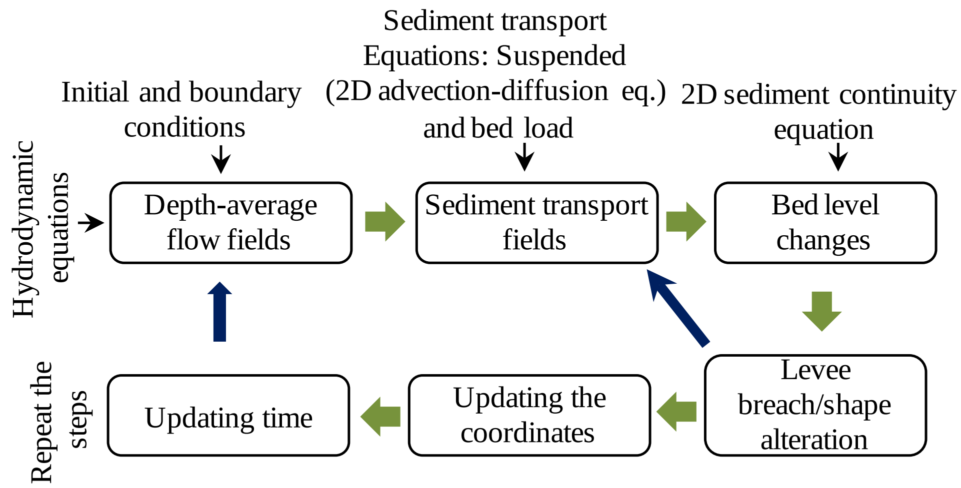


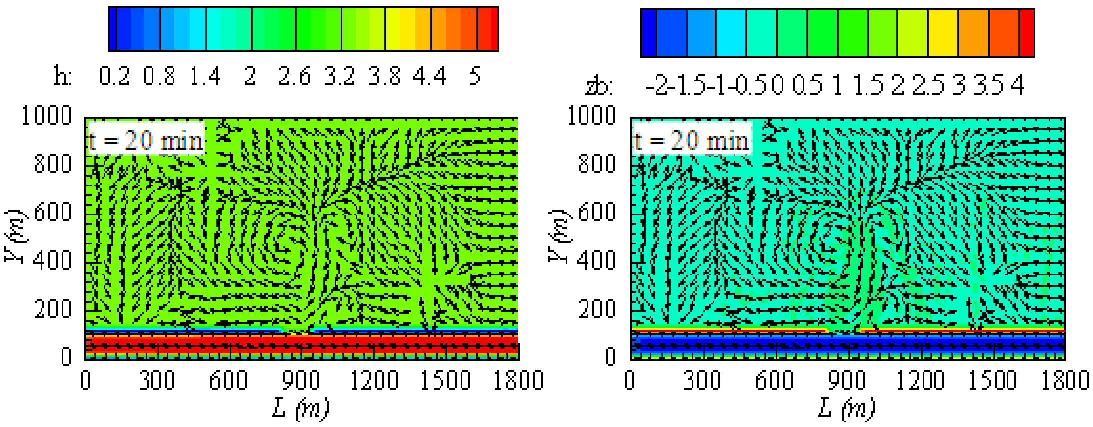
Fig. 5.2 Outline of model computation steps.

This study model result is compared with the numerical data of Tsujimoto et al. (2006) where they observed levee breach process of a river by overflow erosion; it's showed reasonably good agreement. The details of which are not included herein (Chapter 2).

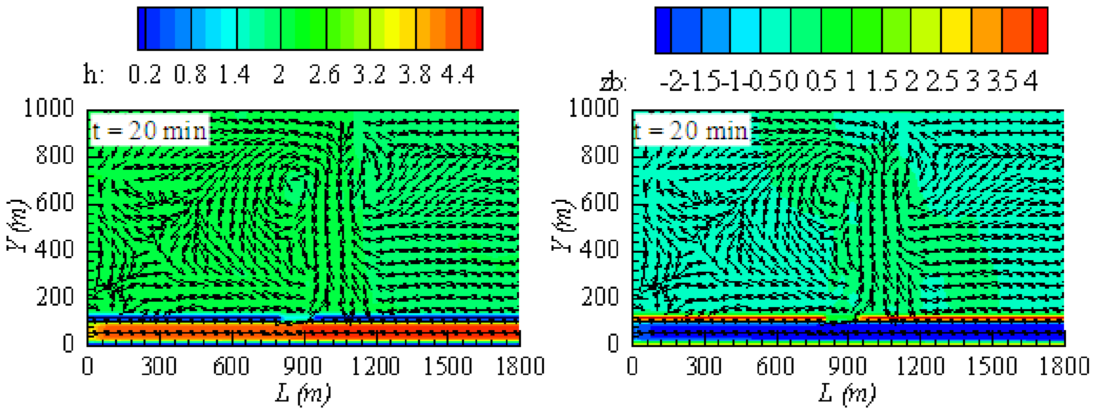
5.3 Results and Discussion

Selected results of the flow-fields and bed topography have been presented in this section to compare the levee breach disasters effect in the floodplain using the typical model fields of Bangladesh and Japan.

In Bangladesh and Japan, floodplain was formed by flooding and levee was constructed by dredging from river bed materials. Normally, the river bed is lower than the floodplain level in spite of the large amount of sediment transport due to elaborate efforts of dredging. Therefore, the river, levee and floodplain have been treated simultaneously in the simulation model. To compare the flow dynamics and morphological changes over the floodplain due to initial levee breach length of 50 m is carried out with an inflow discharge of 750 and 1250 m^3/s for Bangladesh and Japanese model, respectively and duration of 20 minutes, which are shown in **Fig. 5.3**.



(a)



(b)

Fig. 5.3 Characteristics of levee breach flow and morphological changes: (a) Bangladesh Model; and (b) Japanese Model, where h_c=5 m from floodplain; contours indicate the water depth (*h*) and bed elevation (*zb*).

Both of Bangladesh and Japanese model, initially river water depth investigated high, and it is decreased with time in the main channel because of the river water diverted to the floodplain through the breach as processes of time. Floodplain inundation depth increased in certain duration. It can be concluded that after certain period of time at any specific discharges, inundation depth was not increase in the floodplain, although the inflow duration increase. River water passes rapidly at Japanese condition due to higher gradient differences of river bed as compared to Bangladesh. At the same time, floodplain inundation depth is less in Japanese condition because of steep river bed slope, and flow is passed rapidly to the downstream through the river, where as more inundation depth is seen in the model field of Bangladesh. Regarding sedimentation, levee breach floodplain sediment deposition area and thickness are more in Japanese case due to high velocity of flow passes through the breach, and it causes more erosion in the breaching section and this sediment is deposited along the flow direction around the breach and settles over the floodplain with time. The sediment deposition thickness decreased gradually towards the downstream of the floodplain with increases the distance from the breach location for both cases.

Fig. 5.4 shows the comparison between calculated results of the transverse distribution of velocities components *u* and deviation of bed elevation with time for Bangladesh and Japan. Overtopping water passes from the river to the floodplain by the breach initially at high flow velocity and velocity reduces with time because of elevation difference with the levee crest and floodplain, and expansion of the breach. River's water flows to the downstream in the main channel, and some portion of water diverted to the floodplain through the breach levee. In the figure, it is clearly seen that the high velocity is observed at short duration near the breach inside the river, top of the levee and as well as in the floodplain next to the breach. Along the flow direction, velocity is high, and it is decreased with time. Japanese case showed a higher rate as compared to Bangladesh due to steeper river bed slope, and it causes higher deposition as well as damage to the floodplain. Flow velocity changes with time, and consequences as the floodplain sedimentation is increased with time and it is deposited near the breach and along the flow direction. Obviously, it can be concluded that the levee breach with steep river bed slope is associated with more sedimentation in the floodplain. It has the high risk of flood disasters and as well as more damage to the agricultural production and other's infrastructures in the floodplain, and finally; it is increased the suffering to the inhabitants who are lived in the floodplain.

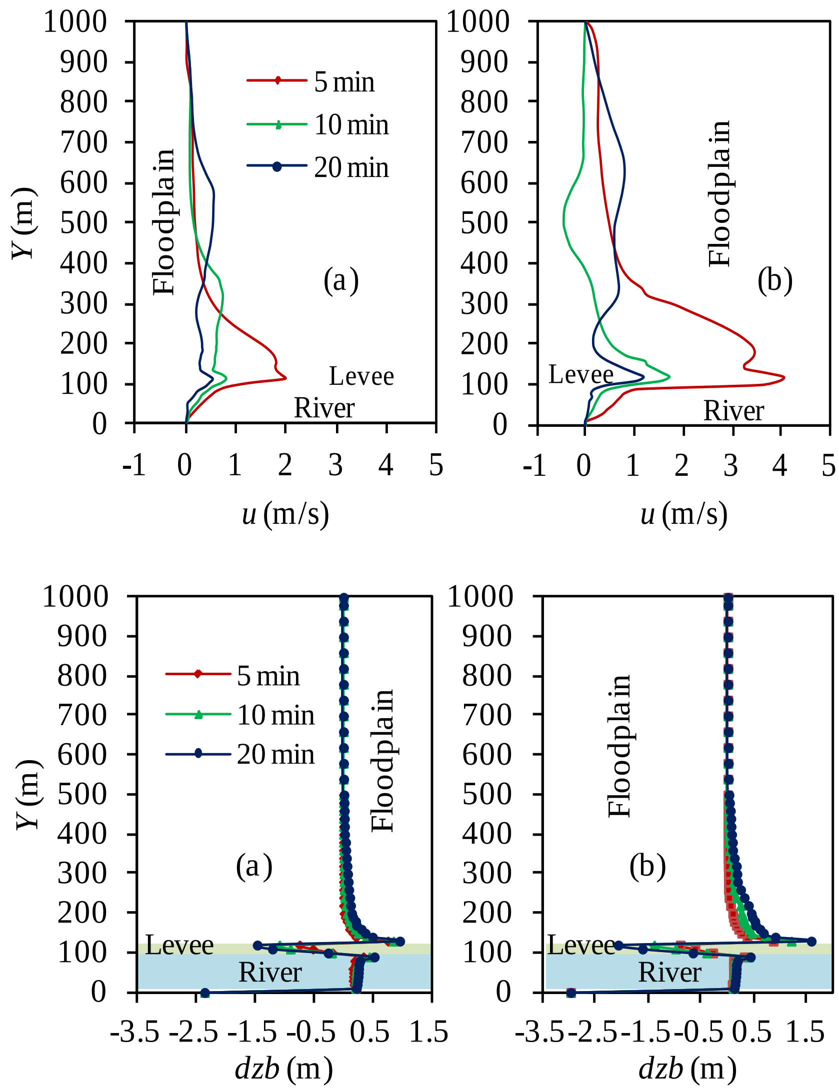


Fig. 5.4 Comparison of transverse distribution of velocity (*u*) and sedimentation (*dzb*) profile at *L*=920 m on breach with time: (a) Bangladesh Model and (b) Japanese Model where h_c=5 m from floodplain

In this section, the discussion has been made on the evolution process of a levee breach with time is compared Bangladesh and Japan, which are shown in **Fig. 5.5 (i-ii)**. The breach evolution is expressed as the temporal growth of breaching section (front view at *y*=115 m) and the temporal loss of the levee cross section (side view at *L*= 920 m). The breaching section for higher duration is higher, and it results that the large amount of discharge causes serious inundation in the floodplain.

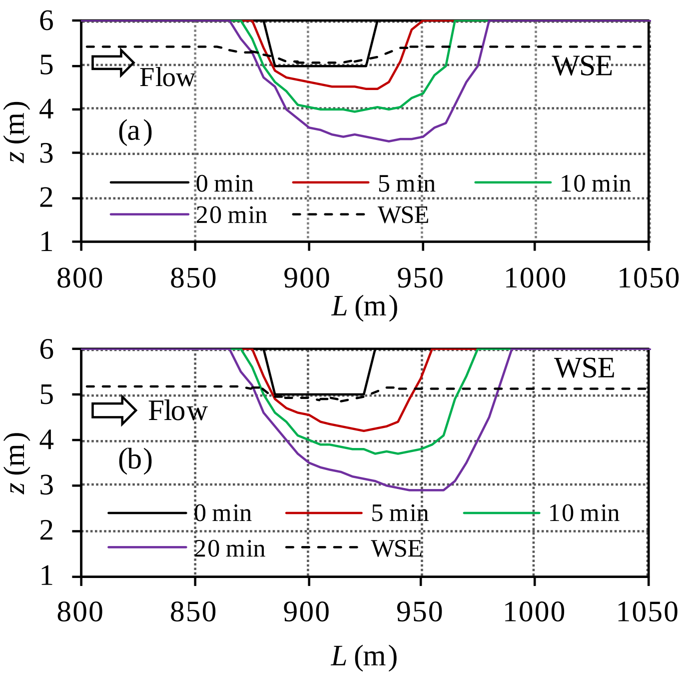


Fig. 5.5 (i) Comparison of temporal growth of breaching section at *y*=115 m with time: (a) Bangladesh Model and (b) Japanese Model.

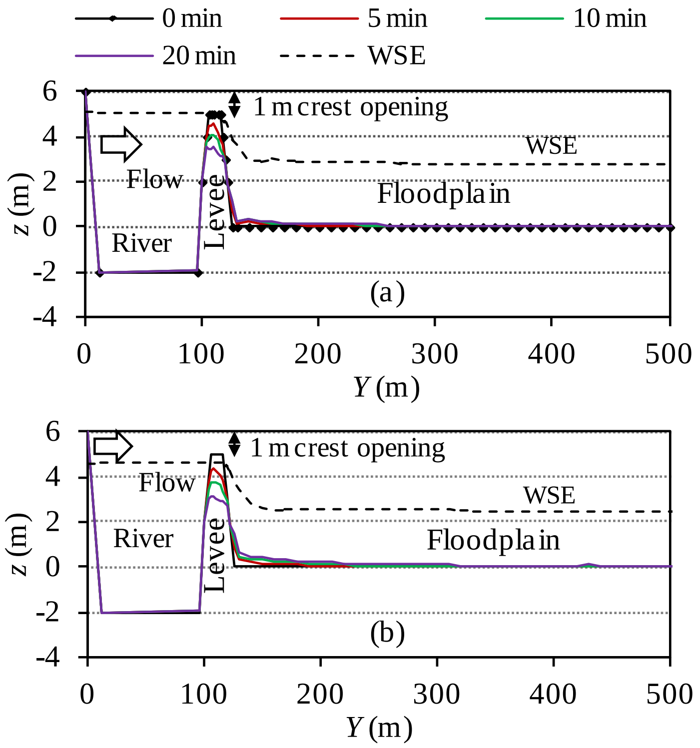


Fig. 5.5 (ii) Comparison of temporal loss of levee cross section at *L*=920 m with time: (a) Bangladesh Model and (b) Japanese Model.

In addition, not only the inundation but also the sediment deposition in the floodplain is more with time, which causes another aspect of a flood disaster inside the boundary of the levee. Comparing the breach evolution processes in both countries; in Japanese case, the high velocity of flow is passed by the breach, and it contributes more erosion in the levee as well as more widening the length than Bangladeshi case, as because of steep river bed slope. However, more damage occurs in the floodplain when the levee breach overflow is happened with steeper river bed slope.

In **Fig. 5.6** shows the relationships between the horizontal breach widening and vertical erosion with time (t=20 min) for Bangladesh and Japanese model using fine and coarse bed material, respectively with an initial opening is provided as 50 m long and 1 m deep from the top of the levee. In both directions, breaching is measured choosing the maximum deformation of the levee with respective time steps. According to the analysis, Japanese model expose more breaching than Bangladesh model as because of very steep river bed slope with high flow rate is passed by the breach to the floodplain.

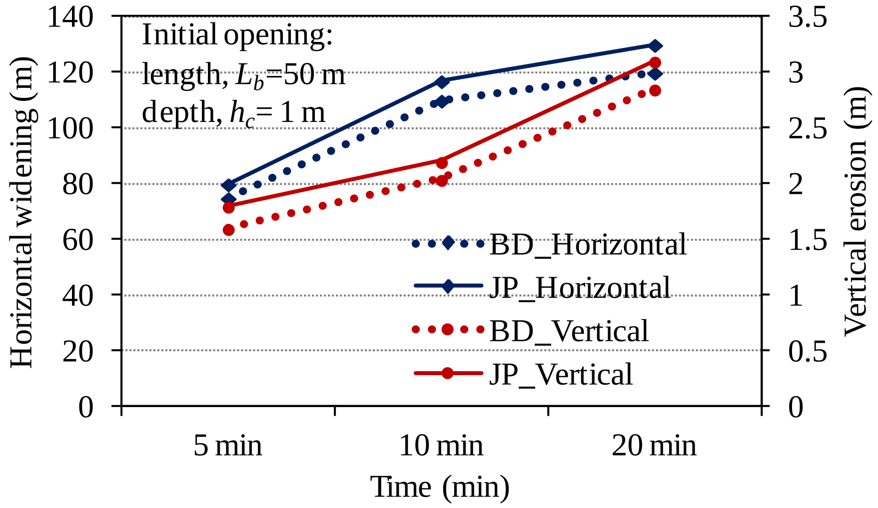


Fig. 5.6 Relationships between horizontal widening and vertical erosion of the levee with time for Bangladesh (BD) and Japanese (JP) model

The river bed variation of the center of the river channel both of the Bangladesh and Japanese model are shown in **Fig. 5.7**. Due to the steeper river bed slope, larger river bed variation is observed in the Japanese model as compared to Bangladesh model.

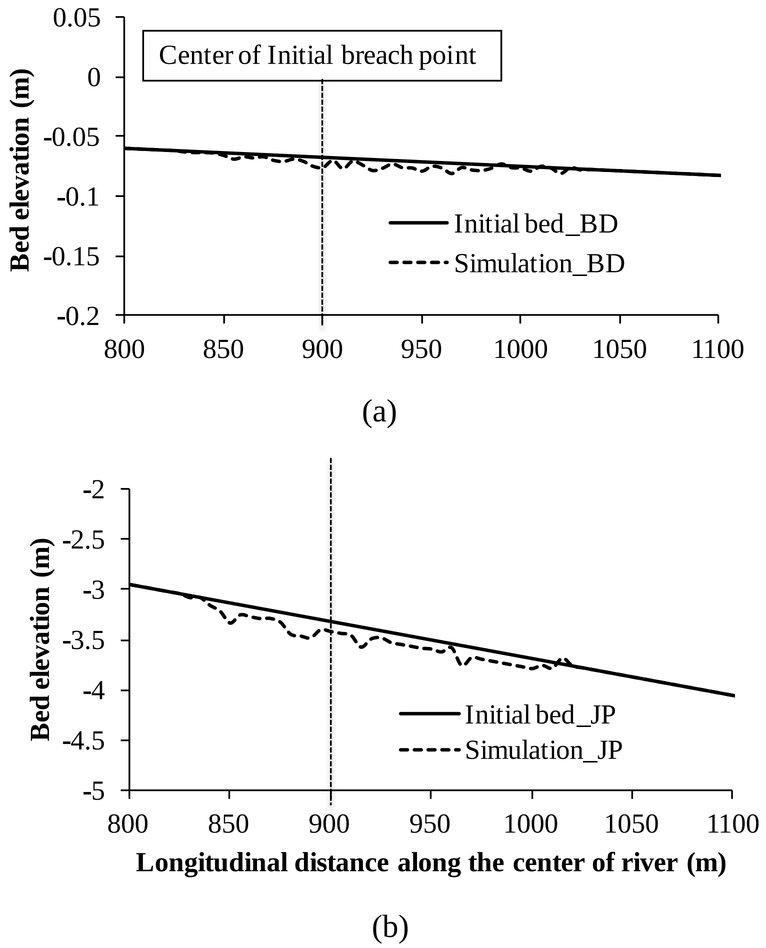


Fig. 5.7 River bed changes along the center of the river: (a) Bangladesh Model and (b) Japanese Model.

5.4 Conclusions

In this research, the investigation is carried out on the levee breach disaster comparisons between two countries utilizing numerical simulation; to understand the basic phenomenon of the process of inundation and sedimentation in the floodplain which were analyzed using simplified model fields. The computation results are shown in **Table 5.2** and summarized as follows:

TABLE 5.2

COMPARISONS OF DIFFERENT PARAMETERS BETWEEN BANGLADESH AND JAPANESE MODEL

Parameters	Bangladesh Model	Japanese Model
River bed slope	Mild	Steep
Bed materials	Fine	Coarse
Flow velocity in river and floodplain	Low	High
Floodplain deposition area and thickness	Less	More
Breach widening length	Less	More

Although the effect of floodplain flow and deposition and breach widening is more in Japanese model but the disaster effect will be more in Bangladesh due to lack of proper management facilities and delay of reclamation process from the disasters after the levee breach. The research results showed that levee breach with steeper river bed slope has the high risk of flood disasters in the floodplain.

CHAPTER 6

Characteristics of Levee Breach Disasters Depending on Landscape on Floodplain

Summery

In floodplain has the different land use pattern, and the disaster is caused by the levee breach is not equal all over the floodplain. Thus, the research is important to recognize the effect of flood disasters on the floodplain; and the attempted have been taken to do through numerical simulation schemes. As for simulation scheme, five types of schematic model flood plains are considered with the conformity of the Sirajganj district, and the channel and flow parameters are selected with the concern river of Jamuna in Bangladesh. RIC-Nays, a two-dimensional simulation model for flood flow and morphology is utilized in this study upon confirmation through another numerical study. Levee breach is considered to initiate in the middle of the levee with crest opening. The flow pattern and the process of sedimentation over the floodplain as well as the levee breaches are analyzed to find out the disasters effects utilizing with the various model flood plains.

General

Bangladesh is most vulnerable to several natural disasters and every year natural calamities upset people's lives in some part of the country. The major disasters concerned here are the occurrences of flood, cyclone and storm surge, flash flood, drought, tornado, riverbank erosion, and landslide. These extreme natural events are termed disasters when they adversely affect the whole environment, including human beings, their shelters, or the resources essential for their livelihoods.

The country is a land of many rivers, and heavy monsoon rains. Therefore, the country is subject to inundation by overflow from the riverbanks due to drainage congestion, rainfall run-off, and storm-tidal surges. Some 30-35% of the total land surface is flooded every year during the wet monsoon (Milliman *et. al.*, 1989). These normal floods are considered a blessing for Bangladesh-providing vital moisture and fertility to the soil through the alluvial silt deposition. Only abnormal floods are considered disastrous, i.e., the high-magnitude events that inundate large areas, and cause widespread damage to crops and properties.

In the years 1988 and 1998, two devastating floods inundated more than 65 % of the geographical area of the country. In the year 2000, Bangladesh faced an unusual flood over its usually flood-free southwestern plain, which also caused loss of life and massive damage to property. Major investment on flood protection in the country began after the devastating flood of 1988. **Fig. 6.1** shows the total damages and number of deaths of peoples after independence of Bangladesh due to effect of flood and embankment failure for some selected years (Hossain, M.Z., 2007).

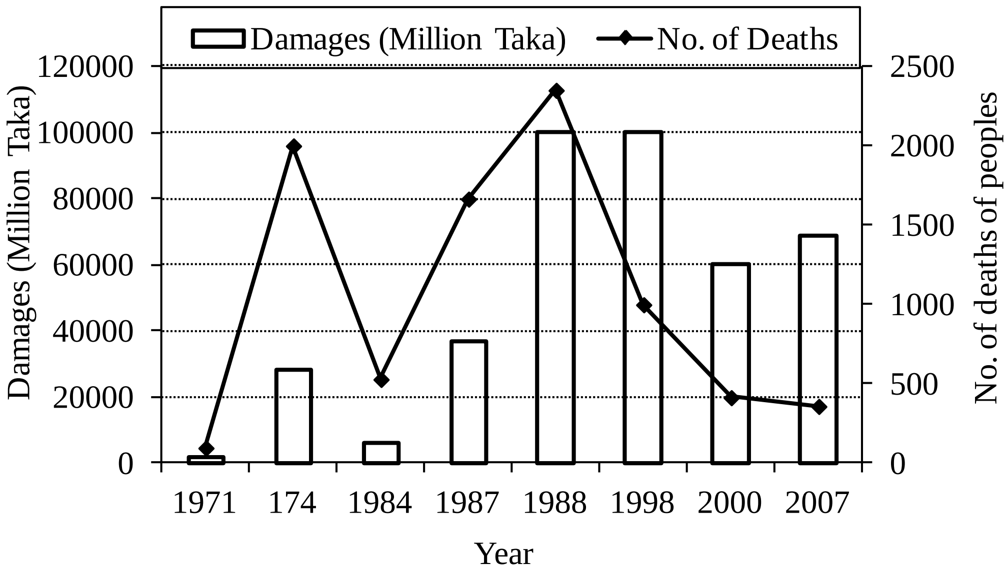


Fig. 6.1 Damages and number of deaths of peoples due to effect of flood and embankment failure in Bangladesh.

During the monsoons (from late June to early October), Bangladesh experiences two forms of riverine floods by the breach of the levee: high frequency localized floods that are considered ‘‘normal’’ or ‘‘minor’’ floods; and low frequency floods of ‘‘extreme’’ or ‘‘major’’ proportions (Boyce, 1990; Rasid and Paul, 1987; Rogers *et al.*, 1989). Due to the flooding, poor households face greater difficulties in adjusting to a given loss of their income (Ravallion, 2000); on the other hand, the poor are less capable of taking protective measures against hazards (Islam, 2001; Varley, 1994).

Bangladesh is a densely populated country. Due to the economic growth and large number of population, rural area is become urbanize by the construction of the infrastructure on it. Particularly, this study tentatively focus on the flood disaster in Sirajganj district, which caused by Jamuna river right bank levee breach. **Fig. 6.2** depicts the floodplain map of Sirajganj district with its settlements.

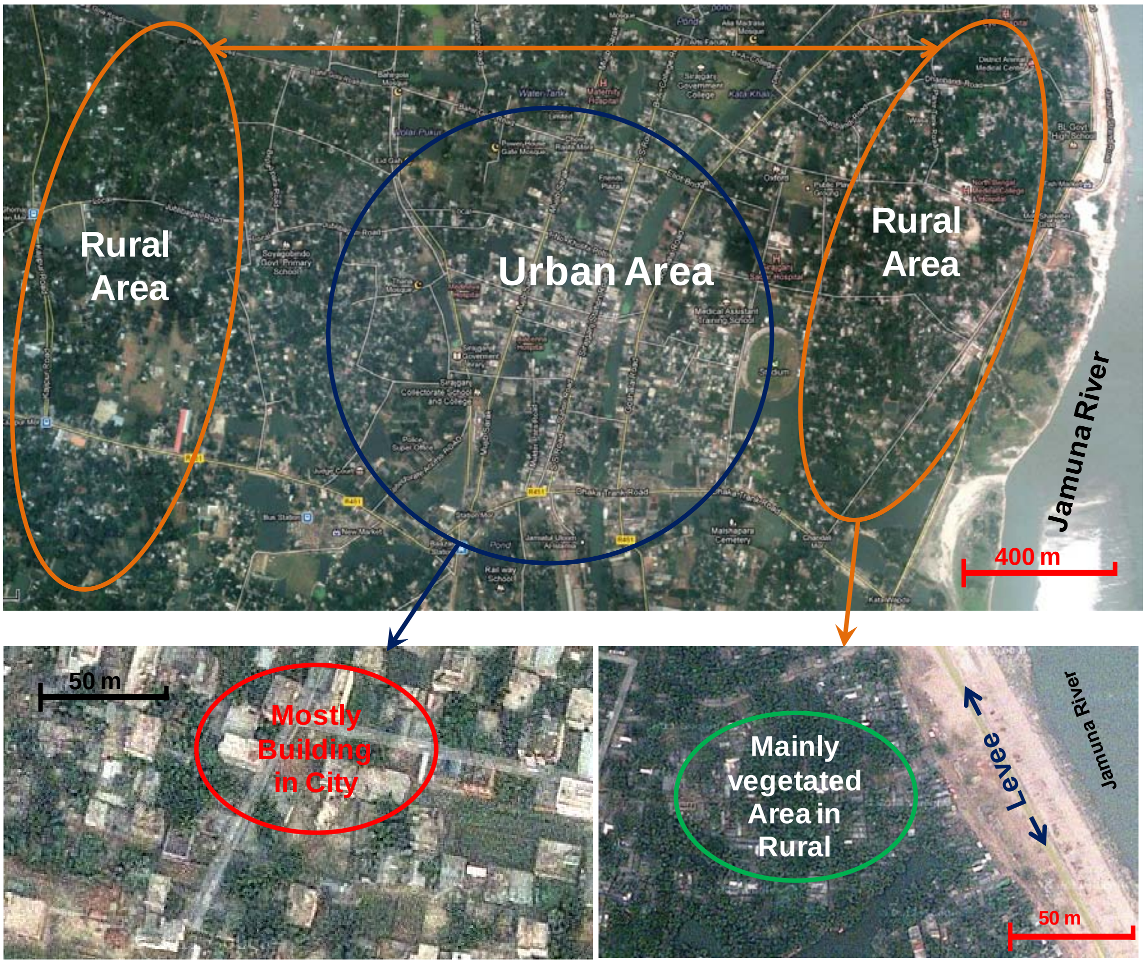


Fig. 6.2 Google Map of Study Area, Sirajganj district in Bangladesh (Source: web)

In floodplain has different land use pattern, the disasters effect is not equal all over the floodplain. This study explores the disaster effects on the floodplain by analyzing the different typical model setting on floodplain with utilizing the levee breach flood in Sirajganj district of Bangladesh. Computational simulation can make comprehensive analysis on levee breach flooding and its impacts on the entire flood plains. Though has various infrastructure (house, roads, farm, agricultural land, ponds etc.) on the floodplain, in simulation analysis simplified model floodplain is considered. Levee breach causes huge damage to the floodplain infrastructure as well as lives and properties. Therefore, it is important to carry out research on investigation of flood disasters over the floodplain during the levee breach. In this chapter, the attempted have been made to analyze the inundation and the process of sedimentation on the floodplain as well as disaster effects after the levee breach utilizing with the different typical simplified model floodplain using a numerical scheme.

6.2 Solution Approach

In this study, RIC-Nays, a two dimensional (2D) model for flood flow and morphology, developed by the foundation of Hokkaido River Disasters Prevention Center, Japan have been utilized.

6.2.1 Model Setup

The process have been analyzed which appears in the different typical model floodplain due to levee breach in a same simulation scheme during flood. This study have been conducted a schematized model field of Sirajganj district in Bangladesh, which has same domain but the changes made on floodplain setting using building and vegetated areas. As for simulation schemes, the main channel, levee, floodplain and flow parameters are selected in the conformity with the model field of Sirajganj district and Jamuna River of Bangladesh. Schematic model area is spatially limited in a part of actual fields. For all case of simulation, computation reach is 1800 m long (L) and 1000 m wide (Y) (river channel=100 m, levee=25 m and floodplain=875 m) with a bed slope of river is 7.5 cm/km. Levee slope is considered as S_l= 1:2 on both country side and river side, and levee height is taken as h_L=5 m from the floodplain and 6 m from the river bed. Idealized flow and sediment parameters are considered in the computation. The inflow discharge in the river before the breach is 900 m^3/s, which is considered as the peak flow of Jamuna river in flooding season, and the median size of sediment is chosen as d_m=0.10 mm for the whole domain. During high flow in the river, overflow starts from the hypothetical notch on top of the levee as a trigger of the breach where the initial breach is 50 m long (L_b) and crest height is 4 m (h_c) from the floodplain. Though the river discharge has a hydrograph in general, a uniform discharges corresponding to the peak is assumed here. Solid boundary is imposed on the left side of the floodplain to protect the direct flow into the floodplain. **Fig. 6.3 (a-e)** depicts the different typical model floodplain for simulation.

The five different typical floodplain models have been considered as:

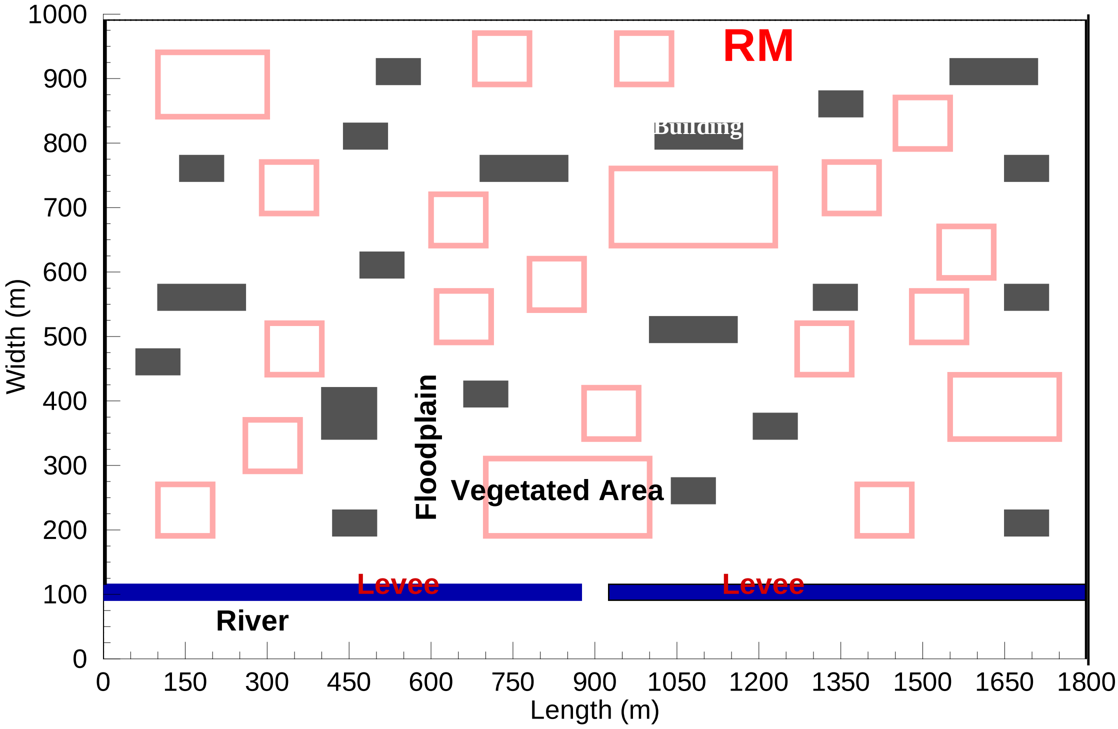
1. Rural Model (mostly vegetated area in the floodplain) floodplain [RM];
2. Rural-Urban Model (upstream of the floodplain is consist of rural area and the downstream is urban area) floodplain [RUM];
3. Urban-Rural Model (upstream of the floodplain is consist of urban area and the downstream is rural area) floodplain [URM];
4. Combined Model (urban area is located center of the floodplain and the all sides are covered by rural area) floodplain [CM]; and
5. Urban Model (mostly building in the floodplain) floodplain [UM].

The selections of the vegetated area and building have been tentatively chosen by using the Google map of Sirajganj district in Bangladesh. **Table 6.1** shows the original and simulation scale setting for the different model floodplain as:

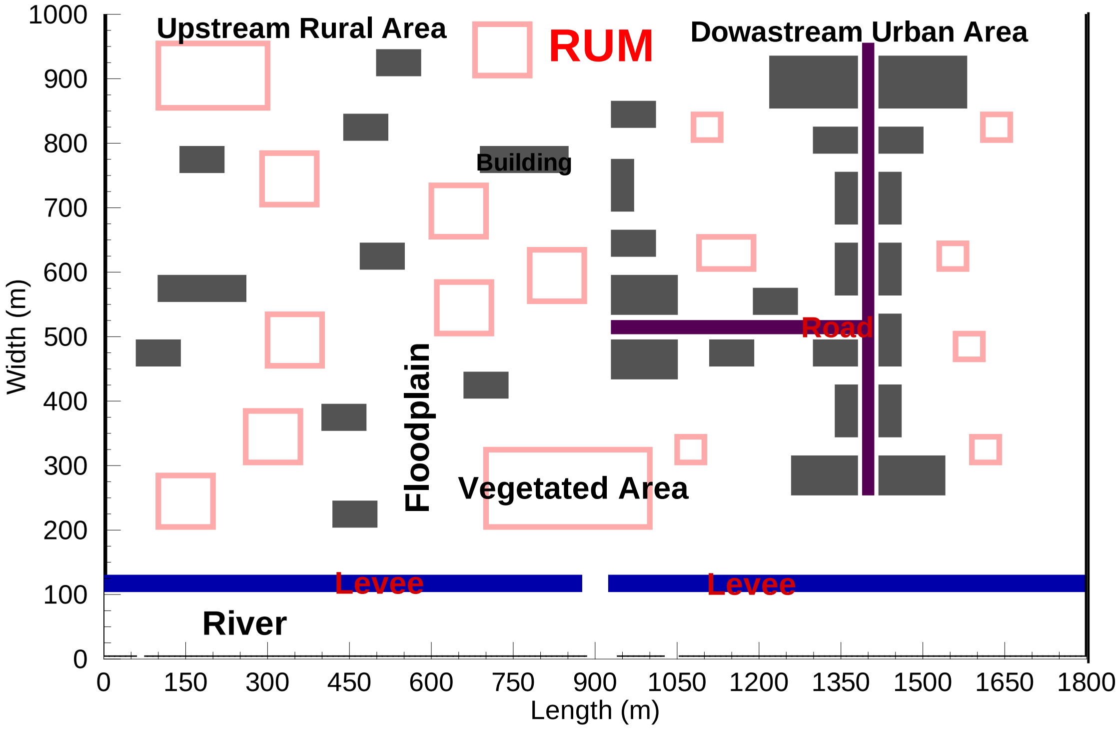
TABLE 6.1

BUILDING AND VEGETATED AREA SETTING FOR DIFFERENT MODELS FLOOD PLAINS

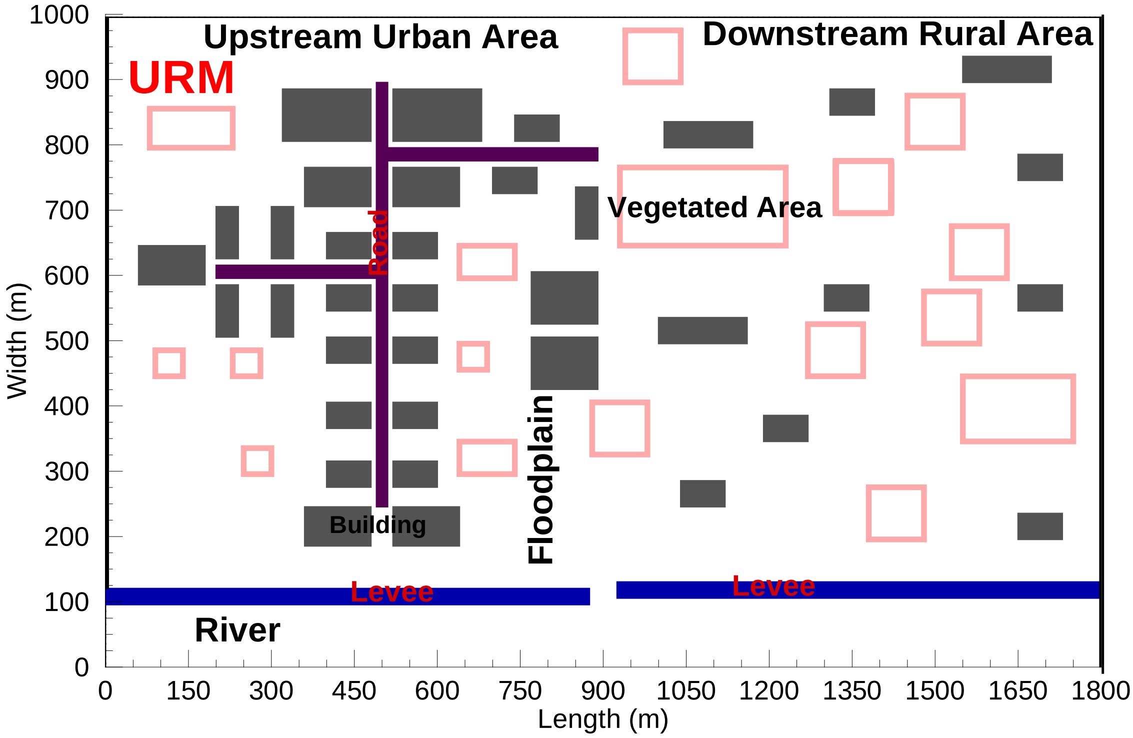
Parameters	Area	Types	Original scale (m)	Unit	Sim. Scale (m)	Sim. Unit	% Area
Building (Impermeable)	Urban	Large	40×20	1	160×80	4	80
		Medium	30×15	3	120×60	12	
		Small	20×10	8	80×40	32	
	Rural	Medium	40×10	1	160×40	4	30
		Small	20×10	4	80×40	16	
Vegetation (Permeable)	Urban	Large	150×60	1	150×60	1	20
		Medium	100×50	3	100×50	3	
		Small	50×40	10	50×40	10	
	Rural	Large	150×60	1	300×120	2	70
		Medium	100×50	1	200×100	2	
		Small	50×40	8	100×80	16	



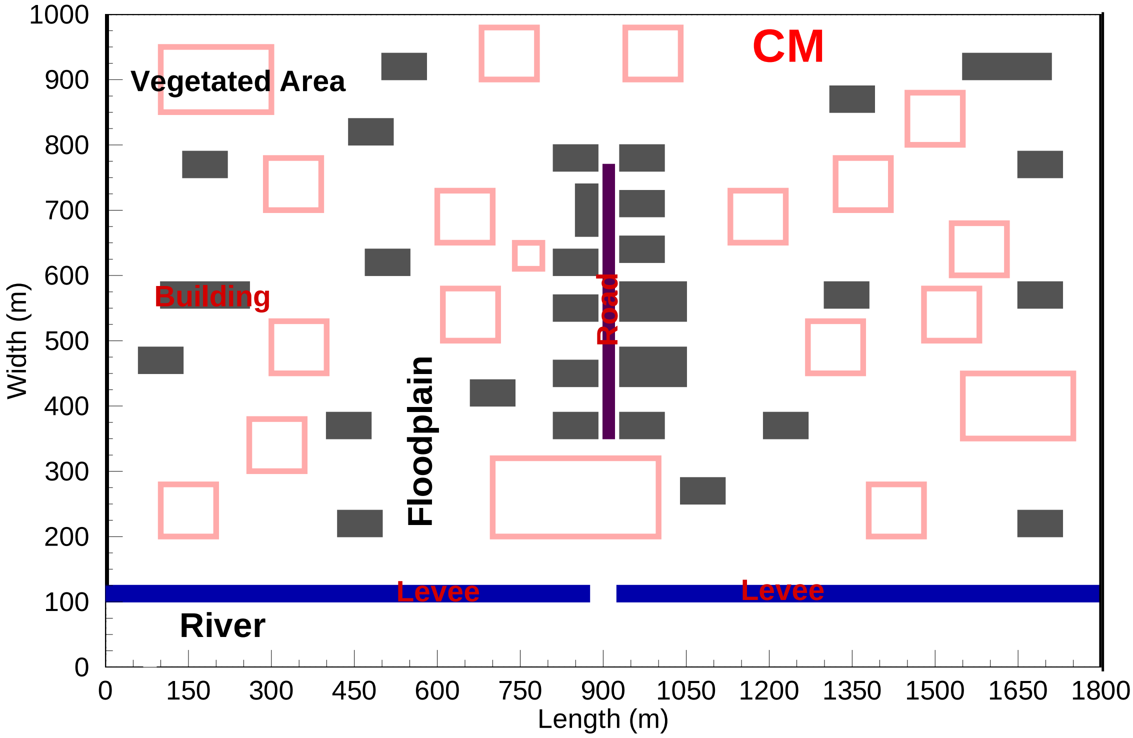
(a) Rural Model [RM] Floodplain



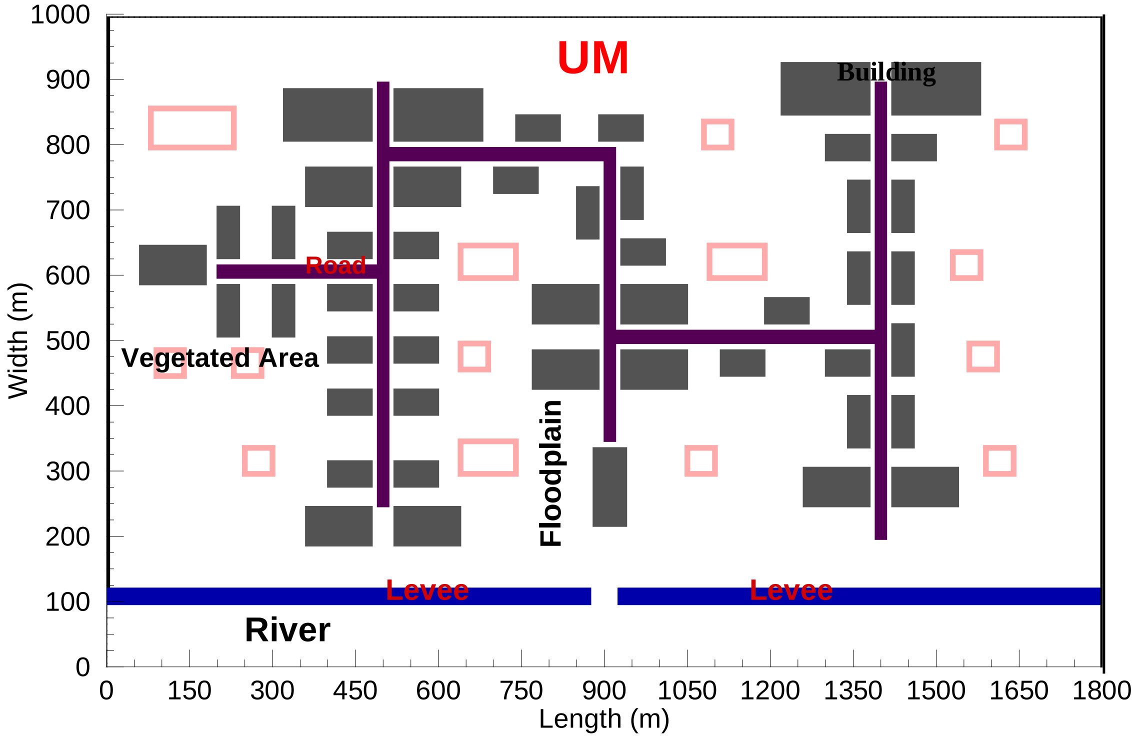
(b) Rural-Urban Model [RUM] Floodplain



(c) Urban-Rural Model [URM] Floodplain



(d) Combined Model [CM] Floodplain



(e) Urban Model [UM] Floodplain

Fig. 6.3 Simulated model set-up showing river channel, breach levee and different setting in the floodplain: (a) RM Floodplain; (b) RUM Floodplain; (c) URM Floodplain; (d) CM Floodplain; and (e) UM Floodplain.

6.2.2 Procedure

The flow model is based on the depth-averaged shallow-water equations. The equations expressed in general coordinate system are solved on the boundary-fitted structured grids using the finite-difference method. Bed-load is calculated by Ashida and Michiue (1972) equation; the effect of cross-gradient and the influence of secondary flow, are taken into account. In considering suspended sediment, an exponential profile of concentration is assumed to know planar distribution of depth-averaged concentration and the 2D advection-diffusion equations are solved. Finally, the bed deformation is determined using the 2D sediment continuity equation. Equations are solved for the unknown nodal values by an iterative process. First the flow field is computed utilizing initial and boundary conditions; the sediment transport field is then computed, to evaluate sedimentation rates, and followed by bed topography changes. The details of the model equation have been described in the preceding chapter (Chapter 2). The number of cell in longitudinal and transverse direction is 180 and 100, respectively. In this study, the computation time step is used as 0.002 second and the model runs are continued for 20 minutes, when the temporal variations of variables are considerably reduced. By numerical calculation, the flow behavior and the sedimentation around the different obstacles in the floodplain can be described with morphological changes (see **Figs. 6.4 to 6.8**), and it would be realized spatial characteristics of the phenomena in the floodplain. This study model result is compared with another numerical study conducted by Tsujimoto *et al.*, (2006); it is showed reasonably good agreement. The details of which are not included herein (Chapter 2).

6.3 Results and Discussion

According to the results of simulation, selected results of the flow-fields and bed topography have been presented in this section to analyze the levee breach disasters effect in the floodplain using the different typical model flood plains. In this study, five different model flood plains have been analyzed by numerical simulation to understand the disaster phenomena in the floodplain.

6.3.1 Flow Pattern and Bed Topography in Different Typical Model Floodplains

6.3.1.1 Rural Model [RM] Floodplain

Basically, the Sirajganj district is mostly covered by rural areas. The areas are largely occupied by vegetation, and the residents built their shelter on the floodplain in some areas. From the Google map, the rural areas are tentatively focused on 5% houses and 15% forest and 80% others (agricultural land, water bodies, etc.). In this study, the simulation has been conducted with the considerations of only the houses and forest, and these two parameters are treated as buildings (impermeable) and vegetation (permeable) areas on the floodplain. **Fig. 6.4** depicts the flow pattern and sedimentation in a rural model floodplain due to levee breach. After the overflow, the inundation flow is passes to the floodplain with sediment by the breach, and the sediment is deposited on the floodplain. The inundation flow on the floodplain is protected by the buildings because of impermeable obstacles, and it is concentrated between the buildings and over the vegetated areas. Near the breach, the high intensity of flow is observed on the both sides of the floodplain with the space between the buildings as well as over the vegetated areas. Larger amount of sediment is deposited near the breach along the flow direction, and the rate is observed high adjacent to the buildings then the vegetated areas.

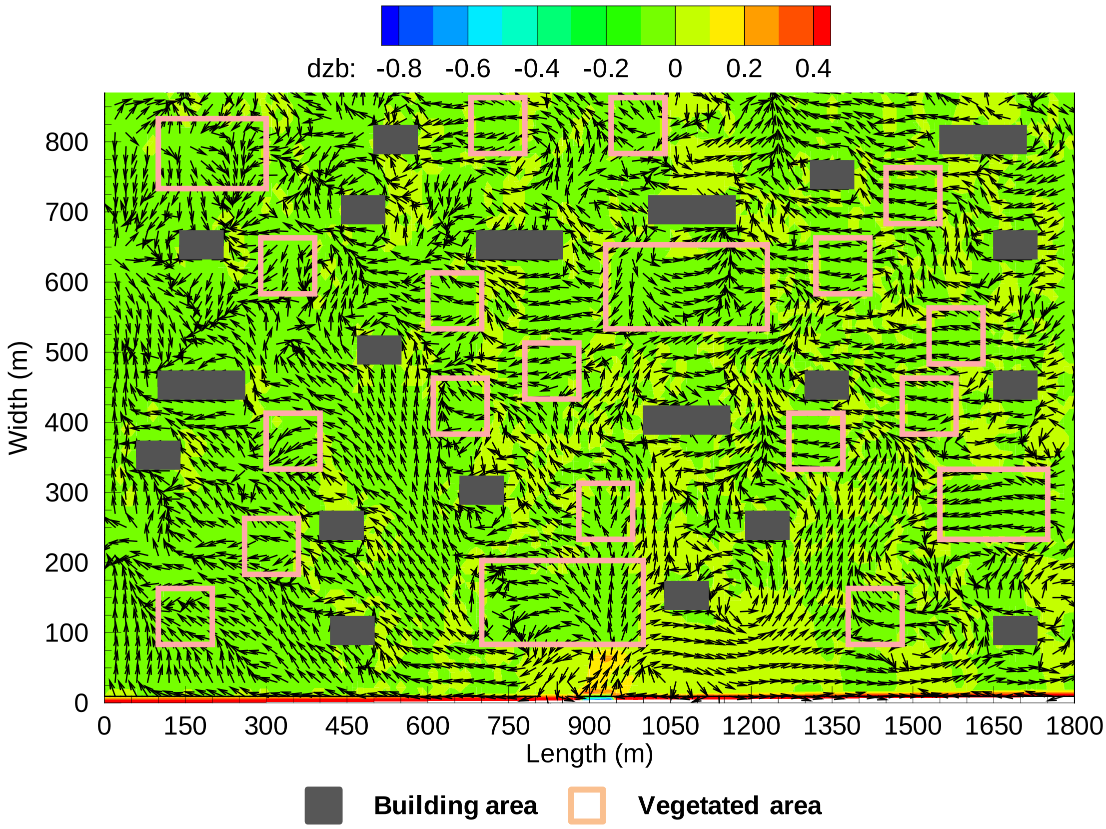


Fig. 6.4 Flow pattern and sedimentation in the floodplain after the levee breach for Rural Model [RM] flood plains.

6.3.1.2 Rural-Urban Model [RUM] Floodplain

In this section, the discussion has been made on flood disaster effect on the floodplain, considering with the rural areas in the upstream of the floodplain, and the downstream is urban. From the Google map survey, the urban areas are tentatively focused on 15% houses and 3% forest and 82% others (agricultural land, water bodies, etc.). The rural areas are occupied mainly with the vegetation, and the urban areas are covered by the buildings. **Fig. 6.5** shows the flow pattern and sedimentation over the floodplain due to the levee breach. The overflow water is passes to the floodplain by the breach. The inundation flow on the downstream of the floodplain is protected by the buildings and roads because of the areas are occupied by urban infrastructure. Afterwards, the flow is return and concentrates near the levee towards the downstream of the floodplain between the space of the buildings, and over the vegetated areas. The floodplain sediment is deposited near the breach and adjacent to the buildings on the urban areas.

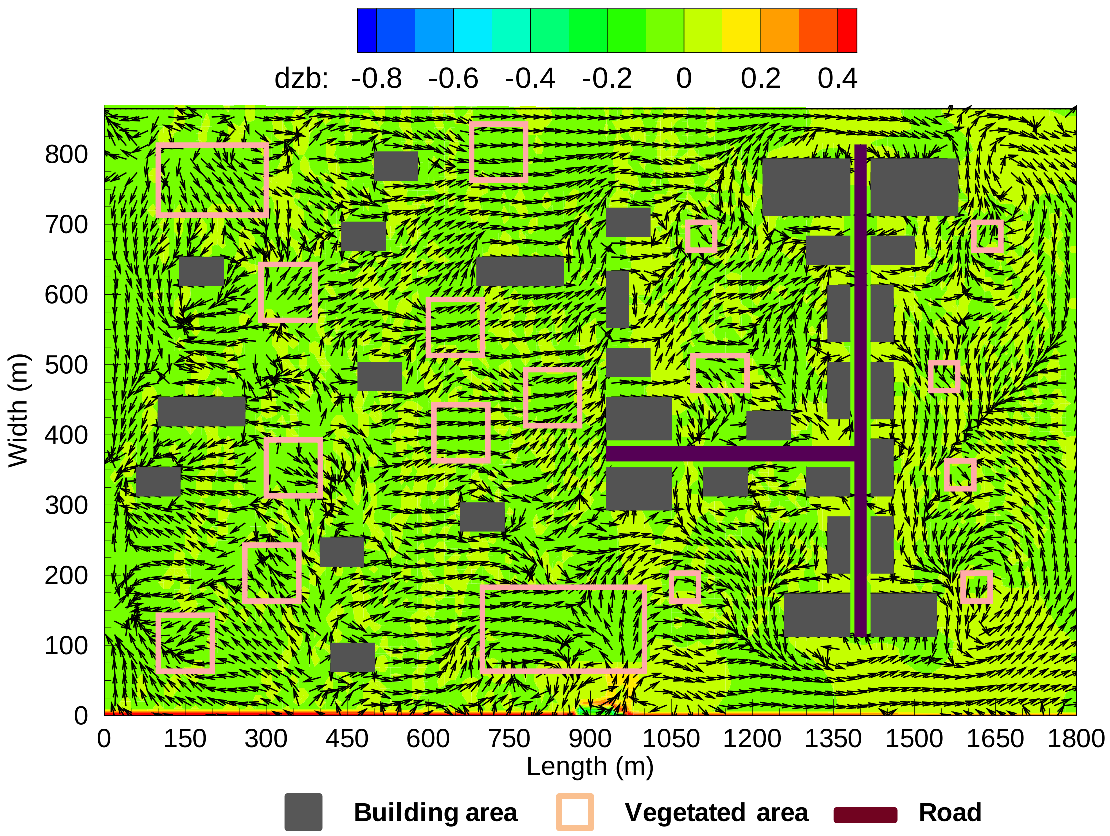


Fig. 6.5 Flow pattern and sedimentation in the floodplain after the levee breach for Rural-Urban Model [RUM] flood plains.

6.3.1.3 Urban-Rural Model [URM] Floodplain

The floodplain models consist of the urban area in the upstream and rural areas in the downstream of the floodplain. **Fig. 6.6** depicts the flow pattern and sedimentation on the floodplain, which is occupied by urban and rural infrastructures. The inundation flow and sediment deposition processes are different from the RUM floodplain, although the flood plains are exposed of rural and urban areas because of the opposite settings on the floodplain. The inundation flow is mainly concentrated to the downstream side of the floodplain between the buildings because of the rural areas and has the less impermeable obstacles on it. In this model also, sediment is deposited near the breach and adjacent to the buildings. Larger deposition area is observed on the upstream side of the floodplain near the building of the urban areas.

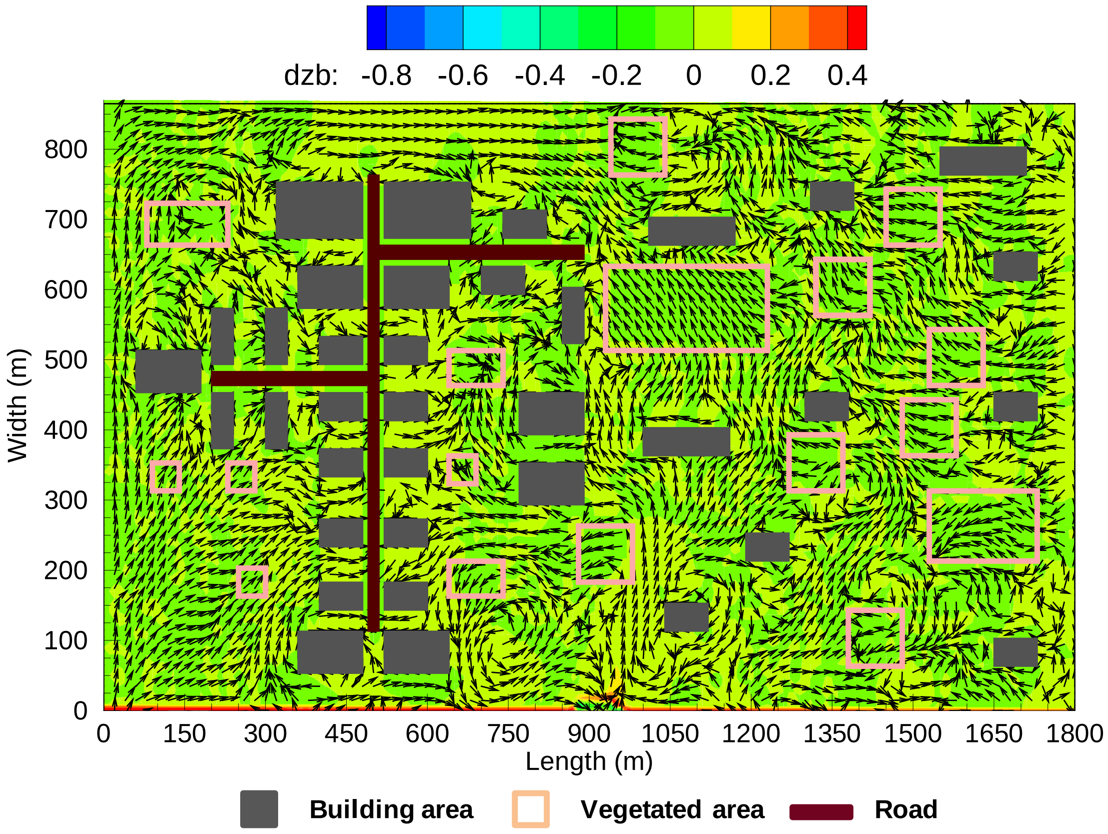


Fig. 6.6 Flow pattern and sedimentation in the floodplain after the levee breach for Urban-Rural Model [URM] flood plains.

6.3.1.4 Combined Model [CM] Floodplain

This is the ideal sitting of the Sirajganj district (**Fig. 6.2**), which is concern area of this study. The center of the flood plains is urban and around the urban areas is the rural territories, and the urban areas are fare from the levee. **Fig. 6.7** shows the flow pattern and sedimentation over the floodplain by the breach of the levee. After the breach, the flow is passes to the both sides of the floodplain with sediment through the breaching section. The high velocity of flow is tended to passes over the floodplain between the buildings, and over the vegetated areas. The higher depth of sediment is deposited near the breach as well as adjacent to the buildings of the urban areas and along the flow direction on the floodplain.

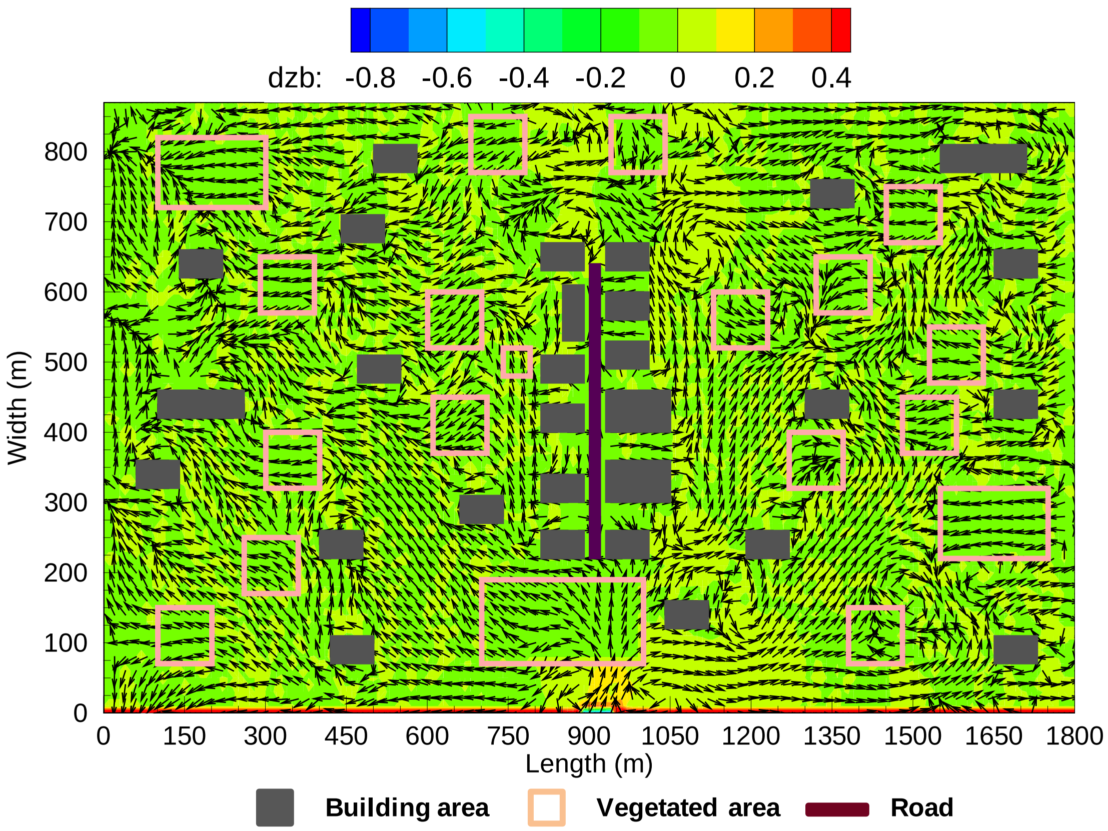


Fig. 6.7 Flow pattern and sedimentation in the floodplain after the levee breach for Combined Model [CM] flood plains.

6.3.1.5 Urban Model [UM] Floodplain

Due to the population and economic expansion, the urban areas become increases in the future. Therefore, the scenario of the floodplain will be occupied mostly by the building. For the simulation, the future floodplain models are considered with only the city areas, and the analysis has been carried out to investigate the disaster effect on the urbanized floodplain due to the levee breach. **Fig. 6.8** depicts the flow pattern and sedimentation over the floodplain due to levee breach with urbanized floodplain. The inundation flow is passes by the breach to the floodplain. In urban model, the intensity of the buildings (impermeable obstacle) on the floodplain is higher, and the flow is protected by the impermeable obstacles and return to the levee section, then it passes along the both sides of the floodplain between the buildings and the levee. Due to the backward velocity effect, the vortex appears in the floodplain near the breach, and the higher depth of sediment is deposited over there. In this case also, the deposition is occurred near the breach and adjacent to the buildings.

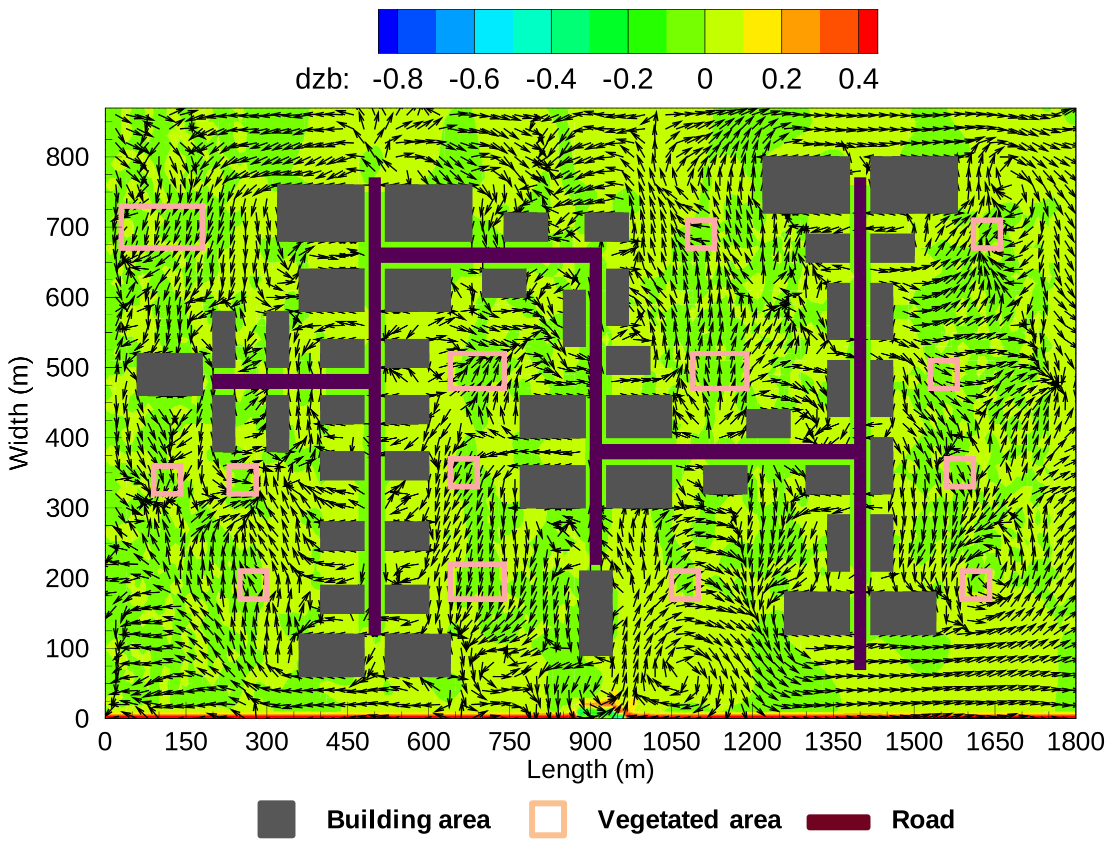


Fig. 6.8 Flow pattern and sedimentation in the floodplain after the levee breach for Urban Model [UM] flood plains.

6.3.2 Comparisons of Flow Velocities on the Floodplain

In the **Fig. 6.9**, shows the longitudinal velocity profile in the floodplain (*y*=45 m) along the levee with time. After the overflow breach, the longitudinal velocities are observed high at the downstream side of the floodplain for the model flood plains of RM, RUM and CM both in the shorter and longer duration. It is noted that the high velocity of flow is moved to the right-side direction of the floodplain along the levee by the breach.

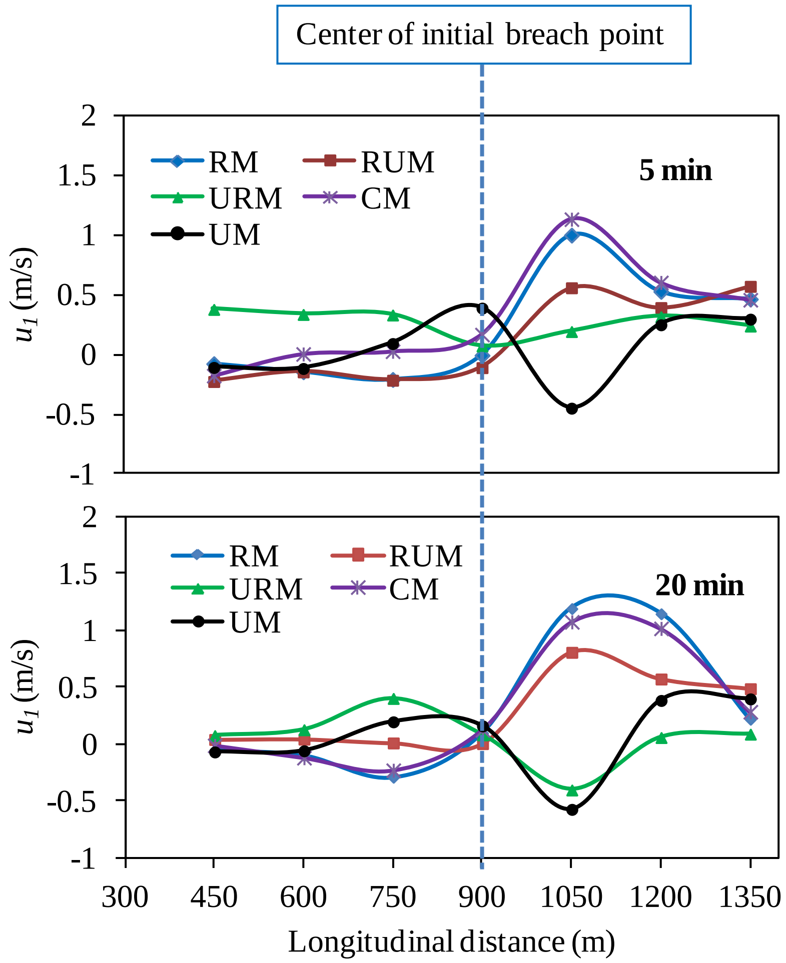


Fig. 6.9 Longitudinal velocity profile in the floodplain (*y*=45 m) along the levee for different model flood plains.

The transverse velocity profile in the floodplain (y= 45 m) along the levees are shown in **Fig. 6.10**. In parallel to the initial breach, the high velocities are observed on the floodplain for the model flood plains of RM, CM and UM at shorter duration. However, in the long run the same rates are maintained for the Rural Model [RM] and the Combined Model [CM] flood plains. The higher rates of velocities appear in the downstream side of the floodplain for the UM, CM and RM flood plains.

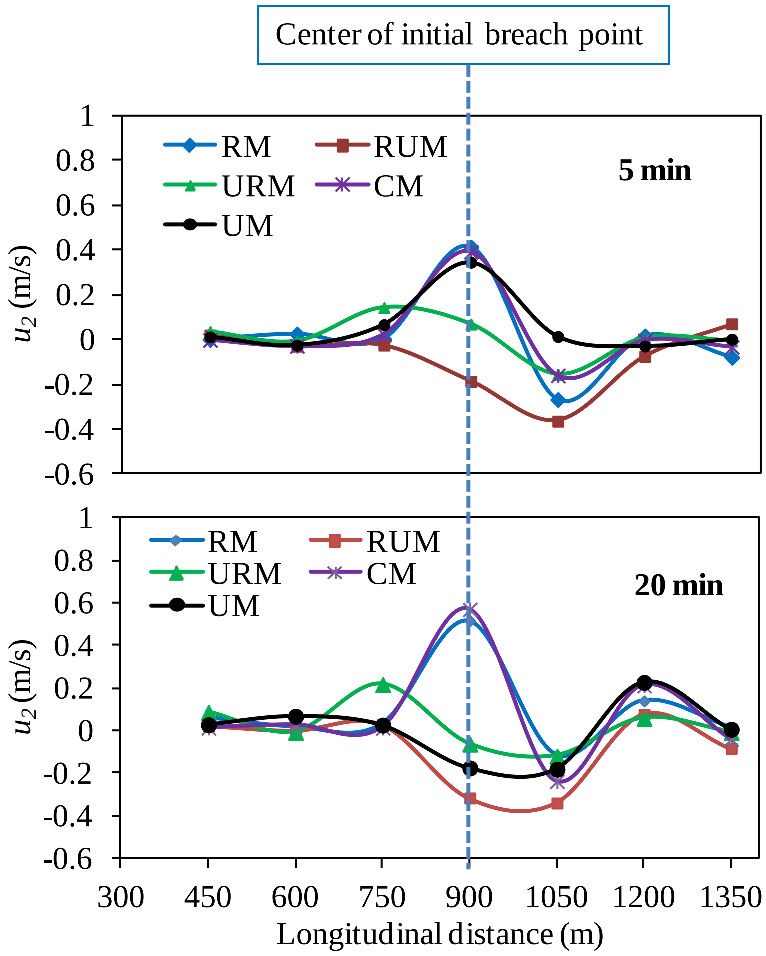


Fig. 6.10 Transverse velocity profile in the floodplain (y=45 m) along the levee for different model flood plains.

The transverse velocities at the center of the initial breach point (L=900 m) of the levee for the different model's floodplain are shown in **Fig. 6.11**. At shorter duration, the high velocities are seen on the RUM and UM flood plains but for the long run, the RM and CM flood plains expose the higher velocities on the breaching section.

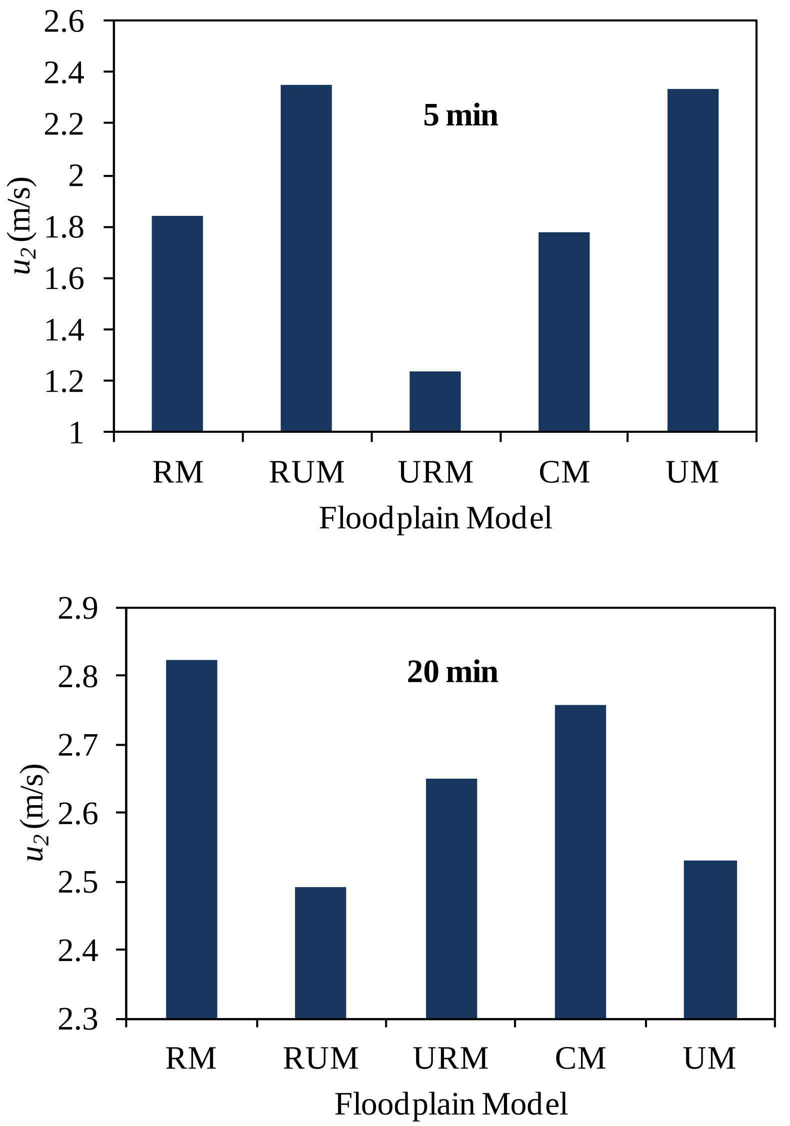


Fig. 6.11 Transverse velocity profile at the center of an initial breach point (*L*=900 m) of the levee for different model flood plains.

6.3.3 Breaching Comparisons in the Levee along the River

The final lengths of breaching are compared among the different model flood plains are shown in the **Fig. 6.12**. The transverse velocities by the breaches are higher for the model flood plains of RM and CM than that of the RUM, URM and UM flood plains.

And, the longitudinal velocities in the downstream sides of the floodplain along the levees are higher for the model flood plains of RM, RUM, and CM than that of the URM and UM flood plains. It is noted that the vertical erosion and horizontal expansion are more in the model flood plains of RM and CM, and only horizontal widening is more in the RUM than that of the URM and UM flood plains.

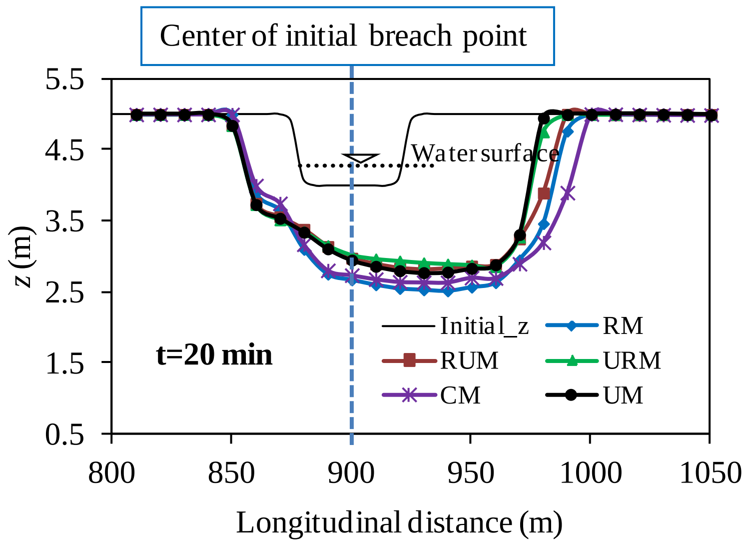


Fig. 6.12 Longitudinal breach length of the levee (top) along the river for different model flood plains.

6.3.4 Comparisons of Sediment Deposition on the Floodplain

In **Fig. 6.13**, shows the floodplain sediment deposition depth along the levee for the different model floodplain. Near the breach, the higher depths of deposition are seen in the Urban Model [UM] and lower in the Rural Model [RM] flood plains because of the variations of impermeable infrastructure on the floodplain. Not only breaching point but also along the flow direction, the higher depth of deposition is observed in the Urban Model floodplain.

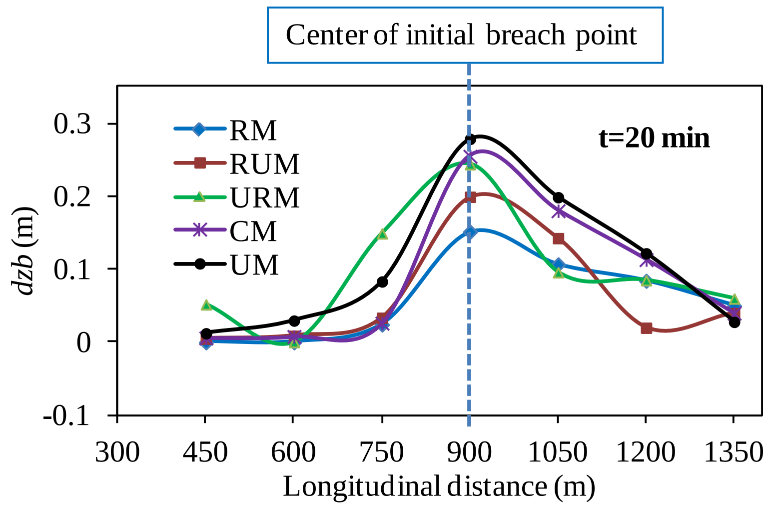


Fig. 6.13 Comparisons of depth of deposition on the floodplain (*y*=45 m) along the levee for different model flood plains.

Total volume of sedimentation on the floodplain at five different model flood plains after the levee breach have been compared to recognize the disaster effect on individual floodplain for the duration of 20 minutes, and each of inflow discharges of 900 m^3/s, which are shown in **Fig. 6.14.** Combined model and rural model floodplain appears the higher deposition on floodplain than other models.

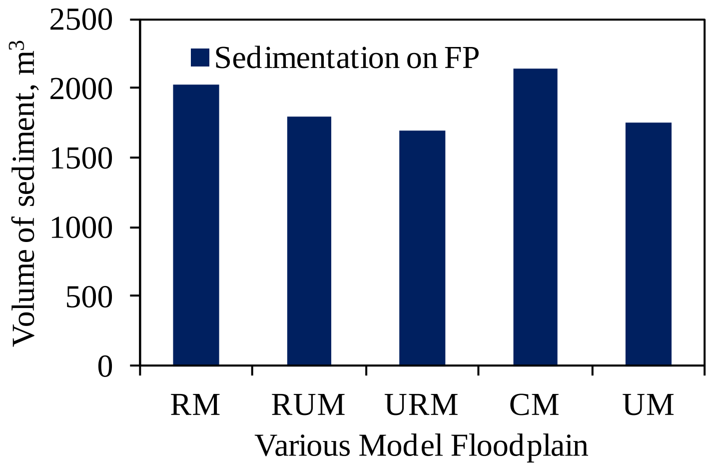


Fig. 6.14 Sediment deposition comparisons on floodplain of different typical model flood plains.

6.4 Conclusions

In this research, the investigations have been carried out using different typical model floodplain to understand the disaster effect on the floodplain due to the levee breach overflow, which is analyzed using numerical schemes. According to the computation results, the conclusions can be drawn as follows:

- The higher inundation flow is passes over the floodplain by the breach for the rural and combined model flood plains as compared to the other models;
- For the urban model, the depth of the deposition is higher near the breach as well as an beside the buildings in the floodplain;
- The horizontal widening along the downstream of the levee is larger, and the vertical erosion is more for the rural and combined model flood plains than that of the rural-urban, urban-rural and urban model flood plains.

CHAPTER 7

Conclusions and Recommendations

7.1 Summery

In the present research, the levee breach and successive disasters in the floodplain have been investigated utilizing with the different aspects of the levee breaching phenomena as well as the river hydrology and morphology compared with the floodplain bed topography. Both of numerical and experimental investigations have been carried out to recognize the levee breaching and the topographic changes not only in the floodplain but also along the river and the levee.

At first, the numerical simulation is carried out to recognize the process utilizing by the inflow discharges with time and various initial levee breaches opening, and the relative height of river bed to floodplain; in addition, a large-scale simulation is conducted to compare the disaster effect between Japan and Bangladesh. Then, the laboratory experiments and the identical scenario simulation analyses are conducted to understand the mechanism of breaching and the disasters effects on the floodplain. Finally, the floodplain landscape management analyses are carried out by numerically using same scheme.

This study emphasizes the knowledge of understanding about the levee breach and the risk of disaster in the floodplain. To fulfill the above criteria, the specific objectives have been discussed in the preceding Chapter 1, Section 1.4.

The individual conclusions are drawn at the ends of each chapter, and the overall conclusions are summarized in the following section. Some of the recommendations and future research directions are given in the section 7.3.

7.2 Conclusions

The previous section describes the brief results of the total works, which have been done to reach the final objective of this study. The findings and the concluding remarks are mentioned in the following headings:

7.2.1 Numerical Approaches to Levee Breach Disasters in Floodplain

The numerical approaches to levee breach and disasters in the low-land have been analyzed by utilizing with the inundation of water and sediment in the floodplain and evolution processes of the levee breaches are investigated as follows:

- Inundation water pass by the breach is increased with time, the inflow discharges and the initial breach length. The breach widening is the rapid and sediment outflow by the breach is more in the higher river bed level than that of the lower one. Therefore, floodplain inundation depth, thickness and volume of sedimentation as well as damages to the floodplain residents are increased.

- The higher river bed has the high risk of disasters in the floodplain. Furthermore, to minimize flood disasters and suffering to the inhabitants on unexpected breach happening, proper dredging techniques is necessary for the river beds, which maintain normal river flow capacity to decrease the risk of the levee breach.

- The levee breach disaster between Bangladesh and Japan has been investigated by utilizing the same simulation scheme, which is analyzed using simplified model fields. The conclusion of this research has been focused on the levee breach with steeper river bed slope and coarser bed materials have the high risk of disasters in the floodplain.

7.2.2 Laboratory Experiments and Same Scenario Numerical Investigations of Levee Breach Disasters in Floodplain

Small-scale laboratory experiments and same scenario numerical analyses have been conducted to understand the levee breaching process and consequences as the risk of flood disasters in the floodplain with utilizing the effects of river bed height, bed material sizes and river bed slopes. The research result showed that the higher river bed not only influences the effect of levee breaching and floodplain deposition, but also it has unlike characteristics in the river bed variation using different bed materials.

- Though have some discrepancies between experiments and same condition numerical analyses, both results showed reasonably good agreement.

- Using different bed materials, starting of the initial erosion and the nature of the erosion process are not uniform, and it causes the various phenomena on the levee breaching as well as its expansion along the levee.

- Higher river bed is exposed to levee breach with rapid widening than the lower and the same bed height, and inundation with more sediment volume to the floodplain not only from the levee but also from the river bed, and this variation is very clear in the finer bed material at the same and high river bed level.

- Furthermore, river and levee section materials are deposited not only in the floodplain but also in the upstream of the river bed, which has the problem for another flood in the future.

7.2.3 Levee Breach Disasters using Different Landscape on Floodplain

The disaster effects in the floodplain are varied with the floodplain characteristics. So, the floodplain land use pattern is the important indicators for the disasters on it. The numerical investigations have been carried out to recognize the flow pattern and the process of sedimentation over the floodplain, and the levee breaches are considered to evaluate the disaster effects on the floodplain utilizing the various model flood plains.

The five different typical floodplain models have been considered in this study, which are:

1. Rural Model (mostly vegetated area in the floodplain) floodplain [RM];
2. Rural-Urban Model (upstream of the floodplain is consist of rural area and the downstream is urban area) floodplain [RUM];
3. Urban-Rural Model (upstream of the floodplain is consist of urban area and the downstream is rural area) floodplain [URM];
4. Combined Model (urban area is located center of the floodplain and the all sides are covered by rural area) floodplain [CM]; and
5. Urban Model (mostly building in the floodplain) floodplain [UM].

- At first, the inundation flows over the flood plains are investigated and found the rates are high for the RM and CM flood plains as compared to the other models;
- The sediment deposition depth on the floodplain is higher for the UM floodplain, and it appears near the breach as well as beside the buildings;
- Comparing the final length of the breach, the horizontal widening along the downstream of the levee is larger and the vertical erosion is more for the RM and CM flood plains than that of the RUM, URM and UM flood plains.

7.3 Recommendations

Although this study has some difficulties during measurements and numerical analysis, the ultimate target has been achieved very satisfactorily. And, the research findings would be utilized in the field of river engineering as well as disaster risk assessment on the floodplain due to levee breach.

The following recommendations can be suggested to reduce the risk of disaster and for the future research regarding on the levee breach:

- This research is basically focus on the levee breach disasters on the floodplain as well as changes on the levee and river bed utilizing with the different aspects of analyses by numerical and experimental approaches. Based on the results of this research, the important investigation is carried out with higher river bed as compared to floodplain level. The levee breach is exposed rapidly, and inundation with more sediment is deposited on the floodplain not only from levee body but also from the river bed. Furthermore, it suggests that the higher bed is revealed degradation to bring 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. This kind of problem is very crucial to mitigate levee breach damage on the floodplain. So, River Management Authority should consider proper designing techniques of a levee before construction particularly for higher river bed levee, need necessary dredging facilities from the river bed, and if the breach is happened need more attention to repair the breached levee, which are pre-requirements to maintain normal flow through the river and decrease the risk of the levee breach. It would be minimize flood disasters suffering to the inhabitants on unexpected breach happening.

- In spite of real field survey data, for the time being this research has been conducted on the model floodplain considered with the river channel and levee, and the idealized flow and sediment parameters were selected with the conformity of the typical field of Bangladesh. It would be better and might be realistic understanding of the levee breaching and disaster effect on the floodplain, if in a real-life situation.

- The levee breaching phenomena and the topographic changes in the river, levee and floodplain were explained by using two dimensional numerical investigations. To evaluate the disaster risk in the floodplain, the detail's explanation behind those regarding the hydrodynamics can be done clearly utilizing with three-dimensional flow models near the breach with corresponding measurements and the process of sedimentation on floodplain.
- In laboratory experiments, the inflow water was supplied without suspended sediment, and the breach is investigated with clear water condition. So, the elaborate laboratory experiments are recommended considering the inflow supplied with sediment.

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APPENDICES

In these appendices represents some of the basic information relevant to the present research that is useful in studying the effective approaches for the investigation of flood disasters during the levee breach overflow in low-land floodplain. The individual appendix as follows:

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Appendix: A

Geographical Position of Bangladesh

Bangladesh lies approximately between 20^{0} 30’ and 26^{0} 40’ north latitude and 88^{o} 03’ and 92^{o} 40’ east longitude. It is one of the biggest active deltas in the world with an area of about 147,570 km^{2}. The country is under sub-tropical monsoon climate. India borders the country in west, north and most part of east. The Bay of Bengal is in the south, Myanmar borders part of the south-eastern area. It has 230 rivers including 57 trans-boundary rivers, among them 54 originated from India including three major rivers the Ganges, the Brahmaputra and the Meghna. Monsoon flood inundation of about 20-25% area of the country is assumed beneficial for crops, ecology and environment, inundation 0of more than that causing direct and indirect damages and considerable inconveniences to the population (**Fig. A. 1**).

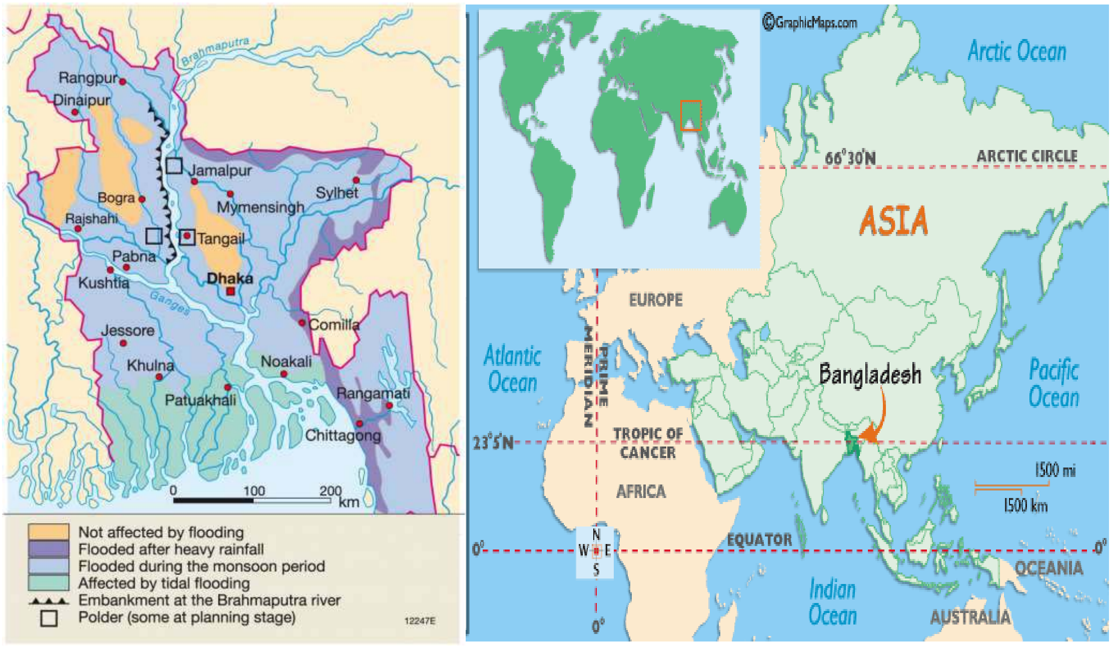


Fig. A. 1 Map of Bangladesh

Appendix: B

Large River, Jamuna in Bangladesh

The river system of Bangladesh **(Fig. A. 2)** is one of the most extensive in the world. The Brahmaputra River, locally known as the Jamuna River, is a braided river channel. From beginning to the end, the river flows 2896 km; 1600 km in Tibet, 900 km through eastern India, and 400 km in Bangladesh (Islam *et al*., 1999). It is the second largest river in Bangladesh and one of the largest in the world in terms of catchment size, river length and discharge. The switch to the present course took place after a major earthquake and catastrophic floods in 1787. Presently the Brahmaputra continues southeast from Bahadurabad (Dewanganj upazila of Jamalpur district) as the old Brahmaputra, and the river between Bahadurabad and Aricha is the Jamuna, not Brahmaputra. The Hydrology Directorate of the Bangladesh Water Development Board (WDB) refers to the whole stretch as the Brahmaputra-Jamuna. It originates in the Chemayung-Dung glacier at an elevation of 5200 m in the Tibetan Himalayas (Sarin *et al*., 1989), approximately at 31°30'N and 82°0'E, some 145 km from Parkha, an important trade centre between lake Manassarowar and Mount Kailas. The Brahmaputra is known as the Dihang in Assam Himalayas before it comes into the Great Plains of Bengal. It enters Bangladesh through Kurigram district (at the border of Kurigram Sadar and Ulipur Upazilas). The width of the river varies from 3 km to 18 km with the average width is about 10 km. In the rainy season the river is nowhere less than five kilometers broad. The river is in fact a multi-channel flow. The channels are of many different sizes, from hundreds of meters to kilometers wide, and of different patterns including braiding, meandering and anastomosing pattern in the country. The width/depth ratios for individual channels of the Brahmaputra vary from 50:1 to 500:1. The gradient of the river in Bangladesh is 0.000077, decreasing to 0.00005 near the confluence with the Ganges.

It has four major tributaries: the Dudhkumar, the Dharla, the Tista and the Karatoya-Atrai system. The first three rivers are flashy in nature, rising from the steep catchment on the southern side of the Himalayas between Darjeeling in India, and Bhutan.

The drainage basin is approximately 640,000 km^2, with 50,505 km^2 located inside Bangladeshi borders (Islam *et al*., 1999). In comparison, the Mississippi River in North America has a drainage basin of 3,270,000 km^2, or 40% of the continental United States (Milliman and Meade, 1983). The Mississippi River's drainage basin is roughly twice the size of the combined Ganges-Brahmaputra River drainage basin; however, the Ganges-Brahmaputra River is ranked first in annual sediment discharge, and the Mississippi River ranks seventh (Milliman and Meade, 1983).

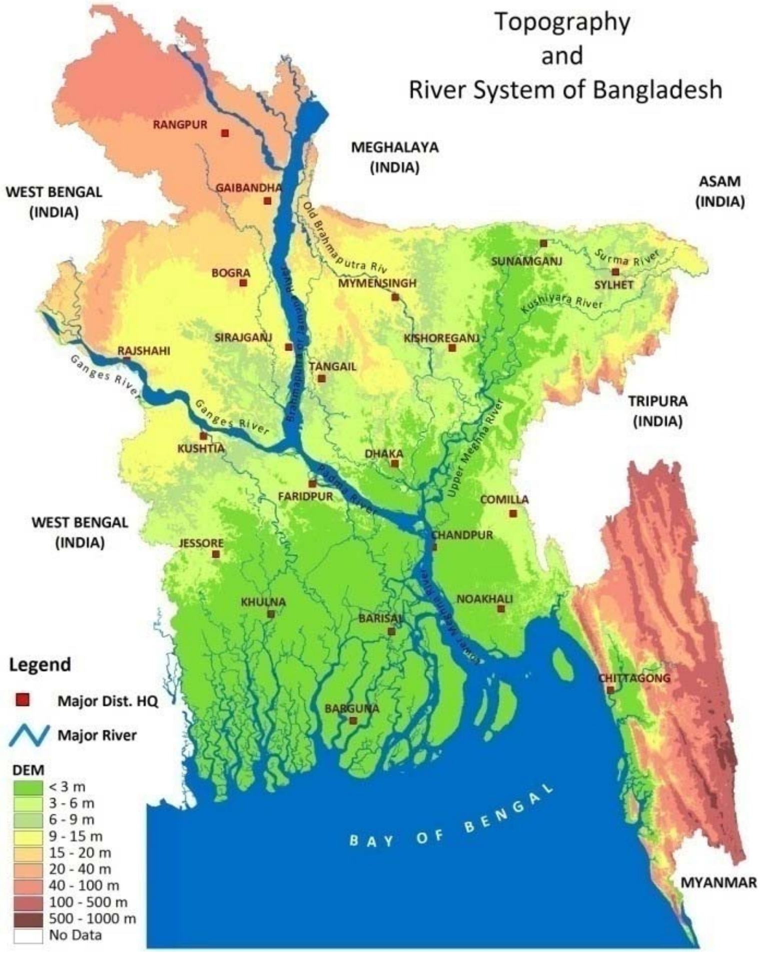


Fig. A. 2 Topography and Major River systems of Bangladesh

The Brahmaputra also has the highest downstream gradient of the three rivers, which is a result of it having occupied its present channel for only 200 years (Barua *et al*., 1994). The Jamuna is braided in nature. As a braided stream, the river is characterized by many channels, shoals, and islands, which is one characteristic of a river with a high sediment load (Coleman, 1969). The Brahmaputra has the highest sediment load of the three rivers, which is widely documented in sediment flux studies (Coleman, 1969; Holeman, 1968; Milliman and Meade, 1983). Galy and France-Lanord (2001) compared the Himalayan erosion rates with the suspended sediment loads of the rivers, and determined that the eastern portion of the Himalayan range is eroding faster than the western portion, which contributes to the Brahmaputra having a higher suspended load than the Ganges. The higher erosion in the eastern region is likely caused by higher precipitation in the eastern region (Fluteau *et al*., 1999; Galy and France-Lanord, 2001).

Appendix: C

Flooding and Its causes

Flooding is the most common environmental hazard worldwide. This is due to the vast geographical distribution of river floodplains and low-lying coastal areas. It is difficult to define exactly a flood is. It is largely classified as 'an overflowing of water onto normally dry land. This encompasses the simple notion that a flood involves an excess of water compared with average water levels. Floods can be categorized as either river floods or coastal floods. River floods are often atmospherically driven, caused by excessive precipitation. They can also occur due to landslides falling into rivers, and by dam or levee failures. Coastal flood are often due to storm surges caused by tropical cyclones or tectonically produced tsunamis.

There are many reasons why floods occur, these can be divided into the following categories:

- *Flash Floods*

These types of flood occur with little or no warning. Flash floods can be deadly due to the rapid rise in water levels and the high flow-velocities of the water. There are factors which contribute to the occurrence of flash floods: rainfall intensity, duration, surface condition and topography. Urban areas are more susceptible to flash floods due to the lack of natural drainage systems and the high amounts of impervious surfaces (concrete, tarmac). These tend to increase the rate of run-off into water systems.

- *Storm Floods*

Storm surges inundate coastal margins due to severe onshore winds, often accompanied by low atmospheric pressure and sometimes high tides. Friction between moving air and the water creates drag. Depending on the distance over which this process occurs (fetch) and the velocity of the wind, water can pile up to depths of over 7 meters. Intense, low-pressure systems and hurricanes (tropical cyclones) often cause storm surges.

- *Dam and Levee Failures*

Dam and levees may be designed to contain a flood at a location on a water way that has a certain probability of a flood occurring in a specific years. If the flood is larger than the one predicted the structure built to contain it will be overtopped and will fail. This causes a sudden burst of water which causes a flash flood downstream. Failed dams and levees can cause catastrophic floods due to the intensive energy involved in the sudden burst of water.

In Bangladesh, there are two distinct seasons, a dry season from November to April (or May) and the wet (flood) season from June to September (or October). Over 80% of the rainfall occurs during the monsoon or rainy season also known as flood season. Long periods of steady rainfall persisting over several days are common during the monsoon, but sometimes local high intensity rainfall of short duration also occurs.

Floods in Bangladesh occur for number of reasons, In **Fig. A.3,** have been exposed some reasons as:

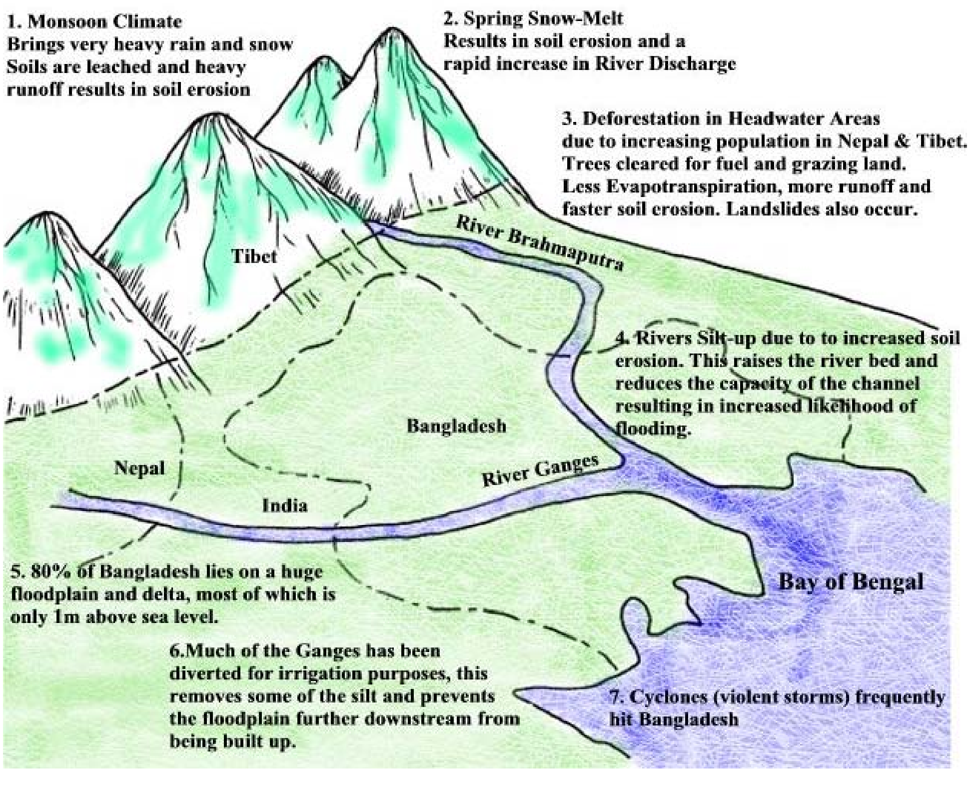


Fig. A. 3 Some causes of flood in Bangladesh

The main causes are excessive precipitation, low topography and flat slope of the country; but others include (BWDB, 2010):

- *The geographic location and climatic pattern*

Bangladesh is located at the foot of the highest mountain range in the world, the Himalayas, which is also the highest precipitation zone in the world. This rainfall is caused by the influence of the southwest monsoon. Cherapunji, highest rainfall in the world, is located a few kilometers north east of the Bangladesh border

- *The confluence of three major rivers, the Ganges, the Brahmaputra and the Meghna*

The runoff from their vast catchment (about 1.72 million km^2) passes through a small area, only 8% of these catchments lie within Bangladesh. During the monsoon season the amount of water entering Bangladesh from upstream is greater than the capacity of the rivers to discharge in to the sea.

- *Bangladesh is a land of rivers*

There are about 310 major and minor rivers in the country. The total annual runoff of surface water flowing through the rivers of Bangladesh is about 12,000 billion cubic meters.

- *Man-made environment*

The construction of embankments in the upstream catchments reduces the capacity of the flood plains to store water. The unplanned and unregulated construction of roads and highways in the flood plain without adequate opening creates obstructions to flow.

- *The influence of tides and cyclones*

The frequent development of low pressure areas and storm surges in the Bay of Bengal can impede drainage. The severity of flooding is greatest when the peak floods of the major rivers coincide with these effects.

- *Long term environmental changes*

Climate changes could influence the frequency and magnitude of flooding. A higher sea level will inhibit the drainage from the rivers to the sea and increase the impact of tidal surges. Deforestation in hilly catchments causes more rapid and higher runoff, and hence more intense flooding.

The spring tides of the Bay of Bengal retards the drainage of floodwater into the sea and locally increases monsoon flooding. A rise of MSL at times during the monsoon period due to effect of monsoon winds also adversely affect the drainage and raise the flood level along the coastal belt.

Appendix: D

Sirajganj District and Its Problem on Breaches of Jamuna River Right Bank Levee

D.1 Description of Sirajganj district

In this study, tentatively focus on Jamuna River Right Bank Levee (JRRBL) at Khokshabari in Sirajganj, which is breached during the high flood flow passed through Jamuna River in August, 2007 and the floodplain area of Sirajganj district were inundated. Sirajganj district is located in the northwestern part of Bangladesh.

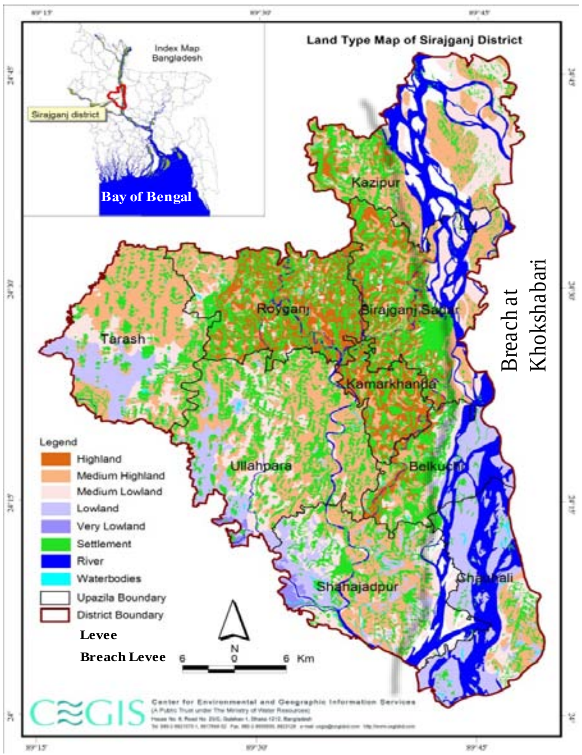


Fig. A. 4 Map of Sirajganj district showing breach levee with adjacent Jamuna River.

Geographical extension, within the area of longitude from 89°20' west to 89°50' east and in latitude it is 24°00' south to 24°20' north. Total area of the district is 2497.92 km^2 and is bounded by Bogra District on the north, Bogra and Nator District on the west and southwest, Pabna District on the south, Tangail and Jamalpur districts on the east. It is relatively a plain land area. Most of the area of this district goes under water during the rainy season. Total cultivable land is 1799.64 km^2, fallow land 157.02 km^2, and forestry 0.50 km^2. The district consists of 4 municipalities, 42 wards, 9 upazilas, 79 union parishads (all are local government administrative units), 117 mahallas, 1467 mouzas and 2006 villages. The upazilas are Belkuchi, Chauhali, Kamarkhanda, Kazipur, Raiganj, Shahjadpur, Sirajganj Sadar, Tarash and Ullahpara. The annual rainfall is 1610 mm. The mighty Jamuna River is following at the right edge of the district. **Fig. A. 4** depicts the map of Sirajganj district. Although this district has various land use pattern we employed a simplified model floodplain with river and levee to know the basic phenomenon of focusing levee breach flood disasters in a floodplain.

D. 2 Breaches and Location on the Jamuna River Right Bank Levee

There are many evidence of breaching of JRRBL during the severe flood years (IWM, 2010), which is shown in **Fig. A. 5** and **Table A. 1**. Our concern breach point is Khokshabari, which is breached of 700 m out of 52 km total length of flood protection levee and the flood water entered into the breached levee at Polashpur, Meghai, Dhekuria and Shubhogaccha areas in Kazipur Upazila of Sirajganj district (The Financial Express, 27 July 2007). At least 3500 homesteads and about 6.07 km^2 of croplands in 35 villages in the five Upazilla has damaged in two weeks. The five affected Upazilla was Kazipur, Sirajganj Sadar, Belkuchi, Shahzadpur and Chauhali (Hossain and Sakai, 2008).

Table A.1 Breach information on JRRBL in different flood years (IWM, Bangladesh)

Flood Year	Location Name	Tentative time of breach occurring	Final length of breach (m)
1998	Khokshabari	August	-
2004	d/s of Sailabari Groyne	July 27	140
2007	Songachha	August	400
2007	Kholishakura	August	650
2007	Khokshabari	August	700

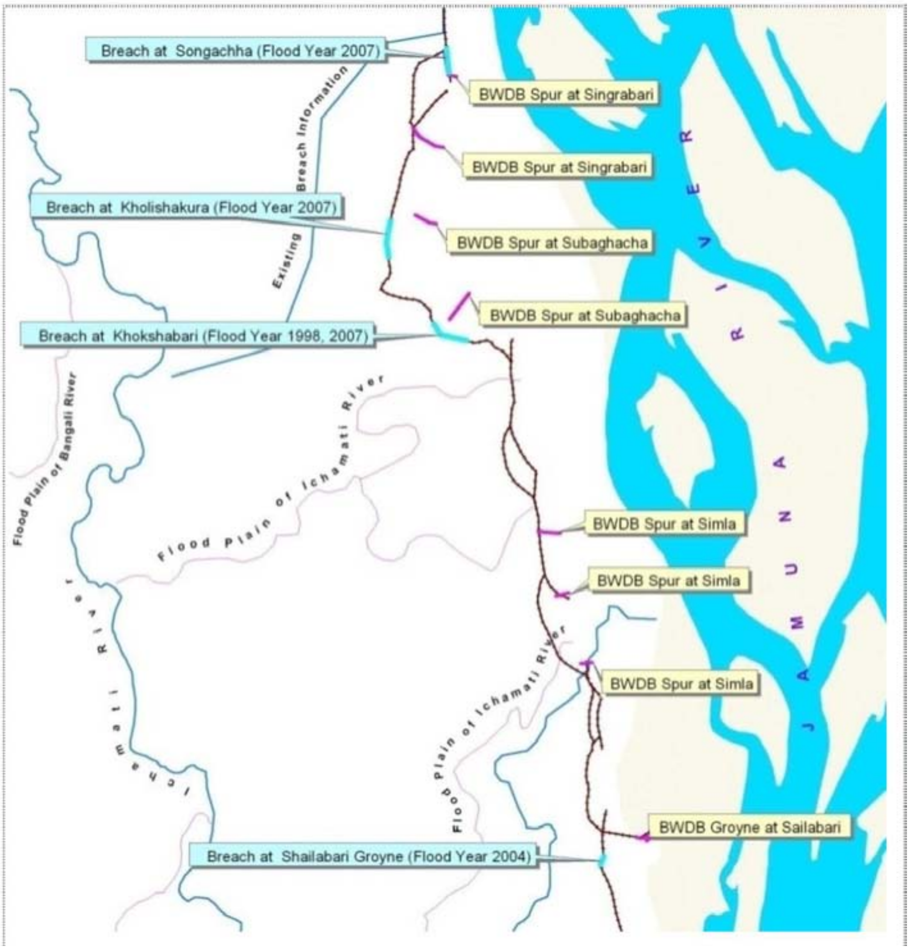


Fig. A. 5 Breaches at Jamuna River flood protection right bank levee.
(Source: IWM, Bangladesh)

D. 3 Levee breaches and Affected Areas Photographs of Sirajganj district

In **Fig. A. 6**, shown some photographs in Jamuna River Right Bank Levee, there are two scenarios, one is before the breach, and another is after flood. Due to this occurrence, the floodplain resident's has suffered with inundation and damages their infrastructures, which is shown in **Fig. A. 7**.

(a)

(b) Source: Field Investigation,

Fig. A. 6 Levee breaches of JRRBL: (a) before breach; (b) after breach.

Fig. A. 7 Levee breach flood affected areas of Sirajganj District and floodplain residents suffered on it (Source: Web)

Appendix: E

River Training Works in Bangladesh

This section focuses on a brief description of the river training works is Bangladesh. River training is a technique to achieve desired course, shape, width and depth of the river". River training works are constructed to constrain the river, i.e. to ensure navigability or to avoid excessive erosion, which consequently restricts the progression of natural changes that occur as a result of the erosion and deposition of sediment. All river training works achieve their objective by protecting erodible material in the bed and banks from the effect of high current velocity and turbulent flow. The structure constructed for the purpose of guiding and taming the flow are called river training works. River training works fulfill the following objectives:

- Protection of surrounding land from flooding;
- Prevention of river bank erosion for protection of towns, cities, villages, monuments, strategic, industrial, commercial structures and agricultural land etc;
- Protection of important hydraulic structures – bridges, barrages, dams etc;
- Maintenance of navigation Channels;
- Directing the river flow in desired direction;
- Reclamation of land.

The practices of major river training measures in the low-laying delta, Bangladesh mainly started after the mid nineteenth century driven by the demands for the safety due to continuous and severe river bank erosion, and to increase the flood damage there. The river training works, which are more or less practiced in the country, can be listed as: levee or embankment, groynes or spurs, revetment works, hard point, cut offs and closures of secondary works, and so on. Among the aforementioned methods mostly used protection works are construction of earthen levee for flood mitigation has been history of Bangladesh like Jamuna River right bank levee which protect Sirajganj district from the high flood flow into the adjacent Jamuna River.

E. 1 Levees/Embankment

A levee may be defined as an embankment aligned generally parallel to the river channel and designed to protect the area behind it from being flooded by high flood flow through the river. The levee can be natural and man-made. In general the man-made levee consists of an earth-fill dyke with or without revetment. The main purpose of a levee is to protect lives and properties from heavy flood. The important design parameters are alignment, crest level and slope, resistance to flow on the river side, and scour depth at the toe. The alignment of the levee is generally determined by the development of land use on both sides of the levee and by the river behavior. Generally, some space between riverbank and the levee is allowed which is called the set back distance. The flood levee of the river determines the crest level of the levee; which flood should be considered to determine the level depends on the degree of safety to be provided for the protected area. The schematic diagram of levee is shown in **Fig. A. 8**.

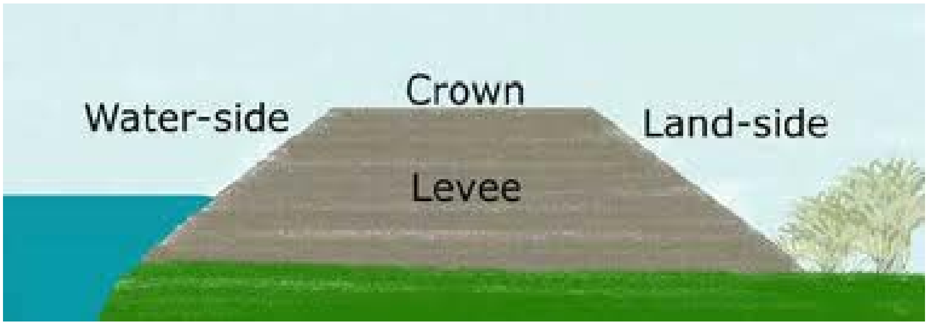


Fig. A. 8 Schematics diagram of levee cross-section

E. 2 Groynes or Spurs

Groynes are the structures extended from the riverbank into the river. There is a preferred angle between the groyne and the bank depending on the purpose of the groyne. Groynes are constructed with stone, gravel, rock, earth or pile structures. Generally, groynes are used to divert the river flow away from the critical zones of bank to protect it from the erosive action of the river; they are also used to constrict the width of the river so that the river will increase its depth, which is important for navigation. The main design criteria to be considered are spacing of groynes, length of groynes, the crest level of groynes (i.e., either at flood plain level or at embankment level), and the possible scour at the groyne. Stabilization of the river bank with a series of groynes is very effective. Bank protection with a single groyne is not effective; most of the time a single groyne creates adverse effect in the surrounding area. A series of groynes can make the flood flow line parallel to the bank which is not possible by a single groyne.

E. 3 Revetment Works

The most common form of river training structure is the revetment or bank protection **(Fig. A. 9)**. River bank erosion is a common feature for all alluvial rivers. Bank protection with revetment works is the method to reduce or stop this erosion process. The riverbank can be divided into an upper and a lower section. The lower part, the part below the low water level, acts as a foundation for the upper part. Erosion of this lower bank, especially at the toe, causes the failure of the bank. The upper part can be eroded by wave attack also. The condition is severe when the current is directly attack the bank. Bank failure can also occur due to the piping (effluent) effect; during low stages piping may occur due to the motion of ground water towards the river. This ground water may carry finer material away from the soil causing the failure of the bank. Revetment work is a well known bank protection method, which is practiced all over the world and there is no exception in Bangladesh. A revetment is a structural protection against wave and current induced loads covering the existing river bank or an embankment. It is not an offensive structure like a groyne. It has several components such as cover layer, intermediate layers between cover and core material that are required for drainage and filtering to allow for a suitable foundation of the overall system and the toe. The cover layer must resist the design impacts, mainly current and wave. Toe protection is required in case of current and/or wave scour, and undermining the toe of a bank or a levee, which are likely to result in sliding of the slope. Sliding of slope endangers the overall stability and function of the revetment which is commonly seen in Bangladesh. Normally the revetment works are done with CC block, boulders, mattresses, open asphalt concrete, and so on.

During revetment works the slope pitching is normally done with 1: 2 to 1:3 according to the soil characteristics and hydrological boundary conditions. Sometimes it is seen that the eroding bank is not uniform. Its slope varies along the bank and in certain locations it it seen very stiff. In that case it should be built with desired slope by using sand filled gunny bags. Otherwise the local scour along the bank will not uniform and in some locations the actual scour could be more than the anticipated value and the revetment will fail. Geobags were introduced in Bangladesh mainly for emergency works to protect the river bank erosion **(Fig. A. 10)**. Now it is being used for a revetment works for protection of bank from erosion, where sand filled geobags are used instead of CC blocks.

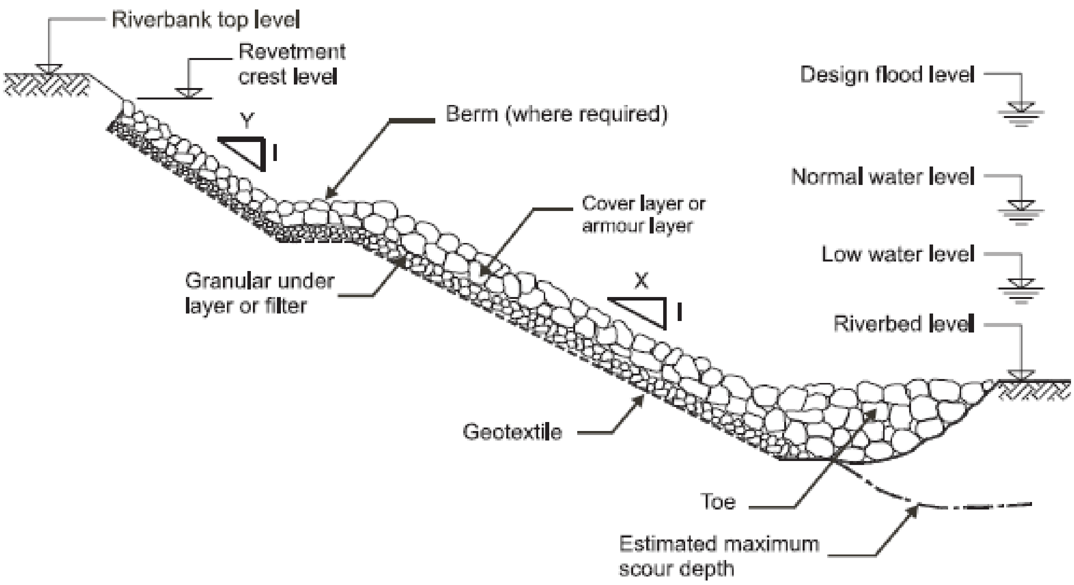


Fig. A. 9 Typical layout of revetment works

Fig. A. 10 Jamuna River Right Bank Levee protection by geobags (Source: Field Investigation, 2007)

E. 4 Hard Points

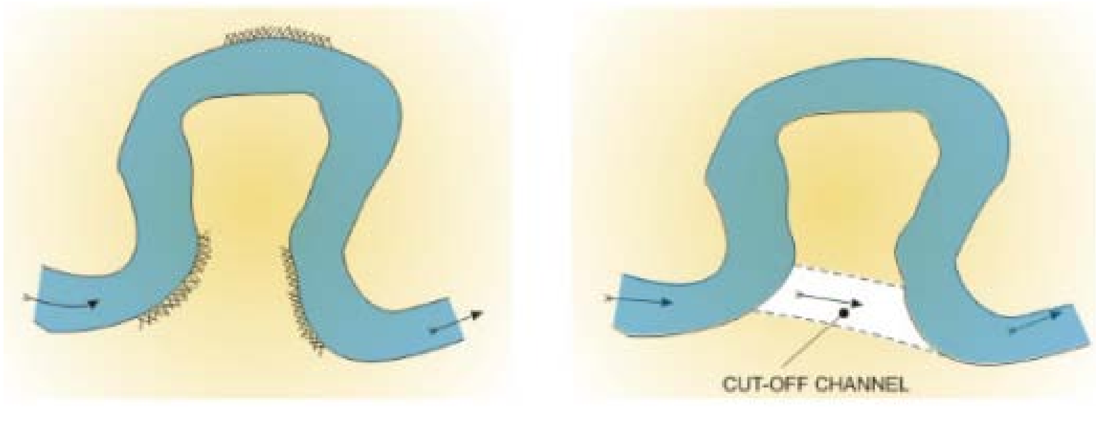
In the concept of 'Hard points', the river is not directly modify, rather the aim is to stabilize the present pattern of the river by limiting the boundaries of the local width of braid belt. Some important places on the bank line are protected by creating 'Hard points', which are isolated bank revetment works with upstream and downstream terminations. These hard points are connected with the flood embankment with the help of cross bar to prevent outflanking of the hard points. The function of the hard points is to limit the extent of erosion. The length and spacing of the hard points determines the extent the area protected from the erosion, and thus the maximum allowable depth of the embankment is permitted in the locations between the structures. After the devastating flood in 1988, River Survey Project (RSP) FAP21 and FAP22 studied river bank erosion problems of the major river of Bangladesh. FAP21 selected the critical location for taking protection measures from erosion along the right bank of Jamuna River (CEGIS report, 2005). Accordingly, during 1996 to 1998 some special protection measures are taken (Sariakandi and Mathurapara Hard points, Sirajganj Hard point **(Fig. A. 11)**, and Strengthening of Kalitola groyne).

Source: Field Investigation, 2007

Fig. A. 11 Sirajganj Hard Points at Jamuna River Right Bank Levee

E. 5 Cutoffs

Cut-off as river training works is to be carefully planned and executed in meandering channel. This is characteristic features of alluvial meandering river. When a river is flowing through a bend, under favorable condition this bend may become a large loop with narrow neck. With increase narrowing of the neck a short-cut channel can be created. So, cut-offs are short channels across the neck of the river bends. By this process a river straightens and shortens itself. Cutoffs can be natural and man-made. Though this process is a very characteristic feature of meandering river, it can also be observed in anabranches of braided rivers. This cut-off process have some beneficial effects like reduction of flood levels, shortening of the river course, exclusion of reaches with excessive curvature along which training structures could be maintained to stop severe bank erosion, and so on. To achieve these beneficial effects, cut-off can be used as a means of river training. Cut-off of bends can be initiated artificially by dredging a pilot channel of adequate dimension, so that flow can start to flow through this channel. This flow will adjust the channel to the required dimensions through further scour. A schematic diagram of cut-off process is shown in **Fig. A. 12**.



(a) **(b**

Fig. A. 12 a) Meandering river with possible threat to bank erosion (marked xxxx….)
b) Cut-off channel

Appendix: F

Flood protection with Levee in Bangladesh

Construction of earthen levee for flood protection has been history of Bangladesh because of cheapest construction cost and availability of materials. In this section, briefly described the levee design criteria, design parameters and causes of levee failure in Bangladesh as well as maintenance and it inspection which is essential to protect levee failure during high flood flow in an adjacent river.

F. 1 Design Criteria of Levee

Levee should be so designed that it must be safe against overtopping, wave action, seepage effect (piping or sloughing), sliding, damage to slope paving, base displacement, river transgression etc. Obviously the criteria for safe design of earthen levee should be such as to guard against all known and anticipated causes of failure. Keeping this in view, the following criteria can be laid down for safe design of earthen levee:

i) *There should be no danger of overtopping*: This involves adequate net freeboard against wave and sufficient allowance for settlement of the levee and foundations. In seismic zone extra allowance is needed for freeboard. An overtopping failure would occur with reservoir full and the flood wave would cause far more damage than the loss of the levee itself.

ii) The seepage line should be well within the downstream face of the levee. This is to prevent ‘sloughing’ of the face and possible failure. If the seepage line meets the country side face, the toe gets softened by saturation and due to adverse seepage forces a local failure at the toe may occur. The steeper surface then left leads to instability up to a still higher level and may lead to ultimate failure of the levee. This is avoided by provision of drainage in the country side portion.

However, the seepage path should not be reduced to such an extent as to make the seepage quantity uneconomically high, or to invite the danger of free flow of water from river side previous zone to country side previous zone.

iii) Water passing through or under the levee should be unable to remove material of the levee or the foundations. This criterion is meets for protection against piping failure and involves provision of a minimum core thickness in the levee section and seepage control measures for foundations.

iv) There should be no opportunity for free flow of water from river side to country side face. Free flow may occur through internal crack, along conduits, at joint with masonry or concrete sections, through layers left loosely compacted by rotten roots of dead trees etc. Once a concentrated leak starts, it is almost impossible to avoid failure. Precautions have to be taken against all these eventualities.

v) The river and country side slopes should be stable against the most adverse conditions to which they can be subjected. For the country side slope, this unusually involves a check against 'drawdown' conditions, and for the country side slope against steady seepage with reservoir full. Both slopes have to be checked for 'end of construction' condition when rapid mechanized construction is carried out, which generates large un-dissipated pore pressures in the compacted layers. Instability may also arise from presence of thin previous seams in clay foundations which may transmit high consolidation pore pressures generated under the levee by its load to lightly loaded areas beyond the toe of the levee and thus cause failure.

In seismic zones, any of these conditions may have to be combined with seismic effects. While a lot has been learnt in recent years about the effect of earthquakes on earth, the criteria and methods of design have not yet been standardized and the designer has to use his judgment in the matter. Past experience indicates that slope failure have generally occurred in levee of clayey soil (Sherard, 1953).

vi) The foundation shear stresses should be smaller than the shear strength to provide a suitable margin of safety. This problem is likely to arise in case of foundations of highly plastic clays, the period just after the construction of levee being the most critical.

vii) The river side face should be properly protected against wave action and the country side faces against the action of rain.

F. 2 Levee Design Parameters

- *Height*

Levee height should be equal to the highest flood levee, transferred to the centre line of the alignment plus free board of 0.9 m for large rivers. This freeboard is usually obtained from consideration of wave height during the design flood.

- *Freeboard*

Freeboard is the vertical distance between the crest of the levee and the highest flood level. Normal freeboard is defined as the difference in elevation between the crest and the normal water level as fixed design requirements. Minimum freeboard is defined as the difference in elevation between the crest of the levee and the maximum water surface that would result should the design flood occur. The normal freeboard must meet the requirements for long-time condition. It must be sufficient to prevent seepage through a core which has been loosened or cracked due to drying out. It must also be sufficient to prevent overtopping of the levee by abnormal and severe wave action of rare occurrence that may result from unusual storm winds of high velocity from a critical direction. Minimum freeboard is provided to prevent overtopping of the levee by wave action which may coincide with the occurrence of the design flood. Minimum freeboard is also provided for safety against many contingencies such as settlement of the levee, over rising of the water level as a result of malfunction of the controlled sluice gates etc. The rational determination of freeboard would require a determination of the height and action of the wave. Various empirical formulas depending on wind velocity and reservoir fetch have been suggested for computing wave heights. For determination of maximum wave height was estimated from empirical formulae developed by Stevenson, Molitor and Gaillard for breakwater design (American Society of Civil Engineers, 1948).The Stevenson-Molitor formula relating wave height with fetch and wind velocity are normally used which are as follows:

$$h_w = 0.032\sqrt{FV} + 0.763 - 0.271\sqrt[4]{F}\ \text{, where } F < 32\text{km} \quad \text{-------------} \quad (A.1)$$

$$h_w = 0.032\sqrt{FV}\ \text{, where} F > 32\text{km} \quad \text{-------------} \quad (A.2)$$

where h_w = height of wave crest to trough (m), V = wind speed (km/h), F = fetch (km).

United States Bureau of Reclamation (USBR) recommended the freeboard to be 2-3 m over the maximum flood level for any height of levee when the spillway is free (Lambe, 1951). USBR recommended the freeboard in the levee (Punmia, 1981) as in the **Table A. 2**.

Table A. 2 Recommended values of freeboard

Fetch (km)	Normal freeboard (m)	Minimum freeboard (m)
Less than 1.5	1.25	1.00
1.5	1.50	1.25
4.0	1.80	1.50
8.0	2.50	1.80
15.0	3.00	2.20

For normal conditions (fetch 2 km, wind speed 150 km/h) in Bangladesh the freeboard is only o.6 m, when the minimum computed freeboard, coming from a realistic design criteria is 1.40 m (Peck *et al*., 1974).Bangladesh Water Development Board (BWDB) recommended the freeboard to be 10% of the levee height as allowance for shrinkage of the levee and another 5% for possible errors during surveys and construction. However, it was recommended by BWDB to adopt a total minimum freeboard of 0.9 m for the levee along the Atrai as well as along the Jamuna River (BWDB, 1984). The freeboard recommended by BWDB for DFC III project was as one quarter of the water depth plus 0.30 m with a maximum limit of 2.0 m. From a series of report and earth manuals (BWDB 1969, 1982 & 1984) and observation it is seen that for ordinary levee a minimum freeboard of 0.8 m to 1. 7 m is normally used in Bangladesh.

- *Settlement Allowance*

While deciding the height of the levee, settlement allowance should be taken into consideration seriously as settlement of levee may be caused by consolidation in the foundation and in the fill over a period of many years. In some areas of Bangladesh a practice of 20% shrinkage on hand placed levee are made (i.e. levee height is built 20% higher than design height). The consolidation settlement however, may be estimated using Terzaghi's (1967) equation (Safiullah, 1988). Based on the experience of road levee/embankments settlement, allowances may be used as shown in **Table A. 3** (BTRS, 1978).

Table A. 3 Settlement allowance to be made on levee height due to consolidation of subsoil

Location	% of Levee height
Shallow ridges and basins of the flood plains valleys of the uplifted terraces	10
Deep basins, beels, peat deposits of flood plains	20
High land areas of the uplifted terraces	5
Hills	0

- *Crest Width*

The crest width design adopted previously in the small or medium schemes was 3 m (UNDP, 1988). The crest width of levee is usually determined by the use to which they are to be put, with a minimum width of about 3.5 - 4 m to permit movement of maintenance equipments. The crest width may be determined by the following empirical expressions (Garg, 1987 and Punmia, 1981)

$$b = H/5 + 3 \quad \text{-----------} \quad (A.3)$$

$$b = 0.55\,H^{\frac{1}{2}} + 0.2H \quad \text{-----------} \quad (A.4)$$

$$b = 1.65\,(H + 1.5)^{\frac{1}{3}} \quad \text{-----------} \quad (A.5)$$

where b = crest width (m) and H = height of levee (m)

Equation (2.3) is applicable for low levee and equation (2.4) is applicable for levee lower than 30 m, also equation (2.5) given by USBR is applicable foe levee higher than 30 m. For people's shelter during high flood or in case of levee failure more 1-2 m would be added to the crest width to be calculated by the above formula.

- *Side Slopes*

The evaluation of slope stability is complicated due to the fact that levee contain heterogeneous soil due to non-uniform compaction and non-uniformity in borrow materials. In many situations the variables that affect the shear strength in the field are only approximately known. Hence, for small project and for levee of low height, it may be adequate to rely for slope section on the available experience for a zone. Although levees are being constructed in Bangladesh for a considerable time, none such experience is on record (Safiullah, 1988).

The slopes of the levee vary widely depending on the character of the materials available, foundation conditions and the height of the structure. The slopes also depend upon the type of levees (i.e. homogeneous, zoned levee type etc.) and on the nature of construction materials and other geotechnical characteristics. **Table A. 4** gives the side slopes for preliminary design of embankments/levee according to Terzaghi and Peck, 1967.

Table A. 4 Side slopes for earth embankment/levee according to Terzaghi and Peck, 1967.

Type of material	River side slope (H:V)	Country side slope (H:V)
Homogeneous well graded	2.5:1	2:1
Homogeneous coarse silt	3:1	2.5:1
Homogeneous silty clay		
i) Height less than 15 m	2.5:1	2:1
ii) Height more than 15 m	3:1	2.5:1
Sand or sand and gravel with a central clay core	3:1	2.5:1
Sand or sand and gravel with reinforced concrete diaphragm	2.5:1	2:1

Ministry of Local Government, Rural Development and co-operatives of Bangladesh recommended the side slopes for flood levee as shown in **Table A. 5**.

Table A. 5 Side slopes both for river and country sides

Type of soil	Permissible side slopes (horizontal: vertical)
Normal soil (silt or silty clay)	2:1 to 3:1
Loose sandy soil	3:1 to 5:1

Master Plan Organization (MPO, 1985) noted that as per the conventional practice of BWDB the country side slope is 1:2 and that for river side is 1:3. BWDB recommended the side slopes for the levee to be 1:2 on the country side and 1:3 on the river side. These slopes are normally adopted for design in Bangladesh since it appears to provide sufficient safety against slope instabilities (NEDECO, 1984). Riverside slope may vary from 1:2 to as flat as 1:4 for stability because of the relatively poor construction materials (Punmia, 1981). Taking into account the geotechnical conditions of Bangladesh, a realistic design should take a value of 1:2 for the country side and 1:3 for the river side. The recommended slopes as a design condition and given soil condition of Bangladesh are 1:3 for river side slope and 1:2.5 for country side slope (UNDP, 1988)

F. 3 Causes of Levee Failures

Levees are not 'fail safe'. Failure of levees always create risky situation to the floodplain inhabitants who are living inside the boundary of the levee. So, construction of safe levee is very essential to protect damage from levee breach disasters. Knowledge about soil mechanics, hydraulics, hydrology, hydrogeology, construction technology should be considered more carefully during levee design and construction. **Fig. A. 13** shows the different causes of levee failures. Levees can fail in a variety of ways; the major causes are as follows:

- *Overtopping*

Levees are designed to provide a certain level of protection. When larger flood events happen, a levee will overtop. The overtopping failure of a levee is a relatively simple event to understand. If water is allowed to flow over the top of an embankment constructed of soil for even a relatively short period of time, the shear stress exerted by the flowing water (velocity) can exceed the critical stress of the soils and the resulting impact is that soil particles will begin to be removed (erosion). Generally, the higher the velocity of flow over the levee, the more quickly that erosion will occur and cause a failure of the levee. Regardless of the standards used to design a levee, the levee can be overtopped by a storm event and therefore, is subject to failure.

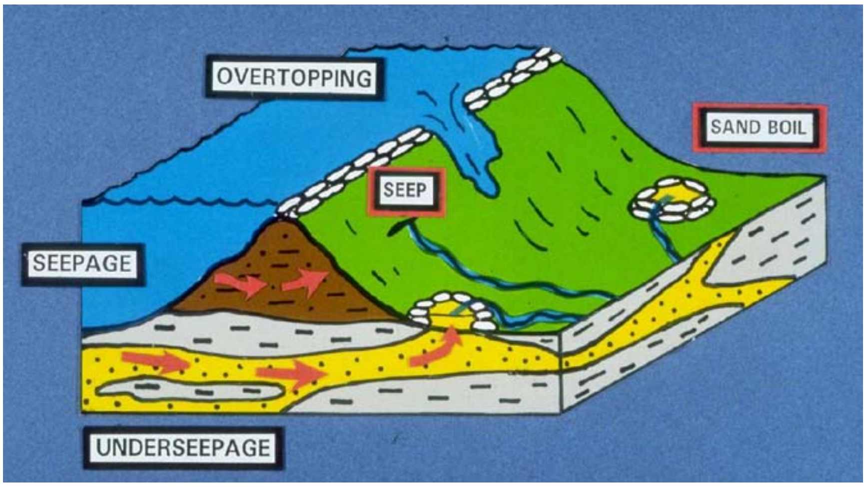


Fig. A. 13 Schematics diagram of different types of levee failure.

- *Piping*

Levees are typically built on top of old alluvial materials and in many cases directly over old stream meander channels. Flood waters tend to travel thru these permeable materials and boil up on the back side of a levee. These ground water ‘conduits’ can cause a levee to fail if sand or material is transported from underneath the levee foundation. Depending on the amount of material removed, the levee may settle unevenly, crack, or even completely fail.

- *Seepage and Saturation*

During rainy season, flood waters on major streams tend to rise slowly and then recede slowly but sometimes this process occur rapidly due to sudden upstream catchment water load which comes from outside of Bangladesh. When water is against a levee for a long period of time, they become saturated. As the levee becomes saturated, seepage through and sloughing of the soil can occur. The result is a loss of levee and foundation material stability and ultimately, failure. Seepage failures can be caused during a major storm event where the hydrostatic pressure imparted to the soils in and under the levee is sufficient enough to create unstable conditions in a portion of the levee or foundation material and the portion of the levee 'collapses'. It is standard design practice to construct relief wells along the interior toe of major levees to assist in reducing foundation seepage pressures.

- *Erosion*

Most levees in Bangladesh are constructed of sand or alluvial materials dragging from river materials. Both are among the easiest to erode. On larger streams and rivers, wave action caused by wind or boats can impact the river side slope of the levee. Levees can fail from gradual wearing down of the levee.

- *Structural Failures*

Structural failures may occur at locations of gates, walls or closure structures. Many times, the lack of maintenance of these structures is a key component in the failure at these locations. In Bangladesh, most of the structures are failed due to poor planning, design and faulty construction.

- *Human Interference*

Levee also can fail by human activities. The most commonly observed failure problems out of the varied human uses noted below:

(a) Travel paths of men or cattle;
(b) Homesteads and agricultural practices;
(c) Cattle grazing;
(d) Public cuts;
(e) Unplanned afforestation of levee slopes;
(f) Uncontrolled animal activities; and
(g) Improper design and construction technique.

F.4 Levee Maintenance and Inspection

Regular inspection of the levee should be performed and at least once in the early rainy season a thorough inspection is required by the responsible engineer. Any damage or defect on the levee should be repaired immediately. Damage of the levee includes damage to the turfed surface, cracks in the levee, erosion due to river action and rainfall, erosion due to seepage, human action etc. Inspection of the levee during high stage should not be limited to the river side slope and the crest but also the country side slope, especially the toe of the levee (internal erosion or piping due to seepage).

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