STUDY ON MORAINE DAM FAILURE AND RESULTING FLOOD/DEBRIS FLOW HYDROGRAPH DUE TO WAVES OVERTOPPING AND EROSION

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ABSTRACT

Glacial lake outburst floods (GLOFs) may cause floods of great magnitudes, loss of life, properties and sediment disaster in the downstream river reaches. About 80% of GLOFs (based on 20 cases with known failure mechanisms) were initiated by displacement waves from ice avalanches that collapsed into the lakes from hanging or calving glaciers and rock avalanches. Therefore, an integrated model is essential for the i) prediction of waves generated by ice/rock avalanche, ii) prediction of outflow hydrograph due to waves overtopping and erosion of moraine dam and iii) flow and sediment routing in the downstream for flood risk assessment. Toward development of an integrated model, this study focuses on experimental study of moraine dam failure due to waves overtopping and erosion. Extensive laboratory experiments are carried out by varying size of ice/rock avalanche, shape of the dam, dam material and lake water level. The outflow hydrographs produced by waves overtopping and erosion consist of multiple peaks. For the same falling block and lake water level, the initial peaks are similar for both triangular and trapezoidal dams. However, magnitude and timing of subsequent peaks are different according to dam shapes and dam materials.

KEY WORDS: *GLOF, waves overtopping, erosion, outflow hydrograph, laboratory experiment*

INTRODUCTION

Glacial lake outburst flood (GLOF) is a release of an enormous amount of stored water in the glacial lake due to failure or breach of ice or moraine dam. Moraine dam failure and GLOF are phenomena closely related to climate change. These events may cause floods of great magnitudes, loss of life, properties and sediment disaster in the downstream river reaches. Moraine dammed lakes and GLOFs are common in different glacierized regions of the world (Lliboutry *et alii*, 1977; Haeberli, 1983; Costa & Schuster, 1988; Yamada, 1998; Clague & Evans, 2000; Richardson & Reynolds, 2000). In the Himalaya, a study carried out jointly by International Centre for Integrated Mountain Development (ICIMOD), United Nations Environment Programme/Regional Resource Centre for Asia and the Pacific (UNEP/RRC-AP) and Asia-Pacific Network for Global Change research (APN) between 1999 and 2003 estimated about 9000 glacial lakes and more than 200 potentially dangerous glacial lakes (see Tab. 1) in Bhutan, Nepal, Pakistan and selected basins of China and India (Bajracharya *et alii*, 2008). Thus monitoring of glaciers, glacial lakes, installation of early warning systems and different hazard mitigation measures are required for proper management of potential GLOF events.

Moraine dams are distinct ridges and mounds of debris lay down directly by a glacier or pushed up by it at the point of its greatest progress. Some moraine

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S. No.	Country	River basin	Glacial lakes		Reference
			Number	Potential danger	
1	Nepal	Koshi, Gandaki, Karnali and Mahakali	2323	20	Bajracharya et al. (2008)
2	Bhutan	Amo Chu, Wang Chu, Puna Tshang Chu, Manas River, Nyere Ama Chu and Northern basins	2674	24	" "
3	Pakistan	Indus River basin	2420	52	" "
4	India	Tista river, River basin of Himachal and Uttaranchal	549	30	" "
5	China	Ganges Basin	824	77	" "
		Total	8790	203	

Tab. 1 - *Summary of glacial lakes and potentially danger-
ous glacial lakes in the Himalaya*

Fig. 1 - *Causes of glacial lake outburst floods (Based on
20 cases with known failure mechanisms)*

Fig. 2 - *Annual maximum instantaneous flood discharge
at Rabuwa Bazar (90km downstream of Dig Tsho
glacial lake), Dudhkoshi river (AWAL, 2008)*

dams contain dead glacier ice. A lake formed as a gla-
cier recedes from its terminal moraine is known as
moraine-dammed lake. Moraine dams generally fail
by overtopping and incision. Potentially dangerous
lakes typically require a trigger mechanism to initiate
a flood. The triggering event is most frequently an ice
avalanche from the toe of the retreating glacier which
generates waves that overtop the dam. Failure of dam
slopes, melting of ice cores and piping are other fail-
ure mechanisms which may cause self destruction of
moraine dam. Earthquake is also an external trigger
which may cause settlement of the moraine dam and
lake outburst. About 80% of GLOFs were initiated
by displacement waves from ice avalanches that col-
lapsed into the lakes from hanging or calving glaciers
and rock avalanches (see Fig. 1). NEA (2005) com-
piled thirty three historical GLOF events that occurred
in Nepal and Tibet (China). The causes of failure of
thirteen events were unknown. The cause of failure of
Dig Tsho was mentioned as rock avalanche however
other studies (VUICHARD & ZIMMERMANN, 1987; YA-
MADA, 1998) have shown that the failure was due to
ice avalanche. Thus, in this study, the cause of failure
of Dig Tsho is classified as ice avalanche. The main
causes of glacial lake outburst floods are shown in Fig.
1 based on twenty cases of glacial lake outburst floods
(with known failure mechanisms) which occurred in
Nepal and Tibet (China). Ice avalanching is a common
trigger for moraine dam failure because many glaciers
have retreated up steep rock slopes and toes of such
glaciers are heavily crevassed and wet, and thus prone
to failure (CLAGUE & EVANS, 2000). The volume of ice
avalanche/rock fall may as large as 1/4 to 1/2 of the
lake volume (XU & FENG, 1994). The recent study of
one of the potentially dangerous glacial lake in Nepal
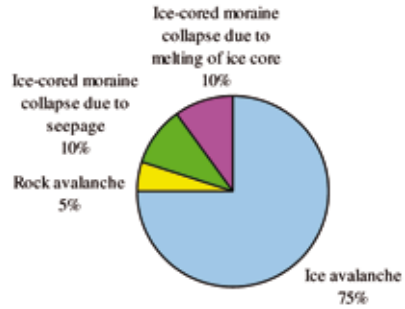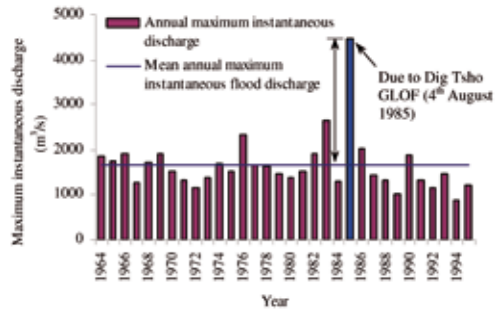(Imja Lake) by WATANABE *et alii* (2009) recommended

to study overtopping of potential surge waves from ter-
minal moraine that may generate by 43m high ice cliff.

The material comprising most moraine dams is
silty, sandy, bouldery till, with minimal clay content.
Most of the moraine dams are steep sided (some ex-
ceeding 40°). Moraine dams are made of loose, easily
erodible materials that are incorporated in the outburst
flood, commonly resulting in a debris flow immedi-
ately downstream. The instananesos flood discharge
due to GLOF event may be very high compare with
mean annual maximum instantaneous flood discharge
due to rainfall. In Fig. 2 maximum instantaneous flood
discharge in 1985 is due to Dig Tsho GLOF (4th Au-
gust, 1985) which is about 2.7 times higher than mean
annual maximum instantaneous flood discharge. There
are two methods to predict probable peak discharge
from potential failure of natural dams. Many empirical
relationships are derived to determine peak discharge
from data set of historic dam failures for landslide,
glacier and moraine dams (COSTA, 1988; WALDER &
O'CONNOR, 1997). However, these empirical relation-
ships are derived from limited number of cases. The
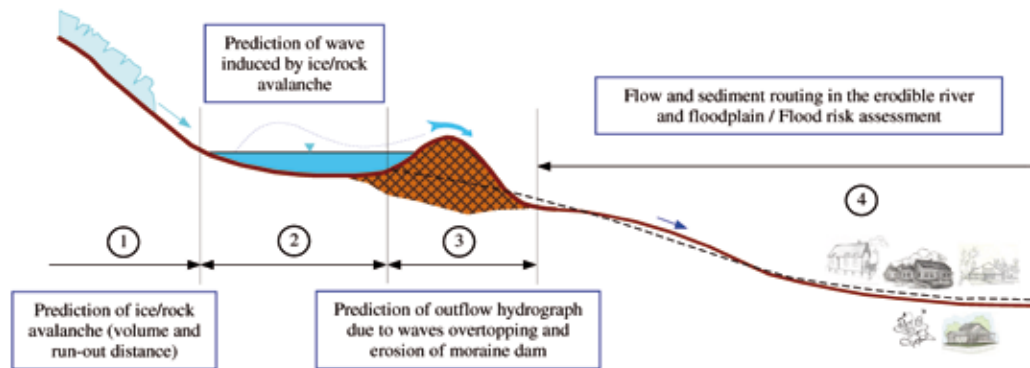other method employs computer implementation of

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Fig. 3 - An integrated model to predict glacial lake outburst flood (GLOF) due to waves overtopping and erosion

physically based mathematical models. Several researchers have developed physically based models (FREAD, 1991; TAKAHASHI & NAKAGAWA, 1994; AWAL *et alii* 2008). However, most of the models are applicable for overtopping and erosion of the dam. An integrated model developed by AWAL *et alii* (2008) is applicable for dam failure due to sliding and overtopping. The mechanism of moraine dam failure in many cases is different from simple overtopping due to snow melt or precipitation. The high amplitude waves generated by ice/rock avalanche produce rapid erosion of moraine dam. Thus, the released water from breached moraine dam will be highly dependent on size, shape and location of initiation of ice/rock avalanche, height and speed of wave generated. However, an integrated model to predict waves, outflow hydrograph and downstream flooding for such type of failure mode is still lacking. In this context, this study has proposed an integrated model for the i) prediction of waves generated by ice/rock avalanche, ii) prediction of outflow hydrograph due to waves overtopping and erosion of moraine dam and iii) flow and sediment routing in the downstream for flood risk assessment. The general outline of proposed model is shown in Fig. 3. Some of the recent studies on glacial lake outburst floods used BREACH model (FREAD, 1991) to predict outflow hydrograph (BAJRACHARYA *et alii*, 2007; WANG *et alii* 2008). However, this model has limitation to represent batter slopes of dam greater than 11° (DAVIES *et alii*, 2007) and does not consider waves overtopping due to ice/rock avalanches.

An experiment on moraine dam failure provides an opportunity to observe failure mechanisms as the failure of a moraine-dammed lake has never been directly witnessed. Most of the experimental studies are focused on prediction of waves generated by landslide/rock avalanche (FRITZ *et alii*, 2004; ZWEIFEL *et alii*, 2007). However, very few studies focused on dam breaking by waveinduced erosional incision (BALMFORTH *et alii*, 2008; BALMFORTH *et alii*, 2009).

In-depth knowledge of the mechanism of the moraine dam failure by waves overtopping and measured data are still lacking. Extensive laboratory experiments are carried out to study such triggering event and failure mechanism by varying size of ice/rock avalanche, shape of the dam, dam material and freeboard between the crest of the dam and lake water level.

EXPERIMENTAL METHOD

The schematic diagram of the flume and other accessories used in the experiments are shown in the Fig. 4. The rectangular flume of length 500cm, width 30cm and depth 50cm was used. The shapes of the moraine dam used in the experiments are trapezoidal with flat crest and triangular. The crest width of trapezoidal dam was 10cm. The height of all dams was 15 cm. In general, most of moraine dams are steep-sided and narrow crest, however some moraine dam has wider flat crest.

Rigid dam of wood and mixed silica sand (Mix: 1-6 and Mix: 1- 7) were used to prepare dam in the flume. The mixed silica sand Mix: 1-6 was prepared by mixing silica sand S1, S2, S3, S4, S5 and S6 in equal portion. Similarly, Mix: 1-7 was prepared by mixing silica sand S1, S2, S3, S4, S5, S6 and S7 in equal portion. The mean dia. of sediment Mix: 1-7 and Mix: 1-6 were 1mm and 1.15mm respectively. The grain size distribution of sediment mixtures are shown in Fig. 5. In general, moraine dams comprise loose, poorly sorted, stratified to massive sediment deposited directly form glacier ice. Some moraine dams consist largely of coarse, blocky and bouldery material with a matrix of sand and gravel
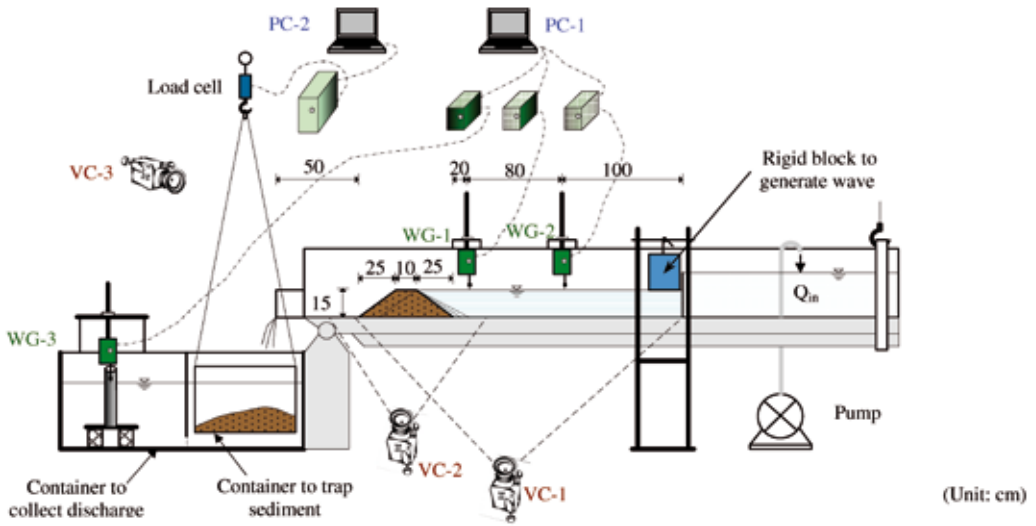
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Fig. 4 - Experimental setup

Cont.

Expt. No.	Dam shape	Flow condition	Slide mass	Free-board (cm)	Dam material	Remarks		Expt. No.	Dam shape	Flow condition	Slide mass	Free-board (cm)	Dam material	Remarks
1	Trapezoidal	FCW	Block A	0	Rigid			17	Triangular	FCW	Block B	2	Mix: 1-7	Upstream Slope 3:7 (V:H)
2	Trapezoidal	FCW	Block A	2	Rigid			18	Triangular	FCW	Block B	2	Mix: 1-7	Upstream Slope 1:3 (V:H)
3	Trapezoidal	FCW	Block B	0	Rigid			19	Trapezoidal	FCW	Block B	2	Mix: 1-6	Stable
4	Trapezoidal	FCW	Block B	2	Rigid			20	Trapezoidal	FCW	Block B	2	Mix: 1-6	
5	Triangular	FCW	Block A	0	Rigid			21	Triangular	FCW	Block A	2	Mix: 1-6	
6	Triangular	FCW	Block A	2	Rigid			22	Triangular	FCW	Block B	2	Mix: 1-6	
7	Triangular	FCW	Block B	0	Rigid			23	Trapezoidal	PCW-C	Block A	2	Mix: 1-7	Stable
8	Triangular	FCW	Block B	2	Rigid			24	Trapezoidal	PCW-C	Block B	2	Mix: 1-7	
9	Trapezoidal	FCW	Block A	0.5	Mix: 1-7	Failed by making channel in the left side		25	Triangular	PCW-C	Block A	2	Mix: 1-7	
10	Trapezoidal	FCW	Block A	2	Mix: 1-7	Stable		26	Triangular	PCW-C	Block B	2	Mix: 1-7	
11	Trapezoidal	FCW	Block B	0.5	Mix: 1-7			27	Trapezoidal	PCW-C	Block A	2	Mix: 1-6	
12	Trapezoidal	FCW	Block B	2	Mix: 1-7	Failed by making channel in the left side		28	Trapezoidal	PCW-C	Block B	2	Mix: 1-6	
13	Triangular	FCW	Block A	0.65	Mix: 1-7			29	Triangular	PCW-C	Block A	2	Mix: 1-6	
14	Triangular	FCW	Block A	2	Mix: 1-7			30	Triangular	PCW-C	Block B	2	Mix: 1-6	
15	Triangular	FCW	Block A	0.65	Mix: 1-7			31	Triangular	PCW-S	Block A	2	Mix: 1-7	
16	Triangular	FCW	Block B	2	Mix: 1-7			32	Triangular	PCW-S	Block A	2	Mix: 1-6	

Note: FCW = Full channel width, PCW-C = Partial channel width (Central channel breach), PCW-S = Partial channel width (Side channel breach), FB = Freeboard
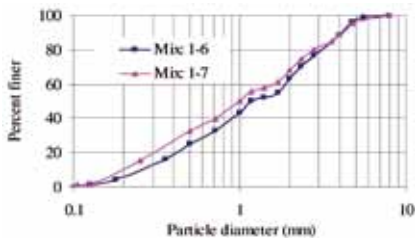
Tab. 2 - Summary of experiments

Fig. 5 - Grain size distribution of sediment mixes

where as other moraine dams consist of silty and sandy diamicton and sandy gravel (CLAGUE & EVANS, 2000). However, details of grain size distribution of most of moraine dams are unknown. Therefore in this study mixed sediments prepared from silica sand were used.

Ice or rock avalanche is a very complicated physical phenomenon. However, for simplicity, in this study block of definite shape was used. A wave was initiated in the lake by falling a rigid block. The volume of Block A was 1/8 of the lake volume (L=25 cm, B=30 cm) and weight was 18.2kg. Similarly, the volume of Block B was 1/4 of the lake volume (L=50 cm, B=30 cm) and weight was 33.5 kg. Servo-type water gauges, WG-1 and WG-2, were used to measure wave height in the lake at two locations as shown in Fig. 4. WG-1 and WG-2 are located at 130 cm and 210cm respectively from end of the flume.

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Load cell and servo-type water gauge (WG-3) were used to measure sediment and total flow in the downstream end of the flume. The arrangement to measure outflow hydrograph both sediment and total discharge at the channel outlet can be achieved by employing container to trap sediment and servo-type water gauge in the downstream tank. The submerged weight of the sediment trapped in the container was measured with the help of load cell at fixed time interval. Similarly, change in water level of container used to collect discharge in the downstream was measured by servotype water level gauge. More details of measurement apparatus can be found in AWAL (2008). Three video cameras were used to capture eroded shape of the moraine dam and propagation of waves.

The summary of experiments is shown in Table 2. Basically experiments can be divided into three categories: (i) waves overtopping over rigid dam, (ii) waves overtopping and erosion from full channel width and (iii) waves overtopping and erosion from partial channel width (central and side channel breach).

RESULTS AND DISCUSSIONS

A wave was initiated in the reservoir by dropping different size blocks. The reservoir was filled with water up to a depth according to desired freeboard. The water was then left to seep through the dam. The block was dropped from height close to water surface when seepage flow reached downstream toe. Propagation of waves generated by falling Block A and Block B (FB=2 cm) are shown in Fig. 6 and Fig. 7 respectively. The waves measured at two locations in the upstream reservoir by using servo-type water level gauge and video captured from side of the flume are shown in Fig. 8 and Fig. 9. The amplitude of waves generated by Block B was higher than Block A. Wave amplitude decreased quickly when the water level was almost full (FB=0) in the reservoir (Fig. 8), however it took

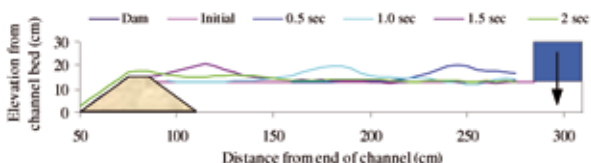*Fig. 6 - Propagation of waves generated by falling block (Block A)*

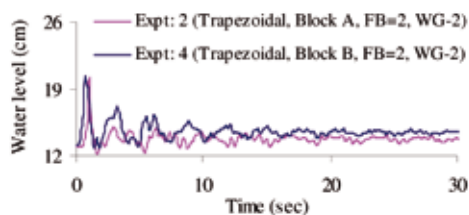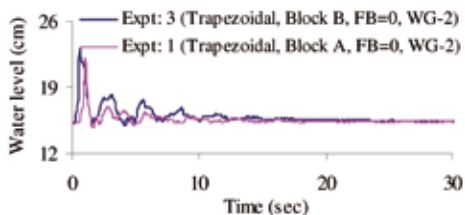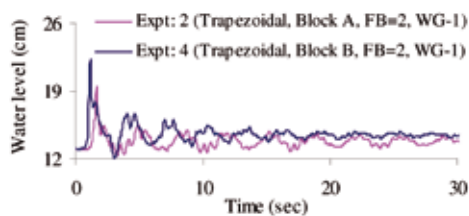*Fig. 7 - Propagation of waves generated by falling block (Block B)*
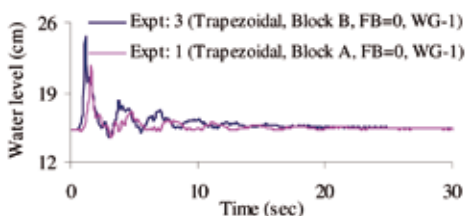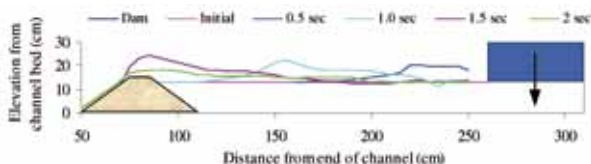

Fig. 8 - Waves measured at different locations in the upstream reservoir for FB = 0

Fig. 9 - Waves measured at different locations in the upstream reservoir for FB = 2 cm

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long time to stabilize the wave amplitude in the reservoir with freeboard of 2 cm (Fig. 9).

In all experiments wave was initiated by employing same method and measured using servo-type water level gauge.

Overtopping waves may carry enough water over stable moraine dam. Rigid dams of wood are used to make stable dam. Most of the glacial lakes are narrow in the width. If the volume of ice/rock avalanche is very big, overtopping may occur from whole width of end moraine. However, most of the wave overtopping occurs from partial width of end moraine from existing channel. Therefore, in this study, we have considered following three cases:

OUTFLOW HYDROGRAPH DUE TO WAVES OVERTOPPING OVER RIGID DAM

Figure 10 shows the outflow hydrographs due to waves overtopping over rigid dams. The resulting peak discharge in the trapezoidal and triangular rigid dams were similar for different initial water depths in the lake and blocks used to generate waves. The total volume of water drained from the lakes with freeboard of 0cm was almost equal in both shaped dams. However, in the case of freeboard of 2 cm the total volume of water drained in the triangular dam was 8 to 15% higher than trapezoidal dam.

OUTFLOW HYDROGRAPH DUE TO WAVES OVERTOPPING AND EROSION OF MORAINE DAM (FULL CHANNEL WIDTH)

Numbers of experiments were done to study the effects of shape of the dam, freeboard, dam material and upstream slope of the dam on outflow hydrograph.

Effect of shape of the dam on outflow hydrographs

Trapezoidal dam with freeboard of 2cm was stable for waves generated by Block A. Figure 11 shows the outflow hydrographs due to waves overtopping and erosion of the moraine dam for flow from full channel width. The waves generated by dropping a block in the lake overtopped moraine dam and produced initial peak discharge in the downstream. Flow was reduced during runback of waves. The reflected waves repeatedly overtopped the dam and produced multiple peaks. Breaching of moraine dam and rapid lowering of lake water level occurred after erosion of crest and overtopping of reflection waves many times. The initial discharge produced
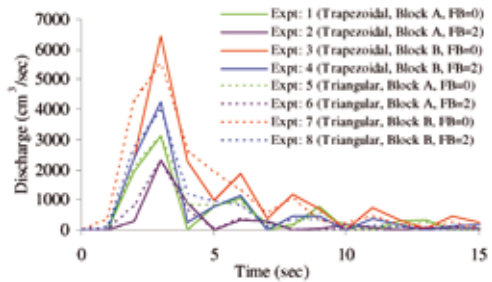

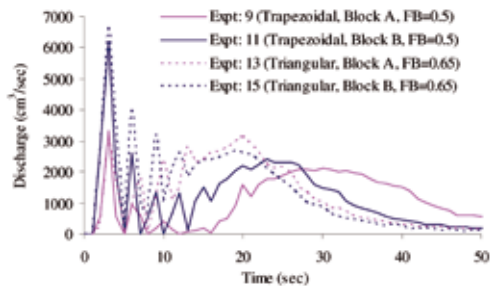Fig. 10 - *Outflow hydrographs due to waves overtopping over rigid dam*

Fig. 11 - *Outflow hydrographs due to waves overtopping and erosion of moraine dam (for dam with different shapes)*

by both rigid blocks, Block A and B in both shape of the dams were similar. However, peak discharge produced after erosion of the dam in the triangular dam was higher and occurred earlier compare with trapezoidal dam. The small difference in freeboard (1.5mm) between two shapes of the dam caused only minimal influence on outflow hydrographs. Erosion of the dam was started from outer face in both shapes as shown in Fig. 12 and Fig. 13. However, it took some time to erode flat crest of the trapezoidal dam, so peak discharge occurred earlier in the case of triangular dam. Thus narrow dams are more vulnerable to overtopping and erosion.

Effect of freeboard on outflow hydrographs

Volume of water drained from the lake and amplitude of wave generated in the lake depends on depth of water in the reservoir. When freeboard is low, the overtopping water depth in the dam crest Initial WL Freeboard Initial WL Freeboard due to waves is higher and erode dam body very fast, so peak discharge occur earlier and magnitude of peak discharge is also higher as shown in Fig. 14. Therefore the lake with little freeboard is more vulnerable to overtopping and erosion by displacement waves from ice/rock avalanches.
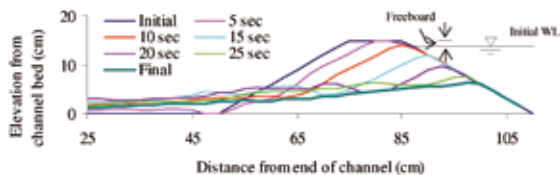
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Fig. 12 - Dam surface erosion (Expt: 11)

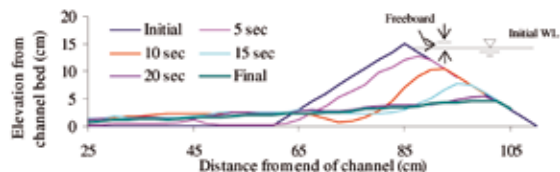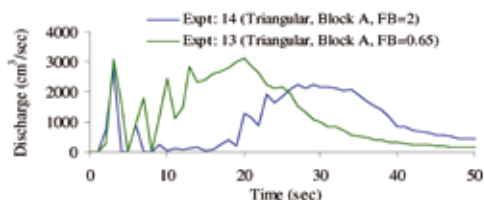*Fig. 13 - Dam surface erosion (Expt: 15)*

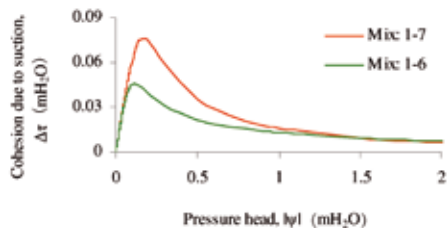*Fig. 14 - Outflow hydrographs for dam with different freeboards*

Fig. 15 - Relationship between Δτ and |ψ|

Effect of dam material on outflow hydrographs

Sediment mixes 1-6 and 1-7 were used to prepare dam. The mean diameter of Mix: 1-6 was bigger than Mix: 1-7. However, shear strength due to suction plays vital role in erosion of unsaturated fine sediments. With reference to Vanapalli *et alii* (1996), increase in shear strength due to suction (Δτ) can be expressed by following equation:

$$\Delta\tau = \left(u_a - u_w\right)\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)\tan\phi = \rho_w g |\psi|\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)\tan\phi$$

where, $u_a - u_w$ is the matric suction, ϕ is the angle of internal friction of soil, θ is the soil volumetric water content, θ_s is the saturated moisture content, θ_r is the residual moisture content and ψ is the soil water pressure head.

The graphical representation of Eq. (1) is shown in Fig. 15. Increase in resisting shear strength due to

suction is higher for sediment Mix: 1-7 compared with bigger sized sediemnt Mix: 1-6. This is the main reason for rapid erosion of the dam prepared from Mix: 1-6 compared with dam prepared from Mix: 1-7 even if the mean diameter of sediment is bigger (see Fig. 16).

Effect of upstream slope of the dam on outflow hydrographs

The longitudinal profiles (see Fig. 17) of some of the potentially dangerous glacial lakes in Nepal (Tsho Rolpa, Imja, Thulagi and Lower Barun) derived from Mool et alii (2001) shows that the upstream slope of end moraines are flatter (9 to 17 degree). The result of experiments 16, 17 and 18 showed the effect of slope of inner face of the moraine dam in outflow hydrographs. Multiple peak discharges due to waves overtopping and erosion of the dam was higher in the dam with steeper slope of inner face (see Fig. 18). The total volume of water drained from the lake was also higher in the dam with steeper slope of inner face. The temporal changes of dam shape for different upstream slopes of the dam are shown in Fig. 19. The eroded slope
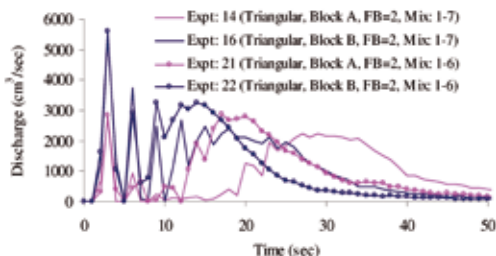

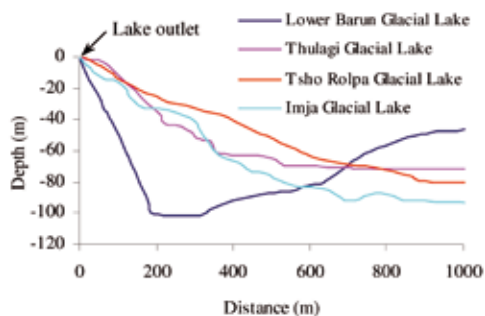*Fig. 16 - Outflow hydrographs for dam of different sediment mixes*

Fig. 17 - Longitudinal profiles of potentially dangerous glacial lakes in Nepal
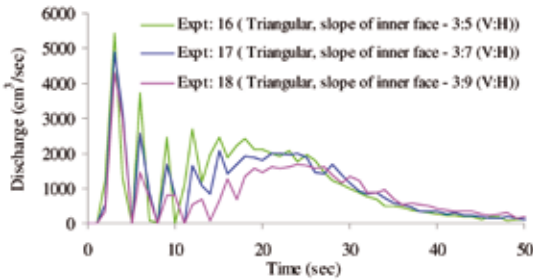
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Fig. 18 - Outflow hydrographs for dam with different upstream slopes

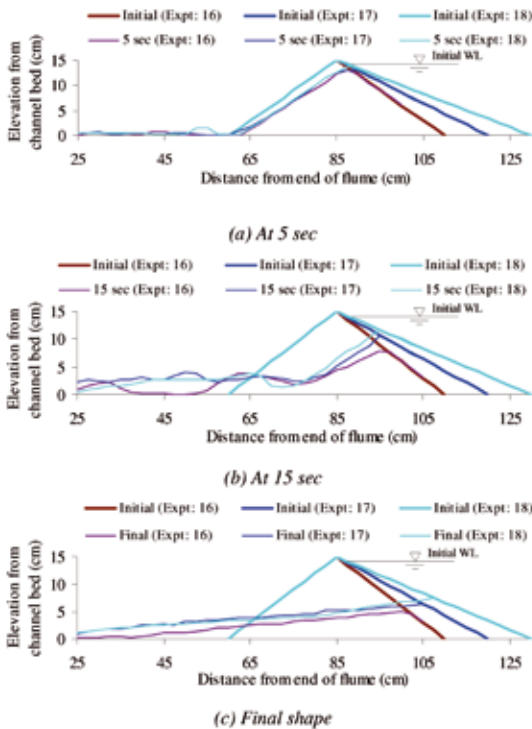*(a) At 5 sec*

(b) At 15 sec

(c) Final shape

Fig. 19 - Dam surface erosion

of outer face of the dam continued to migrate backwards and the height of the eroded dam decreased rapidly in the dam with steeper slope of inner face, so the multiple peak discharges and total volume of water drained from the lake were higher in the dam with steeper slope of inner face.

The multiple peaks in all cases are due to overtopping and erosion of the dam from reflected waves. The magnitude of multiple peaks will be also affected by size (length and breadth) of the reservoir. However, in this study, the size of the reservoir used in all cases is the same.

OUTFLOW HYDROGRAPH DUE TO WAVES OVERTOPPING AND EROSION OF THE MORAINE DAM (PARTIAL CHANNEL WIDTH)

Notch of the width 10 cm and depth 0.8 cm was incised at the center (PCW-C) and side (PCW-S) of the dam crest and downstream face of the dam. At the beginning, overtopping occurred from full channel width. The reflected waves generated in the later stage caused channel breaching. The trapezoidal dam of experiment 23 was stable for waves generated by block A even if overtopping occurred in the beginning. The breaching of channel in the triangular dam was faster compare with trapezoidal dam as shown in Fig. 20. Similarly, breaching of the dam prepared from Mix: 1-6 was faster compare with Mix: 1-7 for both channel breach at center and side (see Fig. 20 and Fig. 21). The temporal change of longitudinal profile of breached channel is shown in Fig. 22, which shows rapid incision of dam prepared by using sediment Mix: 1-6. The section of breached channel at crest was almost vertical (overhanging in some cases) in the dam prepared by using sediment Mix: 1-7. Armouring effect was also negligible compared with dam prepared by using sediment Mix: 1-6. This is the main reason for higher depth of breached channel in the dam prepared by using Mix: 1-7. The shape of breached channel (Front view and top view) for dam prepared by using sediment Mix: 1-7 and Mix 1-6 are shown in Fig. 23.

CONCLUSIONS

About 80% of GLOFs were initiated by displacement waves from ice avalanches that collapsed into the lakes from hanging or calving glaciers and rock avalanches. However, an integrated model to predict waves and outflow hydrograph for such type of failure mode is still lacking. Therefore, an integrate model is essential for the i) prediction of waves generated by ice/rock avalanche, ii) prediction of outflow hydrograph due to waves overtopping and erosion of moraine dam and iii) flow and sediment routing in the erodible river and floodplain for flood risk assessment.

Extensive laboratory experiments were performed to study moraine dam failure due to waves overtopping and erosion. The outflow hydrographs produced by waves overtopping and erosion consist
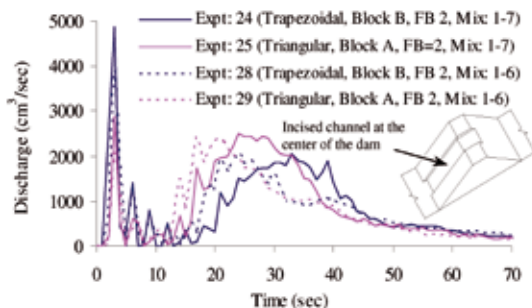
10

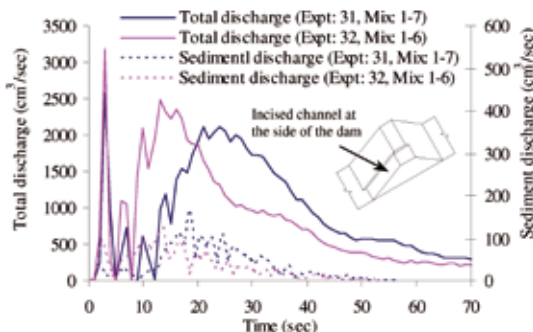*5th International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction and Assessment   Padua, Italy - 14-17 June 2011*

Fig. 20 - Outflow hydrographs due to waves overtopping and erosion of moraine dam (Partial channel width - center)

Fig. 21 - Outflow hydrographs due to waves overtopping and erosion of moraine dam (Partial channel width - side)
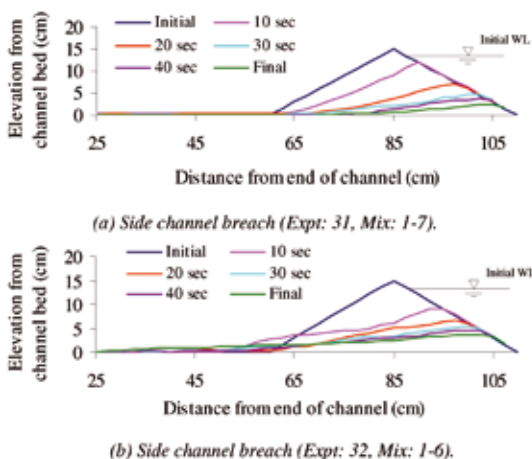

(a) Side channel breach (Expt: 31, Mix: 1-7).

(b) Side channel breach (Expt: 32, Mix: 1-6).

Fig. 22 - Longitudinal profile of breached channel at the flume edge

(a) Side channel breach (Expt: 31, Mix: 1-7).

(b) Side channel breach (Expt: 32, Mix: 1-6).

Fig. 23 - Shape of breached channel

peak discharges due to waves overtopping and erosion of the dam was higher in the dam with steeper slope of inner face. Trapezoidal dam with sufficient freeboard was stable for waves generated by ice/rock avalanche of 1/8 of lake volume. The outflow hydrograph depends on many factors such as dam shape, freeboard, dam material, size of ice/rock avalanche, size of the lake etc, so further study should be directed towards development of numerical model to predict outflow hydrograph resulting from waves overtopping and erosion of moraine dam.

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multiple peaks. For the same falling block and lake water level, the initial peaks produced by overtopping were similar for both triangular and trapezoidal dams. However, magnitude and timing of subsequent peaks were different according to dam shapes and dam materials. The shape of outflow hydrograph also depends on upstream slope of the dam. Multiple
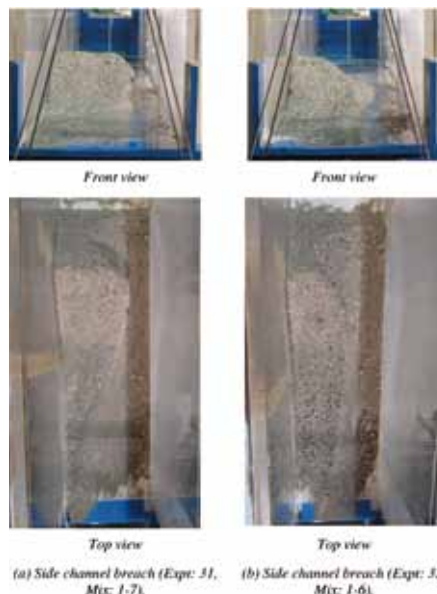
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