Available online at www.sciencedirect.com
ScienceDirect
Journal of Hydrodynamics
2012,24(3):430-441
DOI: 10.1016/S1001-6058(11)60264-3
www.sciencedirect.com/science/journal/10016058

EXPERIMENTAL INVESTIGATION OF THE FAILURE OF CASCADE LANDSLIDE DAMS*

NIU Zhi-pan, XU Wei-lin, LI Nai-wen, XUE Yang
State key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu 610065, China, E-mail: 163niuzhipan@163.com
CHEN Hua-yong
Key Laboratory of Mountain Hazards and Land Surface Processes and Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China

(Received October 27, 2011, Revised April 15, 2012)

Abstract: This paper presents results of model tests for the landslide dam failure of a single dam and cascade dams in a sloping channel. The dams were designed to be regular trapezoid with fine sand. A new measuring method named the labeled line locating method was used to digitalize the captured instantaneous pictures. Under two different inflow discharges, the morphological evolution and the flow patterns during one dam failure and the failure of cascade dams were investigated. The results indicate that when the inflow discharge is large, the deformation pattern of the downstream dam is similar to that of the upstream dam, and both dams are characterized with the overtopping scour throughout the dam failure process. When the inflow discharge is small, the upstream dam is scoured mainly through a sluice slot formed by the longitudinal incision, and the downstream dam is characterized with the overtopping scour. The data set presented in this paper can be used for the validation of numerical models and provide a reference for the flood risk management of cascade landslide dams.

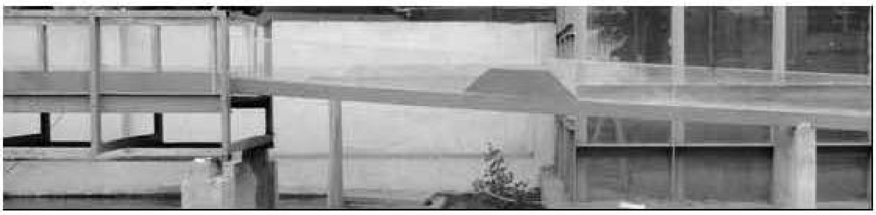
Key words: labeled lines locating method, inflow discharge, cascade landslide dam failure, overtopping, sloping flume

Introduction

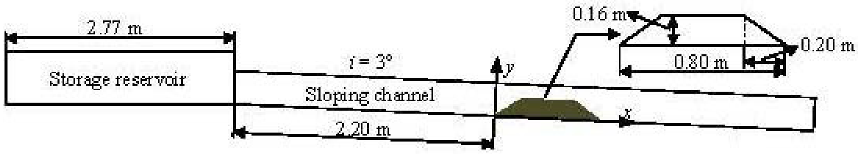
Landslide dams could be formed in a wide range of physiographic settings. The most common initiation mechanisms for dam-forming landslides are excessive rainfalls, snowmelt and earthquakes[1]. The breach formation and the eventual dam failure may be linked to hydraulics, hydrodynamics, hydrology, sediment transport mechanics, and other geotechnical factors. Earthquake, landslide, extreme storm, piping, equipment malfunction, structural damage, foundation failure and sabotage are prominent causes of dam failures[2]. For natural dams, the first three factors are prone to form landslide dams and then cause failure of the dams. Since the structure of a landslide dam is unconsolidated, the blocked water and the continuous incoming flow impounded on the reservoir will endanger the dam security. The downstream life and property can be dangerously threatened as a result of possible extreme dam-break flooding.

Cascading landslide dams caused by geological or climate disasters are well-known occurrences in mountainous regions worldwide. In case of a cascade dam failure, the break of a dam causes a macro flood over successive reservoirs and dams [3]. For example, the peak discharge of Banqiao dam-break flow reached 78 100 m^3/s in 1975 in China, leading to a series of cascade breaks of dams of the downstream reservoirs[4]. Another cascade of events was that of the 1996 Biescas flood, in Spain, which caused the failure of the flood-control dams[5]. The major Wenchuan earthquake of May 12, 2008 in China created numerous landslide lakes located in a cascade distribution layout along the valleys. People lived there are still exposed to the potential hazards even though no real cascade landslide dam failure has occurred since the

* Project supported by the National Basic Research and Development Program of China (973 Program, Grant No. 2007CB714105), the National Natural Science Foundation of China (Grant No. 50909067).
Biography: NIU Zhi-pan (1984-), Male, Ph. D. Candidate
Corresponding author: XU Wei-lin,
E-mail: xuwl@scu.edu.cn

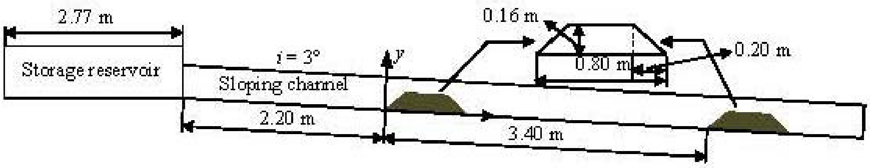


(a) Picture view of single dam laboratory experiment



(b) Sketch map of single dam failure experiment

(c) Picture views of cascade dams laboratory experiment layout



(d) Sketch map of cascade dam failure experiment layout

Fig.1 The Layout of the laboratory experiments

quake. Moreover, the river basin cascade hydropower development is common around the world, so the experimental study in this paper will provide some food of thought for the flood management of the cascade natural or constructed dams.

There were many experimental and computational researches about one single dam break cases[6-8]. For example, Cao et al.[9] carried out a total of 28 runs of large scale flume experiments, with various inflow discharges, dam compositions, dam geometries, and initial breach dimensions. Cao et al.[10] presented a coupled 2-D mathematical modelling study of the landslide dam failure and the flood hydraulics.

But there were few cascade dam failure researches so far. Brambilla et al.[3] developed and validated a model for simulating the dam-break wave propagation in case of cascade arranged multiple reservoirs. Cao et al.[11,12] carried out a series of cascade landslide dam failure experiments with various inflow discharges and dam compositions, and presented an experimental and computational study of the flood flow induced by the cascade landslide dam failure. Huang et al.[13] used a coupled 2-D mathematical model to analyze the Tangjiashan landslide dam breach and the flood. Xue et al.[14] experimentally investigated the dam break flow in cascade reservoirs with steep bottom slopes. However, the experimental investigations of the scouring and discharging characteristics during the cascade landslide dam break process were few.

The dam break discharge is usually accompanied by a large flooding. The boundary conditions of the dams, the flow and the scour rate change very rapidly, which make it difficult to obtain various hydraulic parameters during the dam break process. In this paper, the image technique combined with the labeled line locating method is used to capture the instantaneous water profile and dam's shape. Dam failure experiments for a single dam and cascade dams were carried out under the inflow discharges of 3.9 L/s and 0.8 L/s, respectively. The time evolution of the moving water line, the residual dam profile and the deposition configuration were measured. With one dam and cascade dam break tests, the geomorphic change and the rapid flood wave propagation were studied and compared. The experimental results are promising for the further understanding of the cascade dam failure characteristics.

1. Experimental set-up

1.1 *Flume characteristics and coordinate system setting*

Four kinds of dam failure test cases with incoming flows of 0.8 L/s and 3.9 L/s in the presence of 3^{o} slope channel are considered in this paper. The bed slope is a basic parameter for the collapse of the dam as well as for the development of the flow[15]. Many experimental programs of dam-break simulations were carried out in the horizontal setting[16-18]. The dam body and the river channel usually have some slopes in a real case. Therefore, we analyze the dam break based on an inclined plane.

In view of the large longitudinal scale of natural rivers, if the bed slope of the flume is designed according to some natural river's bed slope, the bed would almost be flat in the limited length of the model flume. It is feasible to study the dam failure of one single dam in a horizontal flume. However, if the dam failure of cascade dams is studied in a horizontal flume, the backwater of the downstream reservoir would submerge most of the upstream dam and would greatly affect the failure process of the upstream. Therefore, the bed of the experimental flume should have a certain slope. With due consideration of the water depth and the backwater length of the downstream reservoir, the bed slope of the experimental flume is designed to be 3^{o}. With its application, the backwater of the downstream reservoir does not reach the upstream dam or just reach the dam toe of the upstream dam, more in consistency with the actual situation.

For the simulation of the cascade dam failure, a longer flume is often required. But some dam breaking experiments carried out in small scale flumes would also provide some valuable results[19-21]. According to the site situations, the flume used in this paper is a small scale flume. The flume and building dimensions are shown in Fig.1. The experimental model consists of three major parts: a circulating water system, a storage reservoir and a sloping channel. The storage reservoir is 0.8 m wide and 2.77 m long. The channel made of transparent organic glass is 0.4 m wide and about 12 m long, with a slope of 3^{o} and a rectangular cross section. The Manning roughness of the flume is equal to 0.01. The coordinate system as shown in Fig.1 has its origin at the point of the intersection between the upper dam heel and the dam central axis. In the cascade dam failure cases, the two dams are located at 2.2 m and 5.6 m, respectively, from the inlet of the flume. In this experimental program, the zero-time point is set to be the moment when the water level raises up to the dam crest.

1.2 *Imaging apparatus and auxiliary locating device*

An HD video camera is used to film the dam body and the water surface profile in detail through the transparent glass at a rate of 25 frames per second. The resolution of each intercepted image is 1 440×1 080 pixels during the filming. When the camera is used to take photos directly, the resolution of individual image is 3 680×2 760 pixels. Two normal cameras were used to take photographs from other angles of the dam to capture the transient flow processes and the dam's morphological evolution.

In order to acquire the time evolution of the three-dimensional dam configuration, a new measuring method named the label line location method is used. That is, a grid of labeled nylon lines is fixed from the bottom to the top of the flume to facilitate the digital imaging observation. Each line, with a diameter of about 0.001 m, is coated with red dots as labels at a 0.05 m interval. Small diameters, high toughness and negligible influence on the flow patterns are the major advantages of these nylon lines. These lines help the locations of the nylon grid lines to be digitized to obtain a dynamic profile of the dam body evolution.

1.3 *Incoming flow and test conditions*

We consider two fixed incoming flow rates from the circulating water system in the experimental program, 0.8 L/s and 3.9 L/s. The upper incoming flow is steady when the water flows into the dammed reservoir, after the overfilling of the dammed reservoir, the water flows atop the dam and the failure process of the dam begins. The overtopping erosion is a primary mechanism of the landslide dam failure and it has attracted extensive concerns in recent years. All dam failure patterns considered in this paper are related with the overtopping, where we are to find the failure characteristics of two cascade dams, which was rarely explored so far but is an urgent issue in engineering.

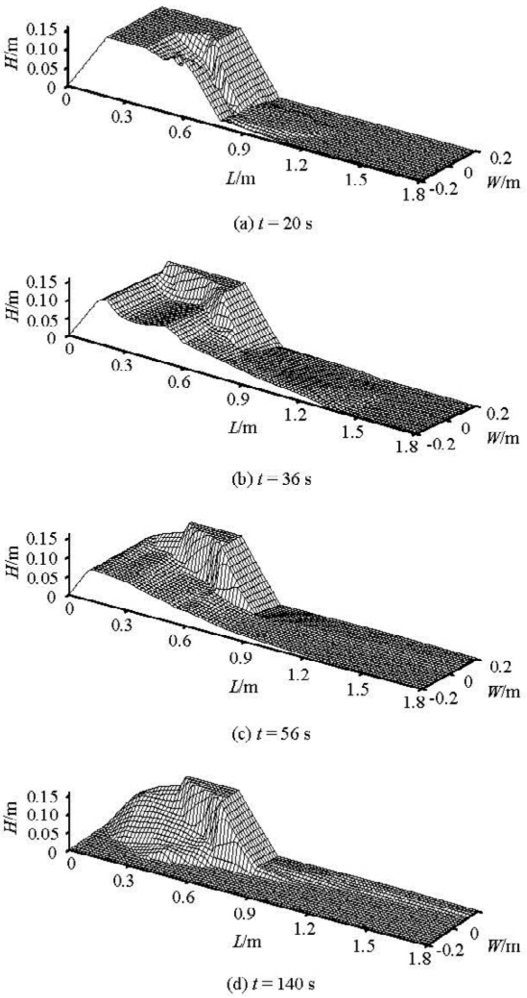


Fig.2 Three-dimensional images of the dam and the deposition configurations at different moments

The dams are designed to a regular trapezoid with fine sand. The dam height is 0.16 m. The dam crest and the dam bottom are 0.4 m and 0.8 m in length, respectively. The particle size of the sand is 0.00037 m, and the permeability is about 0.0004 m/s, and the void fraction of the sand is 0.31. This paper focuses on the difference of the failure characteristics between one dam failure case and the cascade dam failure case, between the upstream dam failure and the downstream dam failure in the cascade dams failure case. A series of 12 test cases were carried out in the experimental program. The four most typical test cases are:

Case 1: One single dam failure with 0.8 L/s inflow discharge.

Case 2: One single dam failure with 3.9 L/s inflow discharge.

Case 3: Two cascade dam failure with 0.8 L/s inflow discharge.

Case 4: Two cascade dam failure with 3.9 L/s inflow discharge.

2. Results and discussions

2.1 *Case 1- one single dam failure with 0.8 L/s inflow discharge*

The incoming flow is 0.8 L/s. At the beginning of the overtopping, there is no obvious erosion. After about 20 s, the scouring and the collapse occur, and then they are extended from the downstream face to the upper reaches progressively. The continued scouring forms a breach. The process of the breach formation is gradual and slow. First, a cutting down of the breach appears, and then the breach is expanded to the dam toe and breaks the right dam abutment. While the left side of the dam body is scoured to a lightest degree, the left side wall of the breach is nearly vertical during the dam failure process. Concurrently, the mud and the sand are deposited at the downstream vicinity of the dam. By the time of 40 s, the scouring is already retreated to the upstream edge of the dam crest. Hereafter, the dam failure process goes on rapidly and severely, around 60 s later the scouring slows down and becomes gentle. Finally, the right side of the dam is washed out and the vestigital of the dam is wider at the upstream and downstream ends but narrower in the middle, which looks like an arc-shaped transition section that connects the two ends. Three-dimensional images based on data are shown in Fig.2. The dam deposition profile and the water profile at different moments are illustrated by data graphs in Fig.3.

This phenomenon is explained as follows. When the water depth of the reservoir reaches the dam crest, the overtopping occurs. Due to the small incoming flow, the outflow is discharged through a part of the downstream dam face, which would induce a partial erosion and form a breach in the downstream dam face. The incoming flow can not be accommodated by

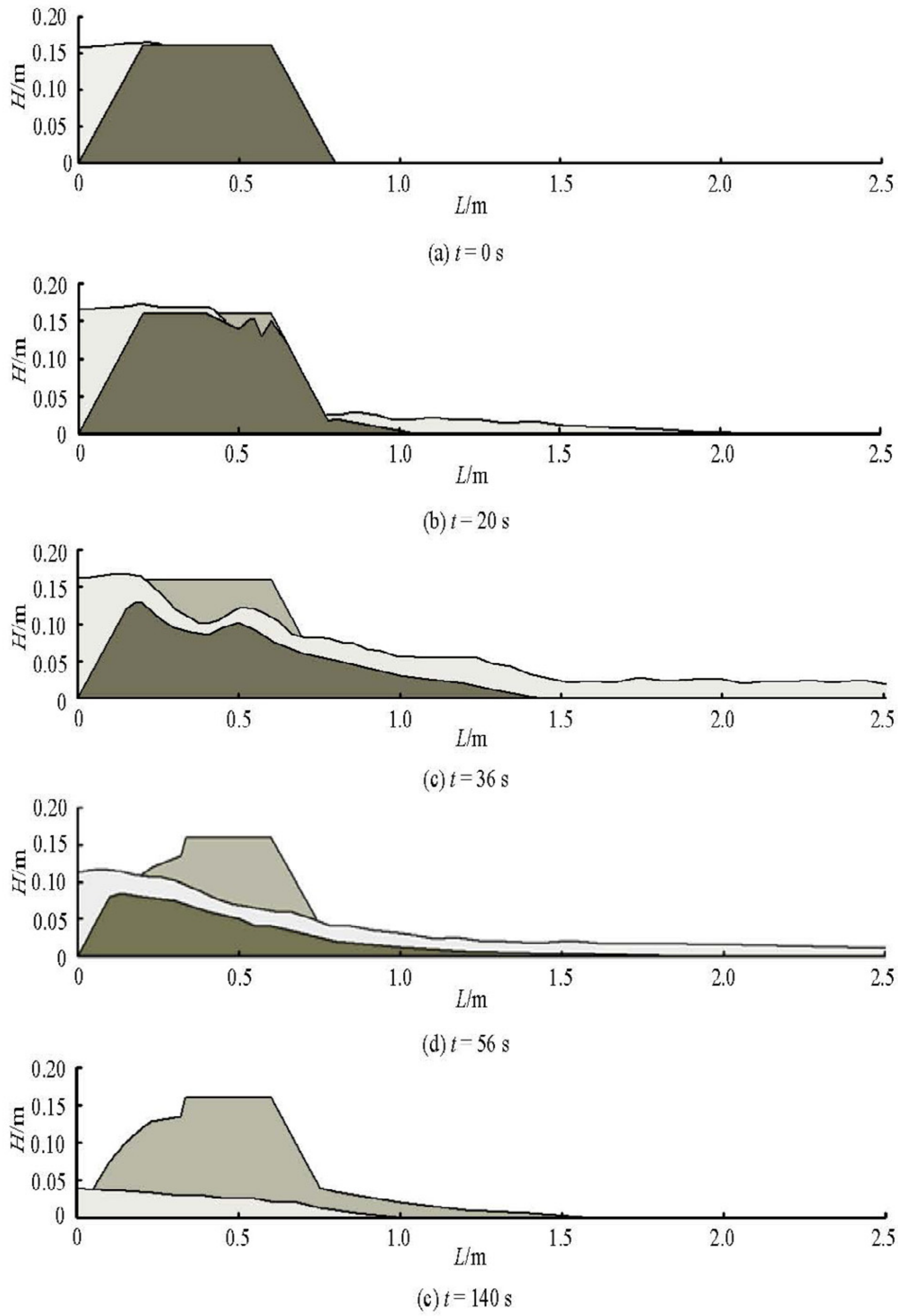


Fig.3 A sequence ... ume, with dimensions in cen...

Fig.4 Dynamic changes in height of the dam and bed deposition along the dam axis at different times

the discharge capacity of the expanding breach, so the dam begins to break from the breach.

2.2 *Case 2-one single dam failure with 3.9 L/s inflow discharge*

The incoming flow is 3.9 L/s in this case, and no breach is formed during the entire scouring process. On each cross section of the dam, one may see the lateral uniform scouring. The dam body configuration and the water surface profile are obtained mainly from digital imaging through the transparent side-wall of the flume. The downstream edge of the dam is slipped after the water flows over the dam, to form a slip surface looking like a curved convexity. The mud and the sand carried by the water are deposited at the downstream vicinity of the dam. The curved convexity and the crest of the deposition move upwards rapidly as the scouring process continues. When the discharging flow encounters the deposition, some water is reflected back while other water flows over the deposition.

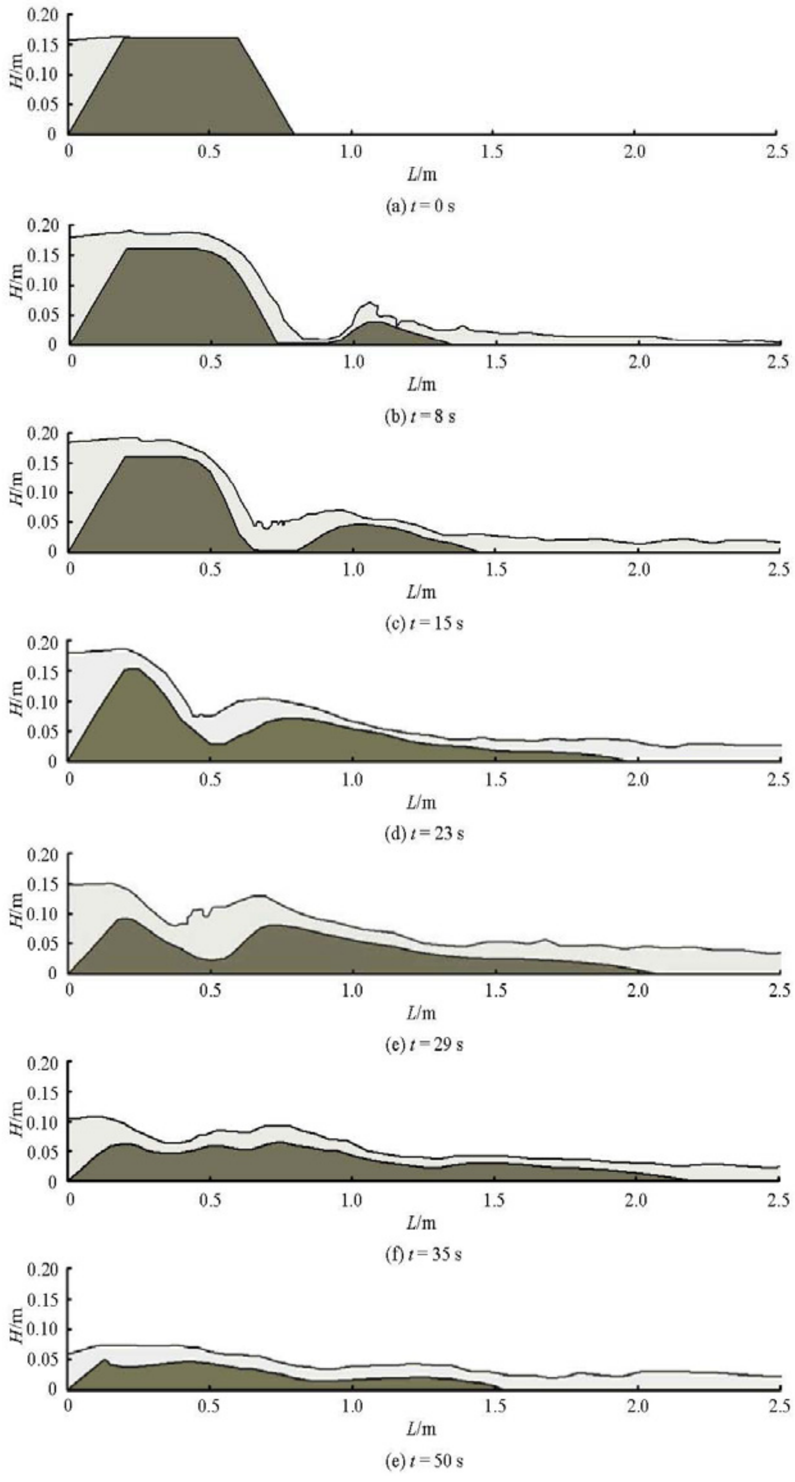


Fig.5 A sequence of data graphs showing the dam deposition configuration profile and water profile in the flume, with dimensions in centimeters

An indentation is formed where the upstream discharging flow meets the water that is reflected back. Simultaneously, a hydraulic jump appears inside the indentation and moves upwards, staying closely together with the indentation. The flow undergoes a deceleration at the hydraulic jump, and the water profile and the bed are discontinuous around the hydraulic jump. Moreover, in the bed configuration, there are two peaks after the hydraulic jump is formed. By the time of 22 s, the erosion is expanded to the upstream edge of the dam crest, and then the scouring process changes faster and more dramatically. The process of the dam-break is accelerated by the strong flow turbulence. The location of the hydraulic jump does not

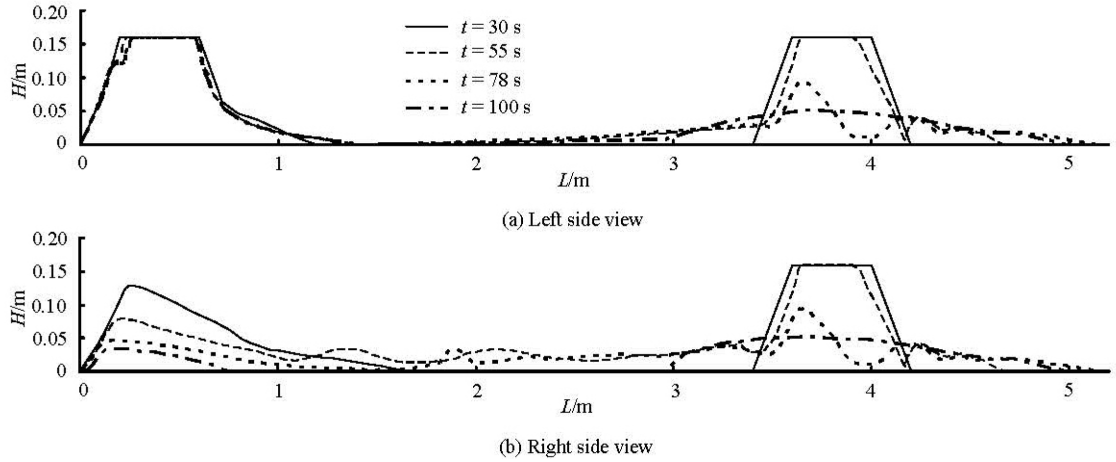


Fig.6 Dynamic changes in height of the dam and bed deposition at different times

change significantly from 22 s to 34 s. After about 35 s, the hydraulic jump disappears and the pace of the scouring slows down, by which the bed deposition configuration and the flow line become smoother and smoother. The dynamic changes of the dam height are shown in Fig.4. The dam deposition profile and the water profile at different times are illustrated by data graphs in Fig.5.

This phenomenon is explained as follows. When the water depth of the reservoir reaches the dam crest, the overtopping occurs. Due to the large incoming flow, the outflow discharges through the entire downstream dam face, which induces the lateral uniform scouring of the dam from the dam's downstream face.

2.3 *Case 3-two cascade dam failure with 0.8 L/s inflow discharge*

Case 3 concerns the dam failure of two cascading dams under 0.8 L/s incoming flow condition. The distance between the two cascading dams is 3.4 m. The dam failure process of the upstream dam is similar to that of one single dam failure experiment under 0.8 L/s incoming flow condition. Erosion is insignificant when the water initially flows over the upstream dam. Breaches are formed and expanded from the lower end of the upstream dam's crest. The sand deposition spreads downward and is accumulated behind the upstream dam. Finally, a large proportion of the left side of the upstream dam is left while the right side is totally washed away. It takes about 45 s for the discharging water to reach the dam crest of the downstream dam via the upstream dam. The failure process of the upstream dam is affected little by the downstream dam during that period. Blocked by the downstream dam and influenced by the bed slope, some discharging water is reflected and moves backwards rapidly as soon as it reaches the downstream dam while other water flows over and begins to scour the dam. The reflected sediment-laden water has no significant effects on the dam-break process of the upstream dam due to the long interval between the two dams. However, the sediment-laden water that flows over the downstream dam would cause a drastic erosion of the dam because the discharging flow from the upstream dam features large discharge and quick flow. Unlike the dam-break process of the upstream dam, the dam failure of the downstream dam does not experience the breach formation process, but starts the lateral uniform scouring of the dam's downstream face. The deposition is accumulated below the downstream dam. An indentation and hydraulic jump in the indentation appears and moves upwards as the scouring process continues. About 100 s later, the downstream dam is nearly swept away. The time evolution of the dam and the bed deposition profile is shown in Fig.6. The dam depositions with water profiles at different times are illustrated by data graphs in Fig.7.

The phenomenon is explained as follows. The upstream dam is scoured partially from a breach in the downstream dam face. The outflow discharge of the upstream dam is accumulated in the reservoir of the downstream dam. The water in the reservoir of the upstream dam discharges quickly into the reservoir of the downstream dam with a high flow rate, so the incoming flow of the downstream dam is large, which induces a lateral uniform scouring of the downstream dam from the dam's downstream face.

2.4 *Case 4-two cascade dam failure with 3.9 L/s inflow discharge*

Case 4 concerns the dam failure of two cascading dams under 3.9 L/s incoming flow condition. The dam failure process of the upstream dam is similar to that of one single dam failure experiment under 3.9 L/s incoming flow condition. After the water flows over the upstream dam, the lower end of the upstream dam's

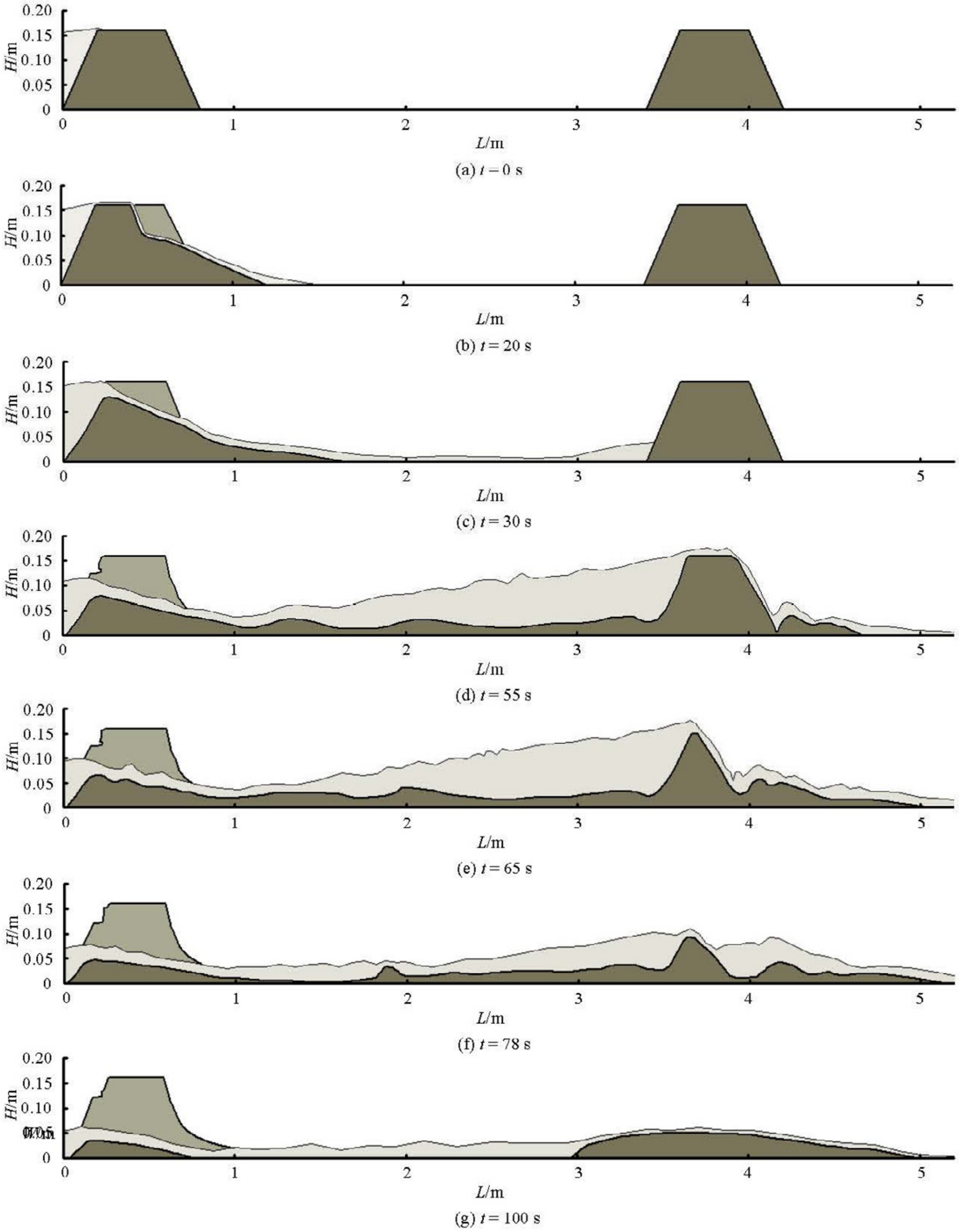


Fig.7 A sequence of data graphs showing the dam deposition configuration profile and water profile in the flume, with dimensions in centimeters. A large proportion of the left side of the upstream dam is left

crest slips downwards and is deposited behind the dam gradually. The slip surface gradually takes a shape of a curved convexity and moves backwards as the dam crest is scoured. The hydraulic jump appears at the deposition area, which makes the streamline and the bed configuration discontinuous. It takes 25 s for the discharging water to reach the dam crest of the downstream dam via the upstream dam. The discharging water flows over the downstream dam, carrying a huge amount of sand. However, there is no deposition below the downstream dam, the sand is washed away directly by the water discharge. The discharge and the flow speed of this stream are much larger than those in any other discharging case in this paper due

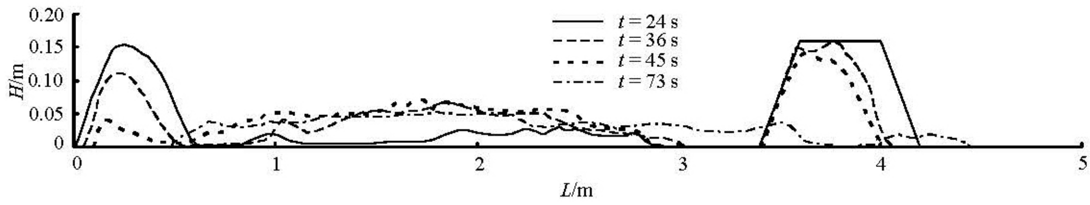


Fig.8 Dynamic changes in height of the dam and bed deposition along the dam axis at different times

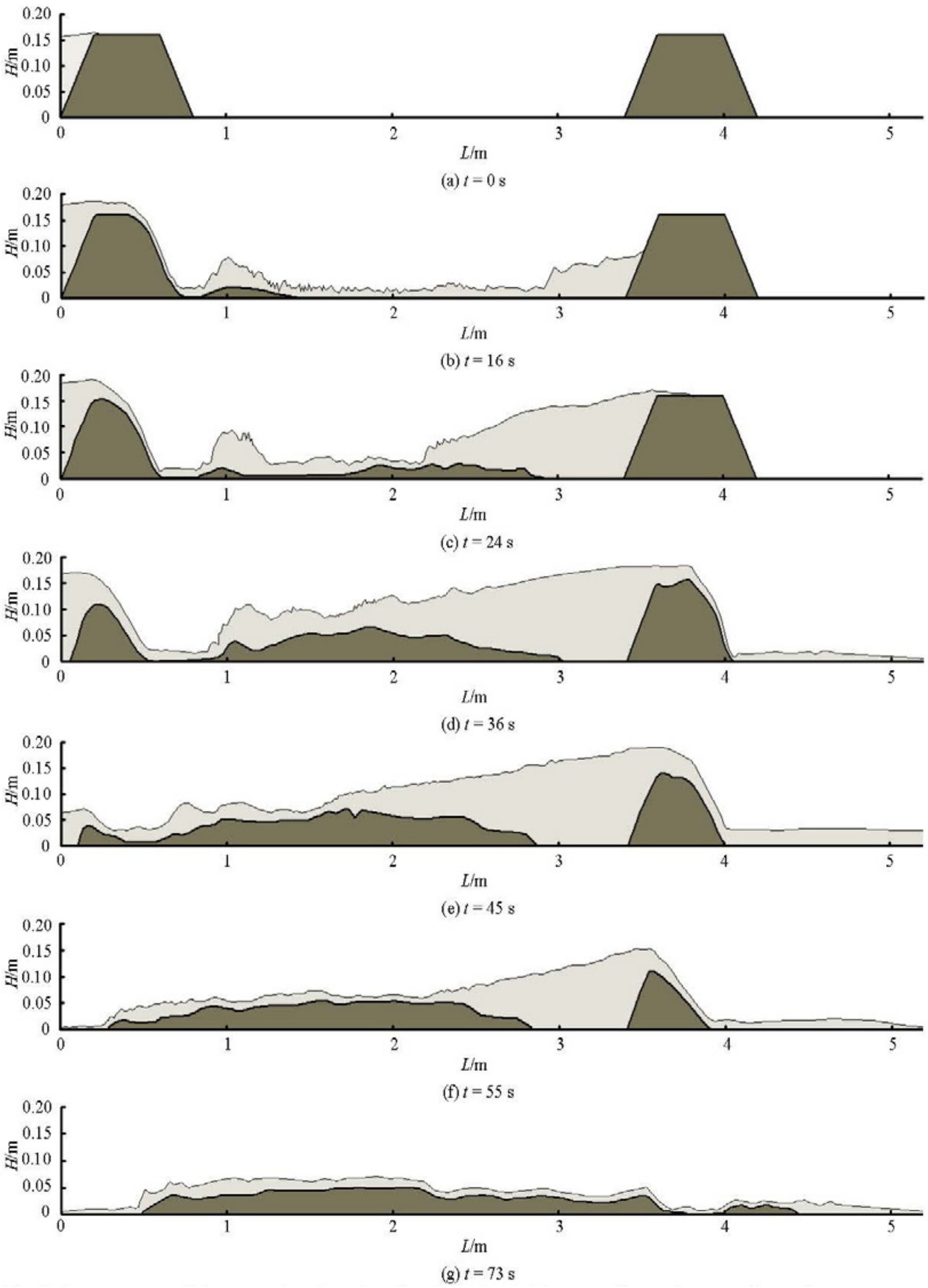


Fig.9 A sequence of data graphs showing the dam deposition configuration profile and water profile in the flume, with dimensions in centimeters

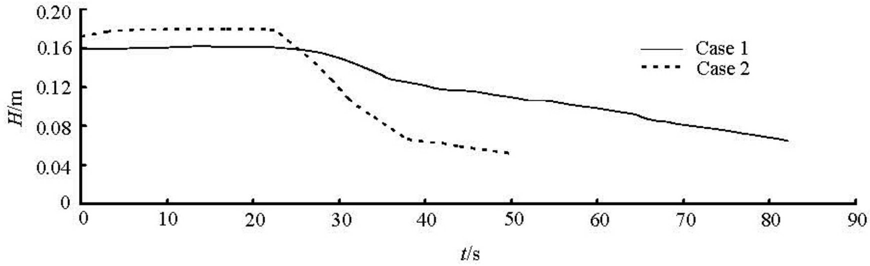


Fig.10 Comparison of water depth before the dam between Case 1 and Case 2

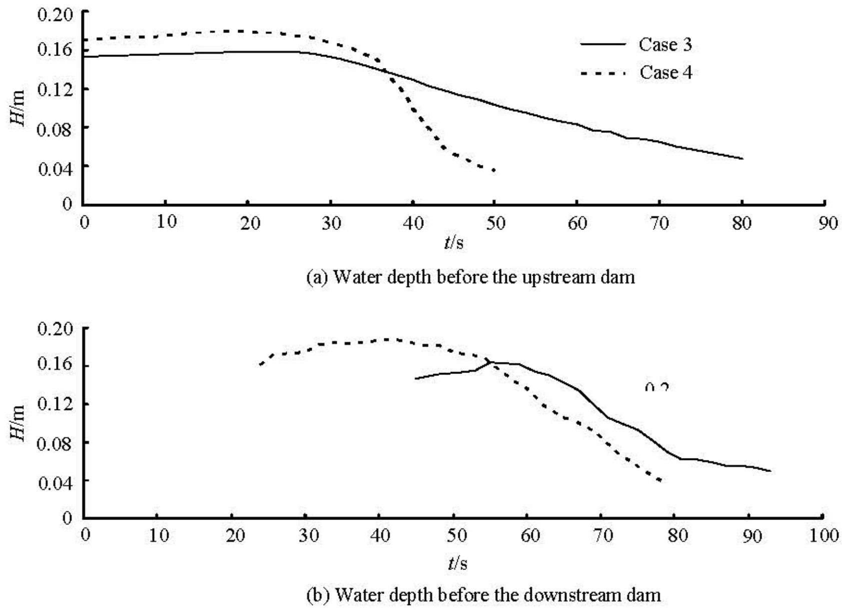


Fig.11 Comparison of water depth before each dam between Case 3 and Case 4

to the larger incoming flow condition, which is the underlying cause of the fierce erosion of the downstream dam. In the scouring of the two dams, there is no breach formation process. The lateral uniform scouring is the main phenomenon during the whole dam failure process. About 70 s later, the two dams are nearly swept away. The time evolution of the dam and the bed deposition profile is shown in Fig.8. The dam depositions with water profiles at different times are illustrated by data graphs in Fig.9.

This phenomenon is explained as follows. The upstream dam is scoured uniformly from the dam's downstream face quickly. The outflow discharge of the upstream dam is large, passing through the entire downstream dam's surface, which induces the lateral uniform scouring of the the downstream dam from the dam's downstream face.

2.5 *Comparison of water depth evolution before the dam crest*

The water depth before the dam is recorded after the water begins to flow atop the dam crest. The comparison of the water depth evolution between Case 1 and Case 2 is shown in Fig.10. During the initial stage of the two test cases, from zero time point to about 25 s, the water depth in both cases changes slowly with time. After about 25 s, the water depth in both cases drops radically. The descending of the water depth in Case 2 is faster than that in Case 1. That suggests that the dam failure process of Case 1 takes longer time than that of Case 2 while the discharge process in Case 2 is more severe than that in Case 1.

The comparison of the water depth evolution between Case 3 and Case 4 is shown in Fig.11. It is indicated in Fig.11(a) that the water depth evolution is similar between one dam failure cases and the upstream dam failure in cascade dam failure cases. That suggests that there is no essential difference between the upstream dam failure in cascade dam failure cases and one dam failure cases. Figure 11(b) shows that the downstream dam in Case 4 begins to fail earlier than that in Case 3. The descending speeds of the water depth in Case 3 and Case 4 are similar.

Descending speed of water level reflects the amount of flow discharge and scouring intensity. Generally, the dam failure process in the cases with a larger incoming flow is faster and severer than those in cases with a smaller incoming flow.

3. Conclusions

The failure of an idealized single and cascade landslide dam in a sloping flume with two different inflow discharge rates is simulated in this paper. The digital image technique and the auxiliary locating device are used to characterize the time evolution of the flow patterns and the dam configurations.

When the interval of the two dams is relatively long, the following conclusions can be drawn:

When the inflow discharge from the upper-river is small ($Q = 0.8\ \mathrm{L/s}$), the upstream dam is characterized with the longitudinal incision, which scours a sluice slot on the upstream dam. The slot is scoured more and more deeply, the flank collapse appears during the failure process. Due to the high velocity of the discharge flow from the upstream dam and the sand deposition in the downstream reservoir, which raises the bed height, the downstream dam is characterized with the overtopping scour throughout the dam failure process. At the end of the dam breaking, the downstream dam is totally washed away, while some vestigial of the upstream dam is left far away from the sluice slot.

When the inflow discharge from the upper-river is large ($Q = 3.9\ \mathrm{L/s}$), the deformation evolution of the downstream dam is similar with that of the upstream dam during the failure process. Both dams are characterized with the overtopping scour throughout the dam failure process. Due to the backwater effect of the downstream dam, a large portion of the sand induced by the upstream dam failure is deposited between the two dams. Simultaneously, a relatively violent hydraulic jump is formed behind the upstream dam. However, there are no hydraulic jump and deposition behind the downstream dam.

Through analyzing the experimental dam failure pattern of each dam under single dam or cascade dam failure cases, we may conclude that when the inflow discharge from the upper-river is small, a breach is formed in the downstream dam face. The dam begins to break from the breach, and the dam failure process is mainly the breach formation and the expansion process. When the inflow discharge from upper-river is large, the dam is scoured uniformly from the dam's downstream face, and each part of the dam's cross section breaks uniformly.

References

[1] COSTA J. E., SCHUSTER R. L. The formation and failure of natural dams[J]. **Geological Society of America Bulletin,** 1988, 100(7): 1054-1068.

[2] U.S. ARMY CORPS OF ENGINEERS. Engineering and design: Hydrologic engineering requirements for reservoirs[R]. Engineer manual 1110-2-1420, Washington D C, 1997.

[3] BRAMBILLA S., FERRARI F. and GATTI D. et al. Cascade dam failure analysis using a lagrangian specification of the flow field[J]. **28th IAHR Confess.** Graz, Austria, 1999.

[4] ZHANG Xin-hua, LONG Wen-fei and XIE He-ping. Numerical simulation of flood inundation processes by 2D shallow water equations[J]. **Frontiers of Architecture and Civil Engineering in China,** 2007, 1(1): 107-113.

[5] BENITO G., GRODEK T. and ENZEL Y. The geomorphic and hydrologic impacts of the catastrophic failure of flood-control dams during the 1996-biescas flood (central pyrenees, spain)[J]. **Zeitschrift für Geomorphologie,** 1998, 42: 417-437.

[6] YAN Jun, CAO Zhi-xian. Experimental study of landslide dam-break flood over erodible bed in open channels[J]. **Journal of Hydrodynamics,** 2009, 21(1): 124-130.

[7] YU Ming-hui, DENG Yin-ling and QIN Lian-chao et al. Numerical simulation of levee breach flows under complex boundary conditions[J]. **Journal of Hydrodynamics,** 2009, 21(5): 633-639.

[8] NIU Zhi-pan, XU Wei-lin and ZHANG Jian-min et al. Experimental investigation of scour dam-break of landslide dam[J]. **Journal of Sichuan University (Engineering Science Edition),** 2009, 41(3): 90-95(in Chinese).

[9] CAO Z., YUE Z. and PENDER G. Landslide dam failure and flood hydraulics. Part I: Experimental investigation[J]. **Natural Hazards,** 2011, 59(2): 1003-1019.

[10] CAO Z., YUE Z. and PENDER G. Landslide dam failure and flood hydraulics. Part II: Coupled mathematical modelling[J]. **Natural Hazards,** 2011, 59(2): 1021-1045.

[11] CAO Z., YUE Z. and PENDER G. Flood hydraulics due to cascade landslide dam failure[J]. **Journal of Flood Risk Management,** 2011, 4(2): 104-114.

[12] CAO Z., YUE Z. and PENDER G. Flood hydraulics due to cascade landslide dam failure[C]. **First IAHR European Congress.** Edinburgh, UK, 2010.

[13] HUANG W., YUE Z. and CAO Z. et al. Coupled 2D mathematical modelling of Tangjiashan landslide dam breach[C]. **Proceedings of 34th IAHR World Congress.** Brisbane, Australia, 2011.

[14] XUE Yang, XU Wei-lin and LUO Shu-jing et al. Experimental study of dam-break flow in cascade reservoirs with steep bottom slope[J]. **Journal of Hydrodynamics,** 2011, 23(4): 491-497.

[15] NSOM B., DEBIANE K. and PIAU J.-M. Bed slope effect on the dam break problem[J]. **Journal of Hydraulic Research**, 2000, 38(6): 459-464.

[16] LAUBER G., HAGER W. H. Experiments to dam-break wave: Horizontal channel[J]. **Journal of Hydraulic Research**, 1998, 36(3): 291-307.

[17] LAJEUNESSE E., MOGNIER J. B. and HOMSY G. M. Granular slumping on a horizontal surface[J]. **Physics of Fluids,** 2005, 17(10): 1-15.

[18] NSOM B. Horizontal viscous dam-break flow: Experiments and theory[J]. **Journal of Hydraulic Engineering, ASCE,** 2002, 128(5): 543-546.

[19] SPINEWINE B., ZECH Y. Small-scale laboratory dam-

break waves on movable beds[J]. **Journal of Hydraulic Research,** 2007, 45(Suppl. 1): 73-86.

[20] LARCHER M., FRACCAROLLO L. and ARMANINI A. et al. Set of measurement data from flume experiments on steady uniform debris flows[J]. **Journal of Hydraulic Research,** 2007, 45(Suppl. 1): 59-71.

[21] BALMFORTH N. J., Von HARDENBERG J. and PROVENZALE A. et al. Dam breaking by wave-induced erosional incision[J]. **Journal of Geophysical Research,** 2008, 113: F01020.