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February 2012

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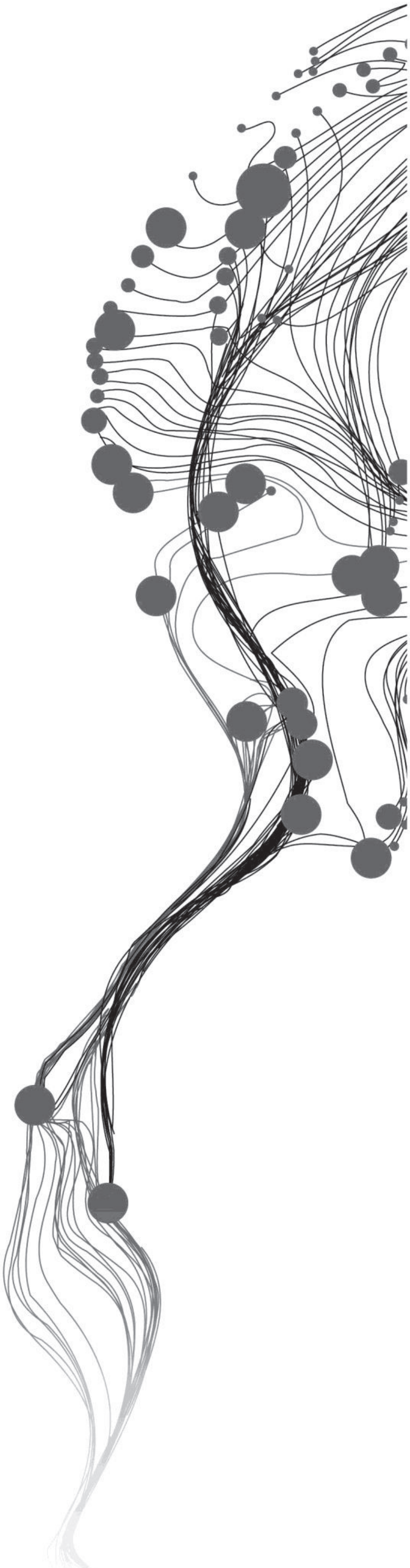

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CHENXIAO TANG
Enschede, The Netherlands, February, 2012

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Disaster Management

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ABSTRACT

Natural damming of rivers by landslides is a very common and potentially dangerous phenomenon all over the world, especially in tectonically active mountains with narrow and steep valleys. Landslide dams always pose severe threats to people and property due to the upstream inundation and possible dam-breach floods to the downstream. The 2008 Wenchuan earthquake (Mw 7.9) occurred in Sichuan, China, highlighted the landslide dam hazard. This devastating earthquake has induced several hundreds of landslide dams. Among them, the most dangerous one is the Tangjiashan landslide dam that had impounded the largest barrier lake with an estimated volume of 3.1×10^8 m^3. The Tangjiashan landslide dam posed a serious threat to 2.5 million people in five towns and the second largest city (the Mianyang city) at downstream. The dam was formed in the monsoon season and has the probability to breach, causing flood to the downstream. Thus, the Chinese government carried out the emergent mitigation measures to excavate the spillway to drain the lake in the controllable way.

This study aims to simulate the Tangjiashan dam break floods of different scenarios, staring from reconstructing the 2008 event up to assuming the dam will total collapse (the most catastrophic scenario). To achieve this goal, the BREACH model and SOBEK 1D-2D model are integrated. The BREACH model is a physically base mathematical model, which can simulate the dam breach process, ultimate breach size and shape, the flood hydrograph at the dam site. Therefore, it was used to get the hydrograph of dam breach regarding to the different inflow to lake (in different scenarios) and also to contribute a better understanding of the dam breach process and mechanism. The output hydrograph was then used as the input to the SOBEK 1D-2D model to calculate the temporal and spatial variation in the hydraulic parameters. The BREACH model was calibrated by the observations of the 2008 event, showing the model results agree well with the observations. The sensitivity analysis of the BREACH input parameters indicate that the inflow to lake, the breach channel slope (gradient), the dam composition material unit weight and porosity are the most sensitive ones to the dam breach. Five scenarios were simulated: 2 years return period flood inflow to the lake; 5 years return period flood inflow to the lake; 20 years return period flood inflow to the lake; dam break naturally assuming there is no spillway (considering the recorded inflow in June 2008 to lake); and the catastrophic scenario assuming the dam collapse totally. The SOBEK 1D-2D simulation results demonstrate that the spillway played a significant role in reducing the flood discharge and postpone the peak arrival time. The other scenarios will all cause the flooding to the downstream with different degree. The most catastrophic one will cause the peak discharge in the Mianyang city above 30, 000 m3/s, which is much higher that the city flood protection of 12, 000 m3/s. The flood will inundate all the five towns and the Mianyang city. The peak discharges of the other scenarios are lower the catastrophic scenario, but they are still beyond the drainage capacity of the Mianyang city. Thus, if the government did not take any measured to break the dam artificially, the dam breach naturally will cause flooding of the Mianyang city.

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1. INTRODUCTION

1.1. Background

Landslides are a major type of geo-hazards, which frequently pose a serious threat to people and property. Natural damming of rivers by landslides is one of the most extreme landslide threats which may occur as a result of a major triggering event (e.g. earthquakes or extreme rainfall) in mountainous areas. Landslide dams are dangerous both on the site where they occur as well as upstream and downstream. Area upstream may be flooded as the impounded lake water level rises and areas downstream may experience severe flooding due to dam breach and rapid release of the impounded water. For example on June 1, 1786, a strong earthquake caused a landslide dam blocking the Dadu River in China (Dai et al., 2005). After 10 days, the dam failed, resulting in a catastrophic outburst flood, causing 1 million fatalities. In 2009, Typhoon Morakot induced the Hsiaolin landslide dam along the Cishan River, which collapsed after about one hour, washing away part of the Hsiaolin village (Li et al., 2011). Recent predictions of climate change suggest that many parts of the world will experience a higher frequency of extreme rainfall events, and will consequently raise the danger of landslide dams in future (Awal, 2008).

Landslide dams are very common and potentially dangerous phenomena all over the world, especially in tectonically active mountains with narrow and steep valleys (J E. Costa, 1988). Several inventories have been compiled to document landslide damming events in different regions, e.g. Japan (Swanson, 1986), Canada (Clague and Evans, 1994) , China (Chai et al., 1995)the northern Apennines, Italy (Casagli and Ermini, 1999) and New Zealand (Korup, 2004). The devastating 2008 Wenchuan earthquake (Mw 7.9), China, highlighted the importance of mitigating the hazards from landslide dams. The earthquake triggered around 60,000 landslides (Dai et al., 2011; Gorum et al., 2011), out of which more than 800 formed landslide dams (Fan et al., 2011). In order to reduce the potential for further catastrophic dam breaks, the Chinese army created artificial spillways in 32 dams using explosives and heavy machinery (Xu et al., 2009). In this study, the dam-break flood simulation of the Tangjiashan landslide dam will be focused on, which had impounded the largest barrier lake with an estimated volume of 3 × 108 m^3, about85 km upstream of Mianyang City, i.e. the second largest city in Sichuan with a population of 1.2 million. Chinese authorities had to evacuate parts of the city until the Tangjiashan landslide dam was artificially breached, and the lake was drained(Liu et al., 2009b).

1.2. Problem Statement

The previous studies on the Tangjiashan landslide dam are mainly a description of the emergent mitigation and estimation of the dam-break flood by the empirical method (Cui et al., 2010; Kuang et al., 2009; Liu et al., 2009a) and predicting the outburst flood hydrograph by the physics-based models (Dai et al., 2009; Wang et al., 2008). However, there is little work on 1D or 2D hydraulic modelling of the dam break flood with combination of physics-based models, considering different scenarios and the validation of the models.

To fill this gap, the Breach model will be applied to understand the dam breach process and the sensitivity of the input parameters then use the results to set up the 1D and 2D numerical models through SOBEK software, extracting the hydraulic parameters and the affected areas of different assumed scenarios. The breach model will be validated by the real spillway drainage situation. The results will contribute to a better understanding of the dam break mechanism and to recommend appropriate emergent mitigation strategies for similar future cases.

1.3. Research Objectives

The main objective is to model the possible scenarios of dam-break for the Tangjiashan landslide and the flood affected areas up to the city of Mianyang assuming that the dam would have broken catastrophically.

Sub-objectives

1. Determine different scenarios for the dam-break of the Tangjiashan landslide dam.

   Research questions:
   - What are the possible mechanisms and how much time will the dam break process take?
   - What would be likely failure scenarios?
   - How many scenarios should be simulated in the study area?
   - What is the worst case scenario, and how likely would that have been?

2. 1-D/2-D simulation of the different scenarios of dam-break flood in the whole section of the Tongkou River up to Mianyang city.

   Research questions:
   - Which model is the most suitable for the dam-break flood simulation?
   - What are the input parameters for the model, and how can they be derived now (given that the dam is no longer there)?
   - How to implement the simulation outputs to do the analysis?
   - Is the available digital elevation data sufficient for the 2-D modelling in the downstream section?
   - How can the digital elevation model be improved by adding heights of embankments and other major obstructions?

3. Use of the emergency spillway discharge record to calibrate and validate the model

   Research question:
   - Do the models present the spillway flood scenario well? If not, what are the reasons?

2. LITERATURE REVIEW

Hazards and risk related with landslide dams were recognized since a long time ago and have been documented in many historic accounts of catastrophic floods from natural dam failures. The 27 largest floods of the Quaternary Period with discharges greater than 100,000 m^3/s were listed by O'Connor and Costa (2004), most of which resulted from breach of dams formed by glaciers or landslides. The largest flood in recorded history was caused by the failure of the earthquake-induced Raikhot landslide dam in 1841 on the Indus River in Pakistan, which has an estimated peak discharge of about 540, 000 m^3/s (Mason, 1929; Shroder JR et al., 1998). The largest landslide dam on Earth is the 550 m high Usoi landslide dam in Tajikistan induced by a large earthquake in 1911 (Gesiev, 1984), Harp and Crone (2006) and Schneider (2009) describe the largest landslide, Hattian slide, triggered by the Kashmir earthquake (M 7.6) in Pakistan, which formed a natural dam impounding two lakes in the Karli river. Duman (2009) studied the largest landslide dam in Turkey and analyzed the characteristics and geomorphometric parameters of the dam and dammed lake. Some other representative cases were studied by Reneau and Dethier (1996), Hewitt (1998), Shroder Jr (1998), Tabata (2002), Cruden and Miller (2002), Hancox et al. (2005), Dunning et al. (2006), and Gupta and Sah (2008). Researches on landslide dams have been reviewed by Korup (2002).

Several large landslide dams and catastrophic dam-break floods have also been documented in China. On June 1, 1786, a M7.8 earthquake in the Kangding-Luding area triggered a large (more than10^6 m^3) landslide dam that blocked the Dadu River. Ten days later, a sudden dam breach caused catastrophic downstream flooding and 100,000 fatalities (Dai et al., 2005). The Diexi earthquake triggered nine large landslide dams on the Min River, three of which (Dahaizi, Xiaohaizi, and Deixi) were up to 160 m high. The three resulting lakes coalesced seven weeks later, eventually emptying in a dam-break flood that affected a downstream distance of 250 km, killing more than 2,500 people (Chai et al., 2000). Of all the recorded cases, the largest dam was formed by the Yigong landslide (about 3×10^8 m^3) on April 9, 2000, along the Zhamu Creek in Tibet. This dam breached two month later on June 10 and caused a flash flood with a peak discharge of about 120,000 m^3/s, resulting in 30 fatalities and more than 100 people missing (Shang et al., 2003).

From the emergency mitigation planning and risk management point of view, the key issues related to the landslide dam hazard assessment are: (1) assessing the dam stability; (2) evaluating the dam breach formation process and mechanism; and (3) predicting the dam-break flood impacts, including the probable peak discharge, the flood propagation, routing, depth, velocity, duration and the spreading area.

With regard to the first issue, it has been a central research theme a long time, but there remain a lot of problems to be solved until. Recently, a geomorphic approach was widely used to correlate the dam and the impounded lake geomorphic features with the landslide dam's stability, e.g. the blockage index and the geomorphological dimensionless index (Casagli and Ermini, 1999; Ermini and Casagli, 2003), another approach is the so-called Discriminant approach (Dong, 2009). However, this method is constrained by ignoring the dam structure and material geotechnical properties (Casagli et al., 2003; Dunning et al., 2006).

Concerning the second issue, Walder and O'Connor (1997) stated that the mechanisms of dam breach formation were still poorly understood, since it involves a variety of processes, including sediment entrainment from the breach floor, the gravitational collapse of breach sides and dam downstream face, and knick point retreat. For the Tangjiashan landslide dam, the detailed field survey and laboratory tested geotechnical parameters allow us to use a physics-based numerical model to simulate the process of dam breach development, predicting the dam-breach flood hydrograph at the dam, the failure time and the ultimate breach geometry. This study applied the widely-used BREACH model (Cencetti et al., 2006; Fread, 1988) to the Tangjiashan dam and used the hydrograph obtained from the real spillway scenario to calibrate the model. Besides, the input parameter sensitivity analysis contributes to a better understanding of the breach mechanism and the recognition of the governing factors.

Regarding to issue three, the peak discharge can be predicted by both the empirical and the numerical simulation methods. The empirical method relies on regression relations between the peak discharge and other parameters, such as the impounded lake volume, depth, and area etc (Evans, 1986; J E. Costa, 1988). The numerical method includes both the physics-based model, e.g. the Breach Model (Fread, 1988; Walder and O'Connor, 1997) and the GIS-based hydraulic model (Li et al., 2011), which can also predict other factors (flood routing, depth, velocity, duration and the spreading area). The empirical model is simple to apply, comparing the numerical models, which require detailed parameters that are hard to obtain in some cases. In this study, the commercial software SOBEK will be used to run the 1D and 2D flood models of the Tangjiashan landslide dam.

3. STUDY AREA

3.1. Overview

The devastating 2008 (Mw 7.9) Wenchuan, China, earthquake occurred on the NE-trending Longmen Shan thrust fault zone (LTFZ) at a focal depth of 14-19 km. The LTFZ separates the Sichuan basin from

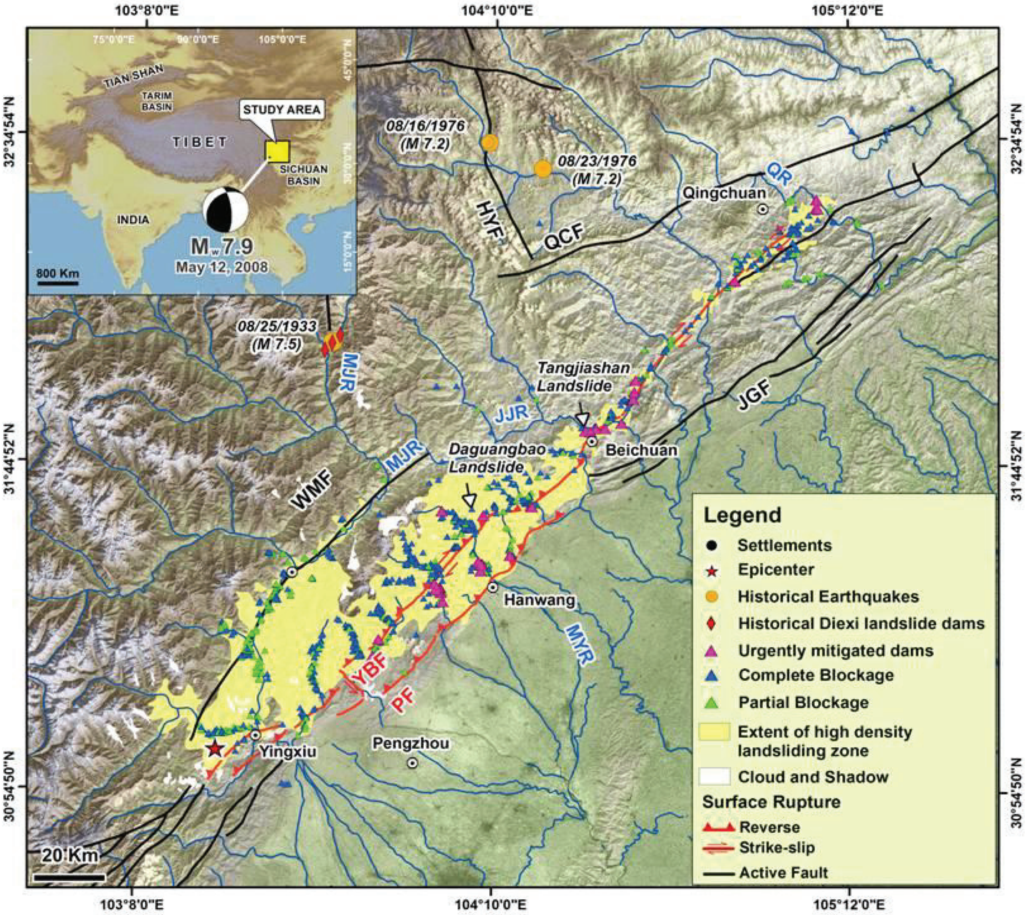

Fig.1 Distribution of landslides and landslide dams induced by the Wenchuan earthquake. The high landslide density zone is defined by a landslide area density >0.1 km–2; also shown are epicenters of historical earthquakes (USGS, 2008) and historical Diexi landslide dams. White polygons are unmapped due to the presence of clouds and shadows in post-earthquake imagery. WMF: Wenchuan-Maowen fault; YBF: Yingxiu-Beichuan fault; PF: Pengguan fault; JGF: Jiangyou-Guanxian fault; QCF: Qingchuan fault; HYF: Huya fault; MJF: Minjiang fault (after Xu X et al., 2009). MJR: Minjiang River; MYR: Mianyuan River; JJR: Jianjiang River (also named as Tongkou river); QR: Qingjiang River.

the steep and heavily dissected eastern margin of the Tibetan Plateau, with elevations ranging from mre than 5,000 m down to 500 m in the Sichuan Basin over a distance of about 50 km. The LTFZ consists of three sub-parallel faults, i.e. the Wenchuan-Maowen (WMF), Yingxiu-Beichuan (YBF) and Pengguan faults (PF) (Fig. 1). The rupture initiated near Yingxiu city (31.06° N, 103.33° E), and propagated unilaterally towards the northeast, generating a 240-km long surface rupture along the YBF, and a 72-km long rupture along the PF (Shen et al., 2009; Xu et al., 2009). Tributaries of the Yangtze River drain the Longmen Shan as deeply incised bedrock rivers flanked by hillslopes commonly more than 30° steep within the LTFZ.

The earthquake triggered more than 60,000 landslides (Dai et al.; Gorum et al., 2011), out of which more than 800 formed landslide dams (Fan et al., 2011). 68, 000 fatalities were estimated to be caused by the earthquake, of which one third were caused by co-seismic landslides. Fig.1 shows the distribution of landslides and landslide dams. The Tangjiashan landslide dam had impounded the largest earthquake lake with an estimated volume of 3 × 10^8 m^3. The dam is located at 31.84° N, 104.43° E, about 3.2 km upstream of the Beichuan town and about85 km upstream of Mianyang City, i.e. the second largest in Sichuan (Fig.2). The dam blocked the Tongkou river with an upstream catchment area of 3, 550 km2. There are 5 towns located downstream of the Tangjiashan dam (Fig.2). Once the dam break, it will affect about 2.5 million people in these towns and the Mianyang city.

The water supply of the Tongkou River is mainly from rainfall. According to the record of the Beichuan hydraulic station, the average discharge of the Tongkou river is $81m^3/s$, and it increases to $167m^3/s$ during the masoon season from May to October. The discharge of floods with different frequency (return period) of the Tongkou river is shown in Fig.3 and Table 1. The inflow of the barrier lake determines the speed of its water level rise, and is crucial for estimating the time that the dam will be overtopped.

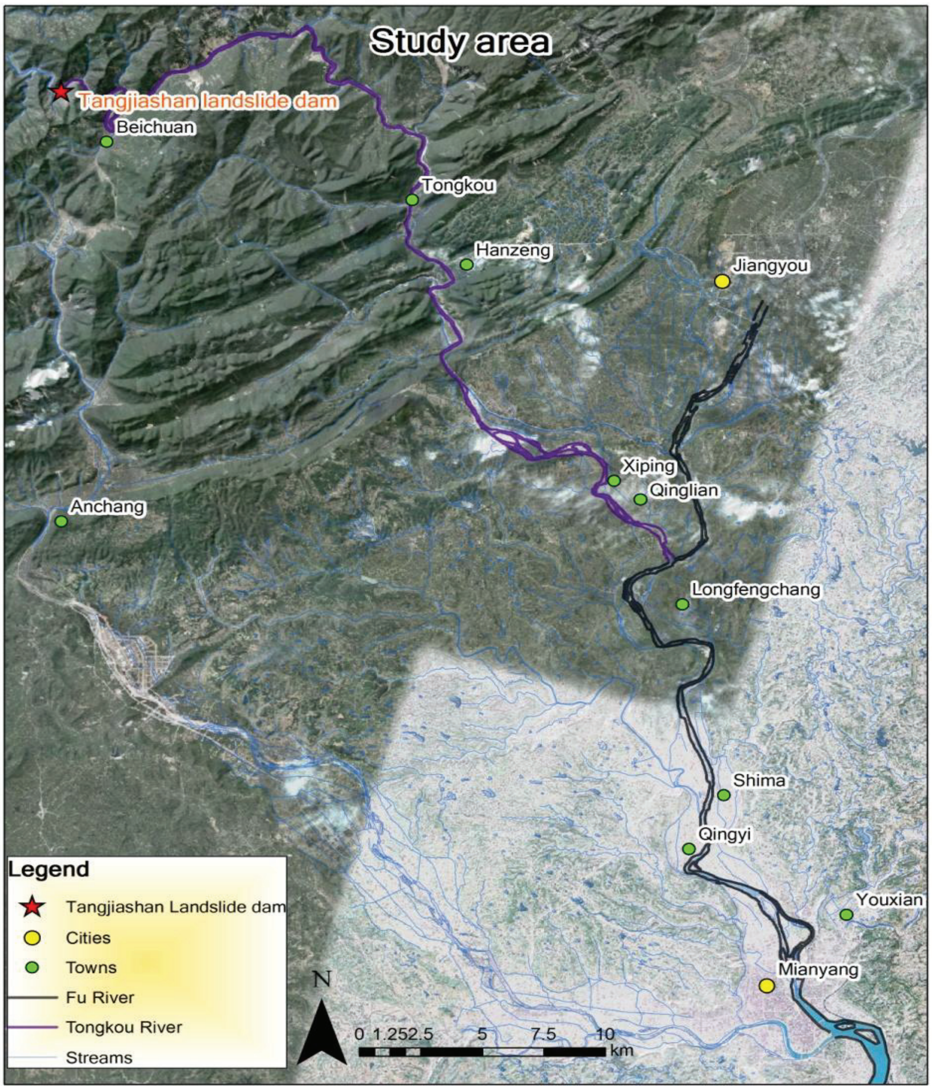

Fig.2 Location of the study area

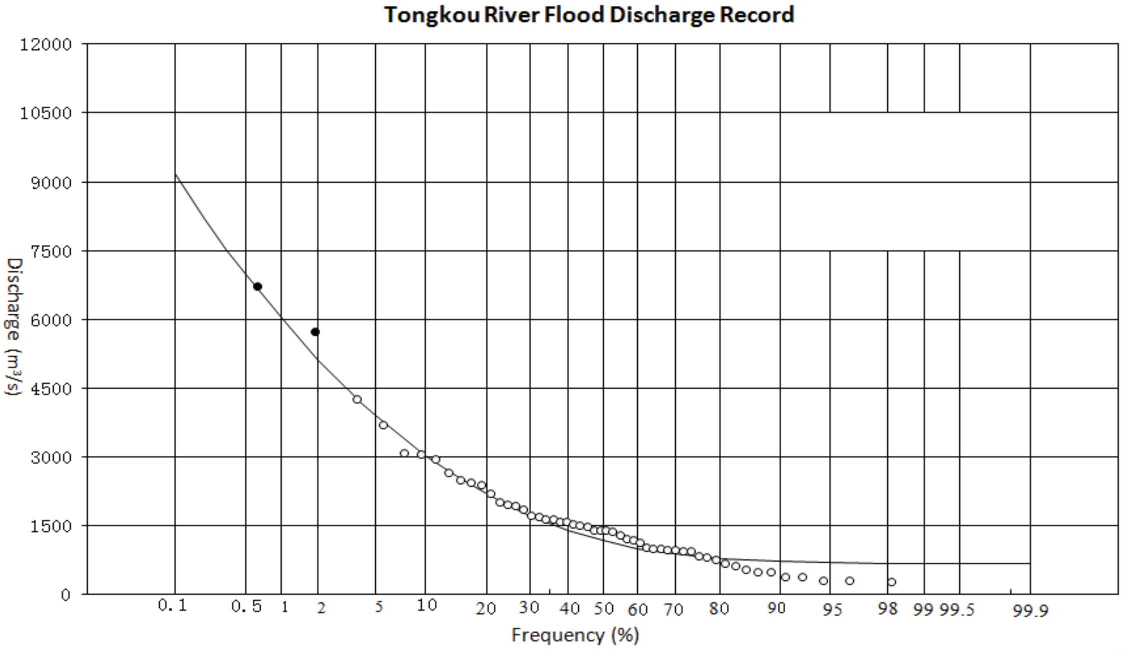

Fig.3 The flood discharge record of the Tongkou River (Source: Science Research Institute , CHIDI , CHECC)

Tangjiashan landslide dam and barrier lake

The Tangjiashan landslide dam is formed by a rockslide in interbedded soft rock and hard rock strata, which were formed from grayish black siltstone of the Qingping Formation of Cambrian age (Fig.4 and Fig.5). The landslide vertically dropped down around 540 m, forming a clear scarp (Fig.6). It also ran up on the opposite side of the valley. Its height varied from 82 m to 124 m, and its volume was estimated to be 2.04×10^7 m^3 based on the field estimation(Xu et al., 2009). The dam crest extended approximately 600 m across the valley and 800 m along the valley (Fig.4 and Fig.5). A DEM with 5-m spatial resolution from a contour map with 2 m intervals is generated, the dam volume was able to be calculated more precisely by comparing it with the pre-earthquake 25-m DEM (Fig.7). The landslide volume is calculated to be about 1.7×10^7 m^3, a bit lower than the field estimation.

The dam basically has a three-layered structure (Fig.5). The top layer is composed of fragmented rocks with soil; the middle layer contains mainly boulders and blocks while the bottom layer consists of very weathered strata which retain its original structure. The average size of the boulders is 2 m to 3 m with a maximum of 5 m. The blocks vary from 0.2 m to 1.5 m. The top layer and middle layers comprise approximately 10% boulders, 60% blocks, 20% fragmented rocks and 10% soil. Consequently, the bottom layer is relatively more consolidated and has a lower permeability than the middle and top layers.

The maximum capacity of the Tangjiashan barrier lake is estimated to be 3×10^8 m^3. From May 12 to June 7, 2008, the Tangjiashan landslide dam had impounded 2.47×10^8 m^3 of water. Except the inflow discharge as indicated in Fig.3, the relationship between lake volume and lake water level is also important to predict the dam overtopping time and to make the mitigation plan, which was analyzed by using the pre-earthquake DEM and ILWIS volume calculation function. Fig.8 indicates the lake covered area and the water level variation. The correlation between the lake volume and lake water level is shown in Fig.9.

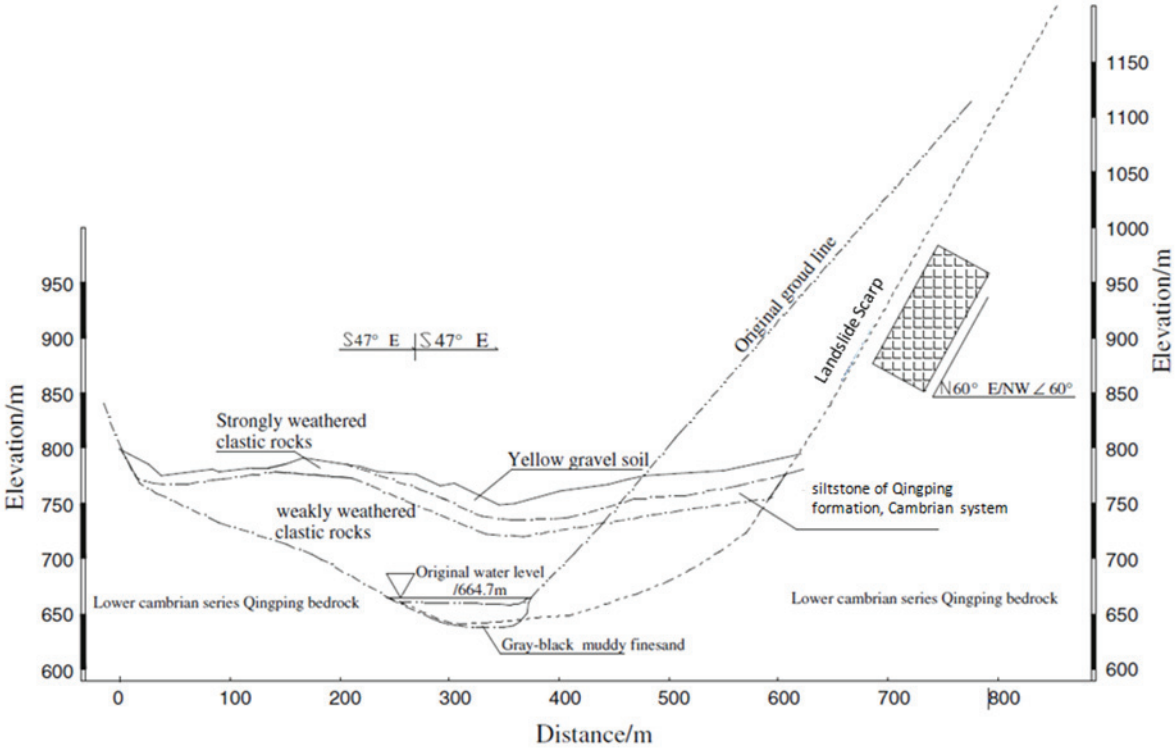

Fig.4 Geological profile of the Tangjiashan landslide dam(Cui, Dang et al. 2010)

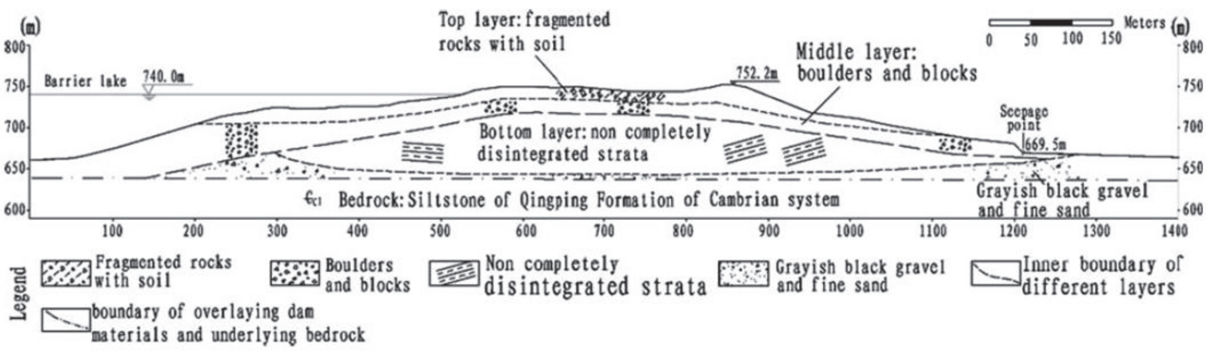

Fig.5 Longitudinal section of the dam body. Left is upstream. (Xu, Fan et al. 2009)

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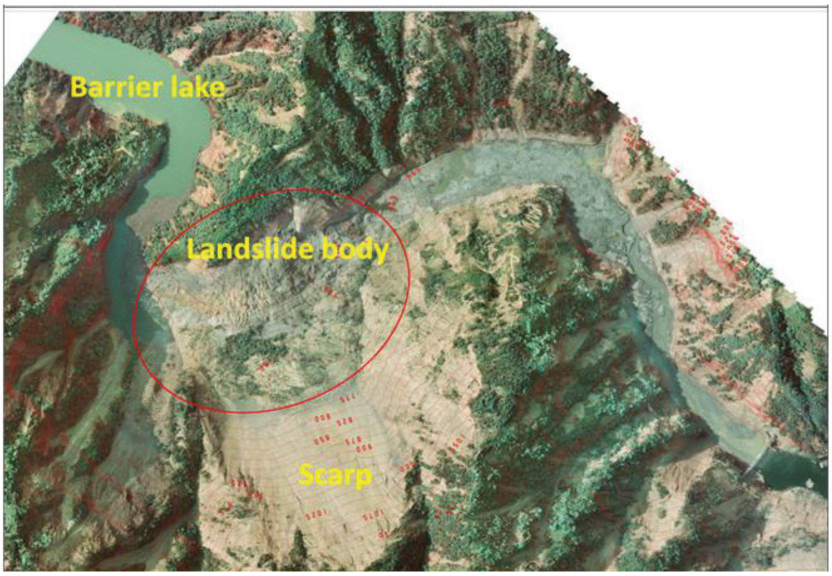

Fig.6 An aerial photo of the Tangjiashan Dam

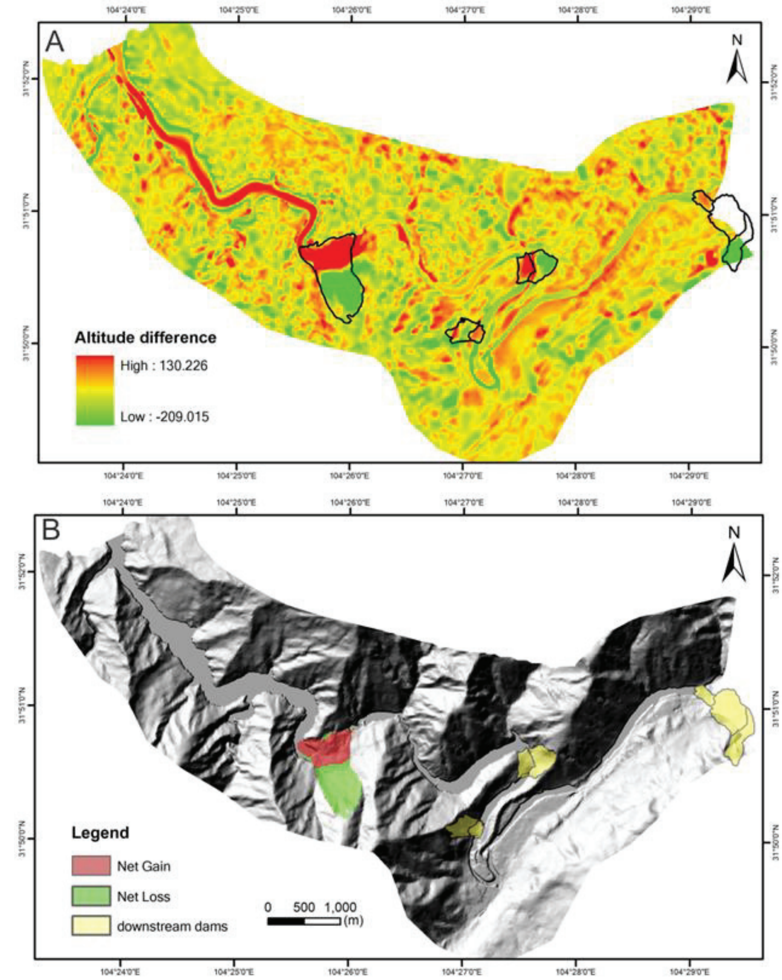

Fig.7 Elevation difference of the pre-and post-earthquake DEMs; B. the volume calculations of the Tangjiashan landslide dam

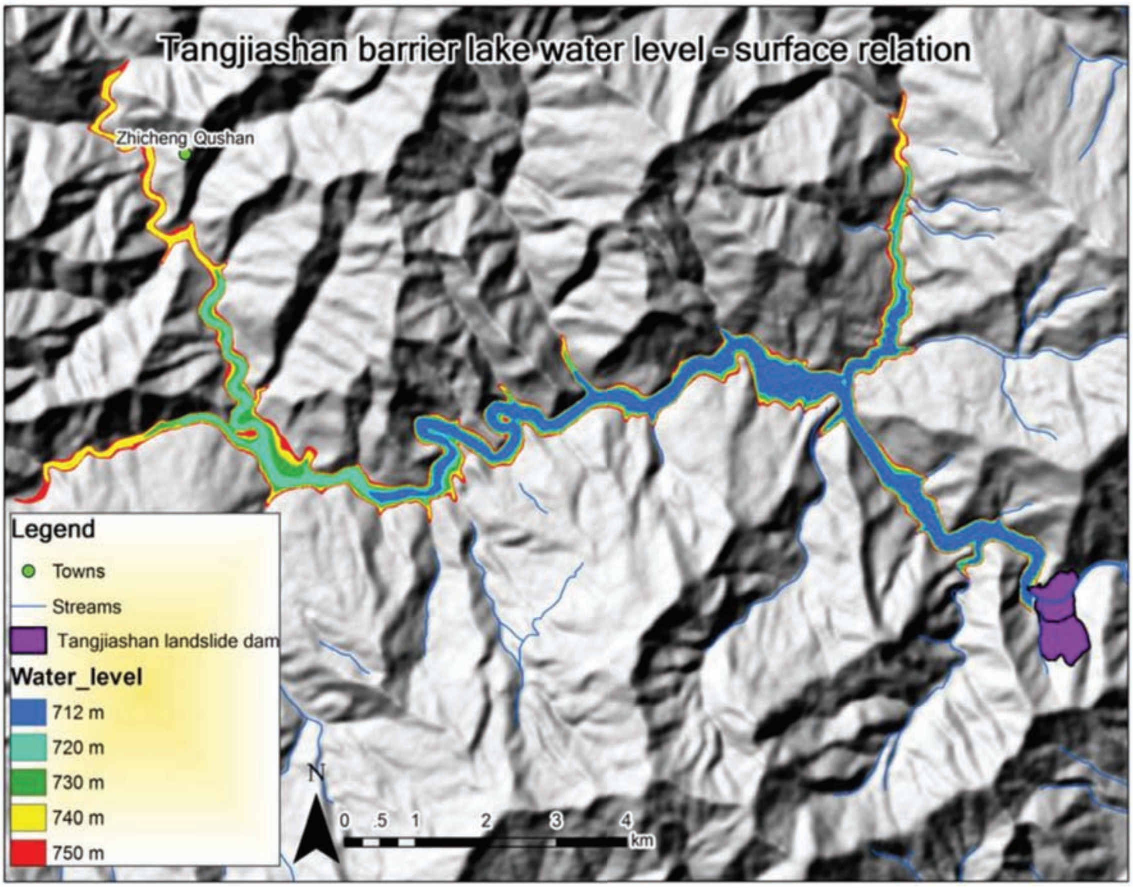

Fig.8 The Tangjiashan barrier lake covered area and lake water lever variation

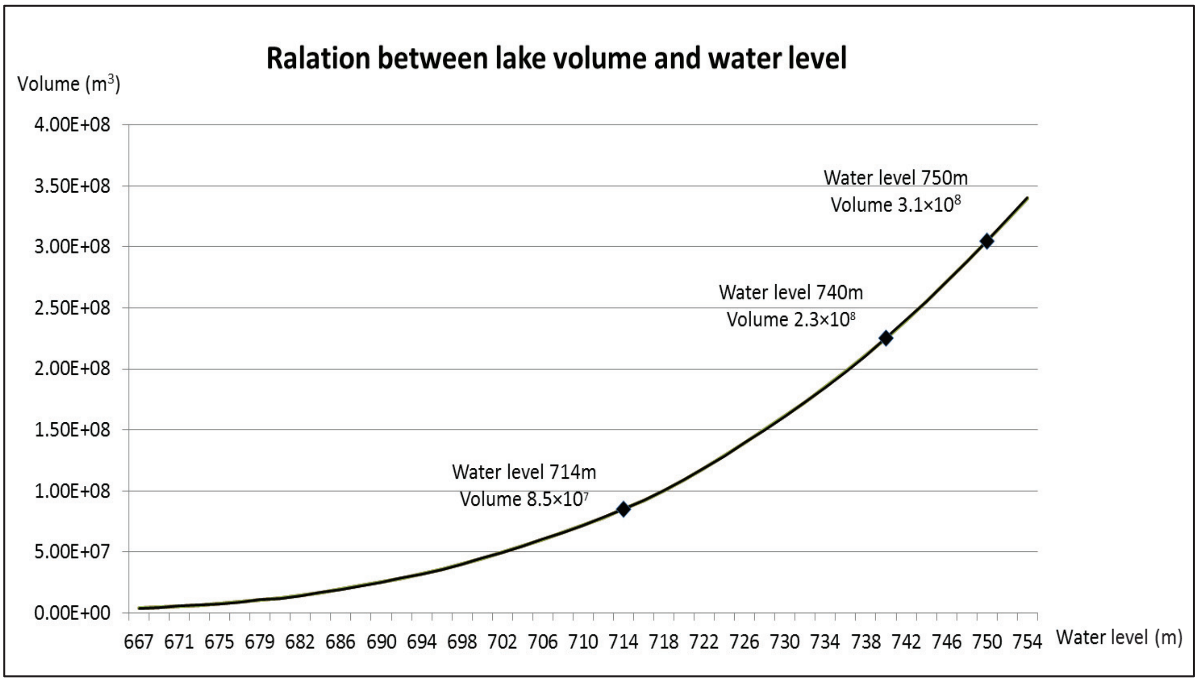

Fig.9 Relationship between the lake volume and water level. 750 m is at the lowest part of the dam body before the spillway made. 740 m is the elevation of the spillway bottom. 714 m is at the spillway bottom after the draining the barrier lake.

3.2. Mitigation measures

The Tangjiashan dam was formed during the rainy season and suffering aftershocks, therefore it has a high lake water level rise speed and the possibility of an uncontrolled release and might pose a serious threat to people downstream (Cui et al., 2010). To reduce the dam-break flood risk, the Chinese government has carried out several mitigation measures. An on-site Emergency Response Centre was formed by geologists, hydrologists and engineers. This centre was responsible for the dam and lake monitoring, flood prediction, carrying out the mitigations works and assisting the government to make the decisions. The mitigation measures mainly include two parts: excavating the spillway to release the water and evacuating people who might be affected by the possible dam-break flood.

3.2.1. The spillway

After assessing the dam stability and the possible dam-break flood, the government decided to excavate a spillway to release the impounded water. It was designed as a trapezoid cross-section with the slope proportion of 1:1.5 on both sides of the channel. The bottom elevation of the spillway is 740 m. It is 8 m wide and 13 m deep from the top to the bottom of the channel. The total length of spillway is 695 m. The longitudinal gradient of the discharge channel consists of a gentle section of 0.6% at the upper reaches and the steep sections of 24% and 16% individually at the lower reaches(Liu et al., 2009b). The construction of the spillway started on May 26 and was completed on June 1. The spillway was designed to be able to convey 1160 m^3/s (Liu et al., 2009). Due to the spillway, the lowest point on the dam crest was reduced from 750m to 740 m. The water level continued to rise and on 7 June 2008 at 7:08 it reached the spillway level at 740m. The peak discharge was 6500 m^3/s at 12:30 on 10 June 2008 (Liu et al., 2009b). An amount of 1.86×108 m^3/s water was released from 7 to 11 June, and the channel bottom elevation decreased to 714m. Even though it was a controlled breach, the flood severely damaged the still remaining buildings in the destroyed town of Beichuan, which was completely abandoned by that time.

3.2.2. The evacuation

On May 27, 2008, the local government started to evacuate more than 2.5 million people from the possible flooding area at downstream to higher places nearby. Among them, 1.2 million are from the Mianyang City (Mianyang_Information_center, 2008.) People were resettled in the temporary tents. The evacuation plan was made based on the 1/3 of the dam body collapse scenario.

4. DATA AND METHODS

4.1. Overview

This study aims to simulate the dam-break flood of the Tangjiashan landslide dam based on several designed scenarios, from the realistic spillway scenario to the most catastrophic whole of the dam breach scenario. The physics-based BREACH model (Fread, 1988) is used to compute the flood hydrograph at dam site, to understand the dam breach process and to determine the breach size. The BREACH model was calibrated by real spillway scenario. Also the parameter sensitivity analysis is done to better understand the dam breach mechanism and determine the controlling factors of the dam breach. SOBEK 1D-2D flood modelling was used to analyze the flood routing, and to achieve the affected area and other hydraulic parameters in the downstream regions. Second is to carry out hydrographs as boundary condition for 1D-2D simulation. The calibrated BREACH model is used to simulate different scenarios' dam breach. The scenarios are defined by upstream inflow, according to history flood records. Third is to use these hydrographs to carry out 1D-2D dynamic simulation in downstream area in SOBEK (Fig.10).

4.2. Fieldwork

The main objective for field work is to collect data of the river (Table.1), flood histories and terrain information.

In order to carry out 1D-2D flood simulation in SOBEK, 35 cross sections along the river up to Mianyang were measured. Embankments were measured and mapped out during the field survey by GPS and Laser Distance Finder (Fig.11). The flood histories of the Tongkou river and terrain condition before 2008 were obtained through field interviews. Some official engineering reports were collected in the field, which are valuable first-hand information on the dam and lake description, as well as the hydrological data. Most importantly, the post-earthquake topographic map with 2-m contour interval from the dam site to the Beichuan town was collected, which is crucial for the 2D flood modelling near the dam-site and also for reconstructing the event.

Now the dam body is removed artificially (Fig.12), remaining some parts on both sides. Now there is only small part of the dam body is still remaining in the field. The dam was enhanced by concrete to avoid the incision. The current water level of the lake is 712 m, with a volume of 8.7×10^7 m^3. According to the observation station, the discharge at the dam site is normally about 50-200 m^3/s during rainy seasons.

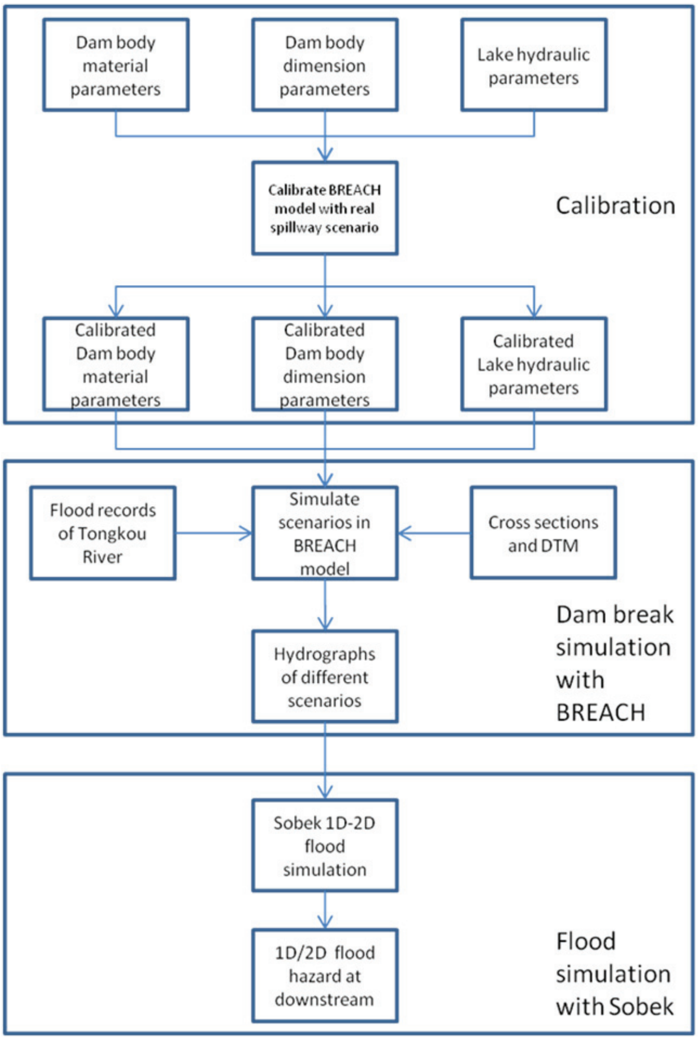

Fig.10 Flowchart of methods used

Field Work Data		
Data	Collect Method	Usage
Cross sections	Laser distance finder & GPS	Build river channel cross sections in SOBEK 1D-2D modelling
River bed material	Observation	Determine friction for the river
Discharge Record of Tongkou River	government agencies	Inflow of the barrier lake
Dam body material parameters	government agencies	Used in BREACH model
Post-earthquake 2m interval contour of the dam site	government agencies	Obtain dam body dimensions
Distribution and building date of embankments	GPS & interview	Improve DTM
Terrain change information since 2008	Interview	Improve DTM

Table.1 Field work data and their collect method and usage

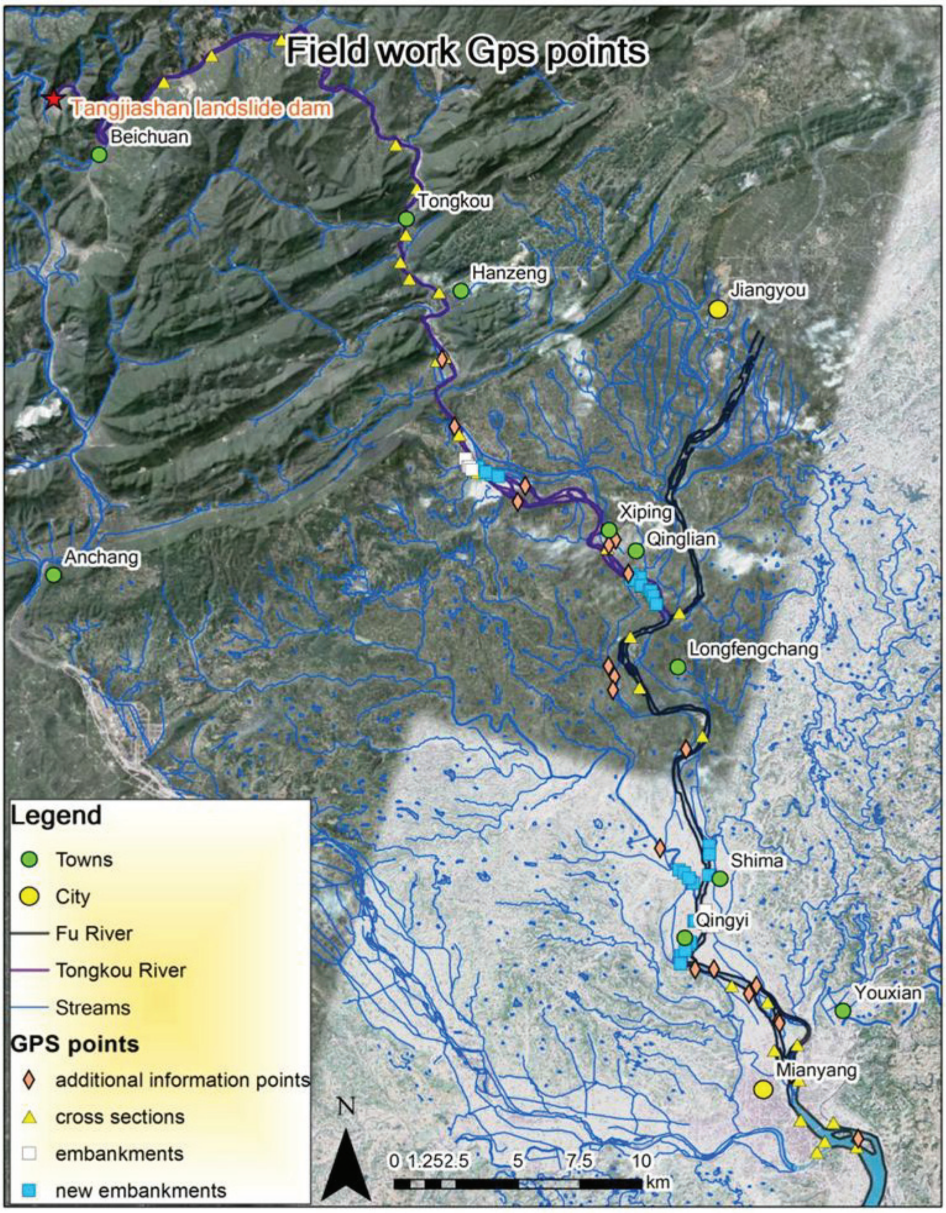

Fig.11 Field work records. Additional imformation points are mainly interviews and other information. New embankments are the embankments constructed after June 2008.

Fig.12 Tangjiashan Landslide dam site in Sep 2012

4.3. Breach Model

4.3.1. Background

BREACH (Fread, 1988) is a mathematical model for predicting the breach characteristics (size, shape, time of formation) and the breach outflow hydrograph. The model is physically based on the principles of hydraulics, sediment transport, soil mechanics, the geometric and material properties of the dam, and the reservoir properties (storage volume, spillway characteristics, and the time-dependent reservoir inflow rate)(Fread, 1988).

Landslide dams usually fail by overtopping, dam body sliding and piping. BREACH model can simulate overtopping and piping failures. Because there was only slight piping found for Tangjiashan landslide dam, only overtopping part of BREACH is introduced here. The following BREACH equations have been used to obtain the dam breach hydrographs:

$$Q_b = 3B_0(H - H_c)^{1.5} + 2\tan(a)\,(H - H_c)^{2.5} \qquad (1)$$

Q_b stands for the discharge in the breach channel, B_o is the instantaneous width of the breach bottom, H is the water level of the barrier lake, H_c is the elevation of the breach bottom, α is the angle that the side of the breach channel makes with vertical(Fig.13).

B_o can be computed by:

$$B_0 = B_r y \qquad (2)$$

In which B_r is a factor based on optimum channel hydraulic efficiency and y is the critical depth of flow in the breach channel. For overtopping failures, B_r=2. Critical depth y can be computed by:

$$y = 2/3(H - H_c) \qquad (3)$$

Beside the initial lake water level, the water level change through time ΔH can be obtained by:

$$\Delta H = \frac{0.0826\Delta t}{S_a}(Q_i - Q_b) \qquad (4)$$

Δt is time interval of each step, and should be around 0.02 hours per step(Fread, 1988). S_a is the lake coverage area in acres at water level H. Q_i is the upstream in flow of the barrier lake. So H_{t+1} at each time step can be easily obtained by:

$$H_{t+1} = H_t + \Delta H_t \qquad (5)$$

The breach elevation H_c is changing by time due to erosion, i.e.

$$H_{c_{t+1}} = H_{c_t} - \Delta H_{c_t} \qquad (6)$$

ΔH_c is depending on the characteristic of the dam itself and sediment transport rate Q_s.

$$\Delta H_c = \frac{3600\Delta t Q_s}{(P_0 L(1 - P_{or}))} \qquad (7)$$

In which L is the length of the breach channel, P_{or} is the porosity of the breach material, and P_o is the total perimeter of the breach. P_0 can be computed by:

$$P_0 = B_o + 2(H_u - H_c)/cosa \qquad (8)$$

H_u is the top elevation of the dam.

The Smart equation(Smart, 1984) is used for sediment transport in BREACH, which is based on flume experiments with well-sorted sediments. This methodology makes this equation not very suitable for describing the material transport over a breached and poorly sorted landslide deposit. Moreover, to evaluate the critical flow conditions (entrainment thresholds), the Smart equation considers the Shields stress, which involves the calculation of the water depth along the breach. Often, however, it is difficult to measure or to evaluate the water depth under turbulent flow conditions(Cencetti et al., 2006). So as Cencetti et al. (2006) recommend, The Schoklitsch formula is used to compute sediment transport rate for the Tangjiashan landslide dam.

$$Q_s = 2500S^{3/2}(Q_b - Q_c) \qquad (9)$$

In this equation Q_s is the sediment transport rate (kg/m^3) and have to be converted into cubic feet per seconds to use in BREACH, S is the slope (ratio of vertical with horizontal) of the breach channel, Q_c is the critical volumetric water discharge.

$$Q_c = 0.26\left(\frac{\rho_s}{\rho} - 1\right)^{5/3} {D_{40}}^{3/2} S^{-\frac{7}{6}} \qquad (10)$$

ϱ_s is specific mass of sediments, ϱ is the specific mass of water, D_{40} is the diameter for which 40% of sediments are finer (m).

The channel erosion is controlled by channel collapse condition. Collapse occurs when the depth of the breach cut depth (H_c') reaches the critical depth (H_k') which is a function of the dam's material properties of internal friction (φ), cohesion (C), and unit weight γ (lb/ft^3).

$$H'_k = 4C cos\Phi sin\Theta'_{k-1}/\gamma(1 - \cos(\Theta'_{k-1} - \phi)) \qquad k=1,2,3 \qquad (11)$$

The subscript k is one three successive collapse conditions; Θ is the angle that the side of the breach channel makes with horizontal. The angle (Θ) or (α) at any time during the breach formation is given as follows:

$\Theta = \Theta'_{k-1}$	Hk ≤ H'k
$\Theta = \Theta'_k$	Hk ≥ H'k
Bo = B'o	k > 1
Bo = Bry	k = 1
Bo = Bry	H1=H'1
$a = \frac{\pi}{2} - \Theta$	
$\Theta'_0 = \pi/2$	
$\Theta_k = (\Theta_{k-1} + \phi)/2$	k = 1,2,3
Hk = Hc - y/3	

The subscript (k) is incremented by 1 at the instant when Hk > H'k (Fread, 1988).

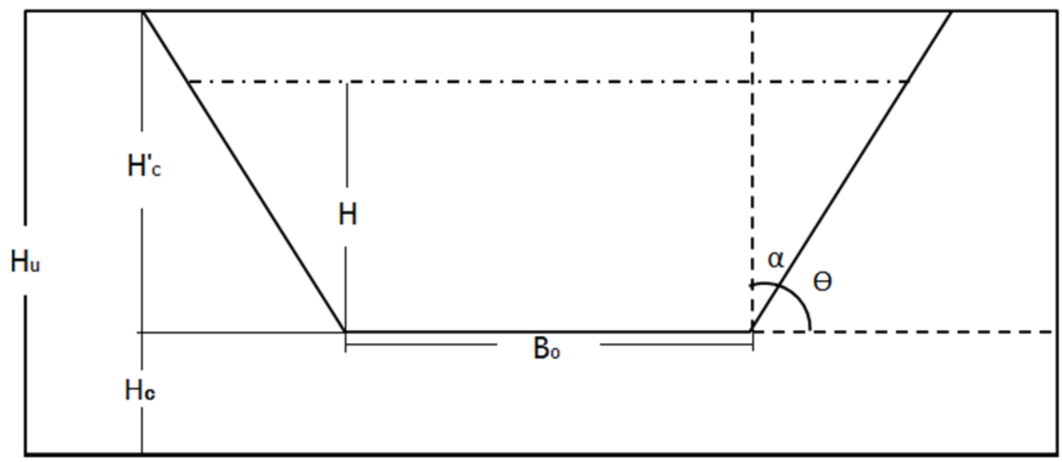

Fig.13 Front view of dam breach channel

4.3.2. Model Inputs

Lake parameters: inflow of the lake (Q_i), lake water level (H), lake volume (V), average depth (D) (can be compute from relation between lake water level rise ΔH and average depth rise ΔD), lake surface area (Sa = V/D).

Dam body dimensions: elevation of the top of the dam (H_u), initial breach bottom elevation (H_c), initial width of the breach bottom (B_o), initial breach angle of side makes with vertical ($\alpha=0$), length of the breach channel (L), initial slope of the downstream face (S). The slope S can be compute by (H_c – pre-earthquake river bed elevation)/L.

Dam body material: material porosity (P_{or}), material mass (ϱ), diameter for which 40% of sediments are finer (D_{40}), cohesion (C), internal friction (φ). The material parameters selected are shown in Table.2.

Others: time step (Δt=0.01 h).

Notice: the BREACH model requires all units are converted into feet, pound (not in the Schoklitsch formula).

P_{or}	0.335	ϱ	2490.2 kg/m^3
C	15 Kpa	φ	35°
D_{40}	0.1 m		

Table.2 selected dam material parameters

4.3.3. Model Outputs

Outflow at each time step (Q_b)

Erosion of side and bottom (B_o, H_c)

Amount of sediment transported (Q_s)

By out flow at time steps (Q_b), hydrographs of each scenario can be generated. Dam breach process can be obtained by Width of channel (B_o) and elevation of the breach channel (H_c). They are the main input for SOBEK 1D-2D flood simulation.

4.4. 1D and 2D Numerical Simulation Using SOBEK Software

4.4.1. SOBEK Software

SOBEK is a 1D and 2D modelling suite for flood forecasting, drainage systems, irrigation systems, sewer overflow, ground-water level control, river morphology, salt intrusion and water quality. In this study, the 1D rural flow model and 2D overland flow model are used to simulate the dam break flood. The flow in one dimension is described by two equations: the momentum equation (13) and the continuity equation (12).

$$\frac{\partial A_f}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat} \tag{12}$$

Where: A_f = Wetted area, q_{lat} = Lateral discharge per unit length [m2/s], Q = Discharge [m³/s], t = time [s], x = distance [m].

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A_f}\right) + g \cdot A_f \cdot \frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2 R A_f} - W_f \frac{\tau_{wi}}{\rho_w} = 0 \tag{13}$$

Where: Q Discharge [m^3/s], t Time [s],x Distance [m], A_f Wetted area [m^2], g Gravity acceleration [m/s2] (=9.81), h Water level [m] (with respect to the reference level), C Chézy coefficient [$m^{1/2}$/s], R Hydraulic radius [m], W_f Flow width [m], τ_{wi} Wind shear stress [N/m2], ρ_w Water density [kg/m^3].

The 1D-2D combinations in SOBEK allows simulate flow in the flood plain area in 2D and calculate the flow in the river in 1D. 1D and 2D networks are two independent map layers, with the 2D network map layer overlapping a 1D network. When water gets over cross section banks, 2D simulation will start. This saved a lot of time to get a dynamic flood result, and the quality still is the same. The 2D dynamic flood simulation can gives a lot of advantage to spatial planning and emergency response planning for local government and residents.

4.4.2. SOBEK Model Inputs

1D simulation: Cross sections, hydrograph from BREACH, meteorological data, channel friction.

2D simulation: 25m filled sink DTM contains embankments.

From Tangjiashan landslide dam to Tongkou, the cross sections were taken from the 25m DTM, because this part of river has been changed a lot since 2008. According to official data, the annual temperature is 15.6℃ and the average wind speed and direction is 1.3 m/s and SW, respectively. Manning friction 0.035 for the valley part and 0.03 for the downstream plain area are selected, according to the grain size of the river bed composition.

The DTM is generated from an official 20m interval contour made about 50 years ago. It is generated in Arcmap with 25m resolution. The contour interpolation tool in Arcmap is based on the ANUDEM program developed by Michael Hutchinson (1988, 1989). Before using the DTM in SOBEK 1D-2D simulation, fill sink operation is used and height of the embankments existing in June 2008 is added.

4.4.3. SOBEK Model Outputs

1D model can generate hydrographs in downstream sections, including real-time depth increase, velocity, arrival time and discharge amount etc., while 2D model can presents these results in a spatial way. The depth, arrival time, discharge outputs from 1D simulation are used for analyzing the dam break flood flow characteristics. The 2D dynamic outputs are raster files, with 50m pixel size and 10 minutes time interval. The 2D outputs of maximum depth, maximum velocity and first arrival time are used for analyzing flood spread in downstream area.

4.5. Model Scenarios

Regarding to the model scenario, previous studies either only reconstructed the event (Dai et al., 2010) or assumed 1/3, 1/2 and whole collapse in term of the dam height (Cui et al., 2010). Since this study integrated the BREACH model and SOBEK 1D-2D model, the dam breach degree was then determined by the BREACH model in different situations. This integrated approach can avoid the arbitrary scenario assumption. The key external factors affect the dam breach are the rainfall and the aftershocks. Rainfall will change the inflow of the barrier lake and the aftershock will affect the dam stability. Due to the lack of seismic data, this study only consider the rainfall effects through adjusting the inflow to lake according to the historical flood record of the Tongkou river. Actually, the emergent mitigation measures were also made based on the possible flood discharges of different return periods. Therefore, five scenarios were considered in this study:

Scenario (1): 2 years return period flood inflow to the lake;
Scenario (2): 5 years return period flood inflow;
Scenario (3): 20 years return period flood inflow;
Scenario (4): real inflow in June 2008 (dam break naturally assuming there is no spillway, also called the natural break scenario);
Scenario (5): the catastrophic whole collapse scenario.

The scenarios (1) to (4) use the dam composition material properties based on the laboratory test from local report and the BREACH model calibration. Only the scenario (5), in order to make the dam breach totally, we have to reduce the dam material strength (properties), because even with the inflow of 20-year return period flood discharge, the dam still cannot breach completely. This is consistent with the conclusion obtained by previous studies (Liu, et al., 2009 and Cui et al., 2010).

5. FLOOD MODELING RESULTS

5.1. Results of the spillway calibration

To calibrate the model with the real spillway scenario, parameters of dam material and dam dimensions are selected (spillway dimensions refer to chapter 3.3, dam material parameters refer to chapter 4.3.2). Among all the parameters, the dam composition material properties, the inflow of the lake and slope of the downstream face are calibrated. The other parameters like dimensions of the lake and the dam body are constant. From the time that lake water level reaches the spillway bottom, the simulation results and the observations are shown in Table.3. The BREACH simulation can generate the flood hydrograph at the dam site and the release volume. Fig.14 shows that BREACH model output hydrograph matched very well with the observation of the flood hydrograph released by the spillway in 2008. Thus, the BREACH model can be used to model other scenarios and the results are believed to be reliable to be inputted into the SOBEK model later. Regarding to the ultimate breach size, the model results show deeper and narrower breach than the observation, which means the modelled breach process has stronger incision than the breach channel side erosion. Due to the model simplification (e.g. the dam three-layer structure was simplified by a whole body with the same geotechnical parameters, the breach channel gradient, the slope were also simplified), the model did not present the time duration from the overtopping start to the peak discharge appeared.

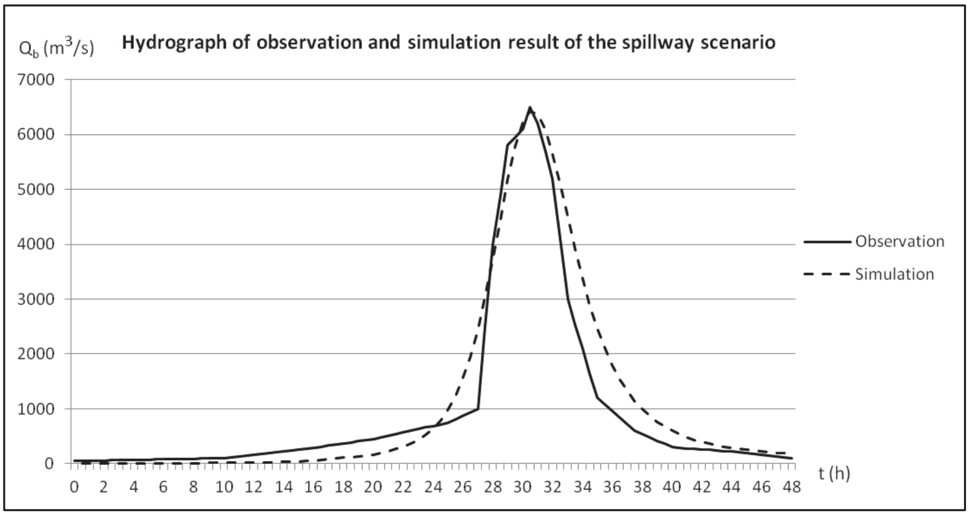

Fig.14 Hydrograph of observation and simulation result of the spillway scenario. The realistic record refers to Liu et al., 2009

	Observation	Simulation
Inflow rate (m^3/s)	90	90
Peak discharge (m^3/s)	6540	6438
Total volume released (m^3)	1.7×10^8	1.88×10^8
Duration (at 1000 m^3/s) (h)	9	12.5
Bottom Eroded (m)	30	36.8
Final bottom elevation (m)	710	703.2
Final breach width (m)	100	68

Table.3 Key outputs of BREACH simulation compared with observed records. The observed record is from Liu, et al. (2008)

5.2. Parameter sensitivity analysis

The spillway simulation is taken as an example to carry out the sensitivity analysis. As the sensitivity analysis shown, the most sensitive parameters are: inflow of the lake (Q_i), slope (S), unit weight (ϱ) and porosity (P_{or}). According to the report of the Tangjiashan landslide dam stability (Fan et al., 2008), the slope of the downstream face ranges from 0.072 to 0.108 in the realistic spillway scenario, the porosity varies from 0.3 to0.6, and the unit weight ranges from 1800 to 2500 kg/m^3. Inflow of the lake can be adjusted from the average inflow on 7 June 2008 – 11 June 2008 (90 m^3/s) to 20 years return period flood discharge (3920 m^3/s), according to official discharge record. The hydrographs change due to different inflow to lake is shown in Fig.15.

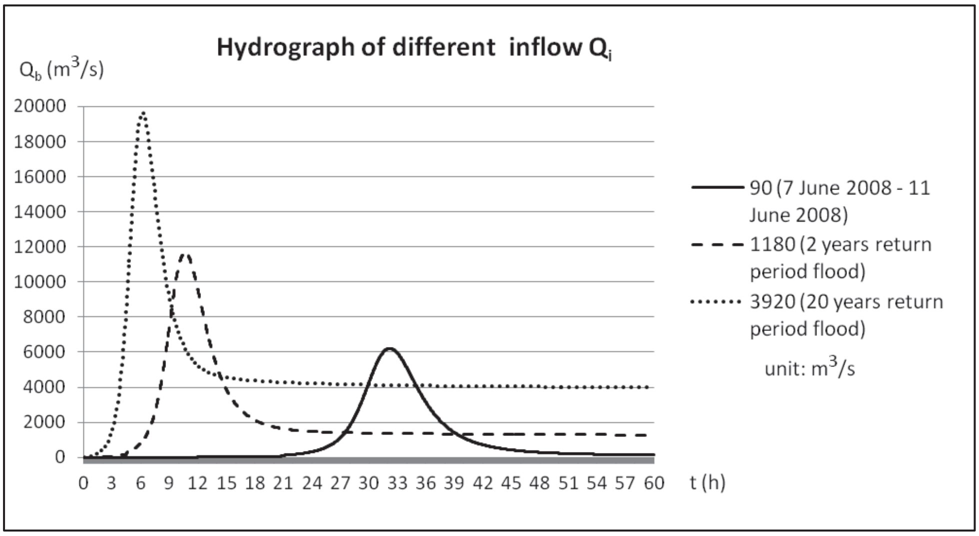

Fig.15 Hydrograph of different inflow rate

As shown in Fig.15, a high inflow rate can cause a sharp hydrograph with early start of quick release, short breach duration, high peak discharge and large amount of total outflow. This is because of a higher inflow rate can lead to a higher lake water level (H) during the breach, and will give a higher outflow discharge (Q_b) according to equation 1. Even more, a high outflow discharge (Q_b) means a high sediment transport rate, and the breach bottom elevation (H_c) will decrease faster, thus the breach will start early and also develop fast (Equation 7 and 9). Besides, according to the equation 4, the high inflow of the lake can decrease the change rate of water level (ΔH), when quick release take place, and gives a high difference between water level (H) and breach bottom (H_c), leading to high outflow discharge.

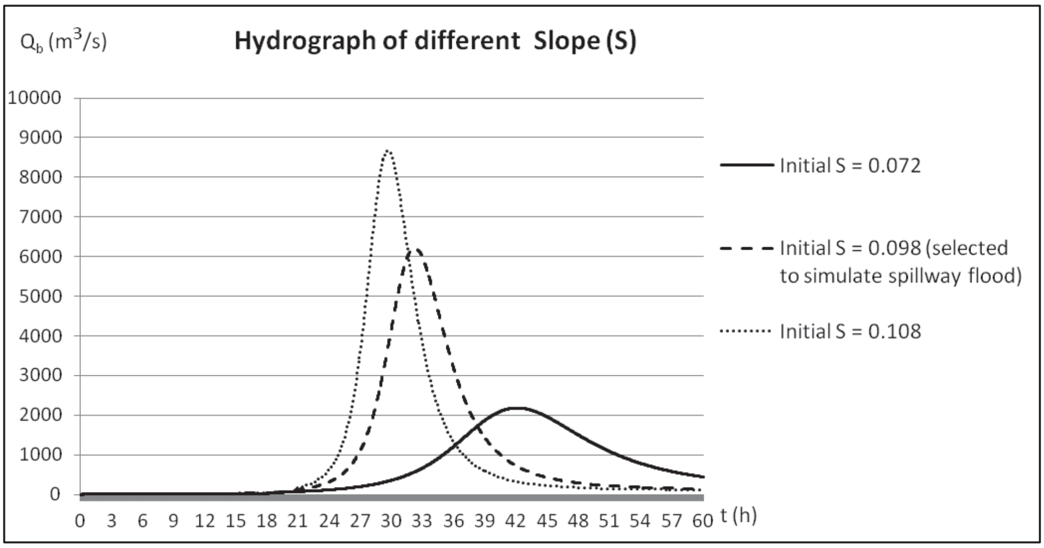

Fig.16 Hydrograph of different downstream face slope

The slope (the spillway gradient) is the ratio of the height of the breach bottom with the horizontal distance of the breach channel. It is a variable because during the breach not only the breach bottom elevation is changing, but also the elevation of the river bed is increasing due to sediment deposition. Steeper slope can cause a higher peak discharge of outflow (Q_b) and shorter duration (Fig.16). A steeper slope will give a slightly earlier start time of quick release and a bit more outflow amount. The main reason is that slope (S) is the main control factor of sediment transport rate (Qs), which has the positive effect on the sediment transport rate (Q_s) as shown in Equation 9. The sediment transport rate (Qs) is positive to the change rate of the breach bottom (ΔH_c), thus a steep slope leads to a high change rate of the breach bottom. High change rate of the breach bottom will give a big difference of lake water level (H) and the breach bottom elevation (H_c), and give a high discharge as equation 1. Moreover high change rate of the breach bottom accelerates the undercutting, and ends the breach earlier than a gentler slope one.

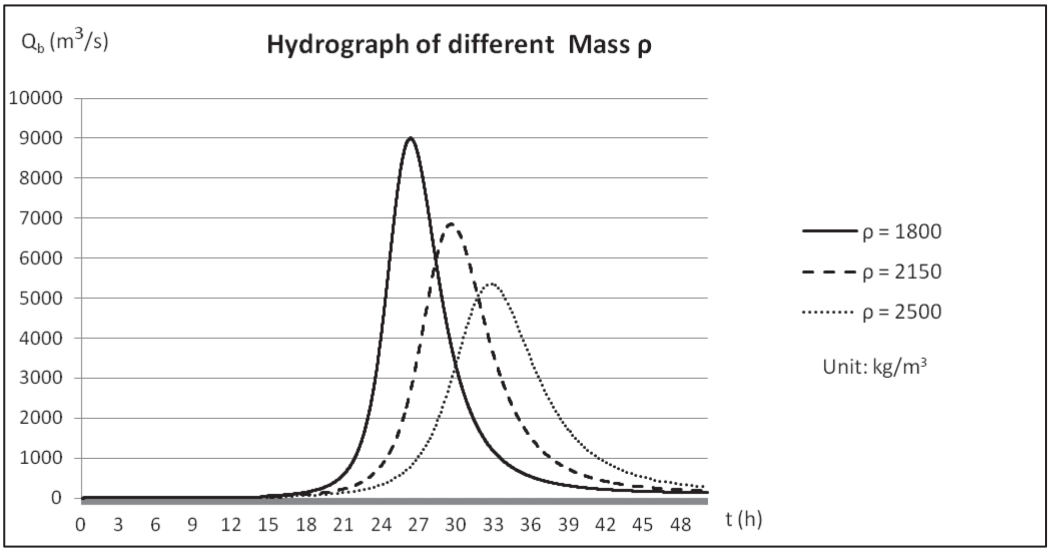

Fig.17 Hydrograph of different unit weight of the dam body material

The unit weight of dam body material (ϱ) is another main control factor of sediment transport rate (Fig.17). The output of Schoklitsch formula (equation 9) is in kilograms per second, and has to be converted into cubic feet per second to be applied in BREACH model. The lower unit weight will generate higher sediment transport rate (Q_s). Basically the sensitivity of unit weight of dam body material (ϱ) is similar with slope (S), but they have contrary effects on sediment transport rate.

The porosity (P_{or}) in the formula directly affects the change rate of breach bottom (ΔH_c) (equation 7). The higher the porosity is, the higher the change rate of breach bottom will be (Fig.18). The sensitivity of porosity is similar with the slope (S) and the unit weight (ϱ), as they all change the hydrographs by affecting the change rate of the breach bottom.

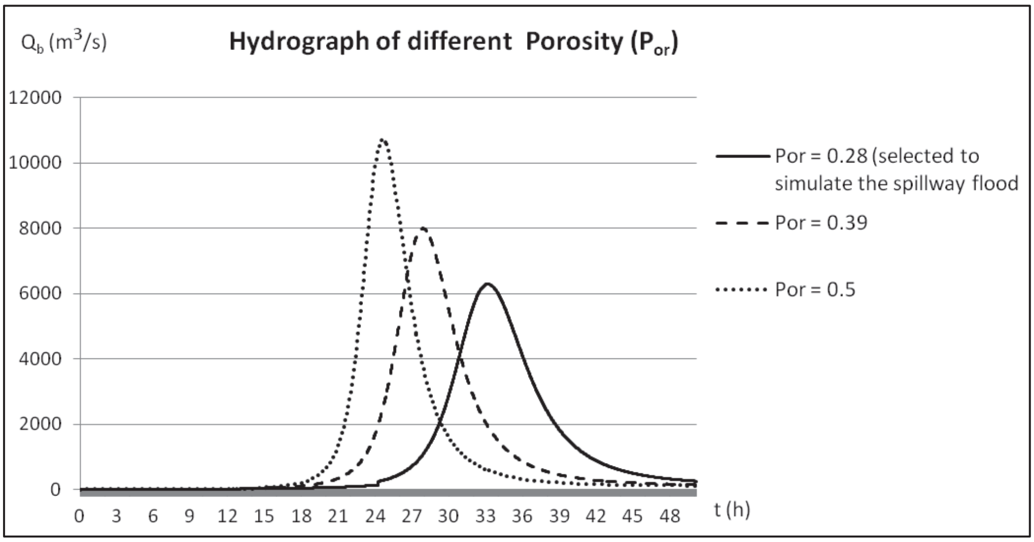

Fig.18 Hydrograph of different porosity of the dam body composition materials

5.3. BREACH model results

As mentioned before in 5.1, the BREACH model was calibrated by the real spillway scenario. Besides, some of the input parameters of the model (e.g. the dam composition material properties) were also determined by the calibration. The model was then used for simulating the floods of different scenarios.

First, the scenarios (1) to (3) with different return period flood inflows to the barrier lake were simulated. As the hydrograph shows, high inflow corresponds to high peak discharge, short duration and short quick release starting time (Fig.19). Table.4 shows the key outputs of the BREACH simulation. As inflow rate increases, the total release volume, bottom and side erosion are increasing, while the duration is decreasing. Due to the flow after the breach cannot lower than the inflow, the duration of quick release is defined at the period of change rate of outflow is greater than 1 $m^3/\Delta t$ (Δt is the simulation time step in BREACH, (Δt=36s).

Inflow return period	2 years	5 years	20 years
Inflow rate (m^3/s)	1180	2190	3920
Peak discharge (m^3/s)	26240.94	29944.53	35040.78
Total volume released (m^3)	4×10^8	4.8×10^8	6.4×10^8
Volume released when ΔQ_b>1 m^3/s	3.63×10^8	4.08×10^8	4.75×10^8
Duration (ΔQ_b>1 m^3/s) (h)	13.73	12.9	11.48
Final breach bottom elevation (m)	688.5	686.1	683.1
Final breach width (m)	86.5	90.4	94.7

Table.4 BREACH model key results of 2 years return period flood, 5 years return period flood, and 20 years return period flood scenarios. The duration of BREACH simulation is 24 hours.

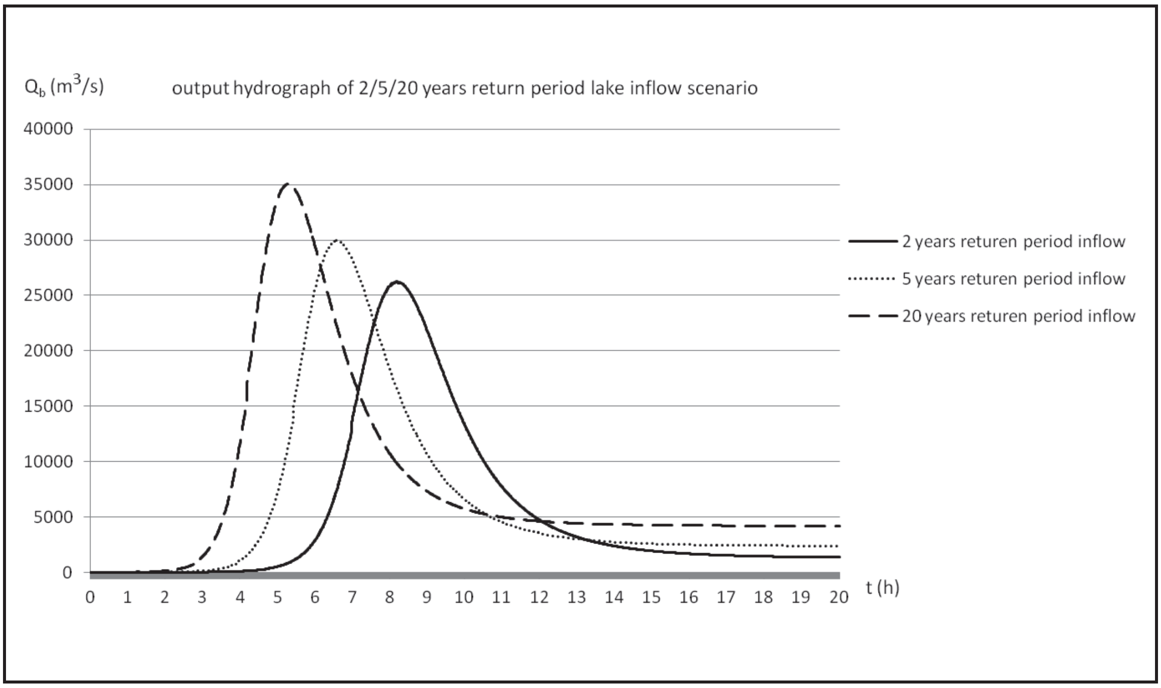

Fig.19 Output hydrograph of 2 years return period lake inflow, 5 years return period lake inflow, 20 years return period lake inflow

Second, as before mentioned, this study reconstructed the 2008 event by simulating the spillway through the BREACH model for two purpose: calibrating the BREACH model and also comparing it with the scenario (4), the without spillway scenario, to see the effect of the spillway. The scenario (5), the whole breach scenario was carried out by reducing the dam composition material properties. For comparing these scenarios, these three scenarios were plotted in the same figure (Fig.20). The outputs are shown in Table.5. The quick release definition is also at the period of change rate of outflow is greater than 1 $m^3/\Delta t$.

Fig.20 shows that the scenario (5), the whole breach has the highest peak discharge of 62, 441.35 m^3/s and the shortest peak duration, with all the storage being released within 6 hours. Besides, the flood will reach 10 hours earlier than the scenario (4), the natural breach scenario. Scenario (4), the natural break scenario has duration about 15 hours with a peak discharge of 20449.9 m^3/s. In the spillway calibration, the dam is lowered and the channel is widened artificially. The spillway significantly reduced the peak outflow rate and extent the duration of release. Table.5 shows the scenario (4), the natural breach and the scenario (5), the whole breach scenario release a very close volume of water, but the peak discharge of the whole breach scenario is 305% of the peak discharge of the natural break scenario. The spillway delays the time of peak discharge by about 13 hours compared with the natural break scenario, and has 20.2 m less bottom eroded, thus mitigates the dam break flood hazard effectively.

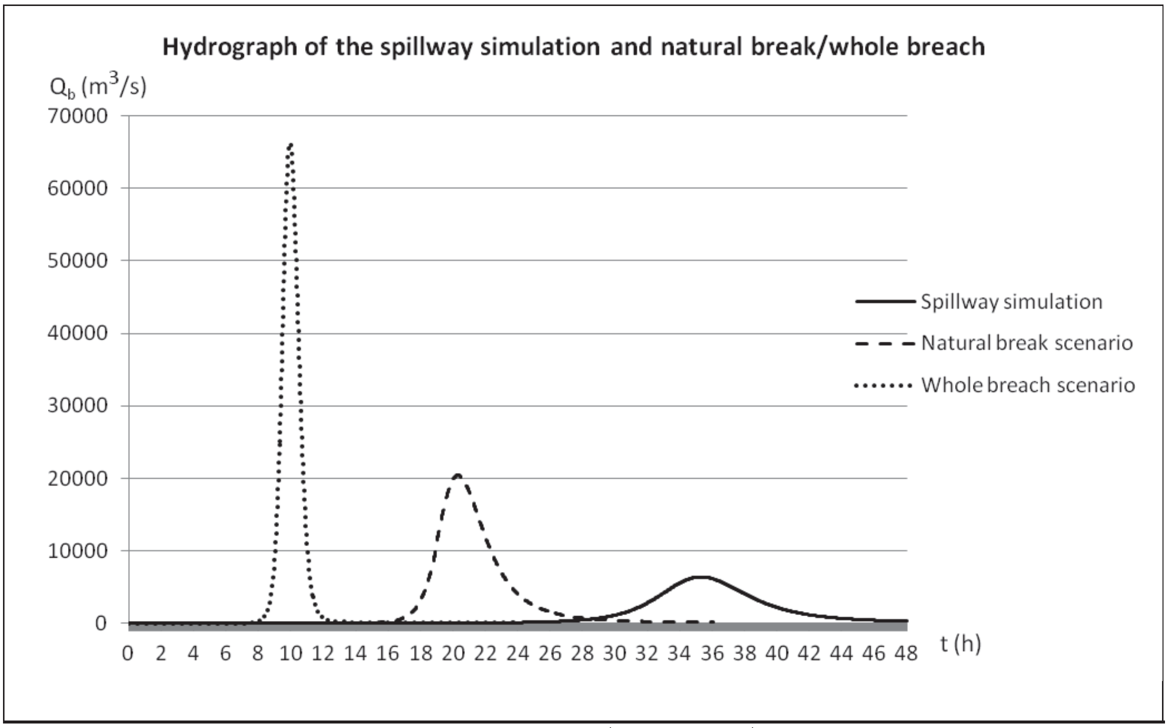

Fig.20 Output hydrograph of the spillway/nature break/whole breach scenarios

	Simulated spillway	Natural break	Whole breach
Inflow rate (m3/s)	90	90	167
Peak discharge (m3/s)	6438	20449.9	62441.35
Total volume released (m^3)	1.88×10^8	3.06×10^8	3.14×10^8
Duration (ΔQ_b>1 m^3/s) (h)	18.23	15.26	6.11
Time from start to peak (h)	35.3	20.31	9.46
Final bottom elevation (m)	703.2	692	668.5
Bottom eroded (m)	37.8	58	81.5
Final breach width (m)	68	79.9	111.26

Table.5 BREACH model key results of the spillway simulation and nature break without spillway scenario using the realistic parameters in June 2008/ whole breach scenario.

5.4. 1D SOBEK modelling results

The hydrographs generated by BREACH are used as inputs in SOBEK modelling. The observed recorded hydrograph(Liu et al., 2009b) is used as input for the first 1D simulation to validate the 1D modelling. The result matches the records well (Table.7).

Table.6 indicates that as the distance from the dam site increases, the flood peak discharge is decreasing, while the maximum depth and peak velocities are depending on the river cross sections. For all 5 scenarios, the higher the peak discharge is, the faster and deeper the dam break flood flow will be. The Tongkou town has the deepest and fastest flood flows and the Mianyang city has the most shallow and slowest flows.

The results show that all these scenarios can cause serious flood hazard in downstream area. For the most densely populated Mianyang city, its dykes are 8 - 10 m high and can stand for 12, 000 m^3/s discharge (According to our interview in Kaiyuan hydropower station, Mianyang). Fig.21 shows the locations that are taken measurements in the 1D modelling. The measurement location of Mianyang is at the entrance of the city, so embankments in the Mianyang city do not affect the results. Due to the 1D modelling output time interval is 5 minutes, the arrival time may have an error of ±4 minutes (±0.067 h). This can be observed in the whole breach scenario and 20 years return period inflow scenario. The peak discharge is very high in these two scenarios, and flow speed is also very fast. 5 minutes time interval can hardly presents their arrival time correctly in the areas that are close to the landslide dam.

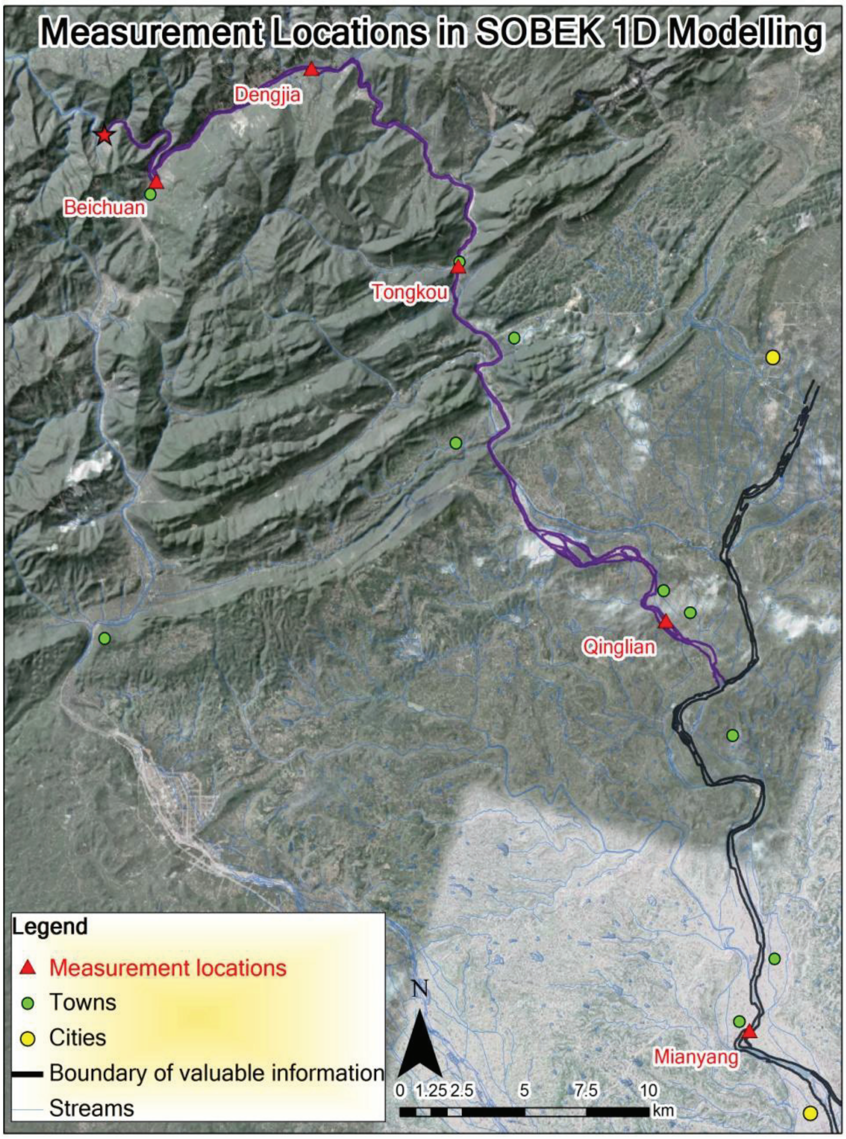

Fig.21 Measurement locations in SOBEK 1D modelling (Red triangles)

Scenario 1: considering the inflow to the lake of 2-year return period flood discharge					
	Distance(km)	Peak discharge(m^3/s)	Max depth(m)	Peak wave arrival (h)	Peak velocity(m/s)
Beichuan	5.3	25899.5	15.1	0.05	5.5
Dengjia	12.3	25278.8	24.5	0.38	4.3
Tongkou	27.3	24865.7	33.4	0.8	8.5
Qianlian	46.7	21978	7.6	2.05	4.3
Mianyang	74.9	19793	5.7	3.63	2.1
Scenario 2: considering the inflow to the lake of 5-year return period flood discharge					
	Distance(km)	Peak discharge(m^3/s)	Max depth(m)	Peak wave arrival (h)	Peak velocity(m/s)
Beichuan	5.3	29459.1	16.8	0.09	5.7
Dengjia	12.3	28606.1	25.6	0.42	4.2
Tongkou	27.3	28139.4	35.4	0.75	8.5
Qianlian	46.7	24688	8.1	2	4.4
Mianyang	74.9	22174.6	6.1	3.59	2.2
Scenario 3: considering the inflow to the lake of 20-year return period flood discharge					
	Distance(km)	Peak discharge(m^3/s)	Max depth(m)	Peak wave arrival (h)	Peak velocity(m/s)
Beichuan	5.3	34545.4	19.2	0.1	5.9
Dengjia	12.3	33604.2	28	0.27	4.4
Tongkou	27.3	32865.2	37.9	0.69	9.1
Qianlian	46.7	28495.9	8.5	1.76	4.6
Mianyang	74.9	25454.9	6.5	3.43	2.3
Scenario 4: Natural break of the dam assuming there is no spillway					
	Distance(km)	Peak discharge(m^3/s)	Max depth(m)	Peak wave arrival (h)	Peak velocity(m/s)
Beichuan	5.3	20306.5	12.3	0.1	5.3
Dengjia	12.3	19869.4	21.7	0.4	4.1
Tongkou	27.3	19593.3	30.7	0.85	8.1
Qianlian	46.7	17705.1	7.1	2.1	4
Mianyang	74.9	16056.8	5.3	3.77	1.9
Scenario 5: Catastrophic whole breach of the dam					
	Distance(km)	Peak discharge(m^3/s)	Max depth(m)	Peak wave arrival (h)	Peak velocity(m/s)
Beichuan	5.3	59228.3	28.1	0.04	7.4
Dengjia	12.3	54603.8	36	0.29	5.4
Tongkou	27.3	51185.3	75.6	0.71	9.2
Qianlian	46.7	38200.6	9.5	1.79	4.9
Mianyang	74.9	30029.1	7	3.21	2.5

Table.6 Sobek 1D dam break flood simulation results. The Peak arrival is the duration between the peak at the landslide dam and the peak at downstream measured locations

	1D simulation using observed hydrograph in 2008			Observed records	
	Distance(km)	Peak discharge(m^3/s)	Peak wave arrival (h)	Peak discharge(m^3/s)	Peak wave arrival (h)
Beichuan	5.3	6464.3	0.17	6500	0.2
Dengjia	12.3	6394.1	0.47	-	-
Tongkou	27.3	6338.3	1.18	6200	1.25
Qianlian	46.7	6159.5	2.13	-	-
Mianyang	74.9	5763	4.07	6100	4.33

Table.7 validation result of 1D simulation

5.5. SOBEK 1D-2D modelling results

In the 1D-2D simulation, 2D simulation starts near Hanzeng. The upstream part from the Tangjiashan landslide dam to Tongkou town is narrow valley and will surely be seriously flooded in all the five scenarios.

Among the scenario (1) to (3) considering the 2 years, 5 year and 20 years return period flood inflows to the lake respectively, the scenario (1) with 2 years return period inflow affects the smallest area in downstream area (Fig.22). The Xiping and Qinglian towns are partly flooded while other towns along the river are completely flooded. The maximum flood depth in the Mianyang city is between 1 - 5.5 m. The deepest part is mainly located in the east side of the river, with the depth of 8.5 m (Fig.22). The results of scenario (2) and (3) show that all the towns along the river are completely flooded. The water depth in the Mianyang city of the scenario (2) varies from 1.7 to 6.1 m, with the maximum depth of 9.2 m, while the water depth of scenario (3) has the depth of 2 m-6.8 m in Mianyang with the maximum depth of 9.7 m.

Among these three scenarios, the 2 years return period inflow scenario (scenario (1)) result has the lowest average maximum depth, lowest average maximum velocity and the longest average arrival time (time of being flooded). The 5 years return period inflow scenario (scenario (2)) and the 20 years return period inflow scenario (scenario (3)) have the similar flood extent, average maximum depth, average maximum velocity. The average arrival time of scenario (3) is 1.36 hours earlier than the scenario (2) (Table.8).

The result shows that the natural break scenario (scenario (4)) has the least severe dam break flood hazard in all 5 scenarios. Its maximum depth in Mianyang is between 0.5 – 4.5m with the maximum depth of 7.5 m. The whole breach scenario (scenario (5)) has the most catastrophic dam break flood. It generates the deepest and fastest flood which covers the widest area in all 5 scenarios. The maximum depth in the Mianyang city ranges from 2m to 7.2 m, with the maximum depth of 11.2 m.

For all the five scenarios, the Xiping, Qinglian, Shima, Qingyi towns and the Mianyang city are flooded in different degree. The Qingyi town will experience the most severe flood. The deepest flood is found in the river valley near the Hanzeng town.

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	2 years return period inflow	5 years return period inflow	20 years return period inflow	Natural break	Whole breach
Flood coverage area (m^2)	5.7×10^7	6.5×10^7	6.4×10^7	5.4×10^7	6.5×10^7
Average max depth (m)	5.82	7.04	6.91	5.09	7.09
Maximum depth (m)	40	46.96	46.38	32.86	44.17
Average max velocity (m/s)	2.31	2.8	2.7	2.05	2.9
Average arrival time (h)	9.88	8.65	7.29	22.01	11.45

Table.8 1D-2D simulation results of all scenarios

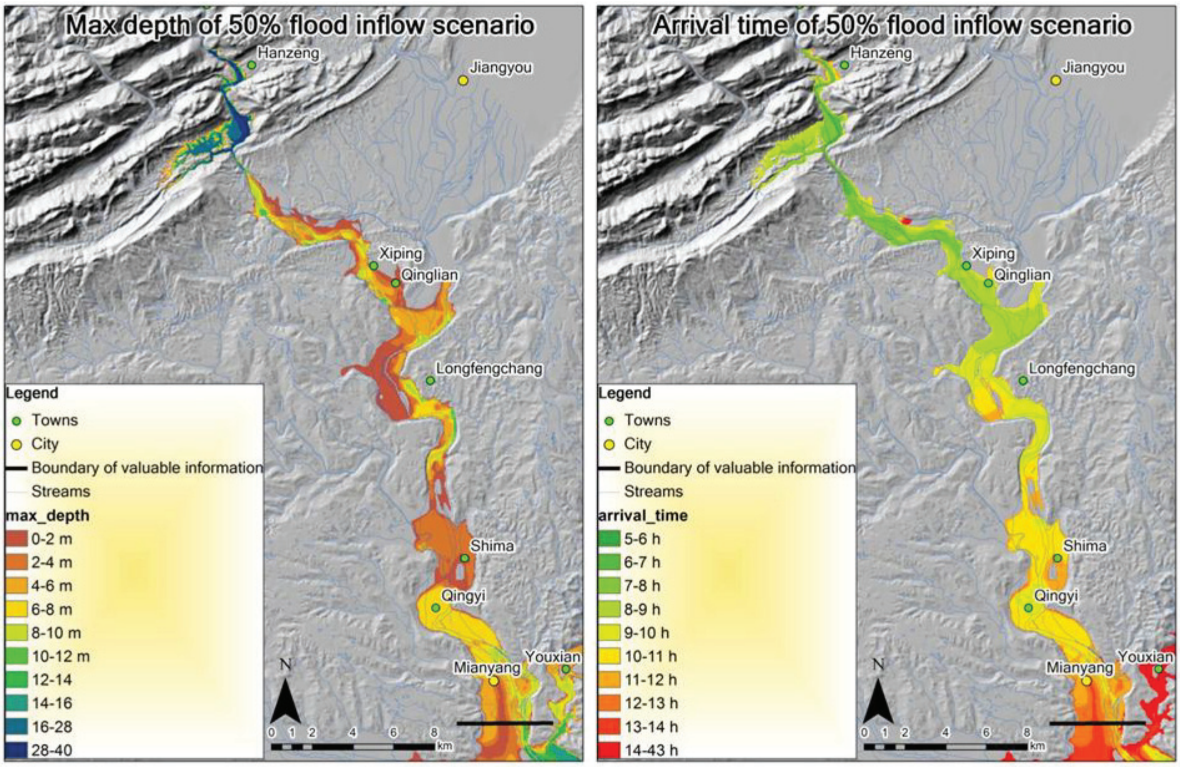

Fig.22 Max depth and arrival time of dam break flood of the scenario (1): 2 years return period lake inflow scenario. The black line at downstream seperates the useful imformation (upstream) and the area affected by the downstream boundary condition apart.

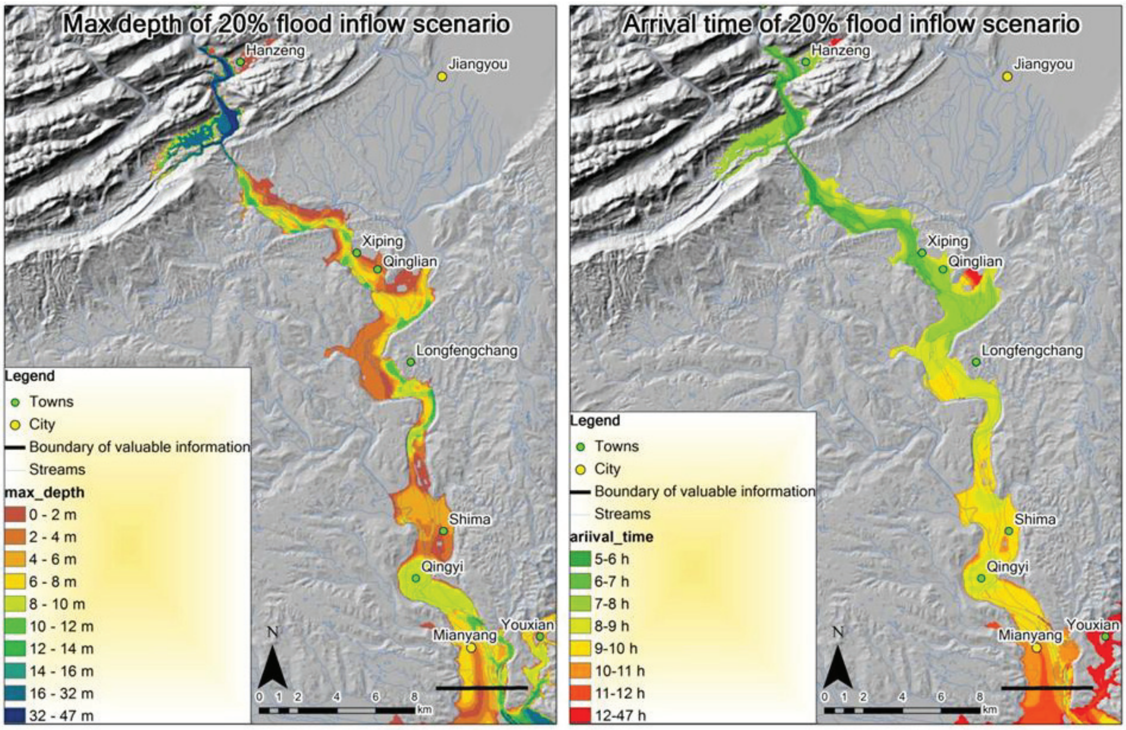

Fig.23 Max depth and arrival time of the scenario (2): dam break flood of 5 years return period lake inflow scenario. The black line at downstream seperates the useful imformation (upstream) and the area affected by the downstream boundary condition apart.

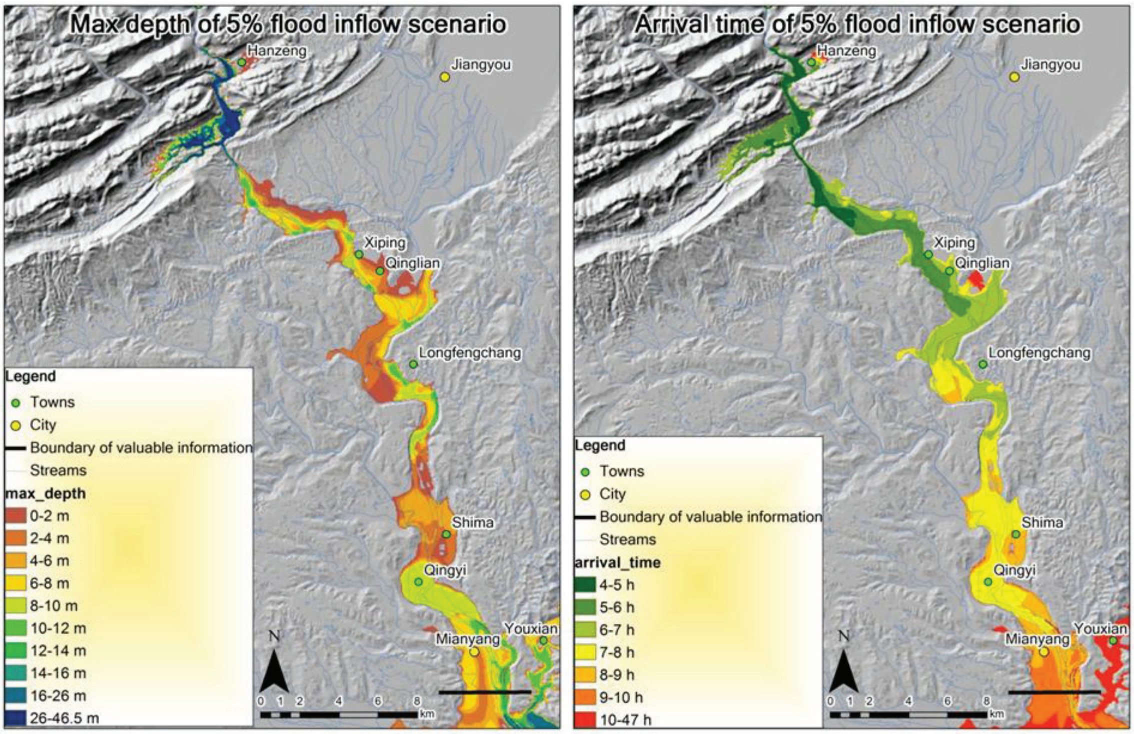

Fig.24 Max depth and arrival time of the scenario (3): dam break flood of 20 years return period lake inflow scenario. The black line at downstream seperates the useful imformation (upstream) and the area affected by the downstream boundary condition apart.

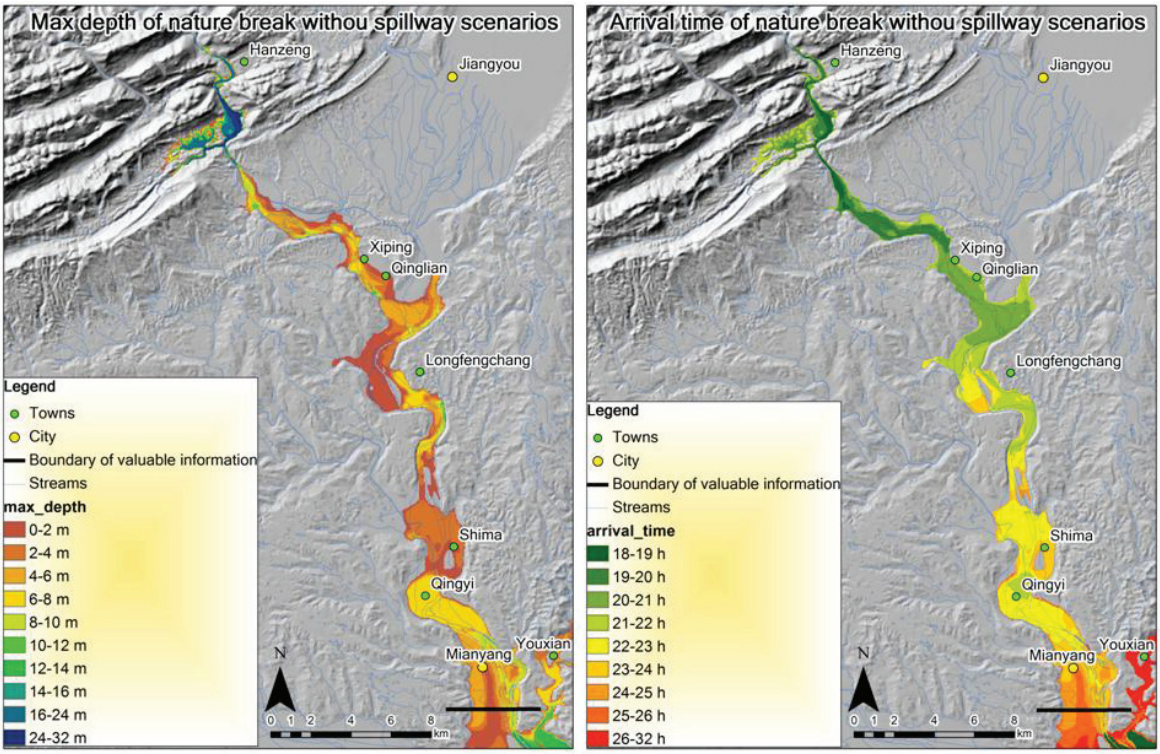

Fig.25 Max depth and arrival time of the scenario (4): dam break flood of natural break scenario. The black line at downstream seperates the useful imformation (upstream) and the area affected by the downstream boundary condition apart.

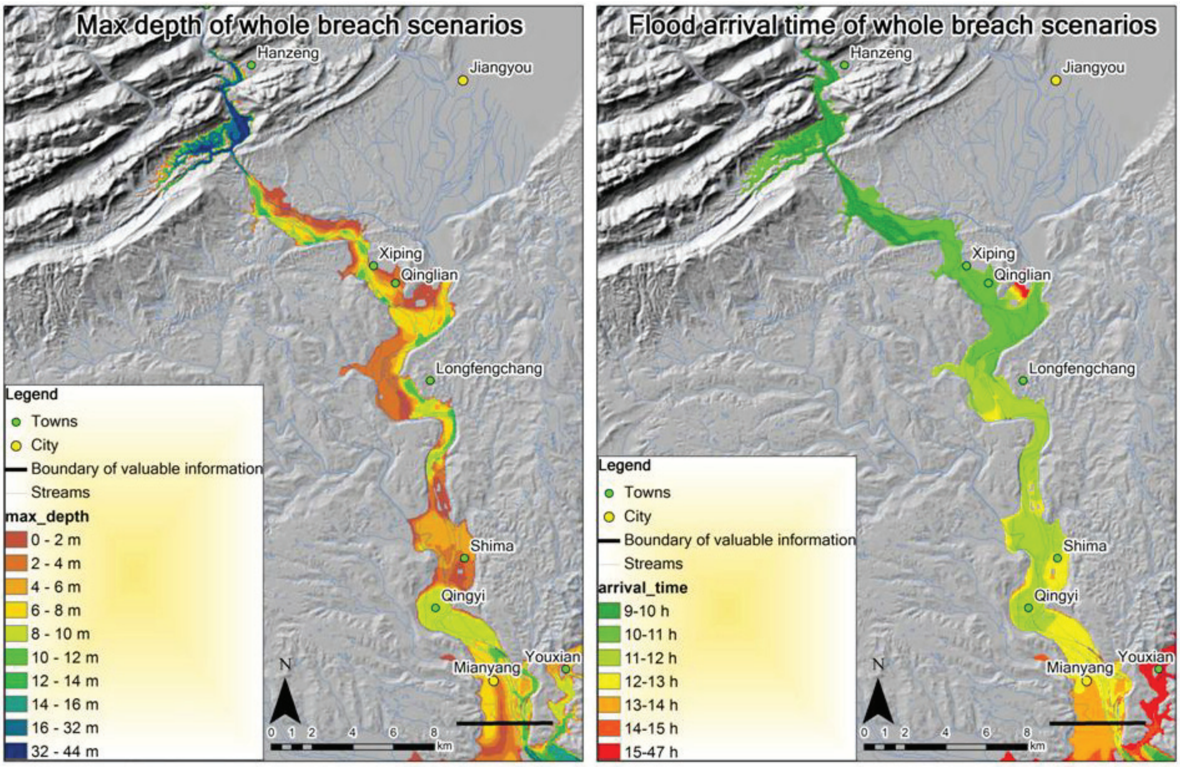

Fig.26 Max depth and arrival time of the scenario (5): dam break flood of whole dam breach scenario. The black line at downstream seperates the useful imformation (upstream) and the area affected by the downstream boundary condition apart.

6. CONLUSION AND DISCUSSION

6.1. Conclusion

In this study, dam break flood simulation of the Tangjiashan landslide dam has been carried out by combining physically based BREACH model and 1D-2D flood simulation SOBEK model. Different scenarios have been set up to study the characteristics of the dam break flood in different situation.

The method is first using BREACH model to calculate the outflow hydrograph of dam breach, then use these hydrographs as inputs for SOBEK 1D-2D flood simulation in the study area. There are 5 scenarios being simulated: (1) 2 years return period barrier lake inflow (1180 m^3/s) scenario, (2) 5 years return period barrier lake inflow (2190 m^3/s) scenario, (3) 20 years return period barrier lake inflow (3920 m^3/s) scenario, (4) the dam break naturally without the spillway scenario and (5) the catastrophic whole breach scenario. These scenarios are designed based on the document collected and the BREACH model mechanism. The setting of the scenarios not only shows the possible realistic dam break flood hazard and the most catastrophic one, but also gives ideas about how possible rainfall events increase the dam break flood hazard.

The realistic spillway scenario in June 2008 is used to calibrate the BREACH model to determine material properties, slope of the downstream face and lake inflow. The simulated spillway scenario can model the real situation relatively well. The simulated peak discharge of 6438 m^3/s show a good agreement with the observed record of 6500 m^3/s. The 24-h released-volume is simulated to be 1.88×10^8 m^3, which also matches well with the observed record of 1.7×10^8 m^3. The result duration of the quick release period and the erosion of the breach channel are not so good but still in an acceptable range.

The BREACH model gives outputs of outflow discharge of the dam break and erosion process of the breach channel. The peak discharge of the scenarios of 50 years return period barrier lake inflow, 20 years return period barrier lake inflow, 5 years return period, natural break scenario and whole breach are 26240.941 m^3/s, 29944.531 m^3/s, 35040.781 m^3/s, 20449.1 m^3/s, 62441.351 m^3/s, respectively, and the total amount water released are 4×10^8 m^3 (in 24 hours),4.8×10^8 m^3 (in 24 hours),6.4×10^8 m^3 (in 24 hours), 3.06×10^8 m^3 (in 36 hours), 3.14×10^8 m^3 (in 24 hours)respectively. The BREACH model results show that the spillway made in 2008 significantly reduced the dam break flood hazard of the Tangjiashan landslide dam. Compared with the natural break scenario, the peak discharge is reduced by 68.5% and the released volume decreased by 61.4% by the spillway. The time of peak discharge taken place is also delayed by 15 hours. Thus, it has a very good effect on reducing the dam break flood hazard. The high inflow caused by possible rainfall will increase the dam break flood hazard greatly, and the time for taking mitigation measures will be shortened.

Sensitivity analysis has been done on the input parameters of BREACH model. The model discharge increase and decrease are mainly controlled by change rate of lake water level and change (ΔH) rate of breach bottom (ΔH_c). When $\Delta H > \Delta H_c$, the discharge decreases. When $\Delta H < \Delta H_c$, the discharge increases. When $\Delta H = \Delta H_c$ the discharge stays the same, and this is the time at peak discharge or the stabilized flow after the dam breach. The most sensitive parameters are: inflow of the lake (Q_i), Slope (S), Mass (ϱ), and porosity (P_{or}). Among these parameters, Qi changes the hydrographs by change both ΔH and ΔH_c while S, ϱ, P_{or} changes the hydrographs by modifying ΔH_c. This can provide better design options of the mitigation spillway. The sensitivity analysis of the spillway related parameters indicate that the spillway with the deep, wide and gentle gradient will help on reducing the erosion and incision, therefore can play a good effect on control the flood.

SOBEK 1D-2D simulation shows the discharge, water depth, velocity of the dam break flood will decrease with the increase of the distance from the dam site. The depth, velocity are much higher in the mountainous valley area from the Tangjiashan landslide dam to the upstream of the Xiping town than in the downstream plain area. Comparing all the five scenarios, the higher the peak discharge is, the larger areas will be flooded, and the flood flow will be faster and deeper. The most catastrophic whole breach scenario (scenario (5)) results in a dam break flood covers 6.5×10^{7} m^2, and its average max velocity is 2.9 m/s and average max water depth is 7.09 m. In the 2D simulation area, the Xiping, Qinglian, Shima, Qingyi towns and the Mianyang city are flooded in different level in all of the secnarios. The Qingyi town has the most severe flood in all scenarios. The Hanzeng town is slightly flooded in the 5 year and 20 years return period lake inflow scenarios (scenario (2) and (3)). The upstream valley area is seriously flooded in all of the scenarios other than the spillway scenario. The results of 1D-2D modelling provide reference for the spatial planning of evacuation and embankments construction for the downstream area.

Besides the BREACH and SOBEK modelling, a relation between lake water level and volume of the Tangjiashan barrier lake is built by calculate with the 25m DTM. The method is using different lake water level subtract with the barrier lake area in DTM, and then calculate the volume by depth multiply with the coverage area of the lake surface. This method can be used on estimating the time for a landslide dam wil be overtopped with a given inflow to the lake.

6.2. Limitations

The BREACH model is designed for the earthen fill dam. Although it has been used in simulating the dam break flood of many landslide dams, the model still needs some improvements to make it more suitable for the rockslide-formed dam with very large grain size, like Tangjiashan landslide dam.

The BREACH model has some simplifications that might lead to the unrealistic results in some cases. For example, the slope of the Tangjiashan landslide dam consists three parts with different gradients, but in the model the slope is assumed only has one gradient. Besides, instead of simulating with different material of the layers of the landslide body, single parameters are used for the whole dam body.

In the 1D part of SOBEK 1D-2D simulation, the channel is controlled by the cross sections, so some of the topographies of the river might be missed, e.g. the branches and some small islands in the middle of the river. There are three hydropower stations along the river, which area also not considered due to time limitation.

In the 2D part of SOBEK 1D-2D simulation, although the DTM has been improved by fill sinks and adding embankments, some terrain changes by intensive sand mining and replacing old embankments are not clear. Due to the SOBEK 2D overland flow model is not sufficient for a precise simulation for big area. The resolution used is 50m and time interval is 10 minutes, and the model takes about 24 – 36 hours to finish simulating of one scenario. 25m resolution DEM was used but the model crashed after 2 days.

There were some small landslide dams located at the downstream of the Tangjiashan landslide dam. They can cause cascading effect in case of the Tangjiashan landslide dam breached, and increase flood hazard in downstream. The cascading effect is not considered in the modeling.

The BREACH model cannot simulate the time from the start of overtopping to the peak discharge taken place, which is 35.3 hours in the simulation result and about 77.5 hours in realistic. This is mainly caused by simplification of the downstream slope and complex realistic situation in June 2008. In the real situation, the downstream face slope of the spillway consists three parts with different gradients. At the barrier lake side of the breach channel the slope of the spillway is only 0.6%, and this can result in very slow channel erosion at the beginning.

6.3. Recommandations

The sensitivity analysis of the spillway related parameters will contribute on optimizing the spillway design. The results indicate that the spillway with the deep, wide and gentle gradient will help on reducing the erosion and incision, therefore can play a good effect on control the flood.

The integrated approach combining the BREACH model and the SOBEK model is proved to be able to produce good results and will help on the dam break flood hazard mitigation planning and hazard prevention.

The remaining lake has a water level of 712 m. The local government started constructing several dykes along the river in downstream areas. In some parts even the river channel is narrowed by dykes or town expansion. This would result in a deep water depth and more elements at risk in the possible flooded area. It is better to have a good spatial planning than modifying the flood hazard by dykes and embankments.

In the study area, there are many sand mining activities along the river. These sand mining activities have greatly damaged the ecosystem of the river. This could cause unexpected flood hazard in the sand mining area by modifying the terrain.

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