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ESCAPE/WMO Typhoon Committee Roving Seminar, Vientiane, LAO PDR, Nov 4-6, 2015

Topic B: Part 2
Disposal of earthquake-triggered barrier dams in mainland China

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Contents

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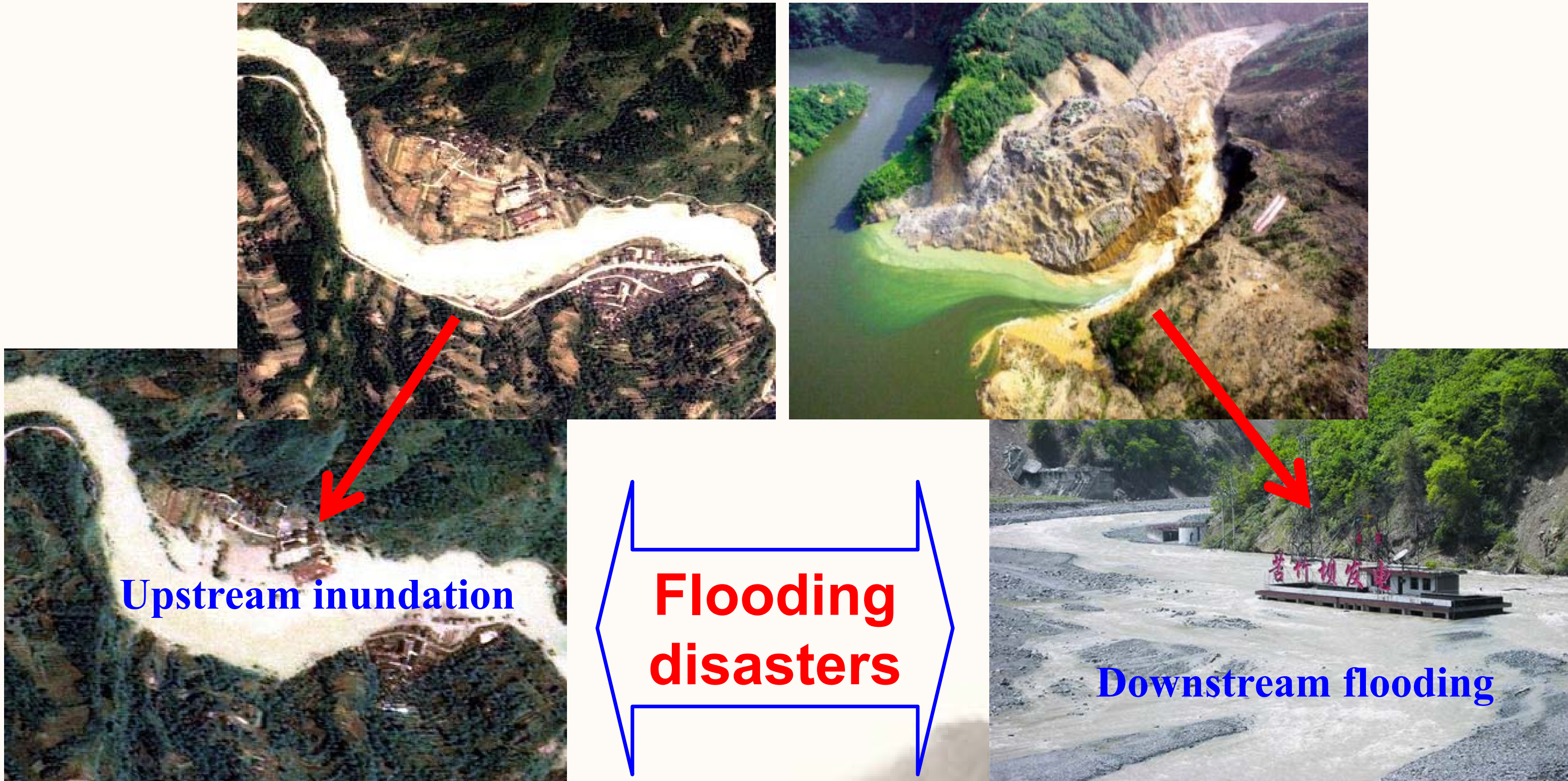
Why barrier dams?

Flooding hazards raised by the Tangjiashan barrier dam
during the “May 12, 2008” Wenchuan Quake

Tangjiashan Barrier Lake



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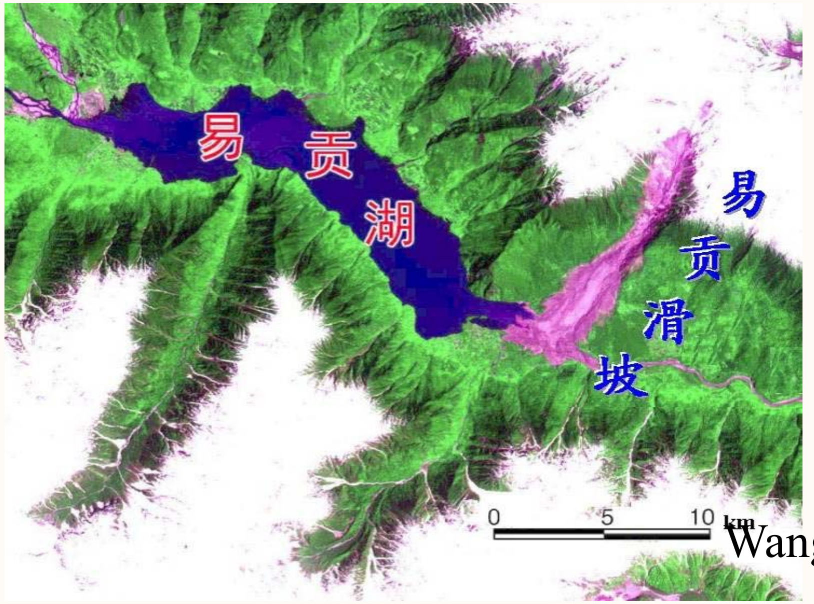
Why barrier dams?

Yigong Zangpo barrier dam (2000, Tibet)

the known largest peak discharge in the mainland



Wang (2015)

Yigong landslide in 2000 → barrier lake (storage 2.9 billion m^3)
→ Outburst peak discharge (124 thousands m^3/s)
→ The air surge leveled off trees above the channel on both sides

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Why barrier dams?

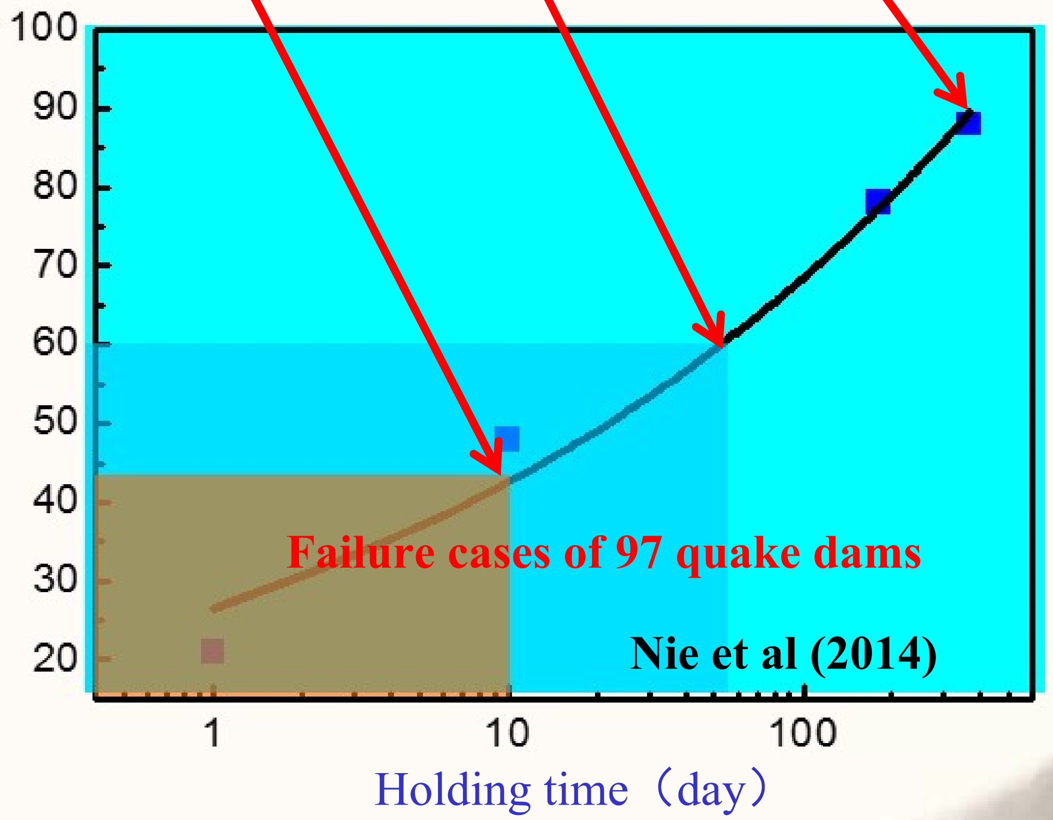
Dam failure: Overtopping or piping

43% failed in 10 days

60% failed in 2 months

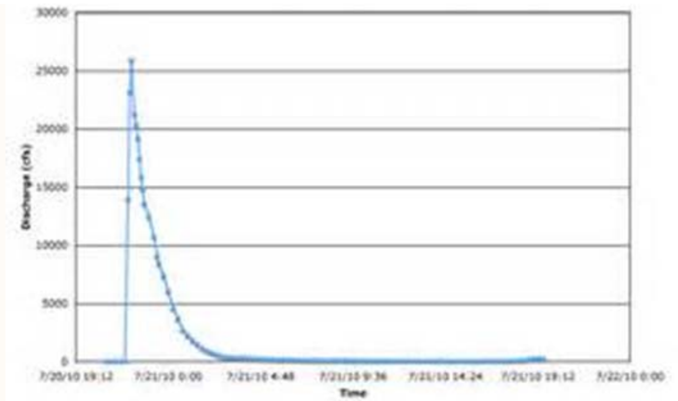
90% failed in 1 year

Dangerous



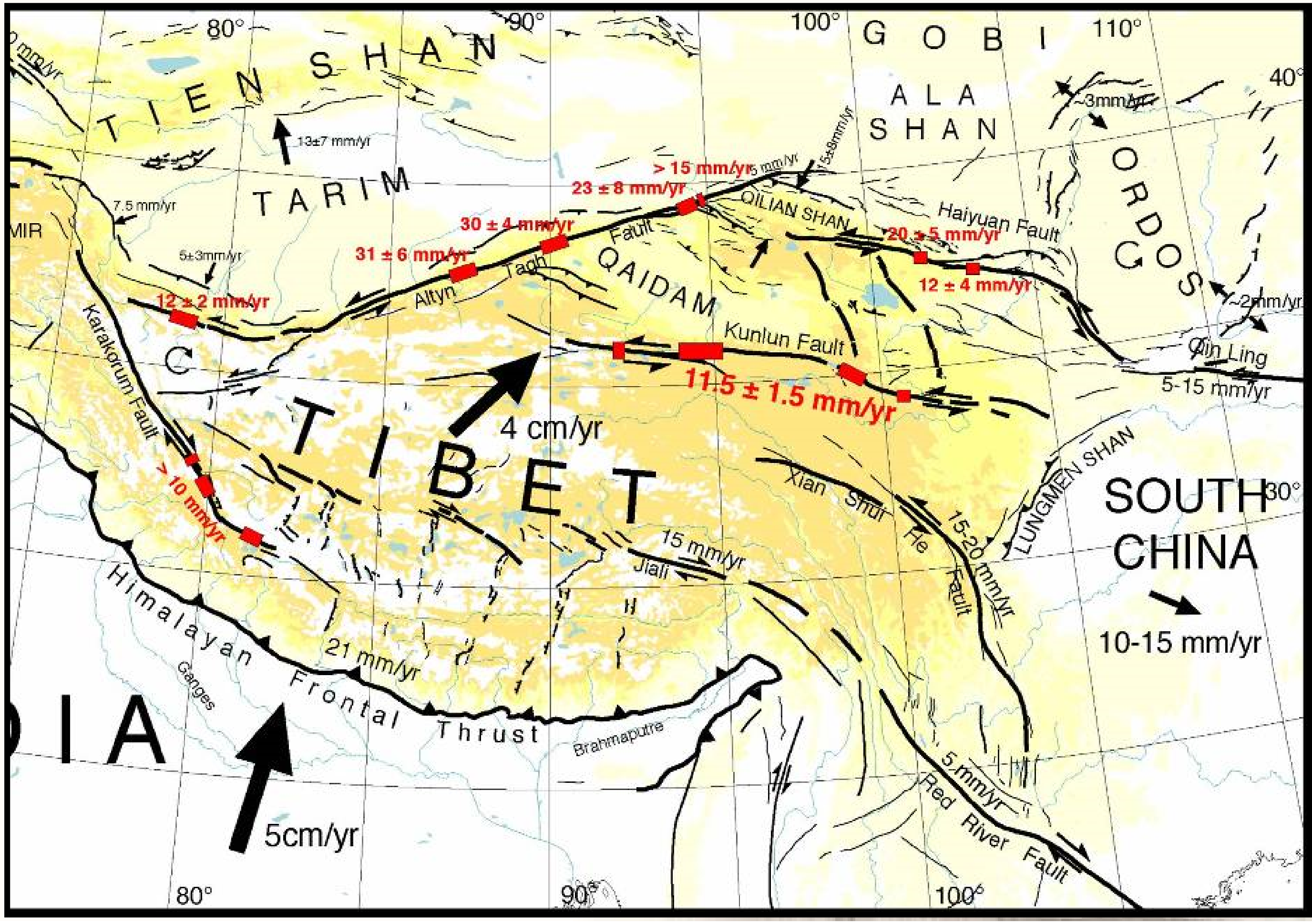
Dam-failure flood

Duration: several hours



Why earthquake-triggered?

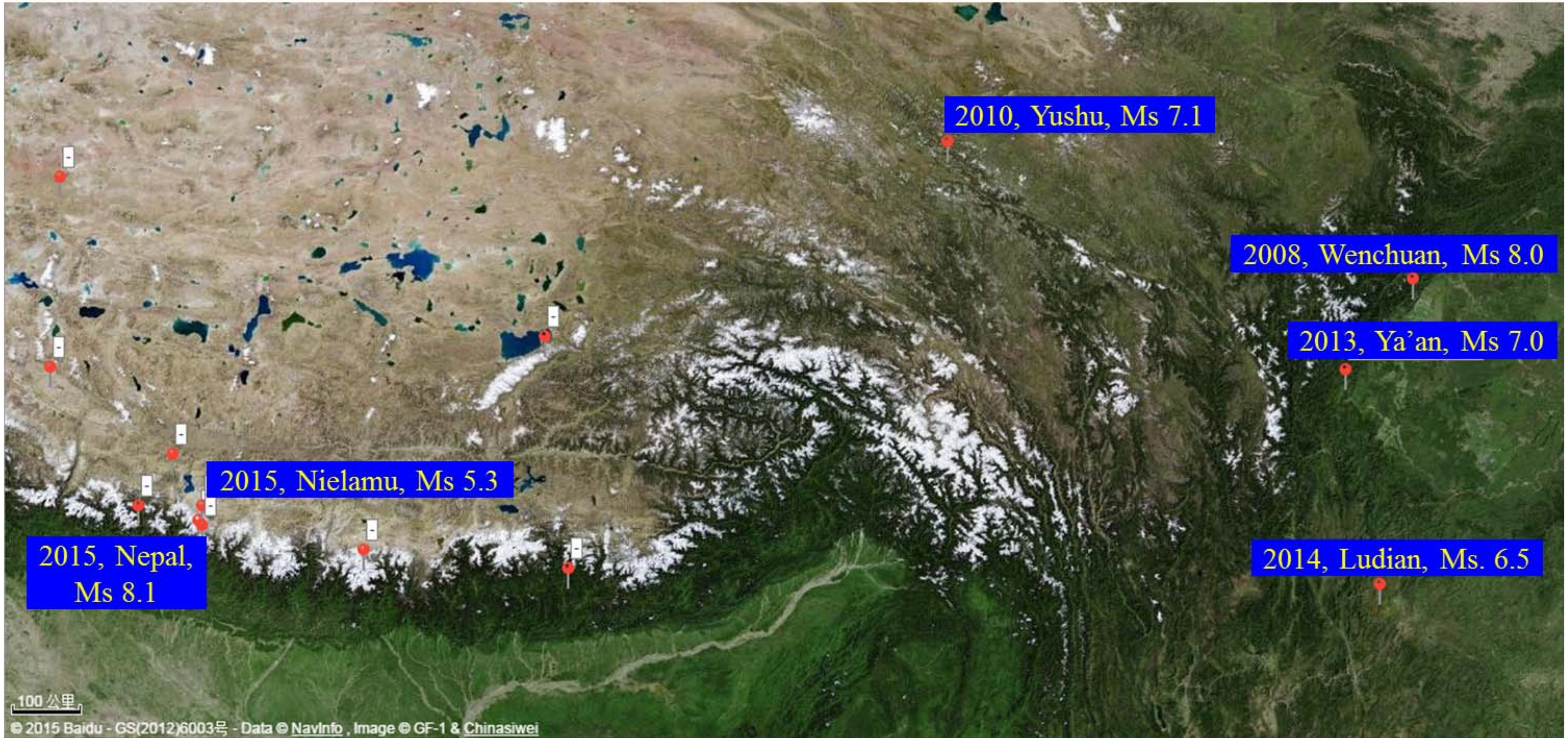
India Plate: moves northward and collides with the Euroasia Plate
Qinghai–Tibet plateau: Continuous uplift (i.e. tectonic uplift)
Yalutsangpo River: Continuous incision



Why earthquake-triggered?

Earthquake larger than Ms 6.0 since 2008

（Data source： http://www.csi.ac.cn/publish/main/813/3/index.html）



Wenchuan Earthquake in 2008: Ms 8.0

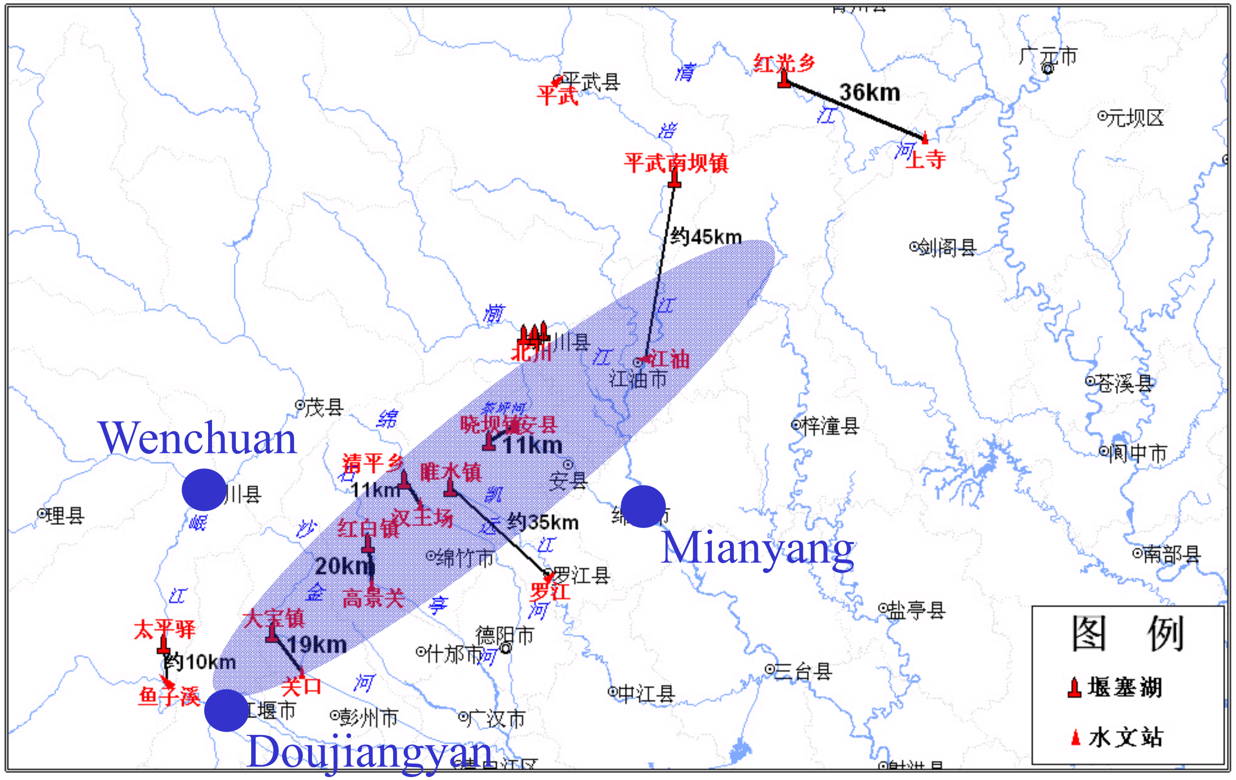
Ludian Earthquake in 2014: Ms 6.5

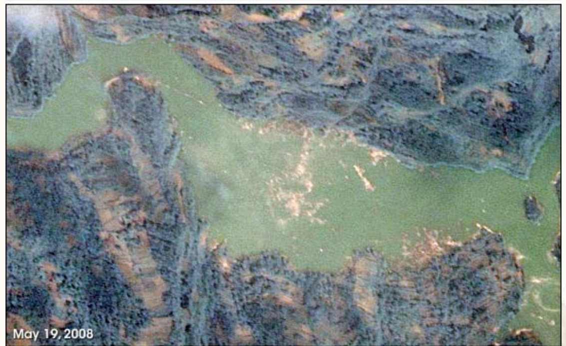
Why earthquake-triggered?

Dam clusters in a area

Wenchuan Earthquake (2008)

- **34** quake lakes and **9** blocked rivers.
- **20** were in moderate or high-risk of dam failure.





http://earthobservatory.nasa.gov/IOTD/view.php?id=8765

Why earthquake-triggered?

Dam chains along a river

Potentially a chain of dam failure
in Wenchuan Earthquake (2008)

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Features of emergency

One barrier dam → dangerous
Cluster/chain of barrier dams → much more dangerous

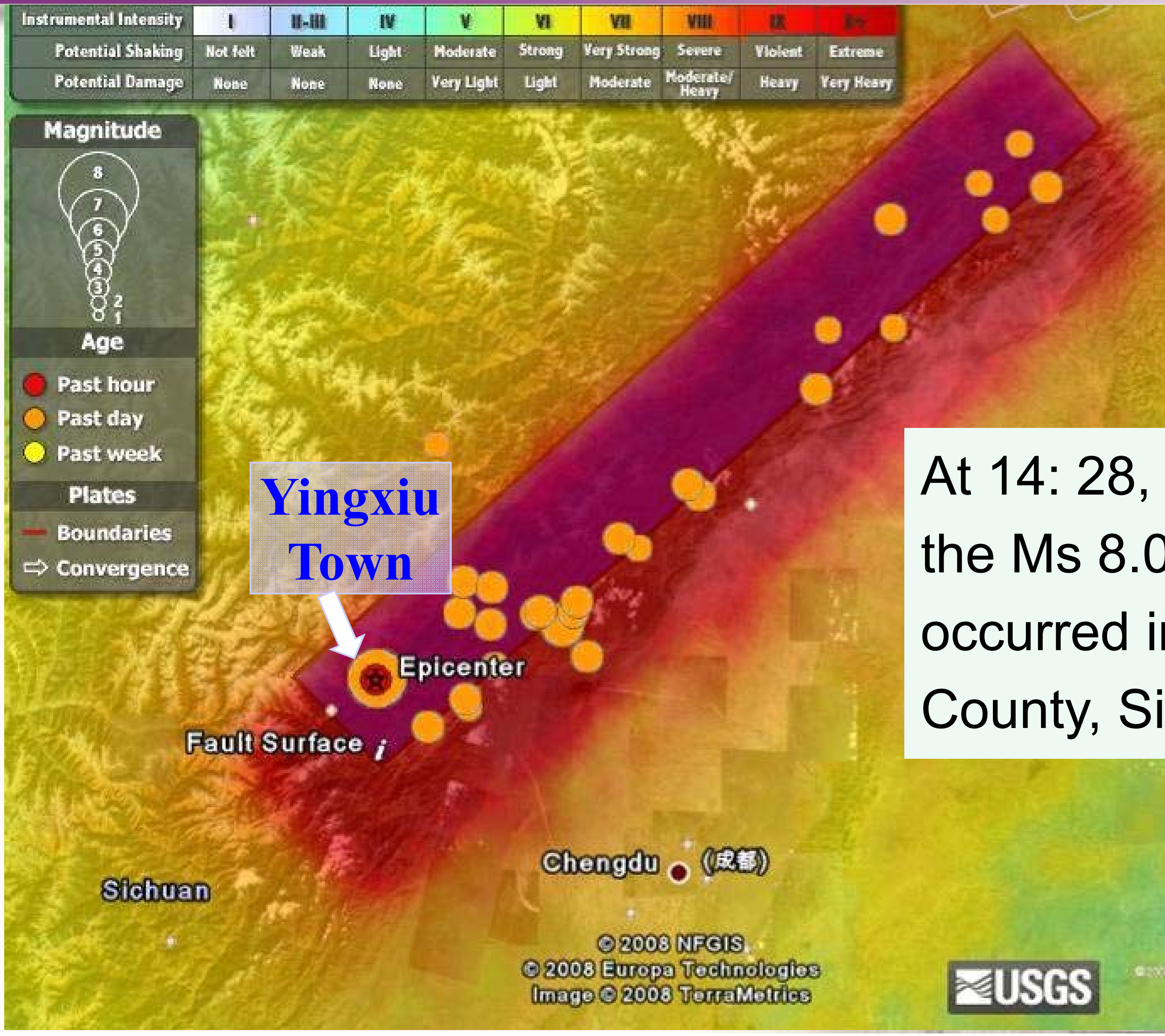
Emergency: **➔How to do?**

1) **Limited time** for risk analysis and hazard mitigation
2) **Increasing risk** with time
3) **Lack of field data**

Field data (topographical, geological, hydrological…)
- difficult to get access to or bring in equipment
- existing gauge stations were damaged

Contents

2.1 Overview



Wenchuan earthquake (2008)

At 14: 28, May 12, 2008, the Ms 8.0 earthquake occurred in Wenchuan County, Sichuan, China.

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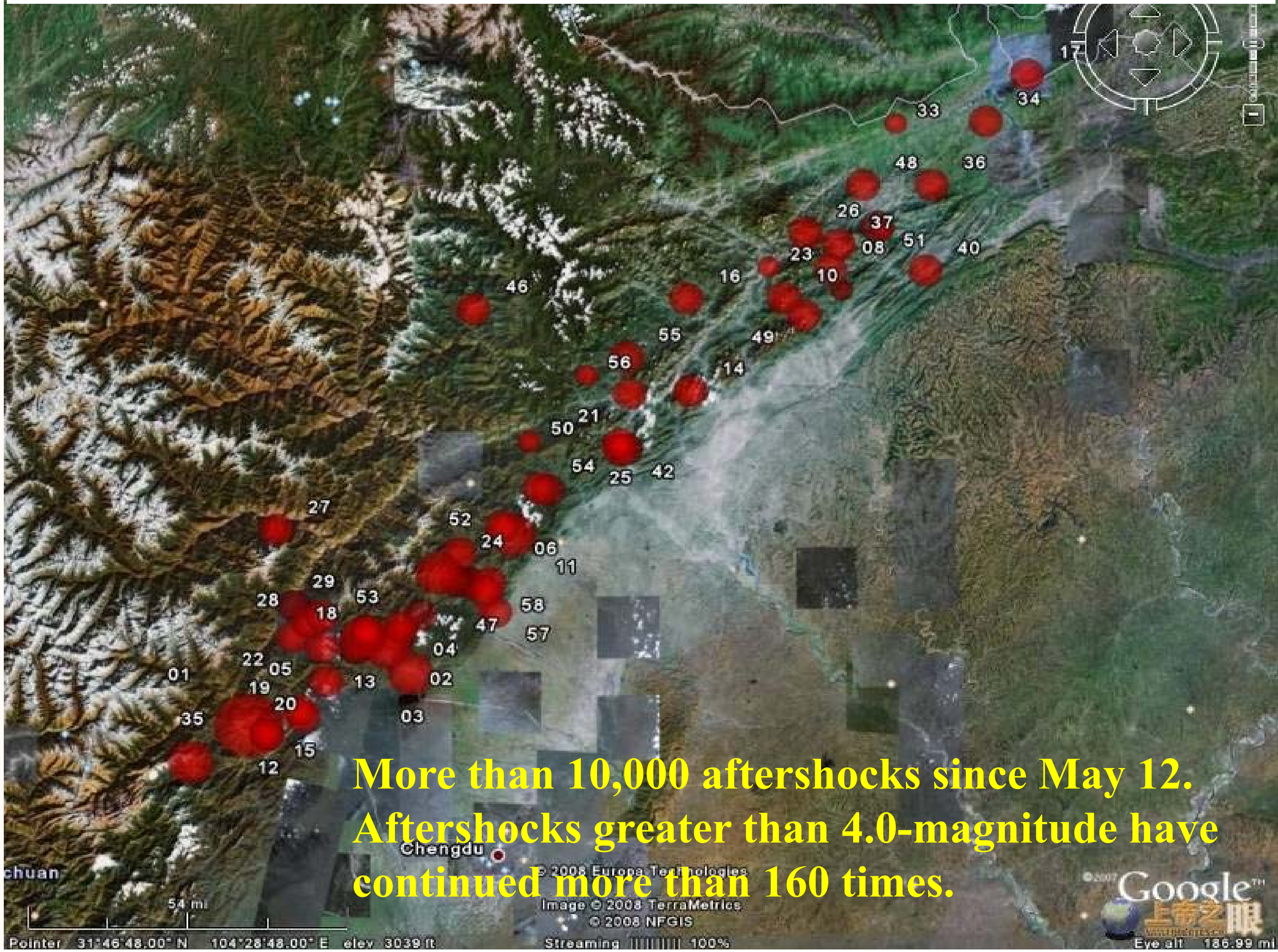
2.1 Overview

Distribution of the main shock and aftershocks



More than 10,000 aftershocks since May 12. Aftershocks greater than 4.0-magnitude have continued more than 160 times.

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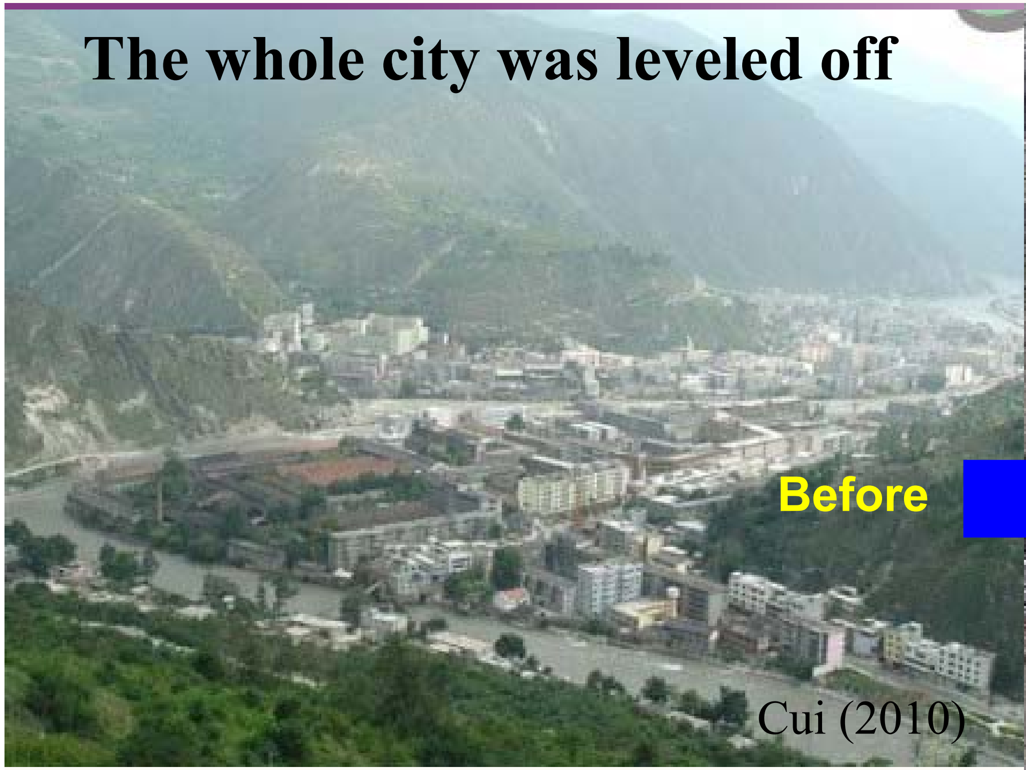
2.1 Overview



Wenchuan City

before and after the earthquake

2.1 Overview

Beichuan City
before and after
the earthquake

2.1 Overview

Cui (2010)

Earthquake and landslides destroyed the old city.

Old city of Beichuan after the earthquake

2.1 Overview

Yingxiu Town

the epicenter area

before the earthquake

Yingxiu Town

after the earthquake

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2.1 Overview

Subsequent flood hazards

caused by barrier lakes

Landslide dams

More than 30 unstable quake lakes

Tangjiashan dam on the Jianjiang river, Beichuan County

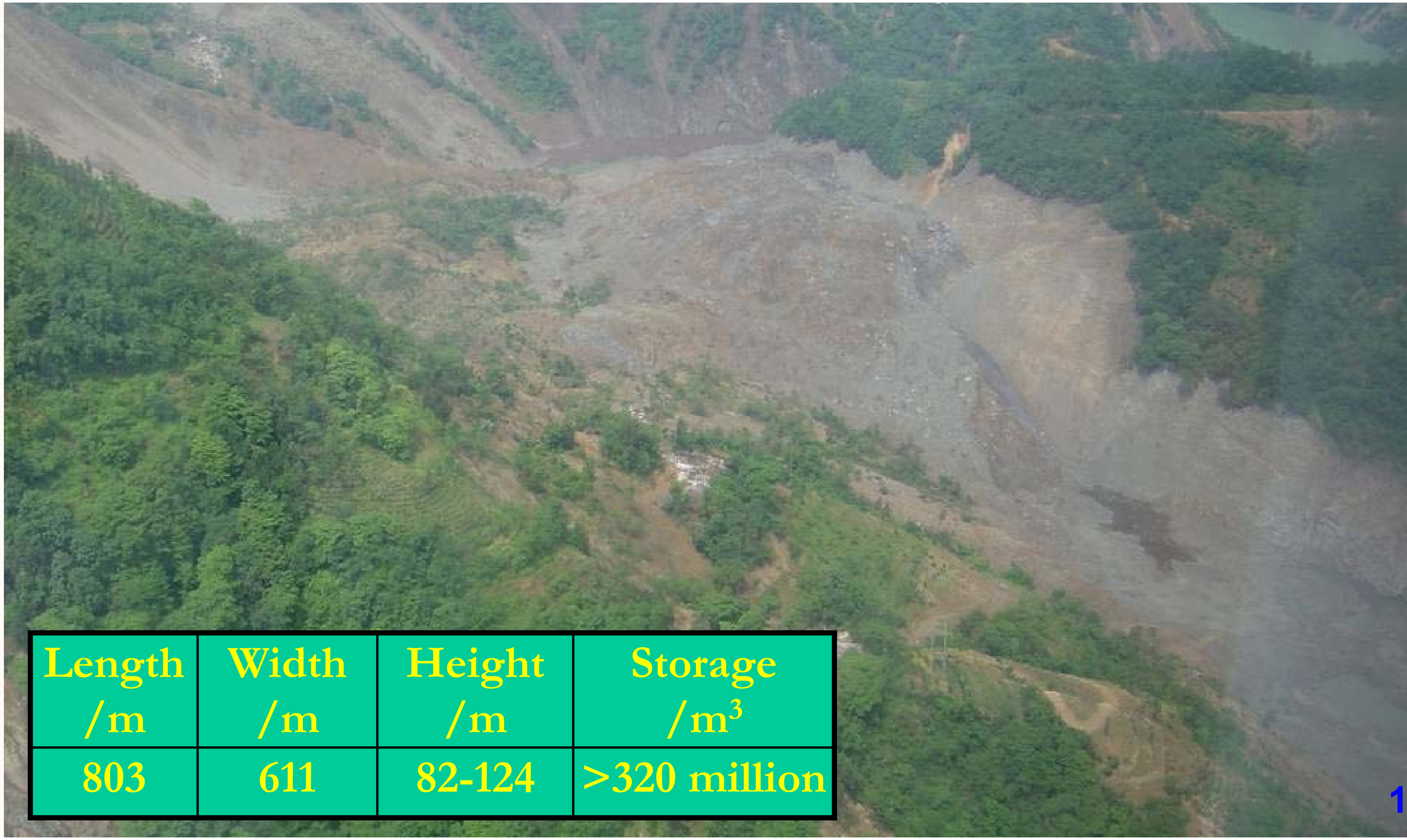
Xiaojiaqiao dam on the Chaping river, An County

2.1 Overview

Tangjiashan barrier dam

on the Jianjiang river, upstream of Beichuan City

The largest and most dangerous quake lake



Length /m	Width /m	Height /m	Storage /m^3
803	611	82-124	>320 million

2.1 Overview

Xiaojiaqiao barrier dam
on the Chaping river, An County
The second largest quake lake

Xiaojiaqiao landslide

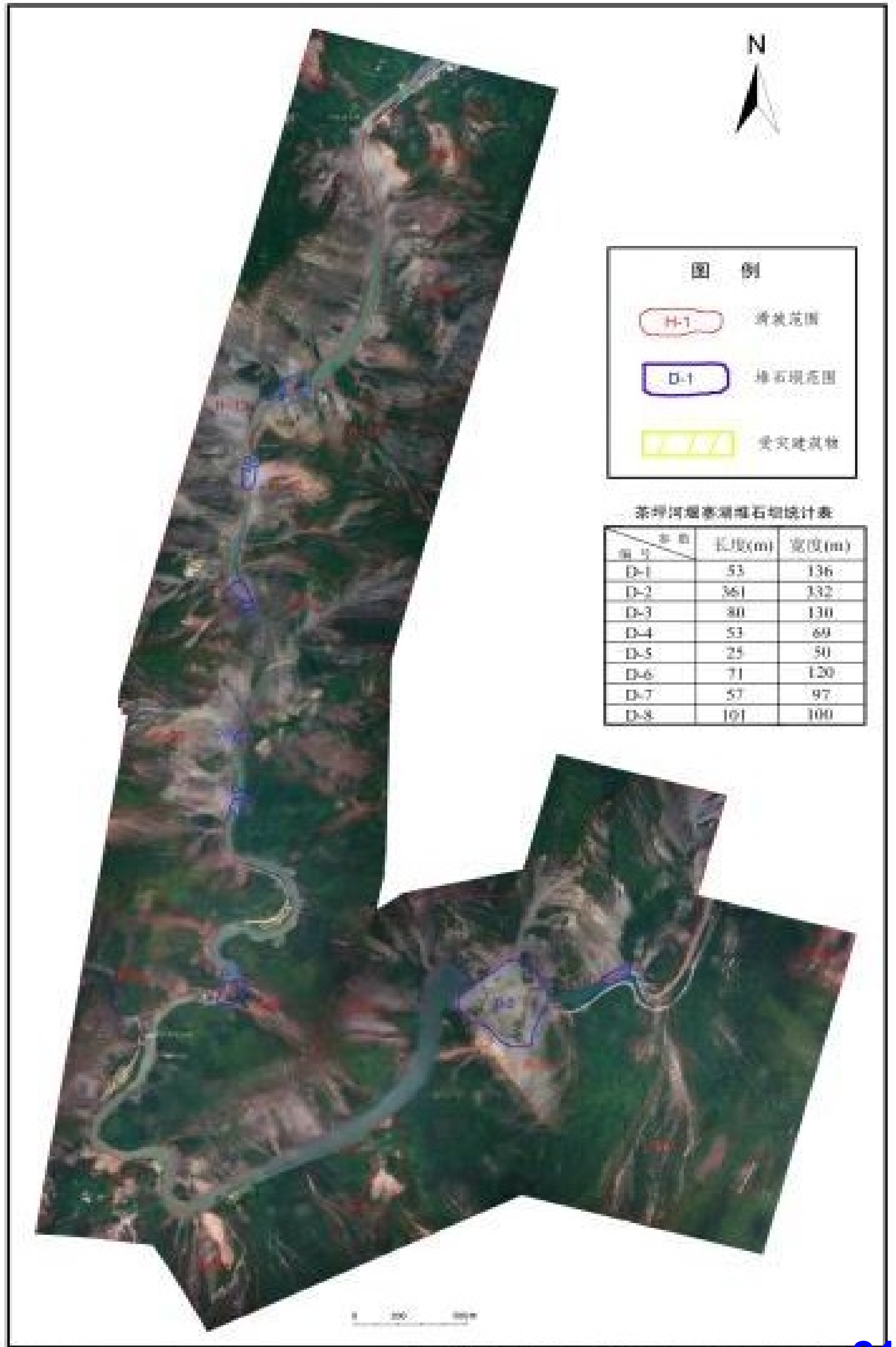
Length /m	Width /m	Height /m	Storage /m^3
272	198	67	>10 million

Xiaojiaqiao Quake Lake

Lake chain:

9 quake lakes formed in 10-km reach of Chaping river, An County.

The chain of lakes would have more horrible threat than one lake.



	长度(m)	宽度(m)
D-1	53	136
D-2	361	332
D-3	80	130
D-4	53	69
D-5	25	50
D-6	71	120
D-7	57	97
D-8	101	100

航摄时间：2008年5月19日7点　　中国科学院遥感应用研究所与电子科技大学联合攻关

2.1 Overview

Emergent threat from unstable quake lakes

- **Increasing volume of inflow into the lake**
  the inundation of upstream areas
  the increasing risk of dam failure

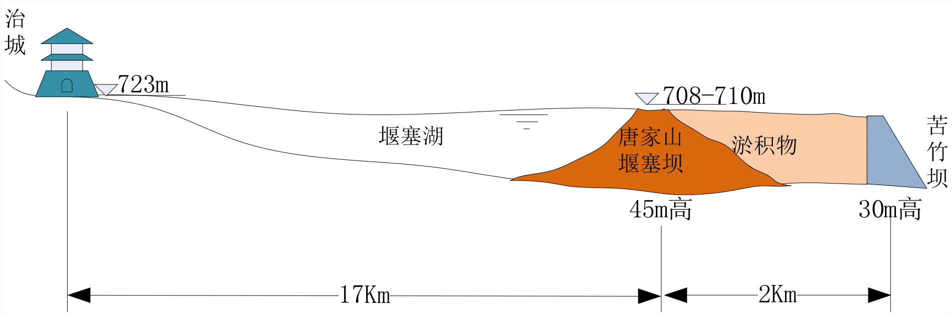
- **Heavy rainfall in upstream mountainous area and aftershocks**
  could cause dam failure leading to flash floods

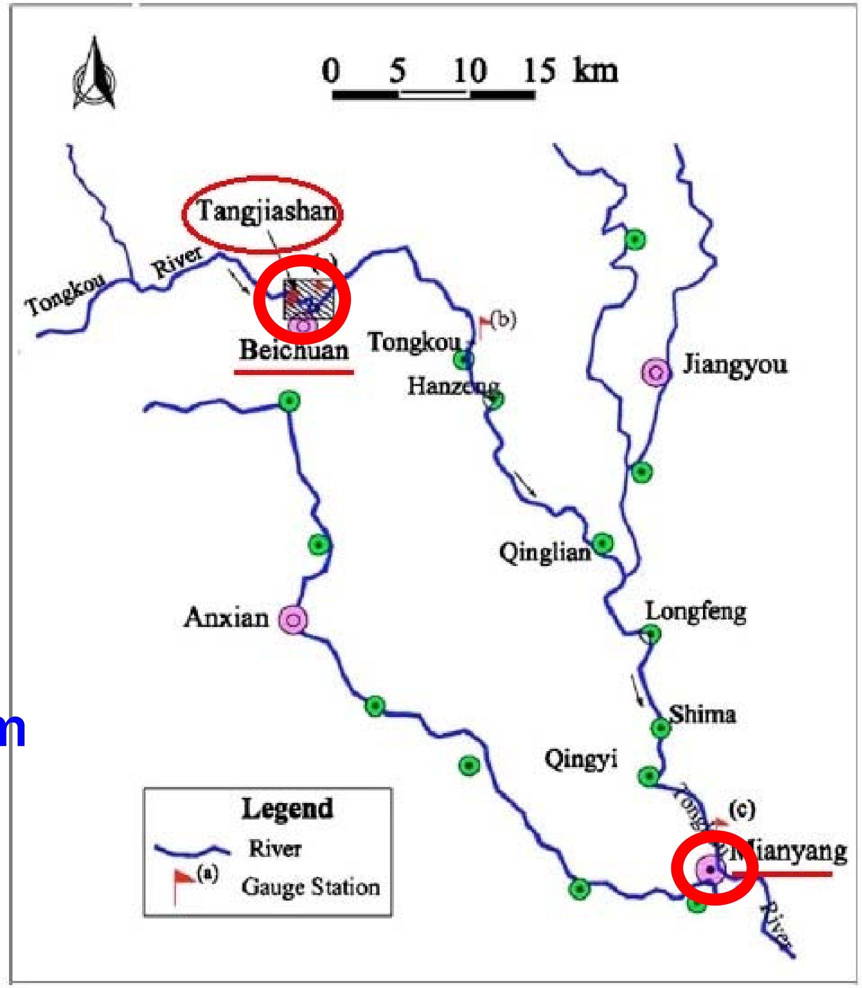
2.2 Tangjiashan dam

Tangjiashan barrier dam

Located on Tongkou River

◆ 17 km from Zhicheng upstream





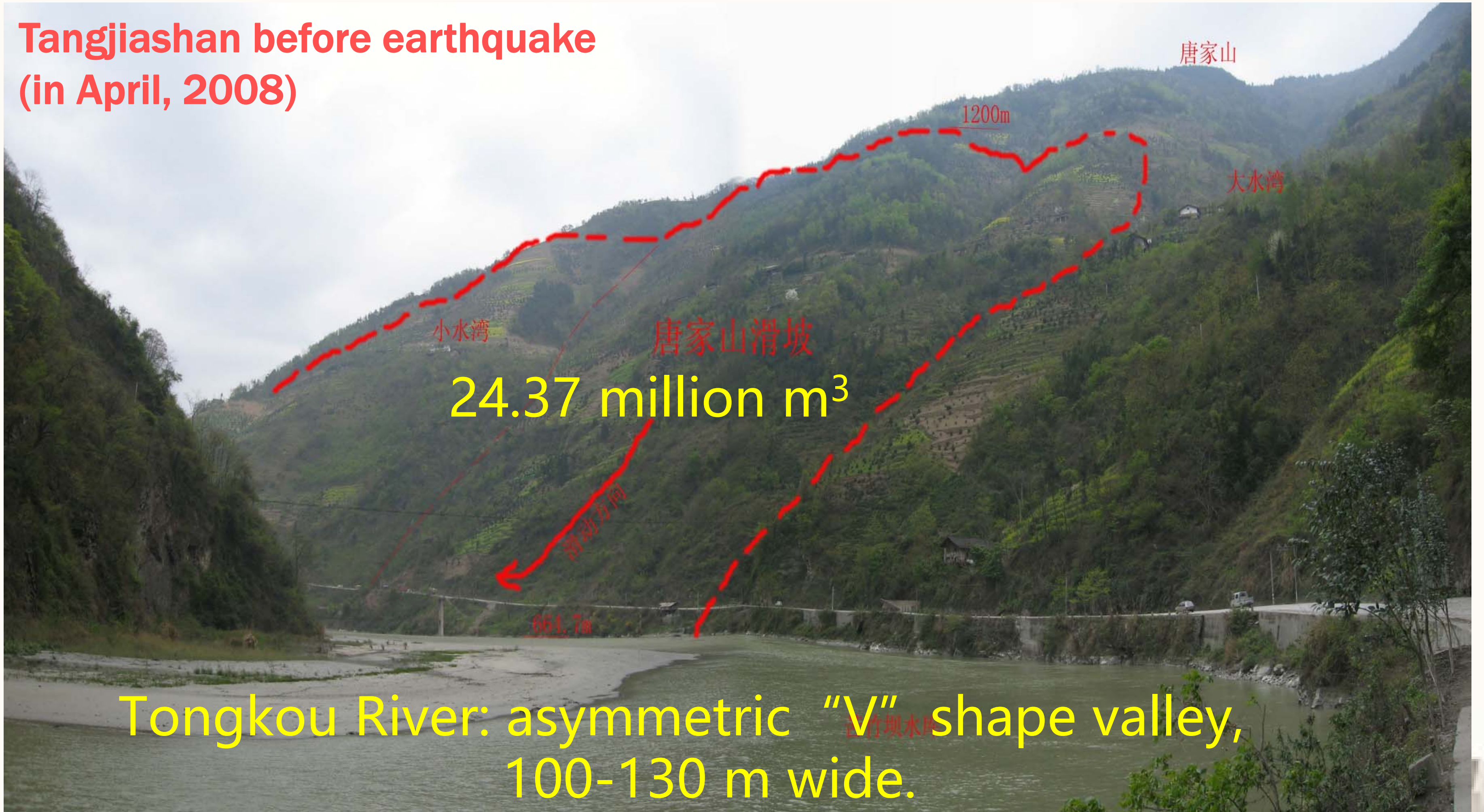
◆ 5 km from Beichuan downstream

◆ 70 km from Mianyang downstream

Mianyang City:
2,000,000 people
Second largest city in Sichuan Prov.

2.2 Tangjiashan dam

Tangjiashan before earthquake
(in April, 2008)



24.37 million m^3

Tongkou River: asymmetric "V" shape valley,
100-130 m wide.

By courtesy of J.X. Zhang

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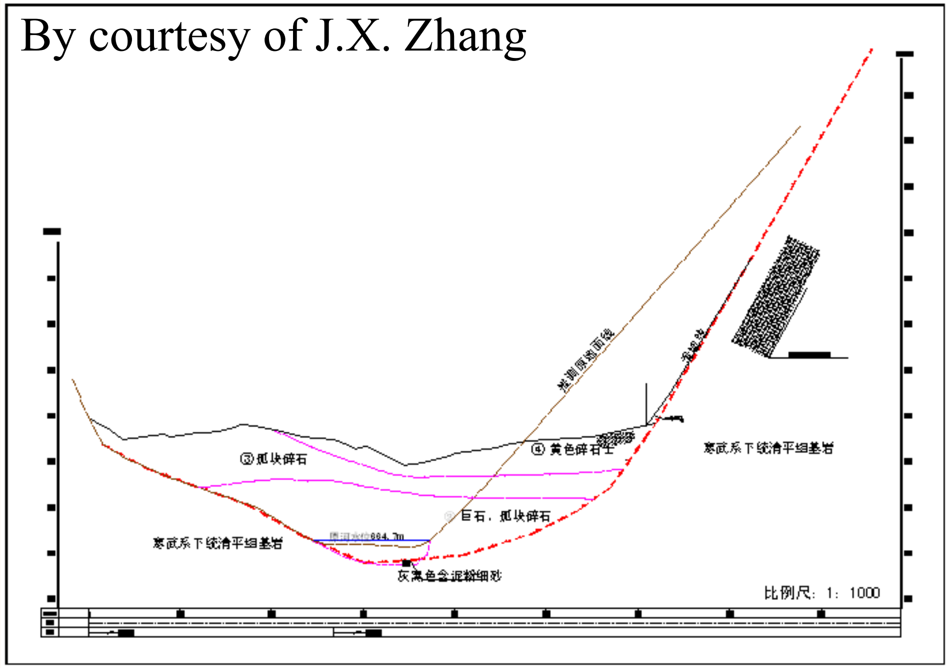
2.2 Tangjiashan dam

Volume of the landslide deposit	24.37×10^6 m^3
Elevations of crest/toe, measured at the highest crest surface of the left deposit	793.9/669.6 m
Elevations of crest/toe, measured at the lowest crest surface of the right deposit	753.0/663.0 m
Length along the river valley (bottom of the deposit)	803 m
Length across the river valley	611 m
Ratio of length over thickness near the left abutment	8.9
Covered area	3.07×10^5 m^2



唐家山堰塞坝工程地质横剖面示意图

2.2 Tangjiashan dam

Potential highest water level without intervention work	753 m
Potential storage of water without intervention works	326×10^6 m^3
Elevation of the original river bed	663 m
Area of the reservoir water surface	3,550 km^2

Tangjiashan Lake after earthquake (in May, 2008)

By courtesy of J.X. Zhang

2.2 Tangjiashan dam

Rising water level in the lake:

- ❖initial rate of 1.2 m/day, and final rate of 0.5 m/day
- ❖about 1 m/day on average

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2.2 Tangjiashan dam

Observed seepage hole: Possible piping failure

On May 29, a seepage hole was identified at the elevation of 700 m. The seepage flow rate was also increasing!

2.3 Disposal process

How to control flood and relieve disaster?

1) Dam safety & potential risk?

2) Hydrometeorological situation?

3) Hazard relief

   Mitigation planning

   Structural measures

4) Imminent forecast

2.3 Disposal process

1) Dam safety and potential risk assessment

Rapid matrix tabulation approach (three indices):

used for emergency case with insufficient data and time

Hazard Level	Storage Capacity/$10^6 m^3$	Material Composition	Dam Height/m
extremely high	>100	mostly soil	>70
high	10~100	soils with some boulders	30~70
moderate	1~10	boulders with some soils	15~30
low	<1	boulders	<15

Tangjiashan barrier dam: extremely high risk

Xiaojiaqiao barrier dam: high risk

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2.3 Disposal process

1) Dam safety and potential risk assessment

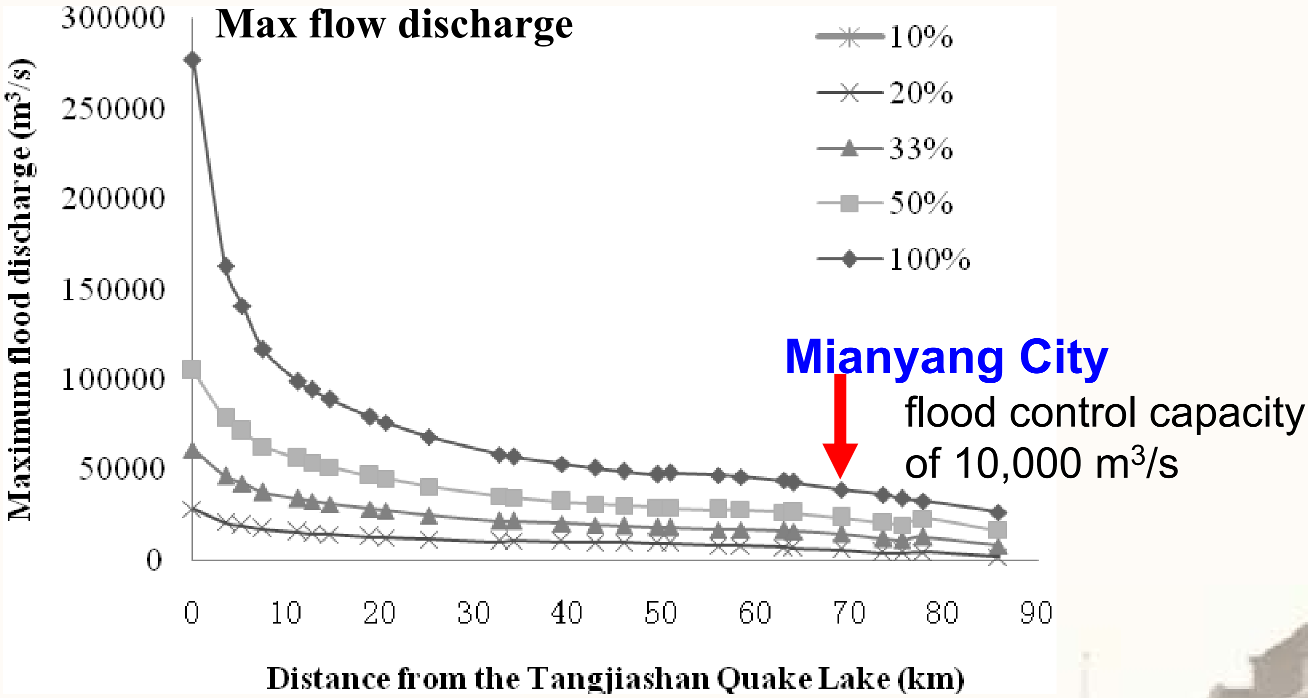
Dam failure analysis: Different failure scenarios

- For a single barrier dam, five scenarios were considered: 100%, 50%, 33.3%, 20%, and 10% of the dam collapsed instantaneously.
- Flood routing was implemented using a modified McCormack Scheme with artificial viscosity.

2.3 Disposal process

1) Dam safety and potential risk assessment

Dam failure analysis: Different failure scenarios

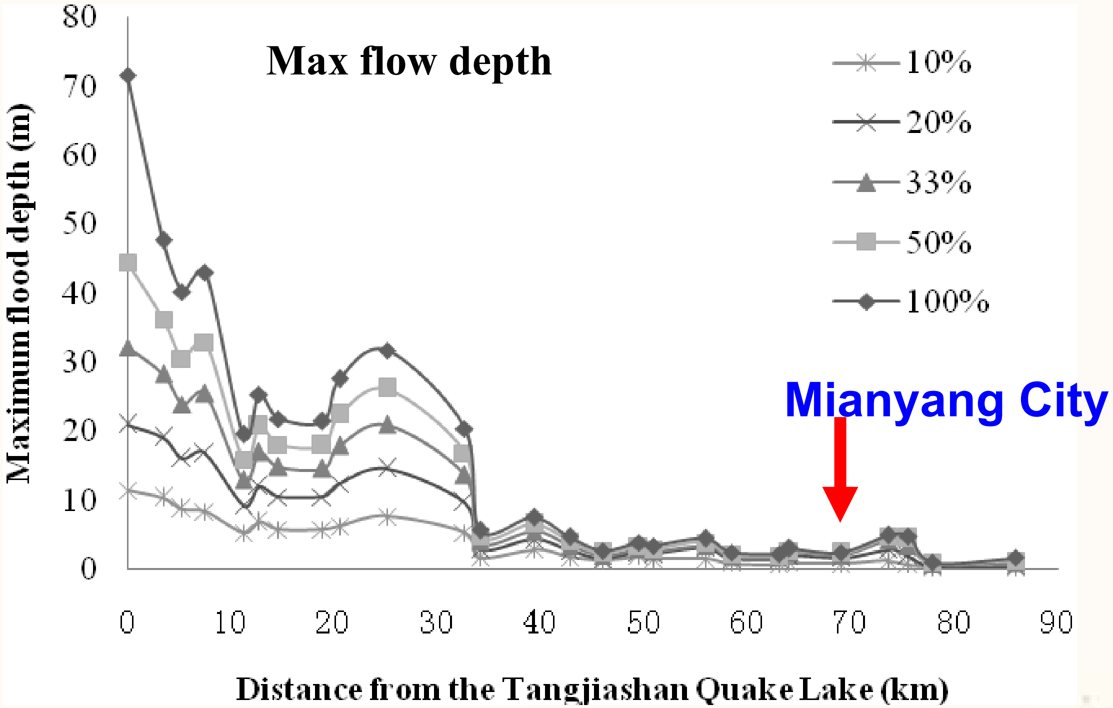


Distribution of peak discharge under different failure scenarios of the Tangjiashan barrier dam

2.3 Disposal process

1) Dam safety and potential risk assessment

Dam failure analysis: Different failure scenarios

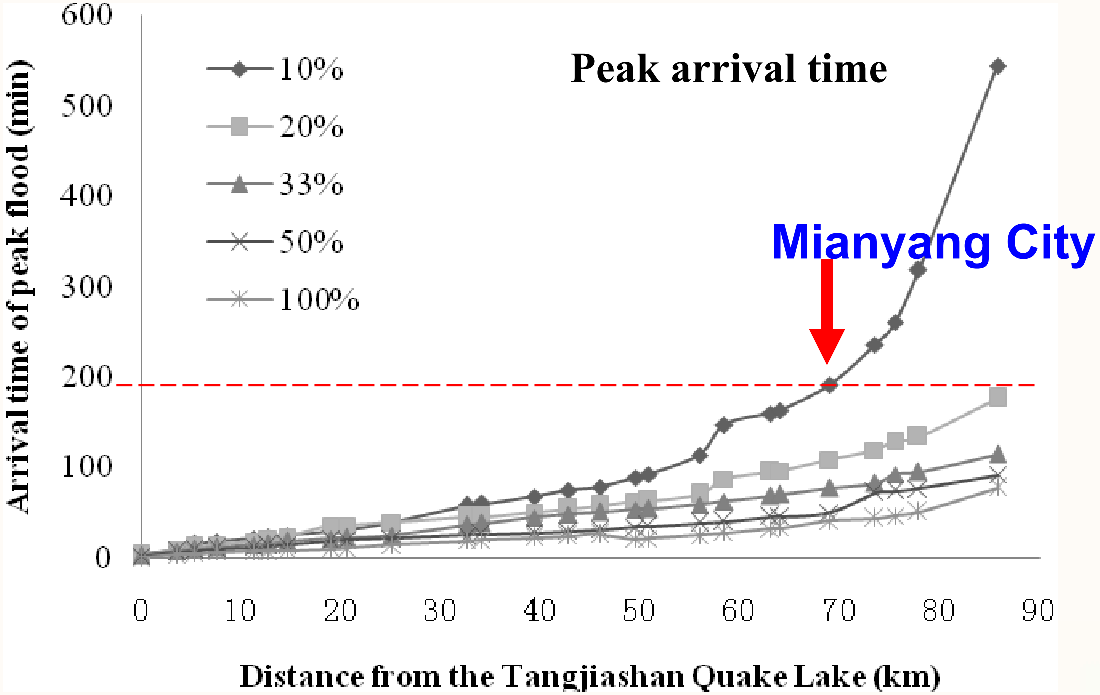


Distribution of maximum flow depth under different dam failure scenarios of the Tangjiashan Quake Lake

2.3 Disposal process

1) Dam safety and potential risk assessment

Dam failure analysis: Different failure scenarios



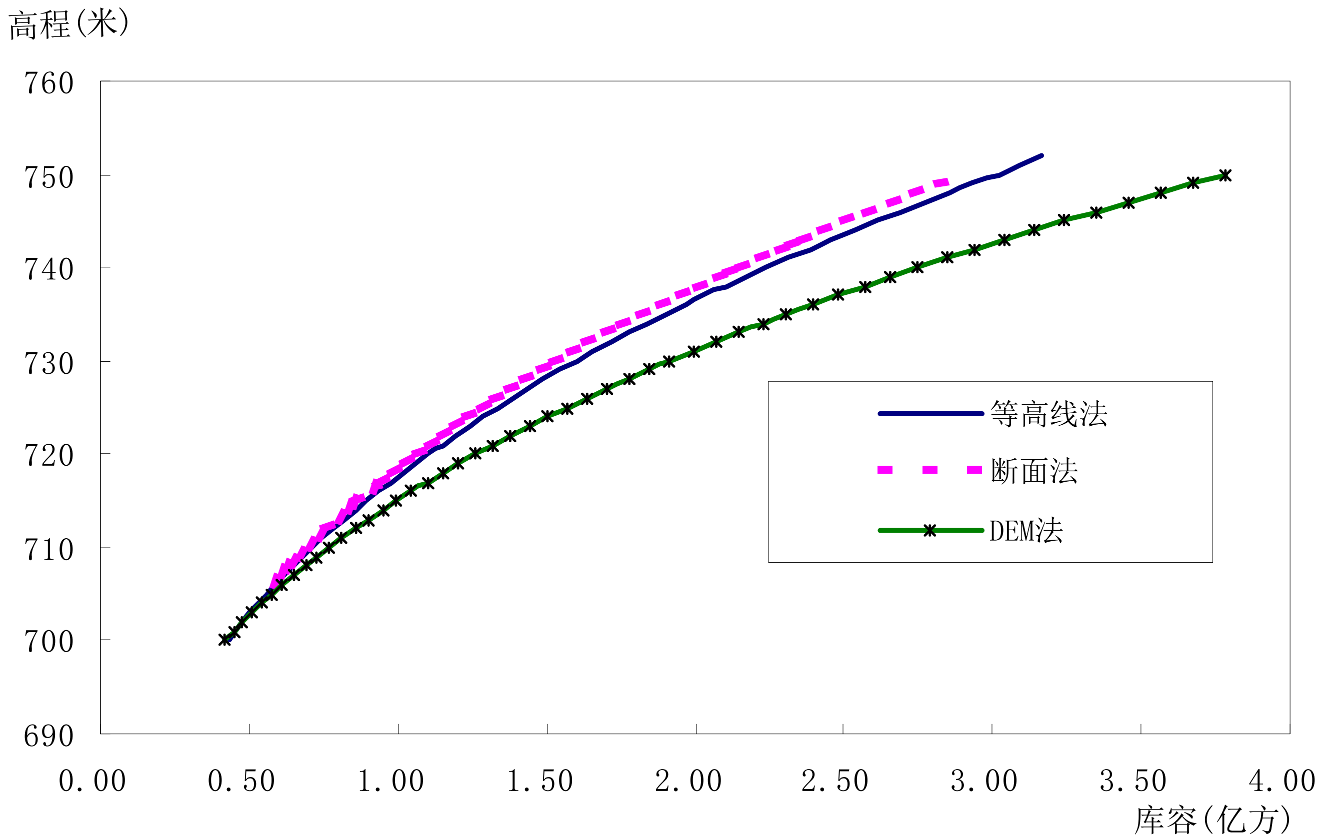
Distribution of arrival time of peak flow under different dam failure scenarios of the Tangjiashan Quake Lake

300,000 people evacuated

2) Hydrometeorological monitoring & forecast

Remote sensing: Overall information of quake lake…

On-site survey and monitoring: geological-hydrological data…



2.3 Disposal process

2) Hydrometeorological monitoring & forecast

Field monitoring:

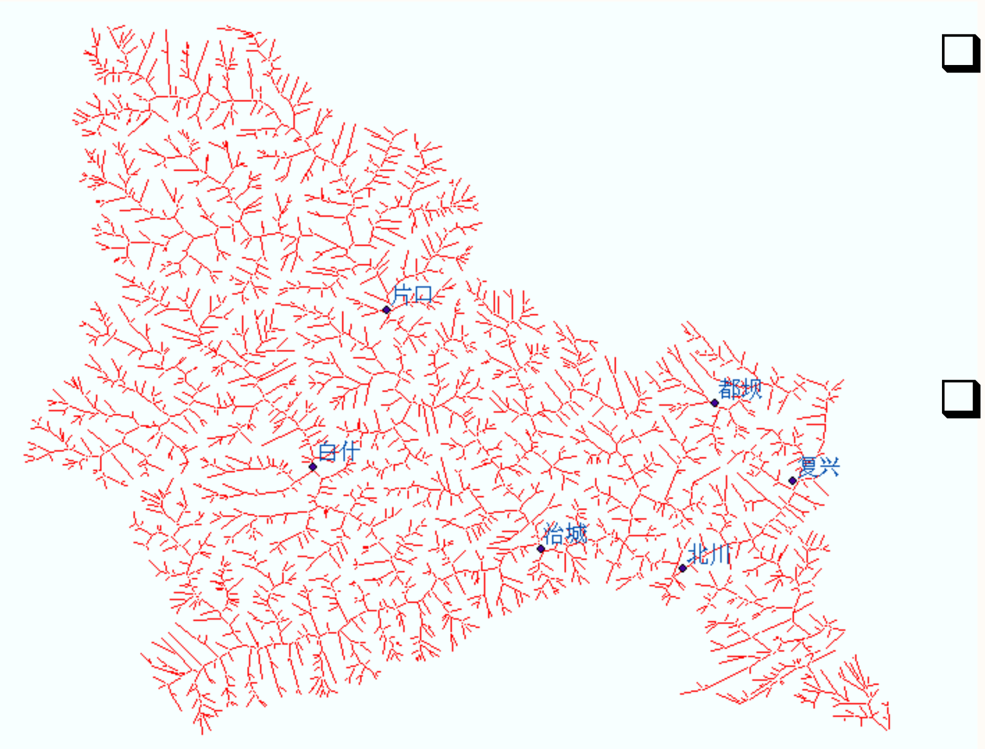
Obtain real-time data of rainfall, inflow, water stage, etc.

Hydro-meteorological monitoring network for Tangjiashan Quake Lake

2.3 Disposal process

2) Hydrometeorological monitoring & forecast

Rolling forecast: incoming flow based on weather forecast

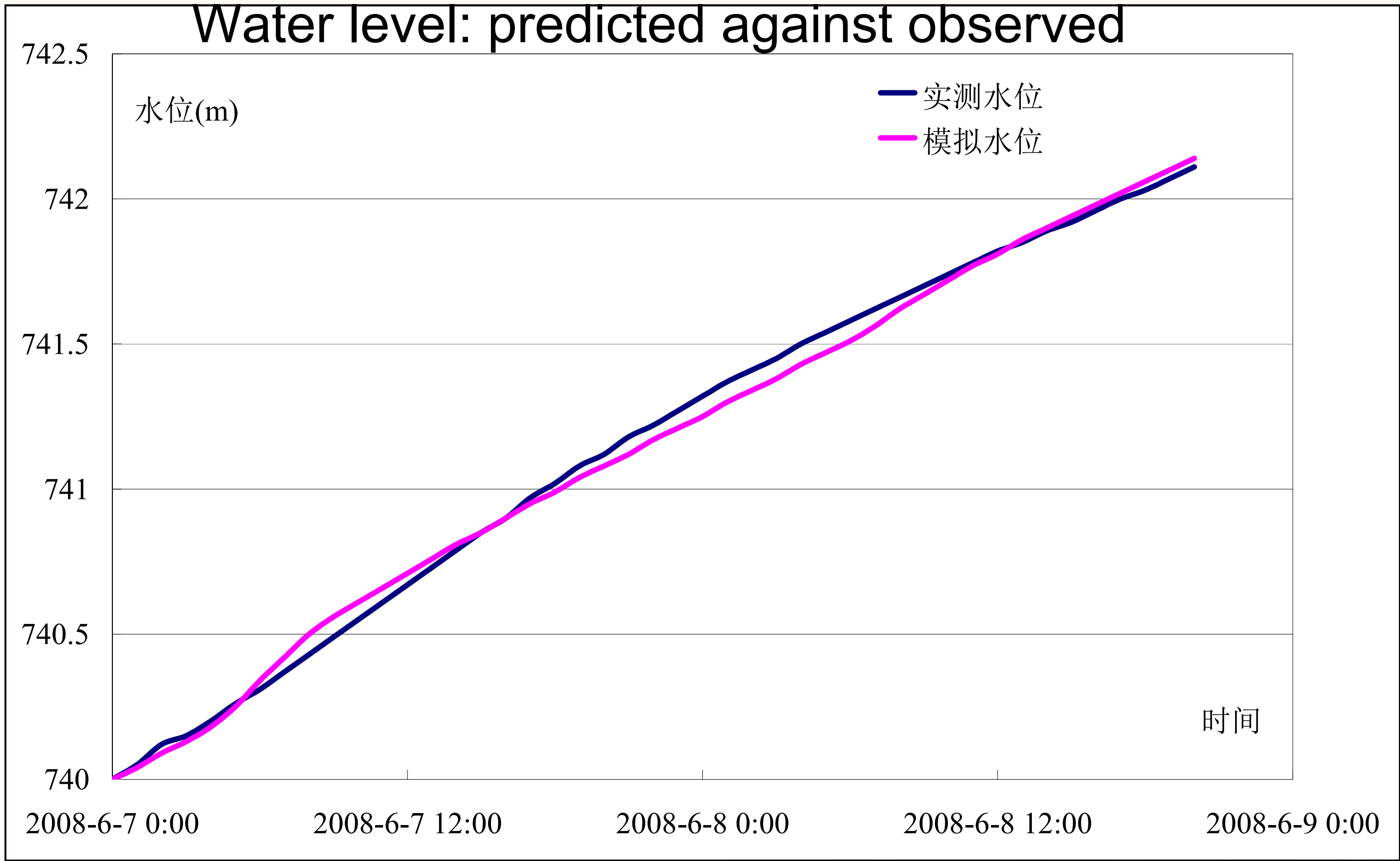


- In case of no rainfall
  - ☆ Only base flow was calculated
- In case of rainfall according to weather forecast
  - ☆ Three scenarios of rainfall were designed for the next three days.
- Based on real time data from emergency hydrological station near the Tangjiashan barrier dam, the predicted water level were reported.

2.3 Disposal process

2) Hydrometeorological monitoring & forecast

Rolling forecasted water level in the lake:

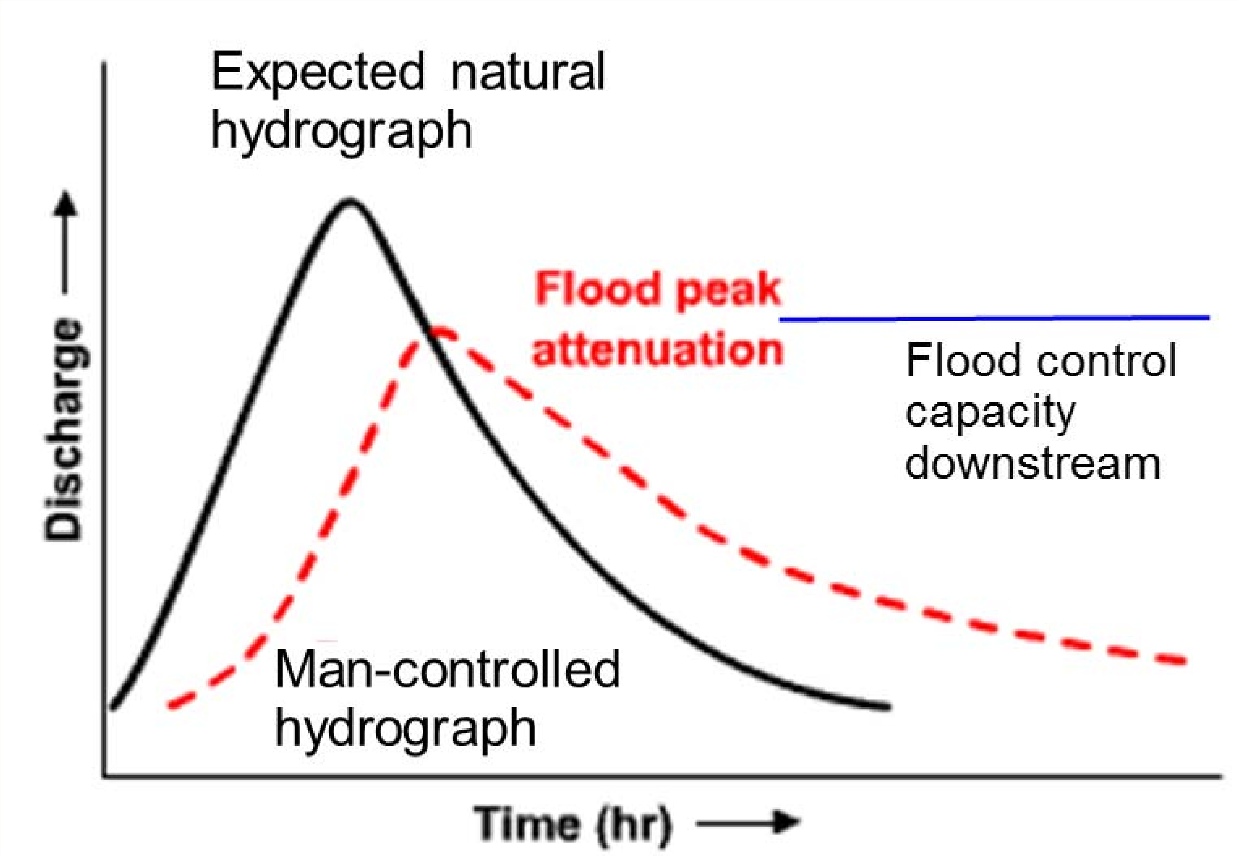


2.3 Disposal process

3) Hazard relief: Mitigation planning & structural measures

Catastrophic dam-failure flood ➔

Man-controlled dam-failure flood

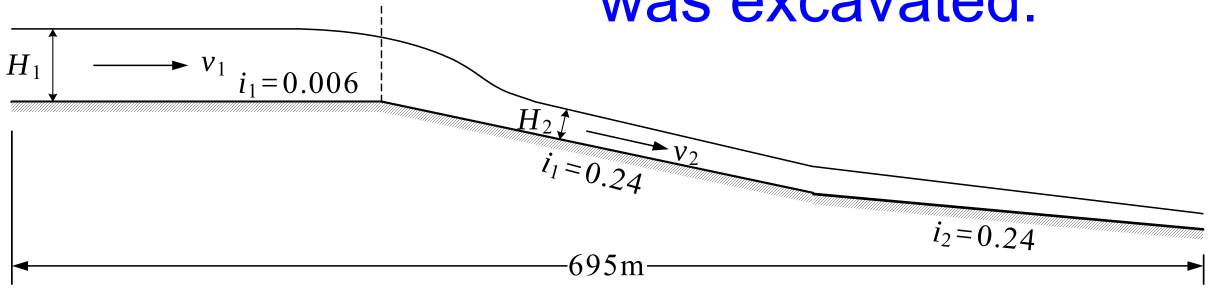


objective

2.3 Disposal process

3) Hazard relief: Mitigation planning & engineering measures

Diversion channel on dam crest was excavated.



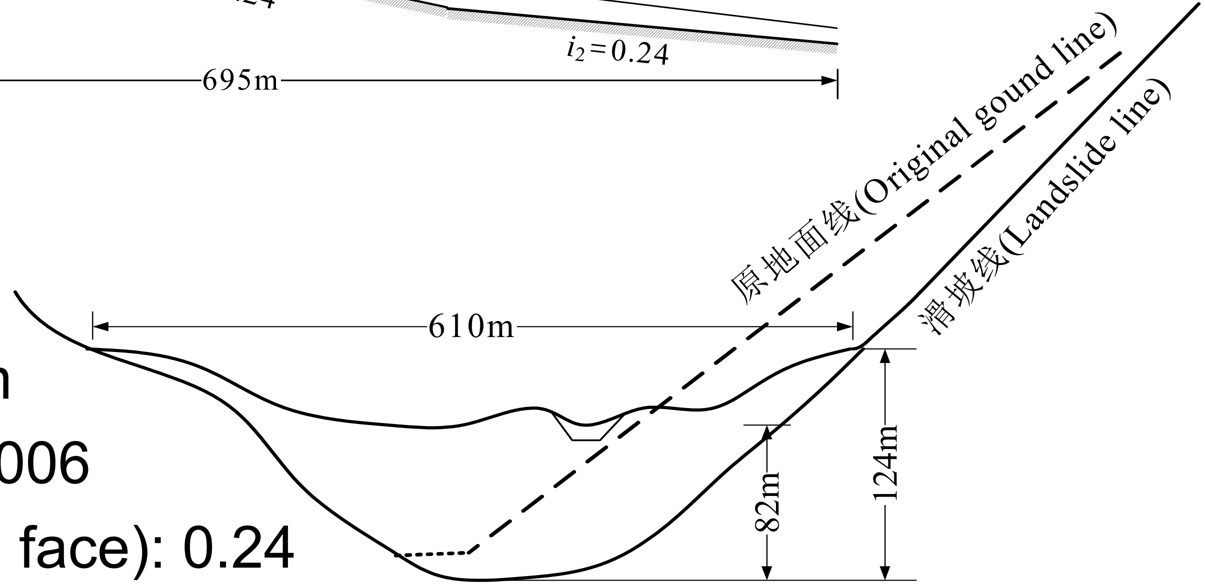
Diversion channel:

Side slope: 1: 1.5

Elevation at inlet: 740 m

Bed slope (on crest): 0.006

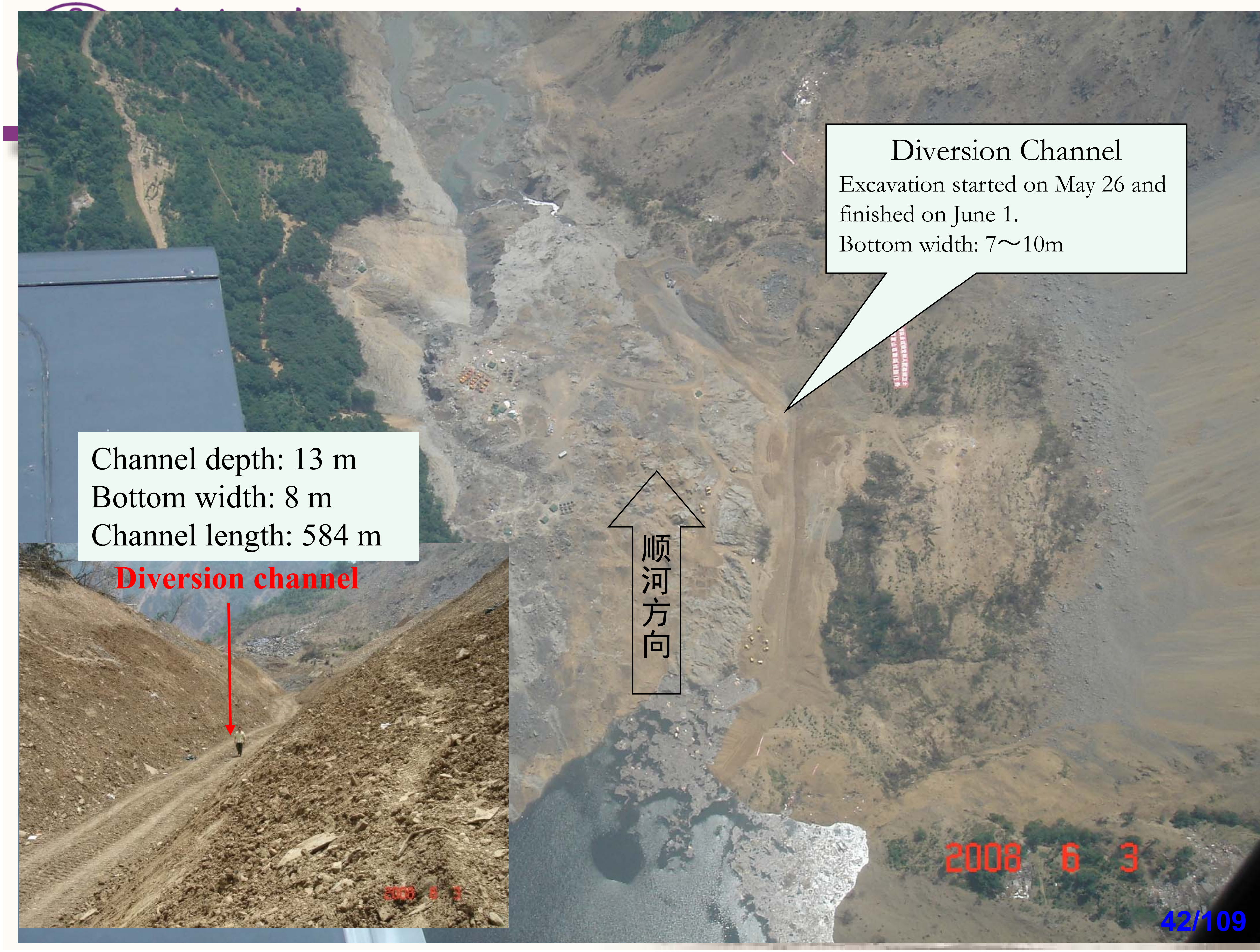
Bed slope (downstream face): 0.24



2.3 Disposal process

3) Hazard relief: Mitigation planning & engineering measures

Excavation started on May 26 and completed on June 1.
Elevation at the inlet: 740m; Channel bed: 7～10m wide


Diversion Channel
Excavation started on May 26 and finished on June 1.
Bottom width: 7～10m
Channel depth: 13 m
Bottom width: 8 m
Channel length: 584 m
Diversion channel
顺河方向
2008 6 3

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2.3 Disposal process

3) Hazard relief: Mitigation planning & engineering measures

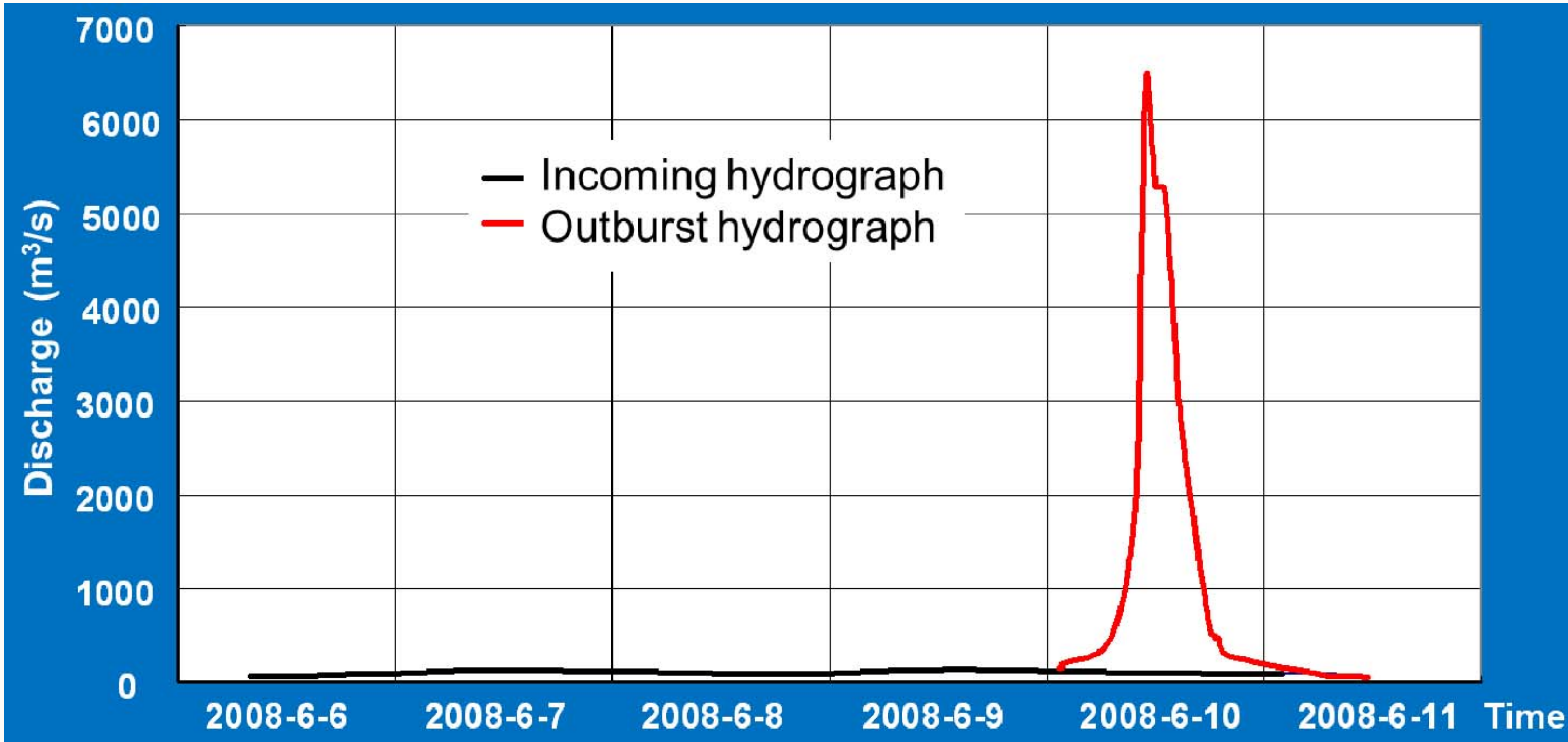
A man-controlled flood was created, preventing from catastrophic consequences (< flood control capacity downstream)

Time	Events
7: 08, June 7	began to drain, water stage: 740.37 m
8: 00, June 10	water stage reached 742.18 m, kept for 1 hour
9: 00, June 10	Water stage decreased sharply from 742.17 m
12: 30, June 10	peak discharge: 6500m^3/s, water stage: 735.81 m
20:00, June 10	failure virtually terminated

2.3 Disposal process

3) Hazard relief: Mitigation planning & engineering measures

A man-controlled flood was created, preventing from catastrophic consequences (< flood control capacity downstream)



2.3 Disposal process

June 7

June 8

June 9

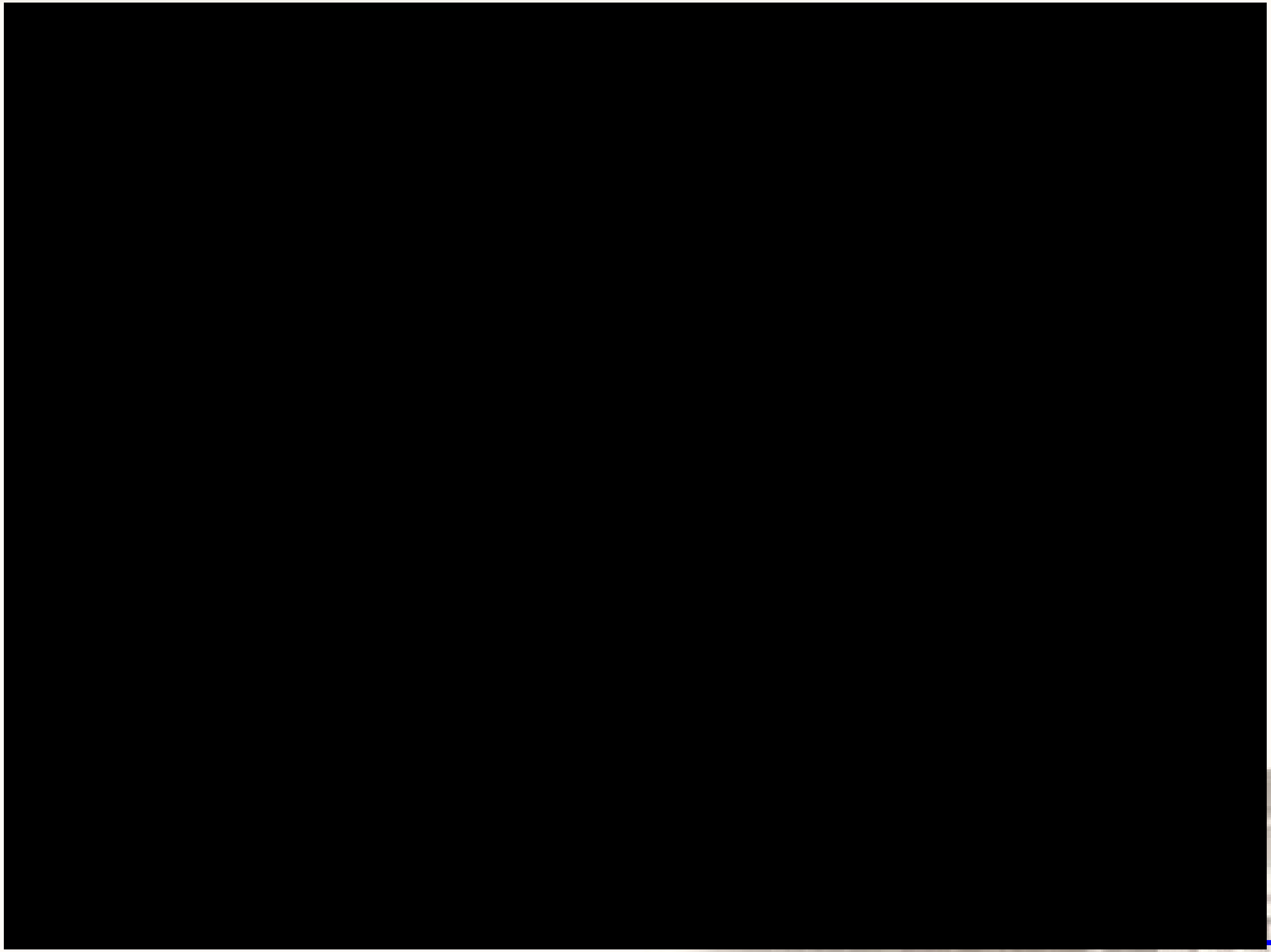
June 10

2.3 Disposal process

June 10, (a) 8:30; (b) 9:30; (c) 10:30; (d) 11:00; (e) 11:30; (f) 12:00

Liu N, et al. Draining the Tangjiashan Barrier Lake–Documentation on a landslide dam breaching case. Journal of Hydraulic Engineering (ASCE), 2010,136(11): 914-923.

2.3 Disposal process



2.3 Disposal process

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2.3 Disposal process

2.3 Disposal process

3) Hazard relief: Mitigation planning & engineering measures

The channel was deepened and widened.

Diversion channel after the failure

New channel:

145~235 m wide (from 7-10 m);

Elevation at inlet:

Reduced to 710 m (from 743 m).

Elevation at outlet:

From 663 m to 695 m

2.3 Disposal process

Diversion channel on June, 12 (after failure)

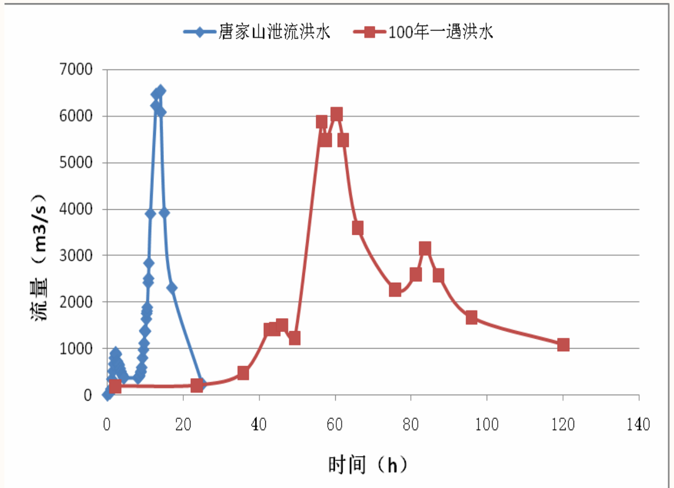
2.3 Disposal process

Diversion channel on June, 13 (after failure)

2.3 Disposal process

Beichuan City during the failure process

4) Imminent forecast



Not fully-understood mechanisms:

- statistical model
- parametric model

} **Easy to use**
Large uncertainties

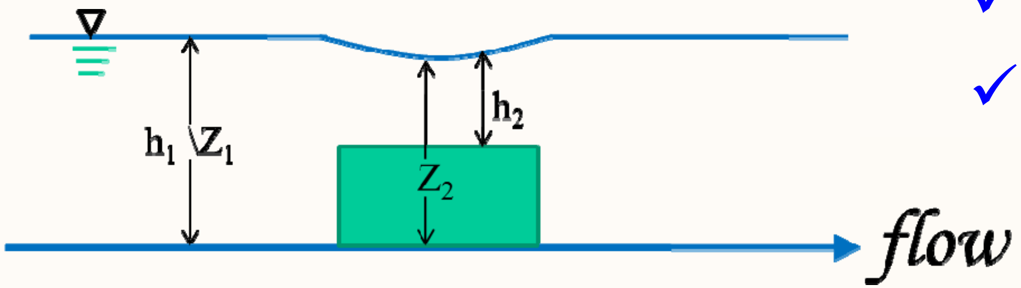
- physically based model
  - have the potential to simulate in details
  - hampered due to lack of understanding about the complicated mechanisms

2.3 Disposal process

1D Flood Routing：Saint Venant Equations

$$\frac{\partial Z}{\partial t}+\frac{\partial (Q/B)}{\partial x}=-Q/B^2\frac{\partial B}{\partial x}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)=-gA\frac{\partial Z}{\partial x}-gS_f$$

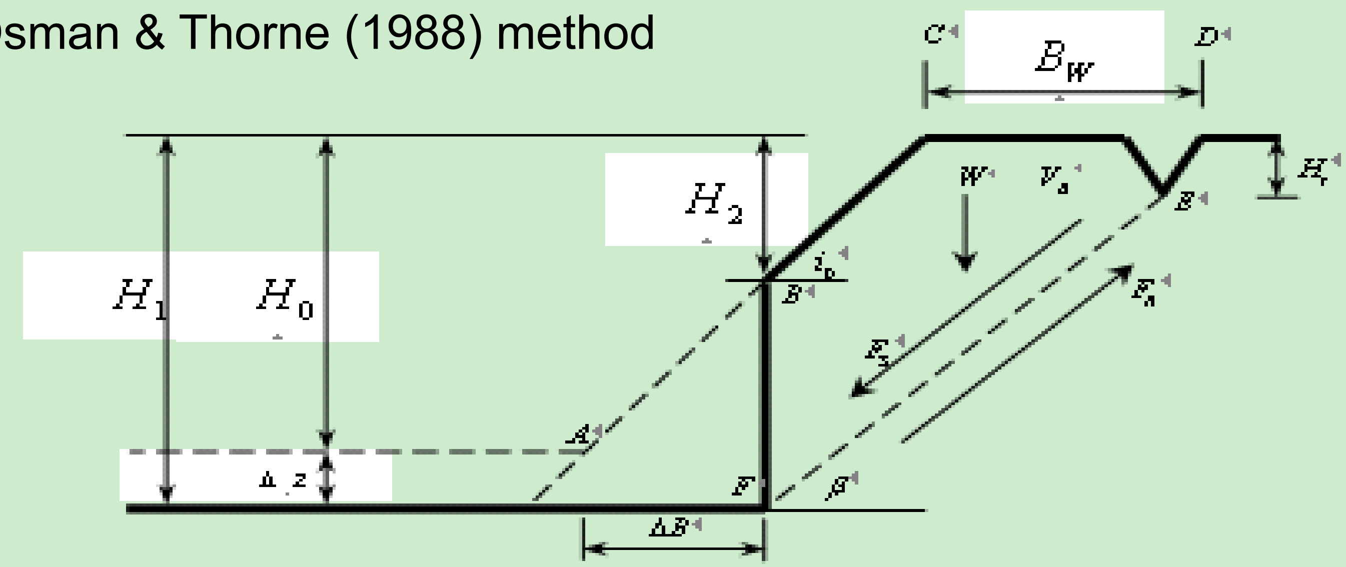


- Conservative, with water stage and discharge as variables
- HLL (Harten-Lax-Leer) Solver
- ✓ High shock resolution
- ✓ Capability to treat complex topography
- ✓ Ease of implementation
- ✓ Time-saving

2.3 Disposal process

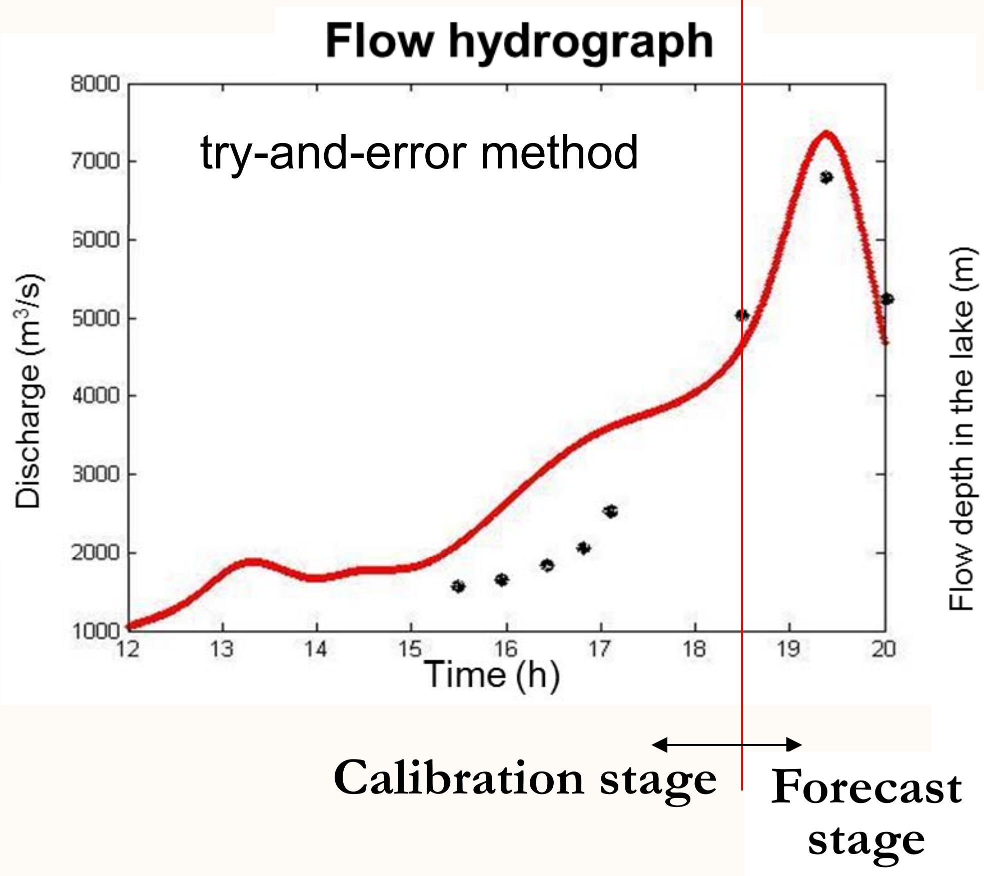
- Erosions in the longitudinal and vertical directions: Xiao Huangxiong's formula
- Lateral erosion: Osman & Thorne (1988) method
- Water level at the inlet: Storage-capacity curve
- Model parameters: calibrated according to the preceding observed data (try-and-error method)

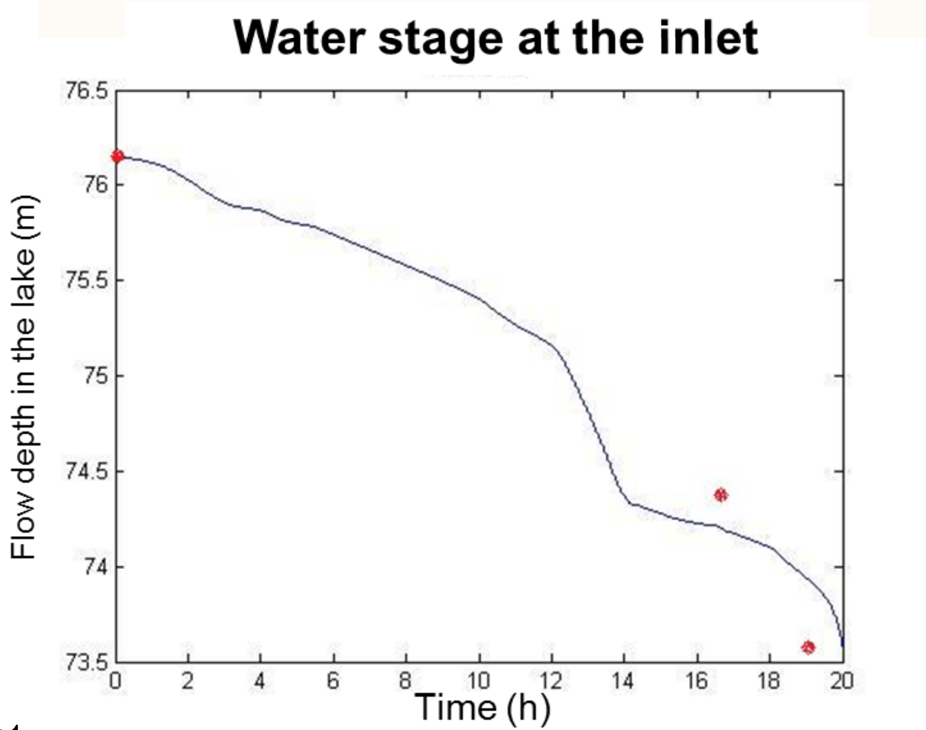
Osman & Thorne (1988) method



4) Imminent forecast

The man-made flood would be under control (< the flood control capacity of 10,000 m^3/s) downstream.





4) Imminent forecast

2D Flood Routing：Saint Venant Equations

Difficulties:

- Unknown material composition of the dam,
- High water level difference and large flow velocity which correspond to complex flow patterns, and
- Quick deformation of river bed.

2.3 Disposal process

(1) Lateral erosion: Osman & Thorne (1988) method

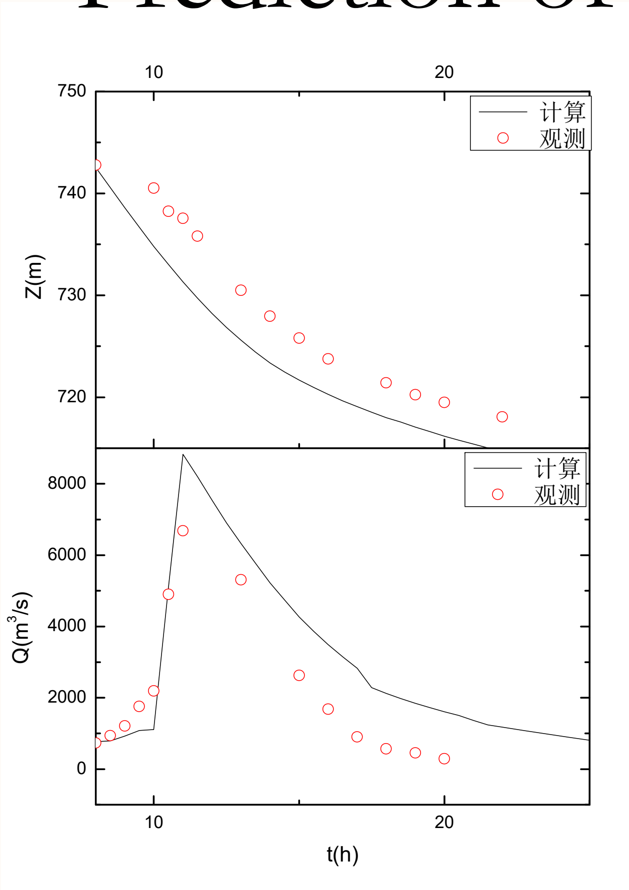
(2) Movement of rocks in bed load

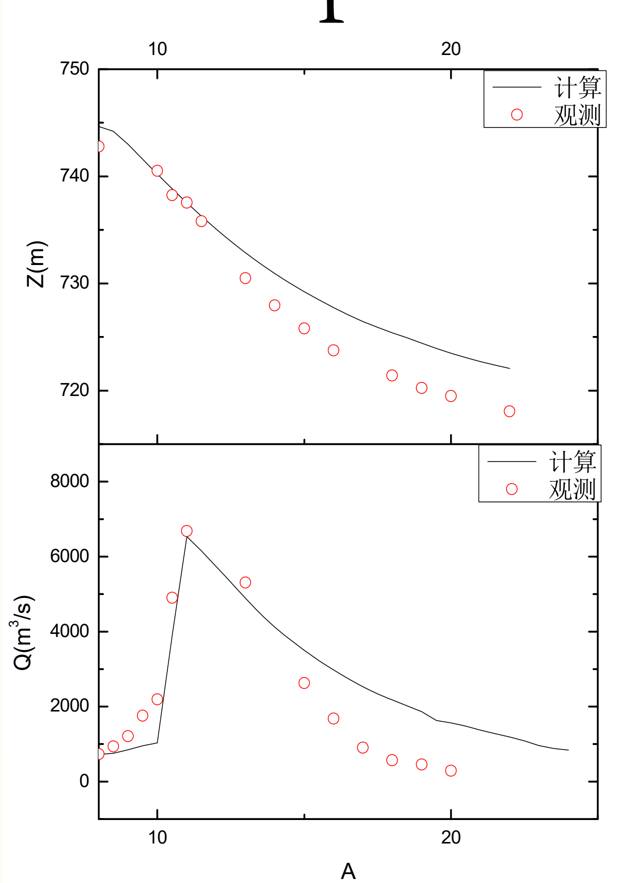
$$q_s = 2.3\gamma_s \left(\frac{\gamma}{\gamma_s - \gamma} \right)^2 \frac{V(V^3 - V_C^3)}{A^2 g^{1.5} R^{1/2}} \left(\frac{D_{65}}{R} \right)^{1/3} ctg\varphi$$

$$V_c = 1.14\sqrt{\frac{\gamma}{\gamma_s - \gamma} gD} \left(\frac{h}{D} \right)^{1/6}$$

$$A = 1.54\ln(D) + 28.48$$

Prediction of dam breach process



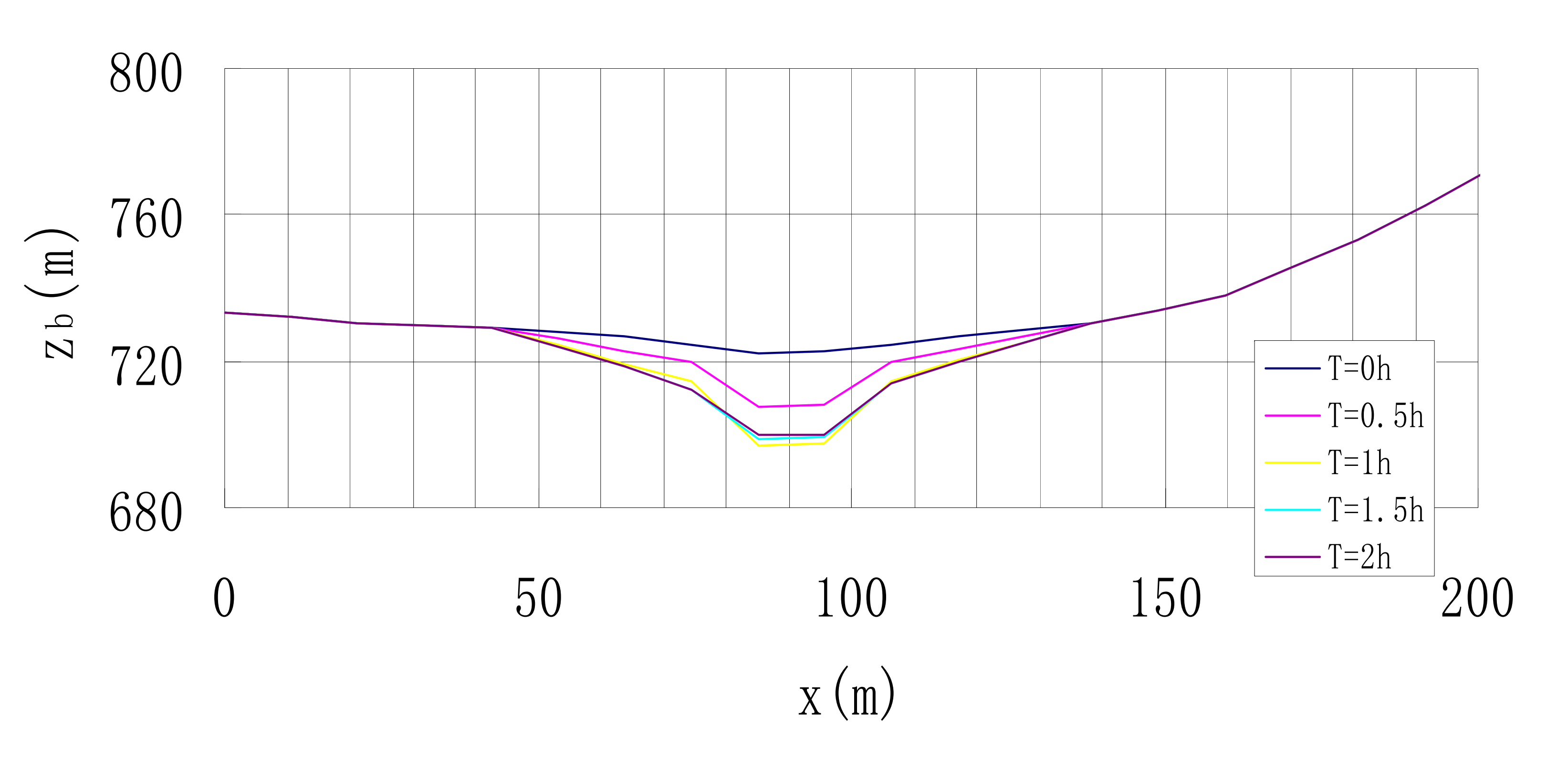


Predicted peak discharge is 8830 m^3/s on June 10.

Modified prediction according to observed data

2.3 Disposal process

Cross-section development of channel

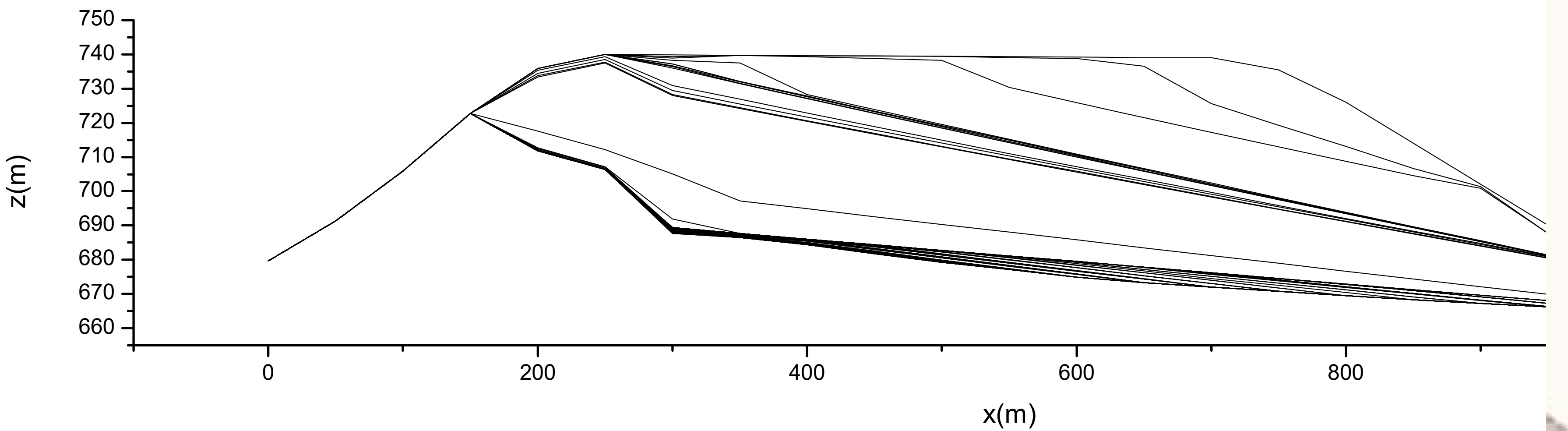


2.3 Disposal process

Head cutting erosion

The erosion develops from downstream to upstream.

Peak discharge occurred when head cutting erosion reached the inlet.



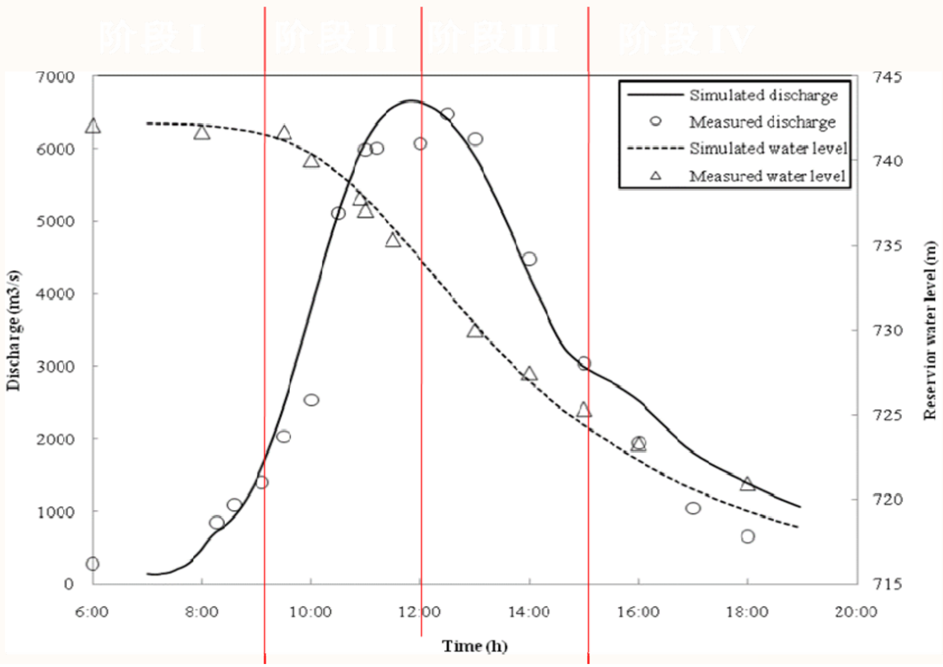
Detailed information but long computation time

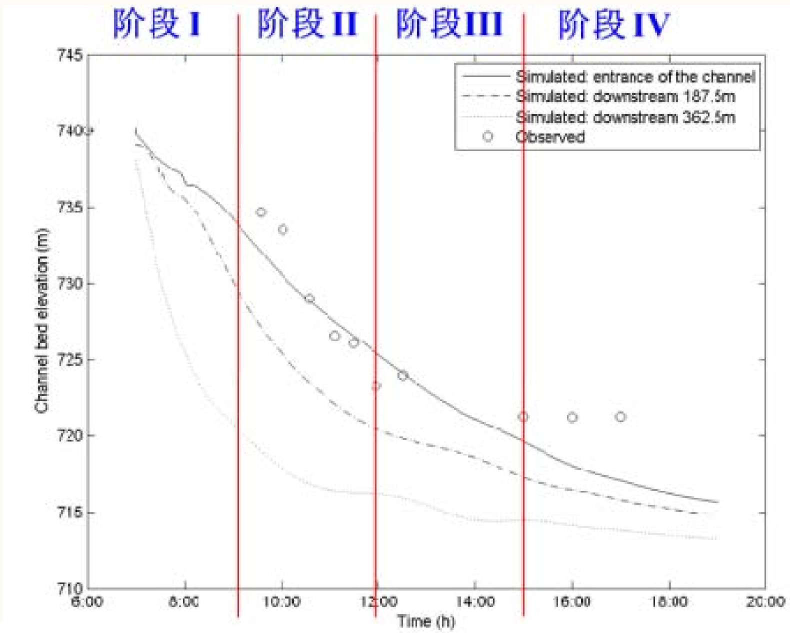
2.4 Subsequent research

Updated 1D model for dam breach simulation

The model can reasonably reproduced the breach process.

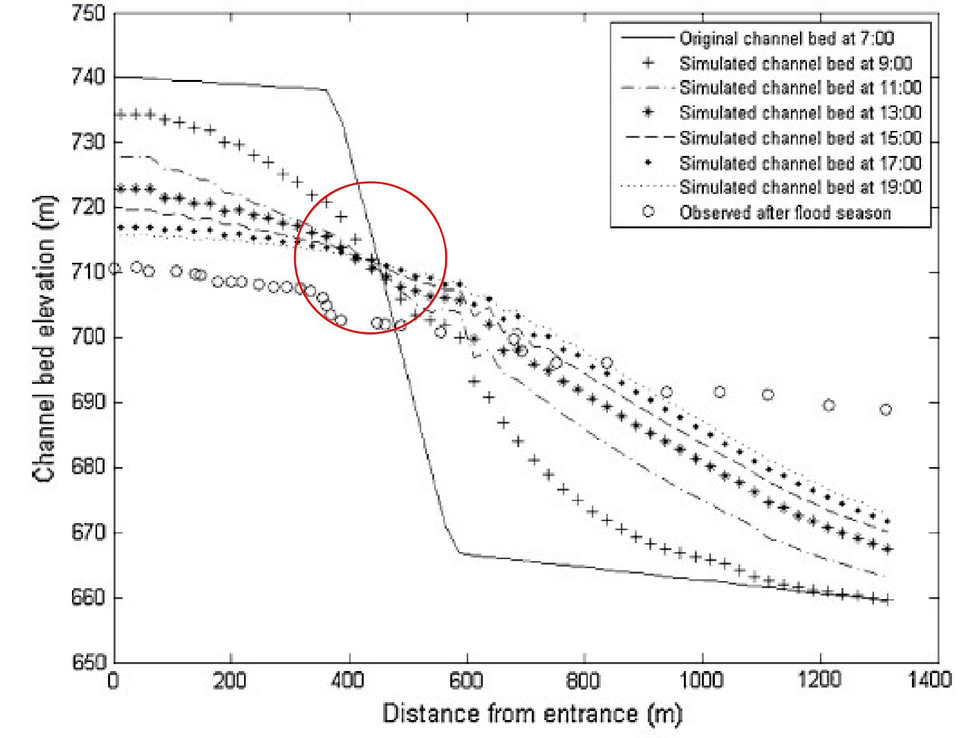
Four phases in the flow hydrograph





Initial Stage Breach Stage Terminated Stage

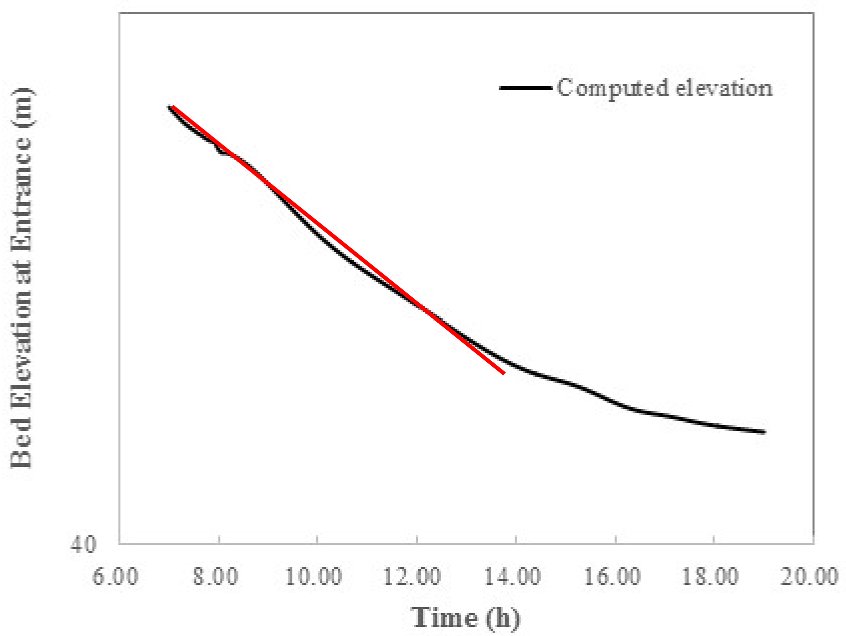
2.4 Subsequent research



upward erosion on the crest;

downward deposition at downstream;

a point with no significant deposition and erosion

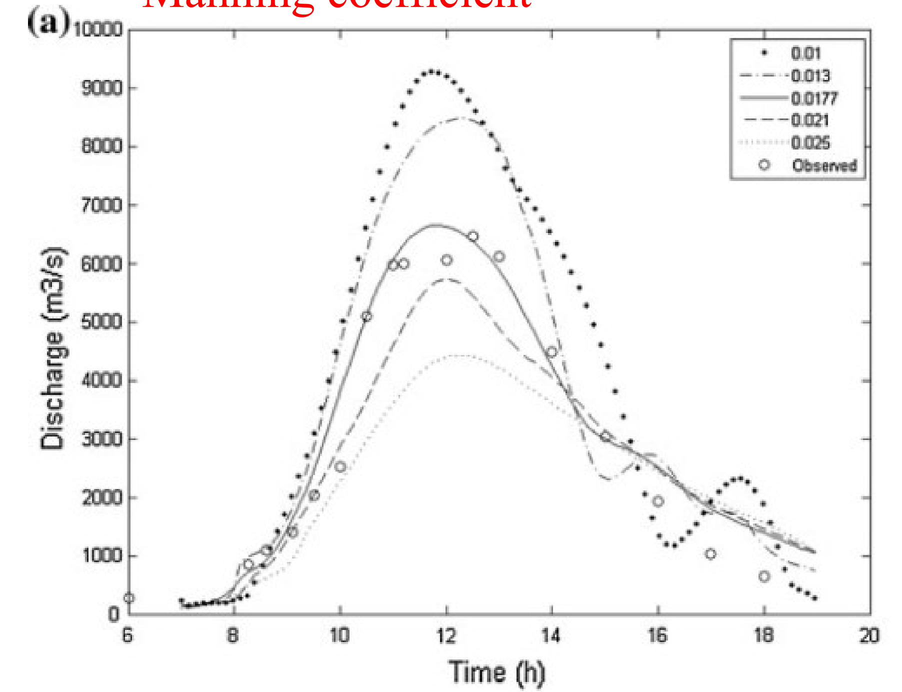


The crest eroded almost linearly before 14:00, indicating the validity of a parametric model.

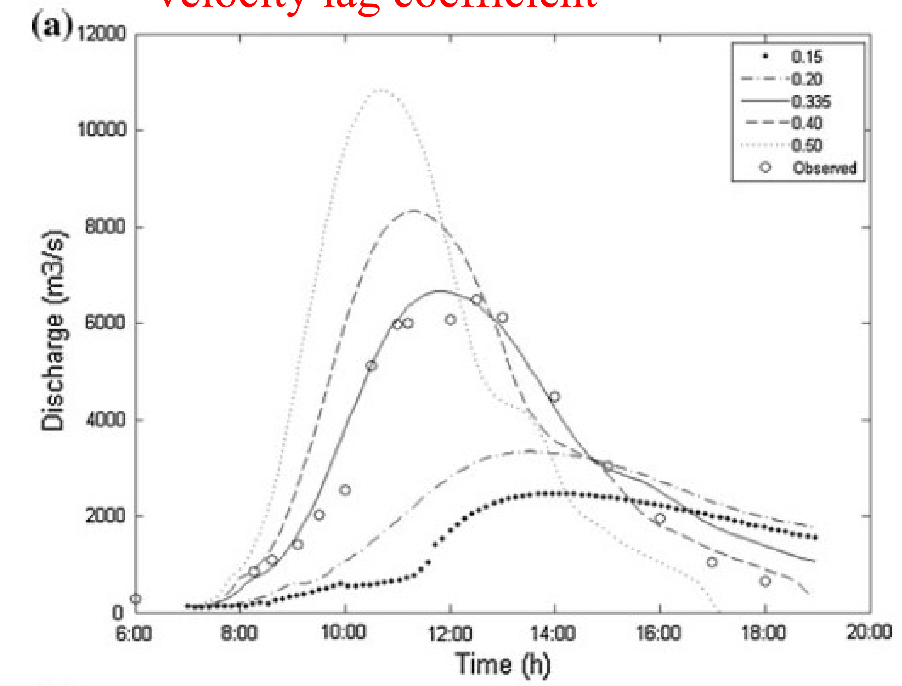
2.4 Subsequent research

❑ Parameter sensitivity analysis

Manning coefficient



velocity lag coefficient

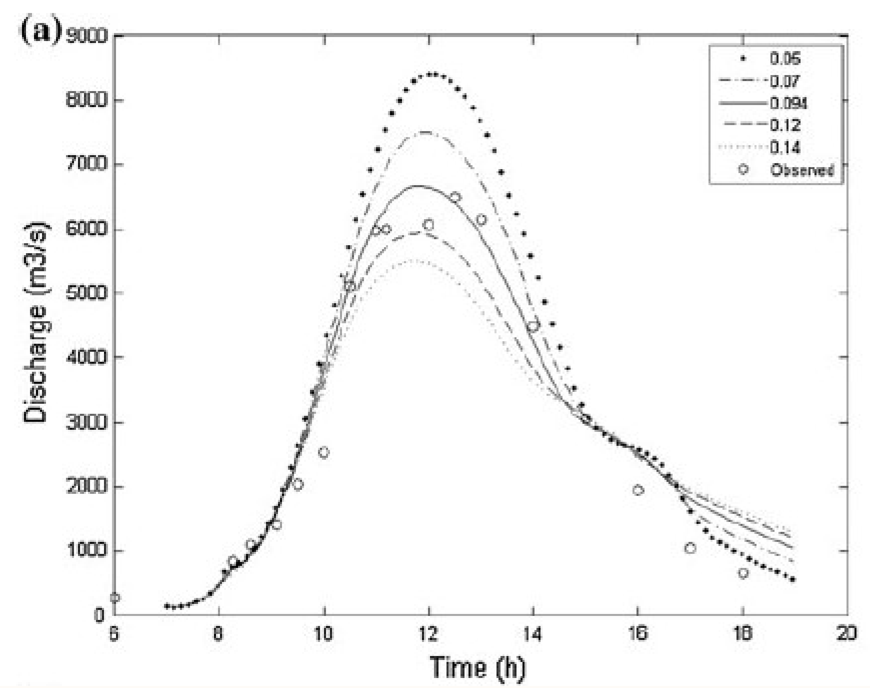


flow resistance ↑
peak discharge ↓ , peak time: keep still

velocity lag ↑
peak discharge ↓ , peak time ↑

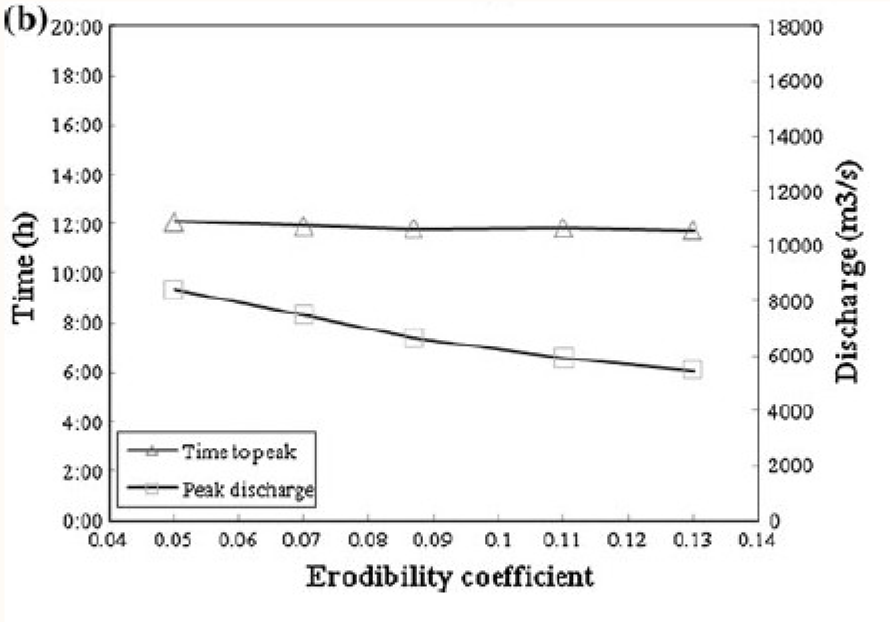
2.4 Subsequent research

❑ Parameter sensitivity analysis



erodibility coefficient:

$$\Delta B = C_l \frac{\tau_f - \tau_c}{\gamma_{bk}} e^{-1.3\tau_c} \Delta t$$



Both peak discharge and peak time are not sensitive to bank erodibility.

2.4 Subsequent research

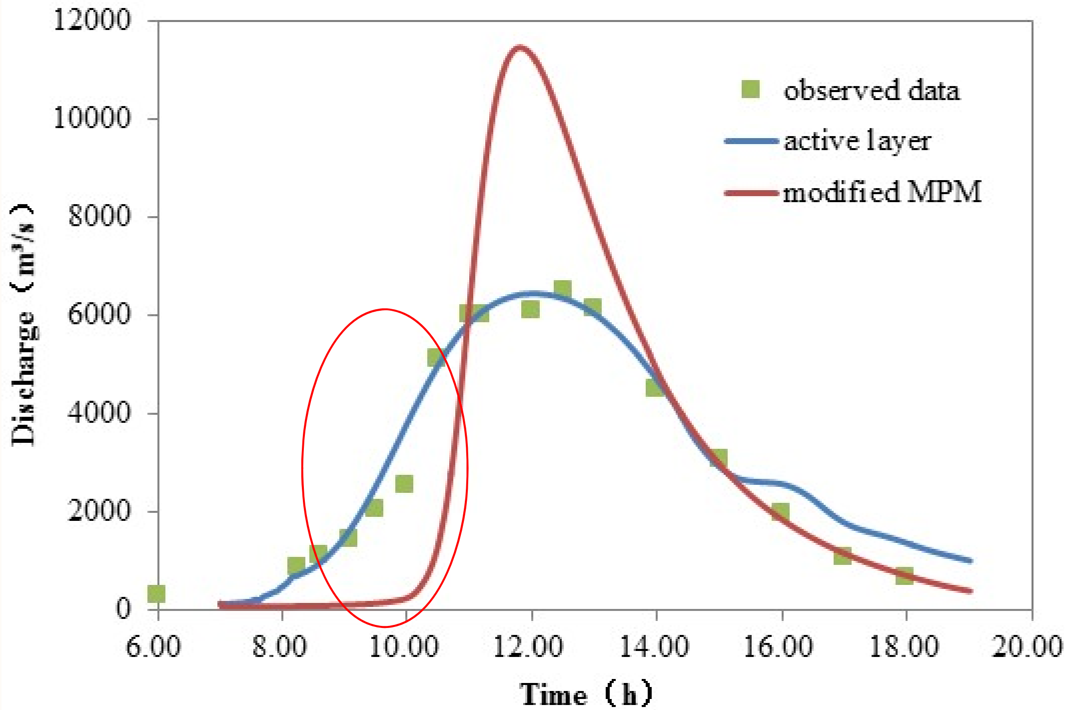
Comparison of bedload transport models

modified MPM formula $q^* = 3.97(\tau^* - 0.0495)^{1.5}$ Wong & Parker (2006)

active layer model $q^* = 4.36(\sqrt{\tau^*} - \sqrt{0.01})$

larger exponent, smaller value

MPM formula underestimates erosion rate in the initial stage.



2.4 Subsequent research

For practicability and computational simplicity, the Walder and O'Connor's parametric model was used in real time simulation.

Simulation Model

$$\frac{dh}{dt} = -\frac{db}{dt} - \left(\frac{w_i^m}{mV_0}\right)\frac{[c_1 r(D_c - b) + c_2 h \cot\theta]g^{1/2}h^{3/2} - Q_{in}}{(h+b)^{m-1}} \quad (1)$$

$$Q_{out} = [c_1 r(D_c - b) + c_2 h \cot\theta]g^{1/2}h^{3/2} \quad (2)$$

$$b(t) = \begin{cases} w_i, & t \leqslant T_0 \\ w_i - \frac{D_b}{T_f}(t - T_0), & T_0 \leqslant t \leqslant T_f + T_0 \\ w_i - D_b, & t \geqslant T_f + T_0 \end{cases} \quad (3)$$

Correlation among parameters

- Case 1: T0 < TP < T0 + Tf $\quad \frac{D_{b2}}{T_{f2}} = \frac{D_{b1}}{T_{f1}} \quad T_{02} = T_{01}$
- Case 2: TP > T0 + Tf $\quad$ never occur.
- Case 3: TP = T0 + Tf $\quad \frac{D_{b2}}{T_{f2}} = \frac{D_{b1}}{T_{f1}} \quad T_{02} = T_{01} \quad T_{02} + T_{f2} = T_{01} + T_{f1}$

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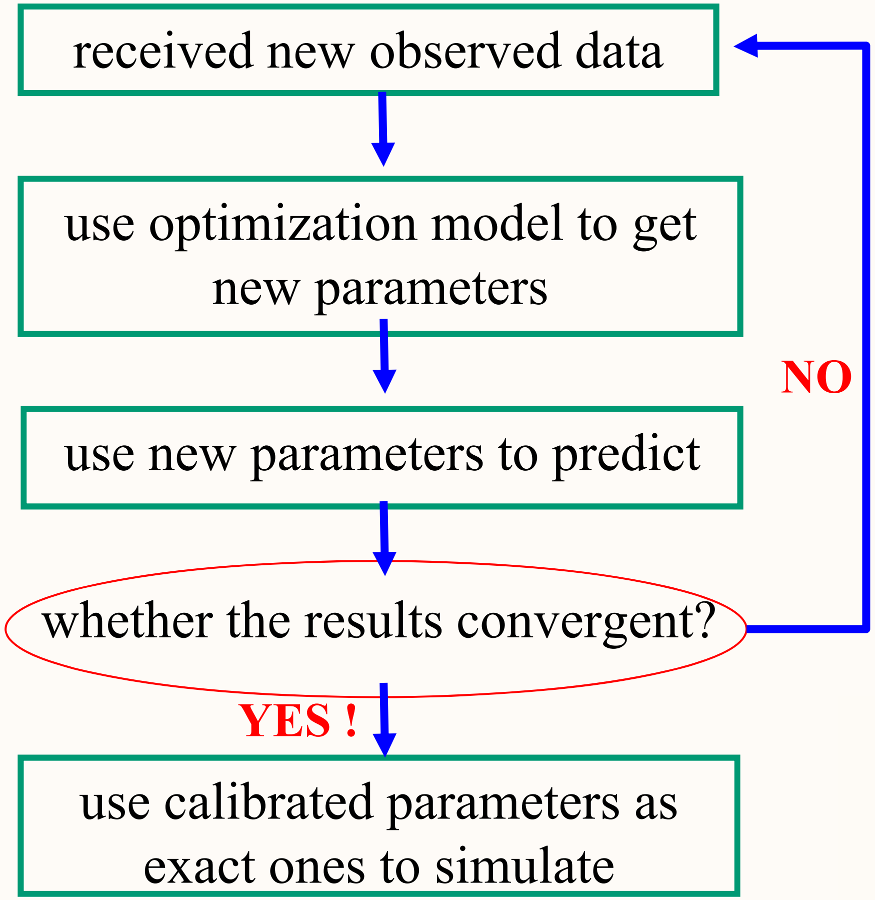
2.4 Subsequent research

In most cases, parameters should be calibrated in real time prediction.



optimization calibration model:

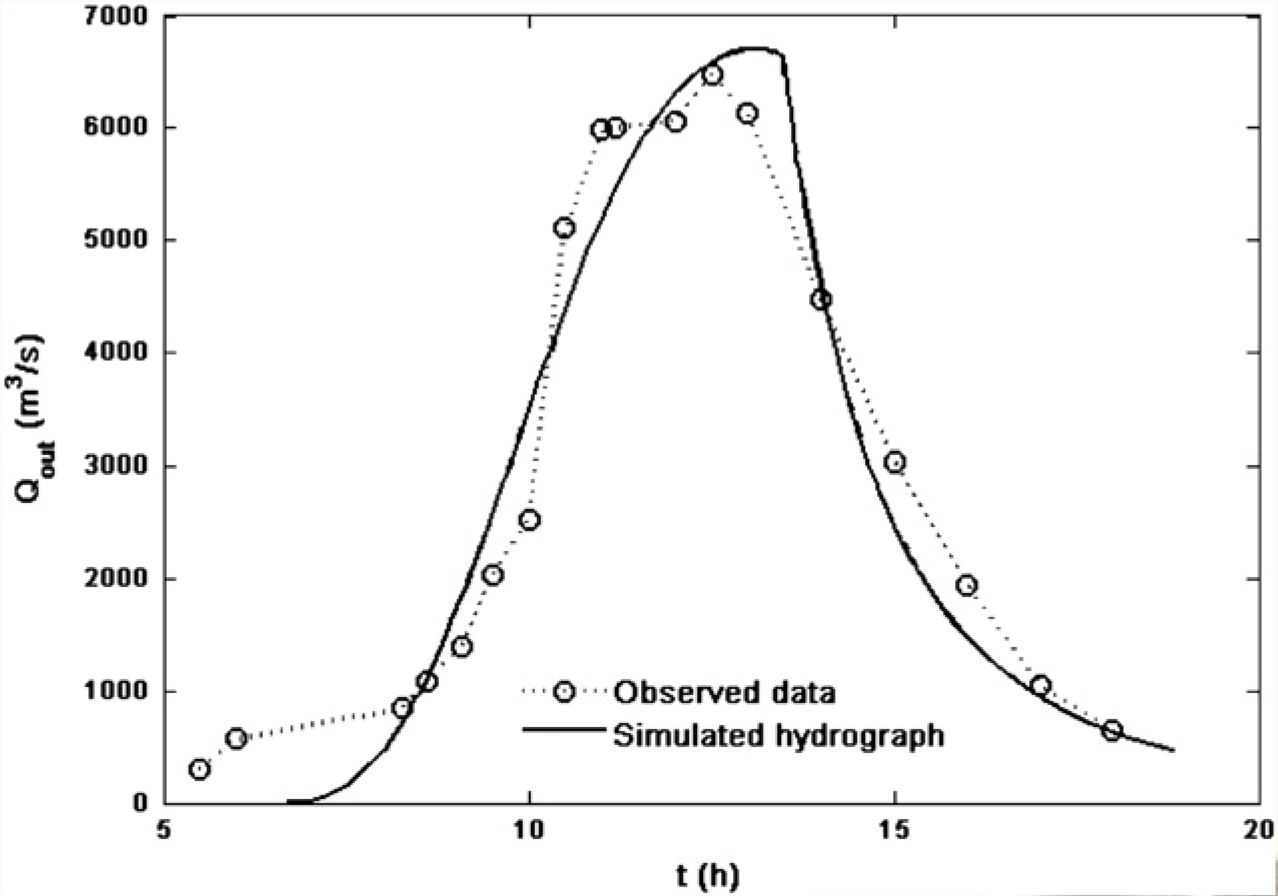
$$\min_{\lambda} SSE(\lambda) = \sum_{i} \left[Q(T_{obsi};\lambda) - Q_{obs}(T_{obsi}) \right]$$

SSE: sum of error squares;

λ : parameters to be calibrated

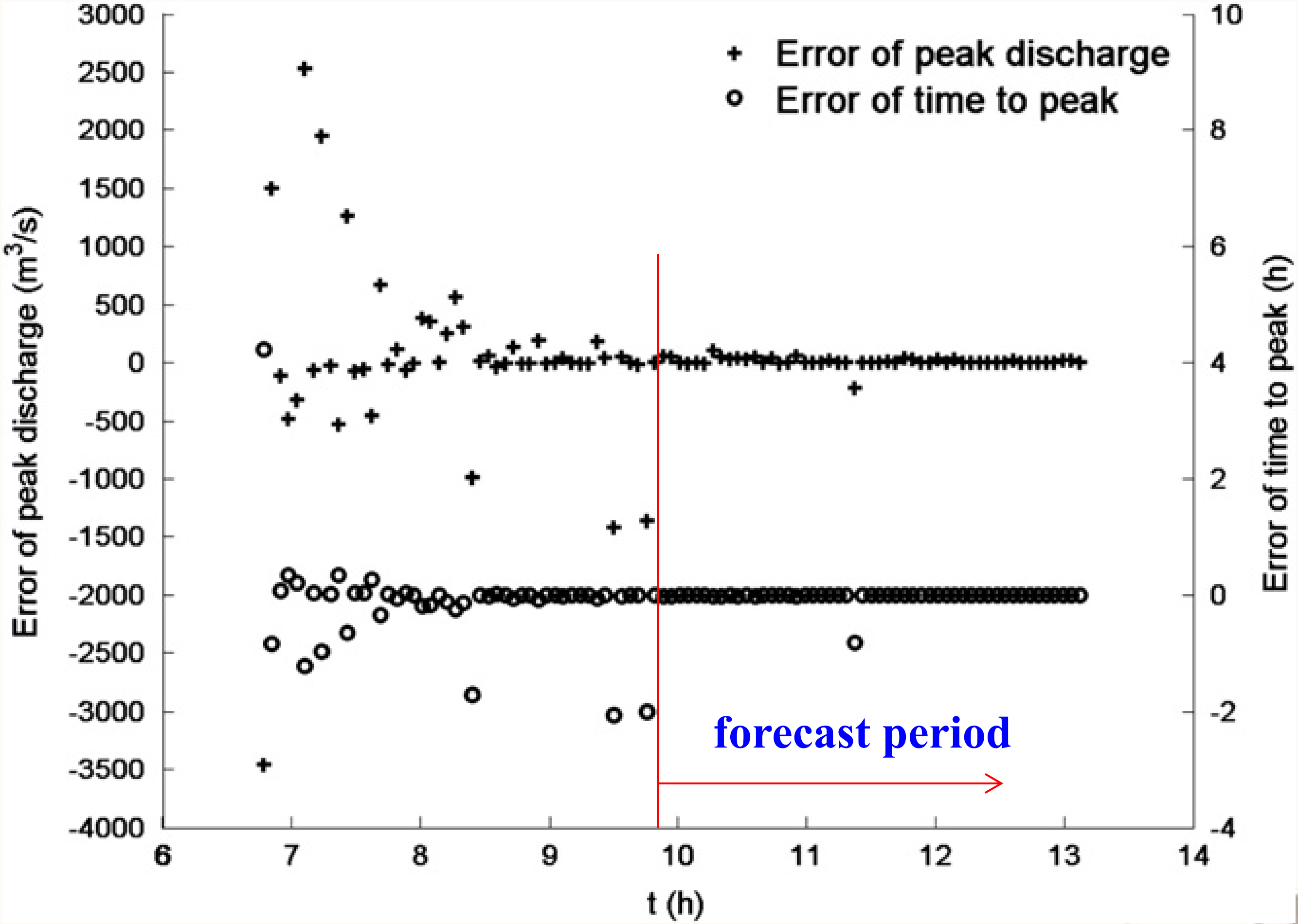
2.4 Subsequent research

- prediction of Tangjiashan Quake Lake (without measurement errors)



Results from simulation model have good agreements with observed data.

2.4 Subsequent research



The model can predict with a lead time of more than 2 hours.

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Contents

Contents

Tangjiashan barrier dam: a single dam

Hongshiyan barrier dam: a chain of dams

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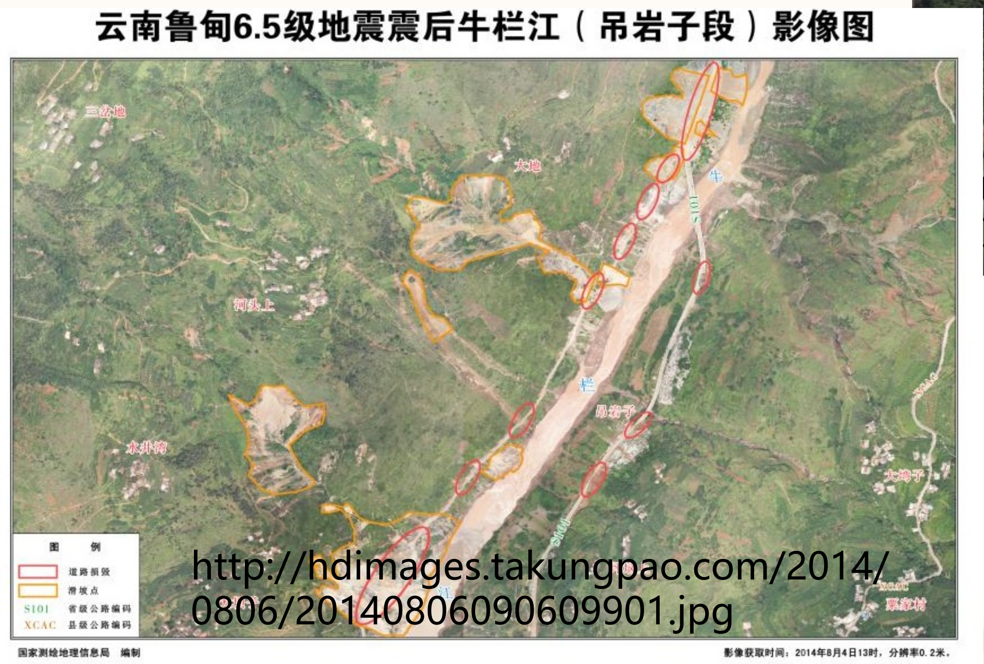
3.1 Overview

◆ The Ms 6.5 Ludian Earthquake on August 3, 2014

ttp://hdimages.takungpao.com/2014
)806/20140806090609123.jpg



http://hdimages.takungpao.com/2014/
0806/20140806090609901.jpg

3.1 Overview

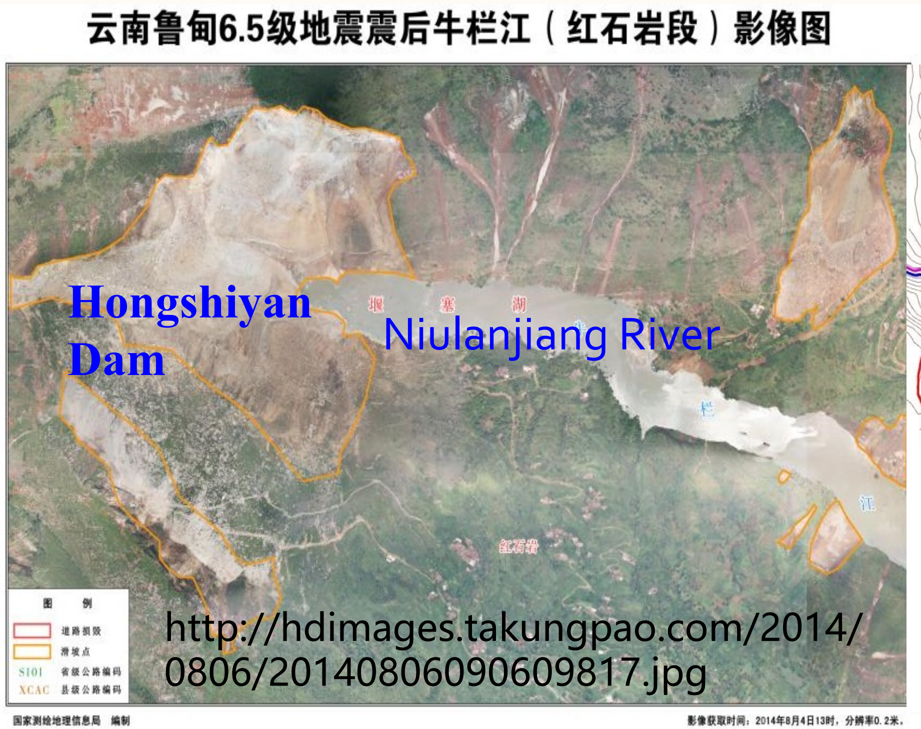
Niulanjiang River: Tributary of Jinshajiang River

- Asymmetric “V” shape valley
- Left bank: 35°～40°; right bank: 50°～60°

3.1 Overview

Hongshiyan barrier dam:

Volume of deposit: $12*10^6$ m^3
Elevation of dam crest: 1222 m
Length along the valley: 753 m
Length across the valley: 286 m



3.1 Overview

Hongshiyan barrier dam:

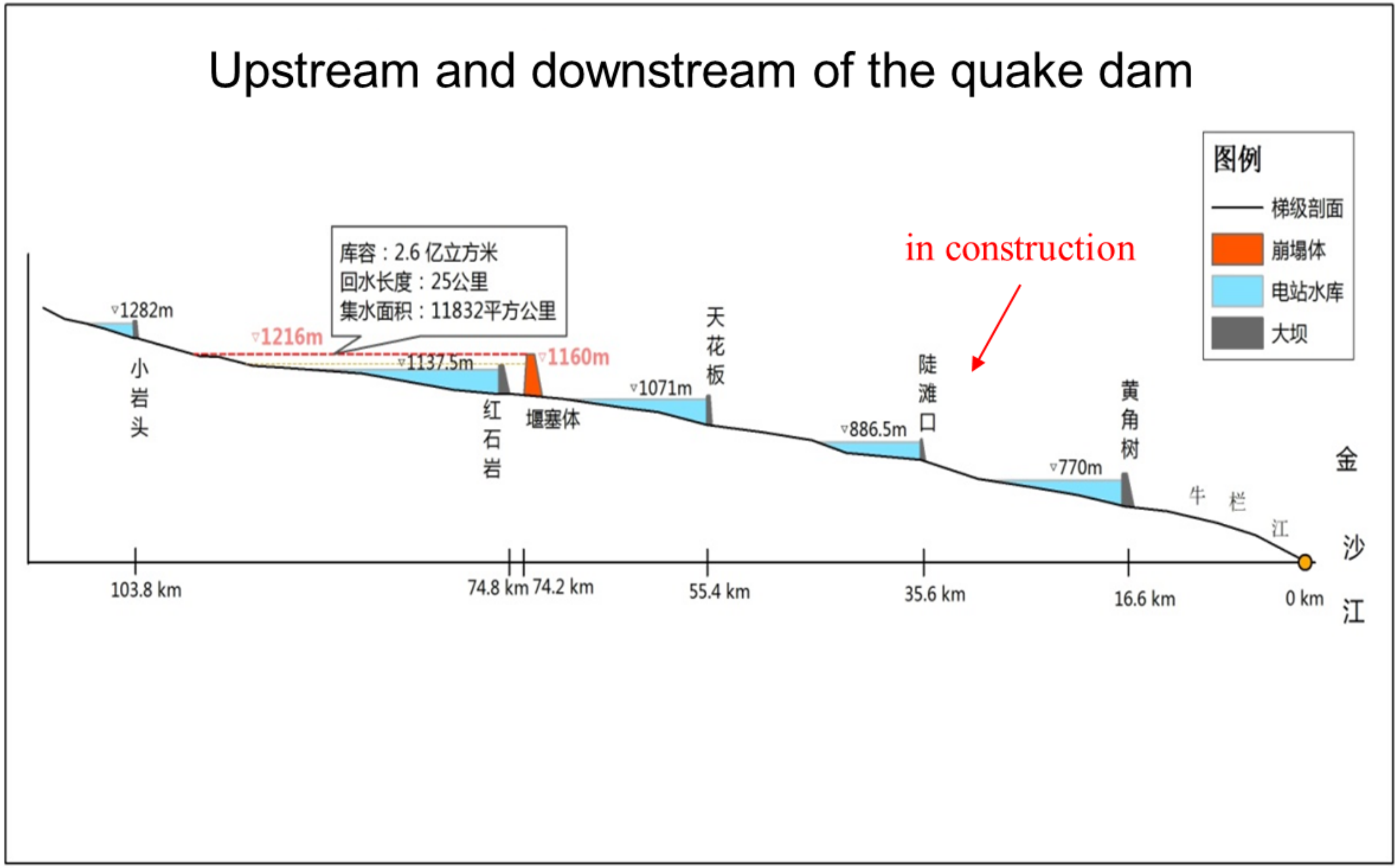
Elevation of the original river bed:	1120 m
Dam height:	83 ~ 96 m
Potential water storage:	$260 \cdot 10^6$ m^3
Drainage area:	11,832 km^2

3.1 Overview

Dam material: sediments from boulders to clays

Size	percent
>30 cm	45%
2~30 cm	40 %
< 2 cm	15%

Affected dams and hydropower stations:



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3.1 Overview

Hydropower stations that might be affected by the quake dam.

Reservoir	Dam height (m)	Elevation of dam crest (m)	Normal water level (m)	Reservoir storage ($10^4 m^3$)
Xiaoyantou	35	1285	1282	286
Hongshiyan	32.77	1146.8	1137.5	69.3
Tianhuaban	107	1076.8	1071	6570
Huangjiaoshu	65	775.0	770	3625

3.2 Disposal process

How to keep from potential disaster?

1) Dam safety & potential risk?
2) Hydrometeorological situation?
3) Hazard relief
    - Mitigation planning
    - Structural measures
4) Post-emergency treatment

3.2 Disposal process

1) Dam safety & potential risk assessment

Grade classification of quake lake

Grade level	Reservoir storage（10^6 m^3）
Large scale	≥100
Middle scale	10～100
Small scale（1）	1～10
Small scale（2）	<1

Hongshiyan belongs to the “large scale” due to its water storage (260*10^6 m^3).

3.2 Disposal process

1) Dam safety & potential risk assessment

Risk degree	Indices		
	Grade in scale	Dam material	Dam height (m)
Extremely high risk	Large	Mostly soil	≥70
High risk	Moderate	Soil with boulders	30~70
Moderate risk	Small（1）	Boulders with Soil	15~30
Low risk	Small（2）	Mostly boulders	<15

Hongshiyan belongs to the “extremely high risk” due to its dam height (83 ~ 96 m) larger than 70 m.

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3.2 Disposal process

Hongshiyan belongs to the "extremely severe" with many hydropower stations upstream and downstream of it.

Classification of severity of landslide dam breach

Dam breach severity	Factors		
	Population in risk	Cities	Infrastructure
Extremely severe	≥106	Prefectural-level city	State-level traffic, electricity, oil line, industrial, hydraulic infrastructure, large-size chemical plants
Severe	105~106	County-level city	Province-level traffic, electricity, oil line, industrial, hydraulic infrastructure, middle-size chemical plants
Relatively severe	104~105	town	City-level traffic, electricity, oil line, industrial, hydraulic infrastructure, small-size chemical plants
Common	<104	village	Other infrastructures

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3.2 Disposal process

Classification of quake lake risk

Quake lake risk	Barrier dam risk	Dam breach loss severity
I	Extremely high danger	Extremely severe & severe
	High & moderate danger	Extremely severe
II	Extremely high danger	Relatively severe & common
	High danger	Severe & relatively severe
	Moderate danger	Severe
	Lowe danger	Extremely severe & severe
III	High danger	Common
	Moderate danger	Relatively severe & common
	Lowe danger	Relatively severe
IV	Lowe danger	Common

Hongshiyan belongs risk “I”

3.2 Disposal process

1) Dam safety & potential risk assessment

Barrier lake risk	Flood reoccurrence interval
I	≥5
II	3~5
III	2~3
IV	<2

According to standards in China (SL450-2009), the Hongshiyan quake lake **should be treated using floods with recurrence interval larger than 5 years.**

3.2 Disposal process

2) Hazard relief for emergency

Non-structural measures + **Structural measures**

1) Evacuate people living nearby
2) Use the upstream reservoir to store income flow
3) Empty the downstream reservoirs, in case the quake dam might failure
4) Implement monitoring system
5) Make disposal plans
6) Repaire the roads to quake dam which was destroyed during the earthquake

3.2 Disposal process

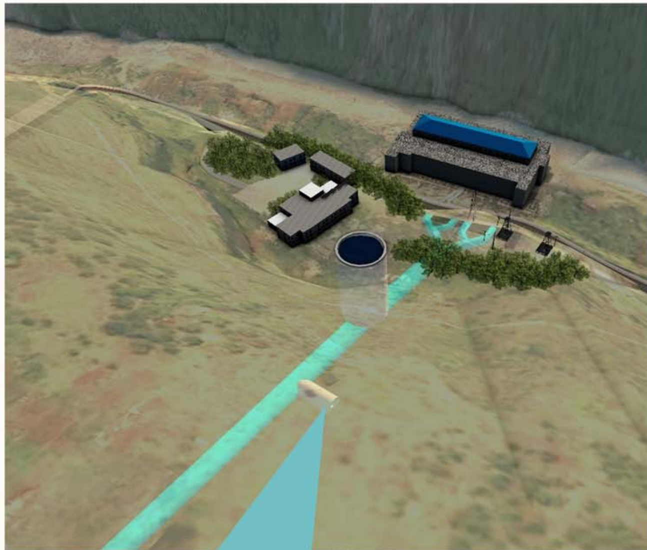
2) Hazard relief for emergency

Non-structural measures + structural measures

No.1 Bulkhead gate was removed to increase the drain discharge

No.2 More water was drained through the surge shaft once it was submerged

施工支洞



施工支洞堵头

3.2 Disposal process

By August 14, 2015, water stage raised to 1180m, and was still raising with the incoming flow.

When the upstream Hongshiyan hydropower station was under the water stage, its surge shaft (调压井) began to drain the water.

3.2 Disposal process

2) Hazard relief for emergency

Non-structural measures + structural measures

No.3 Clean floats on the water to make sure the outlet was not blocked

3.2 Disposal process

2) Hazard relief for emergency

Non-structural measures + structural measures

No.4 excavate diversion channel

- Cross section is trapezoidal with side slope of 1: 1.5;
- 4 plans were made, with channel depth of 6m, 8m, 10m, and 12m.
- Excavation time for the four plans were 4 days, 5 days, 7 days, and 8 days, respectively.

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3.2 Disposal process

2) Hazard relief for emergency

http://pic.people.com.cn/n/2014/0826/c1016-25537558.html

3.2 Disposal process

http://pic.people.com.cn/n/2014/0826/c1016-25537558-2.html

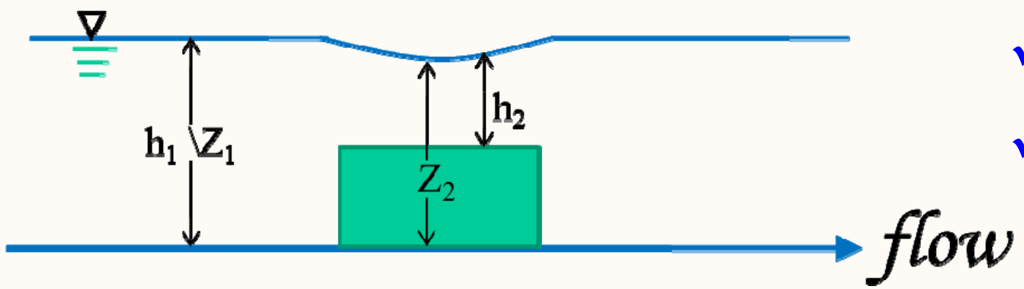
3.3 Flood routing

Flood routing supporting channel design

Saint Venant Equations:

$$\frac{\partial Z}{\partial t}+\frac{\partial (Q/B)}{\partial x}=-Q/B^2\frac{\partial B}{\partial x}$$

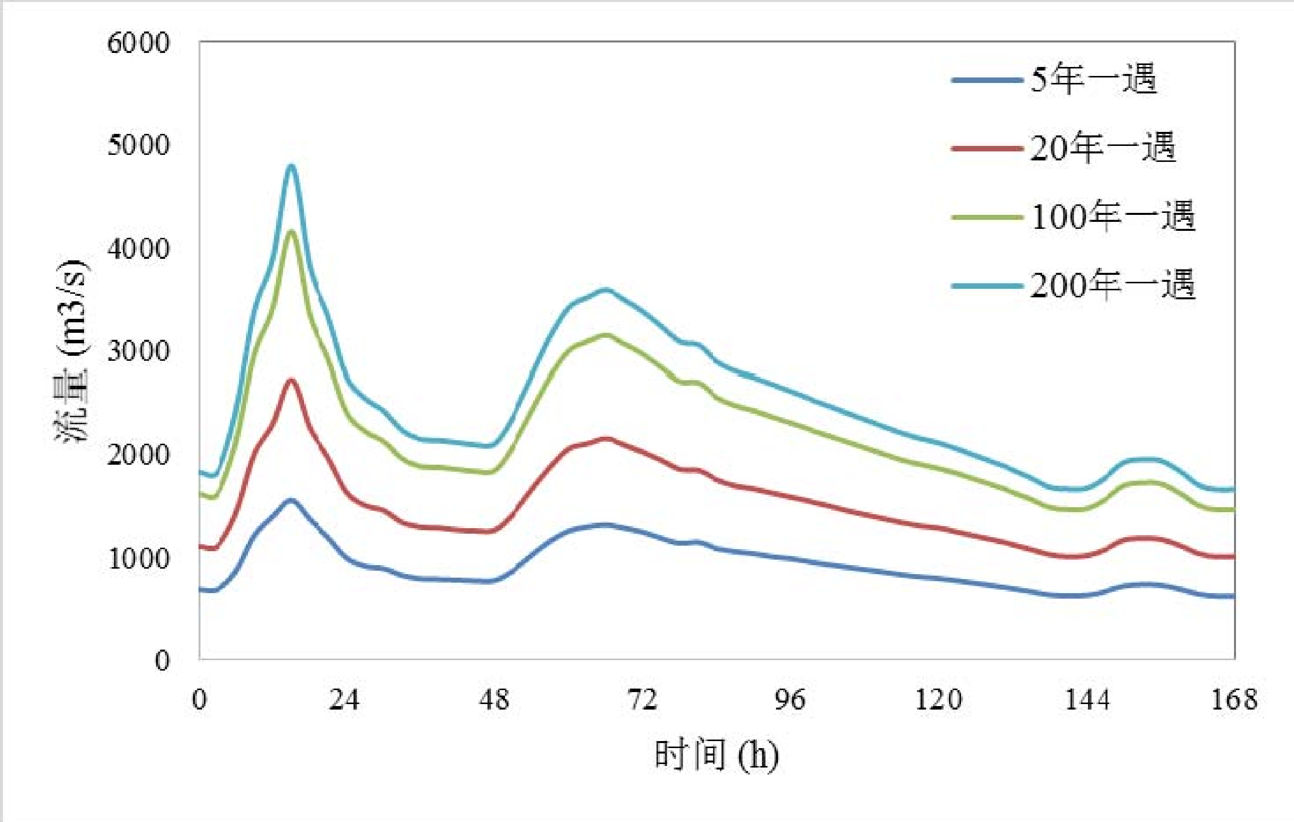
$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}(\frac{Q^2}{A})=-gA\frac{\partial Z}{\partial x}-gS_f$$



- ➢ Conservative with water stage and discharge as variables
- ➢ HLL Solver
- ✓ High shock resolution
- ✓ Capability to treat complex topography
- ✓ Ease of implementation
- ✓ Time-saving

3.3 Flood routing

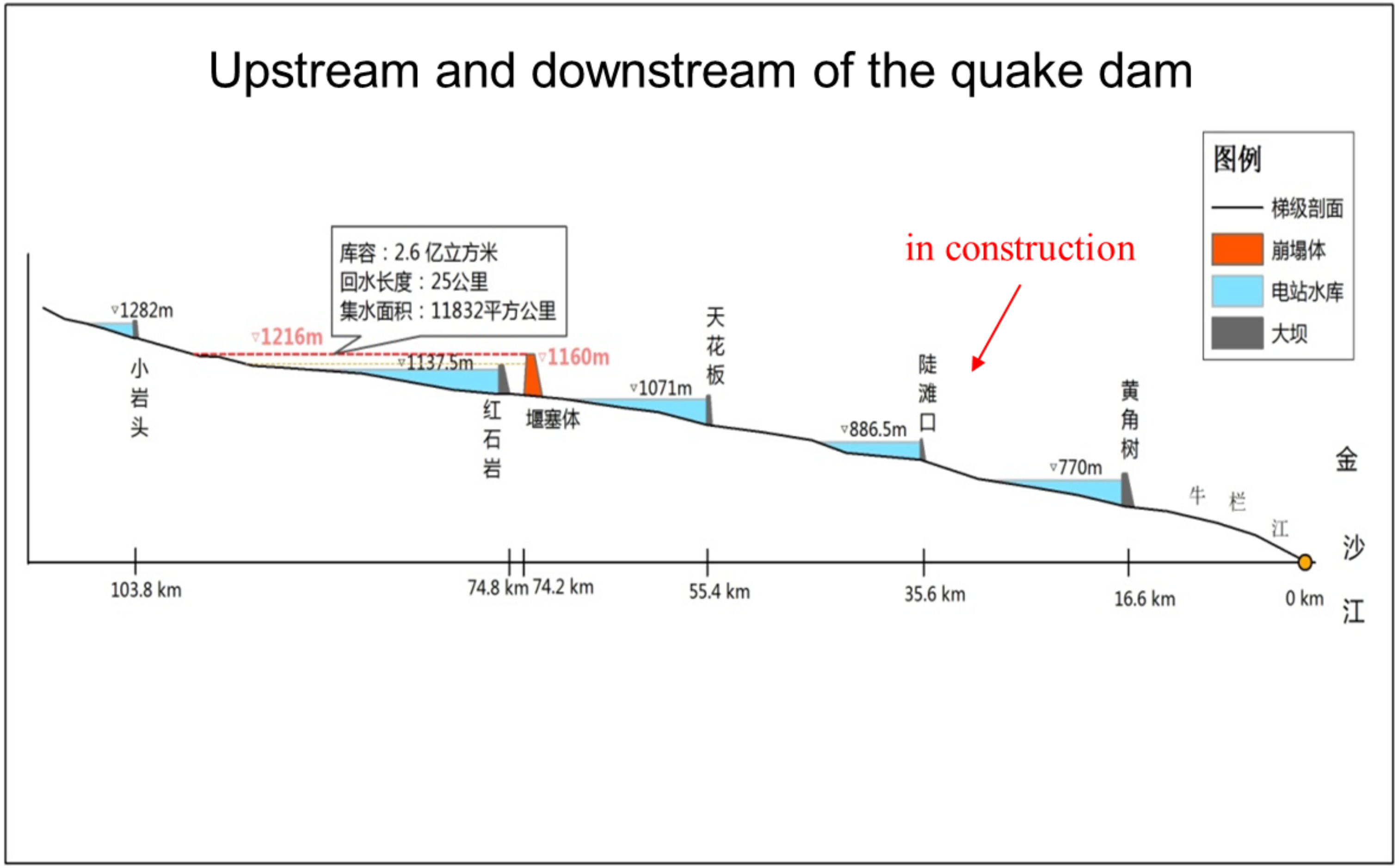
- Consider the 5-, 20-, 100-, and 200-year recurrence interval floods, respectively



Hydrographs of 5-yr, 20-yr, 100-yr and 200-yr floods

3.3 Flood routing

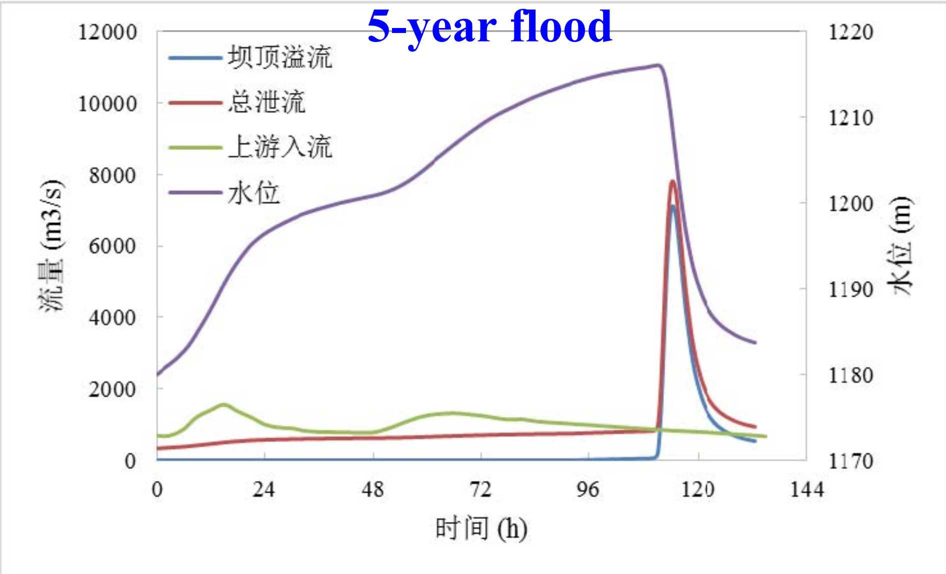
Flood routing among the dams

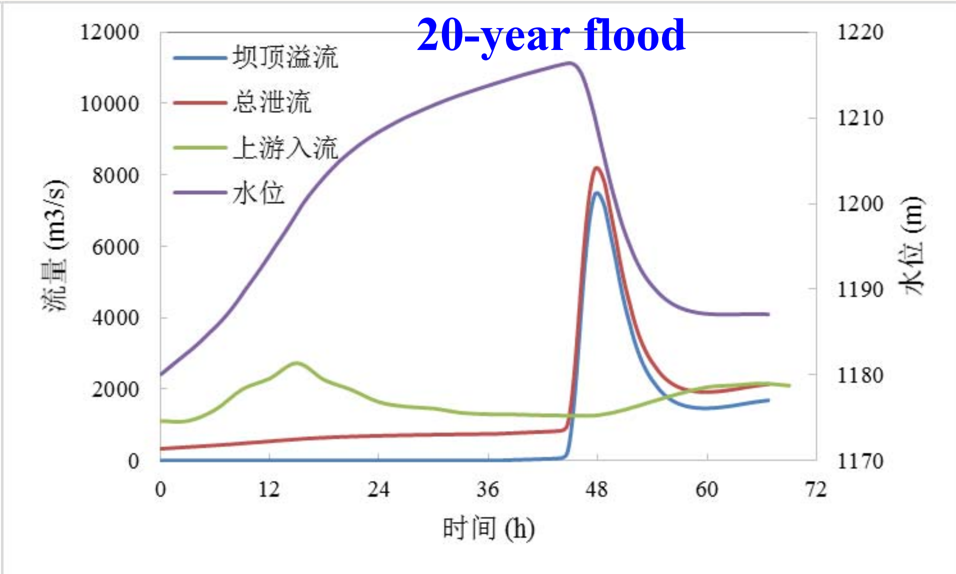


3.3 Flood routing

❑ Dam breach process

With the inflow discharge, water stage in the barrier lake will increase gradually, until it reaches the bottom of the diversion channel and then overtopping occurs.



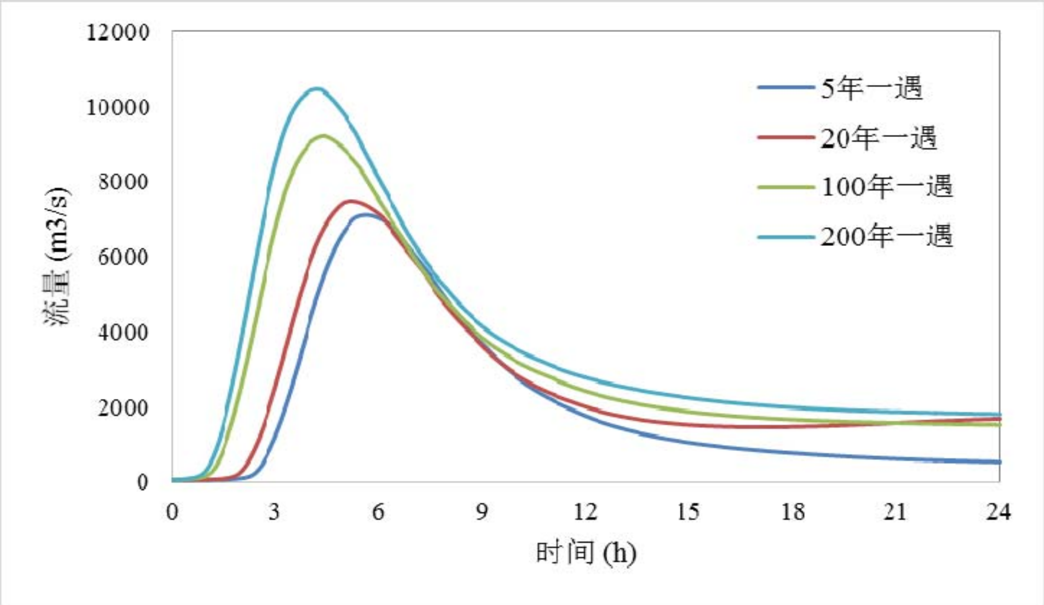


Intial water elevation: 1180 m on Agu 14, 2014

3.3 Flood routing

❑ Dam breach process

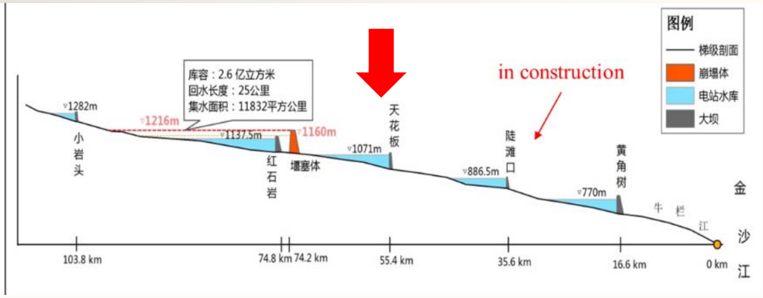
flood	peak discharge (m^3/s)	peak time (hour)	max water level（m）
5-year	7122	5.6	1216.1
20-year	7497	5.2	1216.4
100-year	9229	4.4	1217.5
200-year	10470	4.2	1218.2



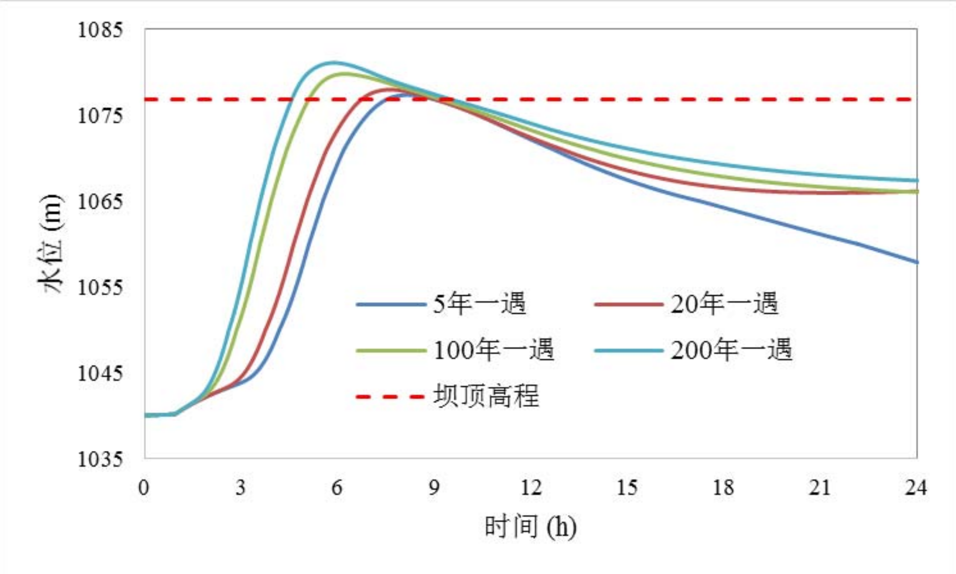
Comparison of outburst hydrograph under different inflow conditions

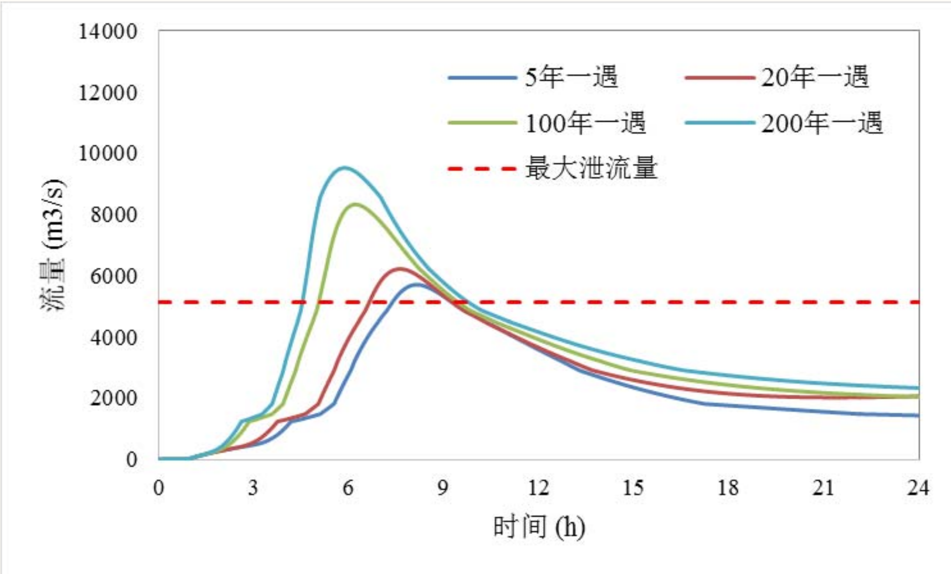
3.3 Flood routing

❑ Flood routing to the Tianhuaban Reservoir



When the dam breach flood arrives at the downstream Tianhuaban Reservoir, water stage will raise until overtopping occurs.





Water stage raise of Tianhuaban Reservoir

Outflow discharge of Tianhuaban Reservoir

3.3 Flood routing

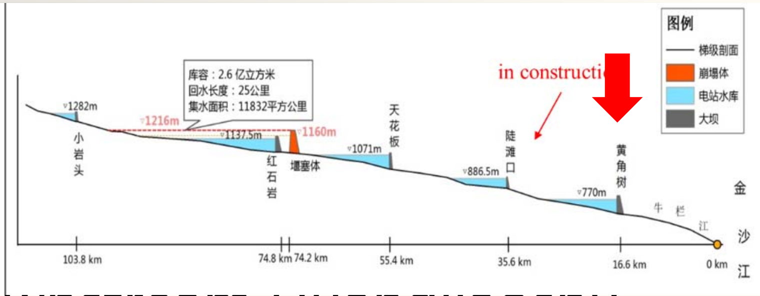
❑ Flood routing to the Tianhuaban reservoir

Flood	Max Water Level / Above Dam Crest* (m)	Max Inflow (m^3/s)	Max Outflow (m^3/s)
5-year	1077.4 / 0.6	7817	5706
20-year	1078.0 / 1.2	8196	6219
100-year	1079.8 / 3.0	9932	8324
200-year	1081.1 / 4.3	11184	9518

Flood Characteristics of Tianhuaban Reservoir in different floods

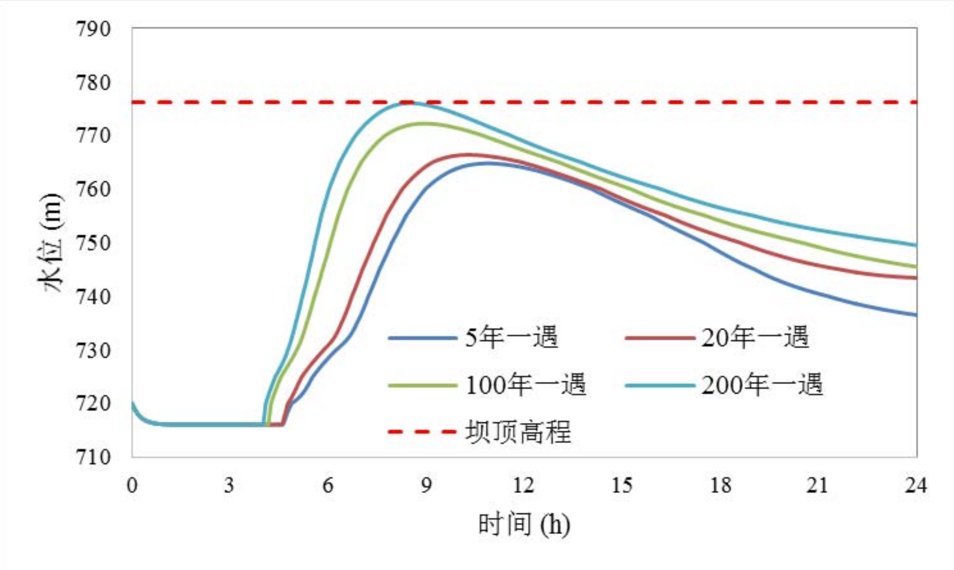
*** Means not reach dam crest**

3.3 Flood routing

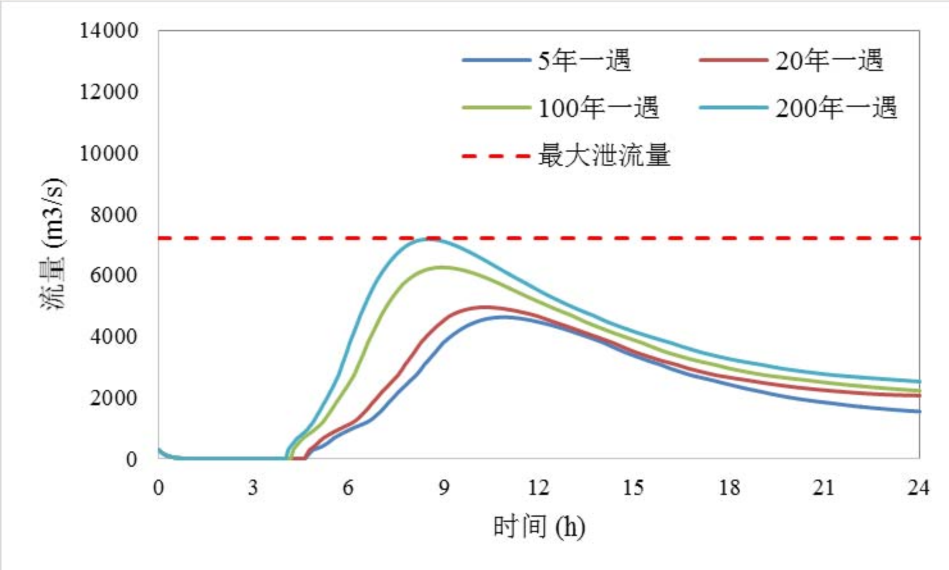


❑ Flood routing to the Huangjiaoshu reservoir

When dam breach flood arrives at the downstream Huangjiaoshu Reservoir, water stage will raise until overtopping occurs.



Water stage raise of Huangjiaoshu Reservoir



Outflow discharge of Huangjiaoshu Reservoir

3.3 Flood routing

❑ Flood routing to the Huangjiaoshu reservoir

Flood	Max Water Level / Above Dam Crest* (m)	Max Inflow (m^3/s)	Max Outflow (m^3/s)
5 year	764.8 / -11.4	5699	4627
20 year	766.4 / -9.8	6213	4953
100 year	772.2 / -4	8313	6257
200 year	**776.0 / -0.2**	**9508**	**7177**

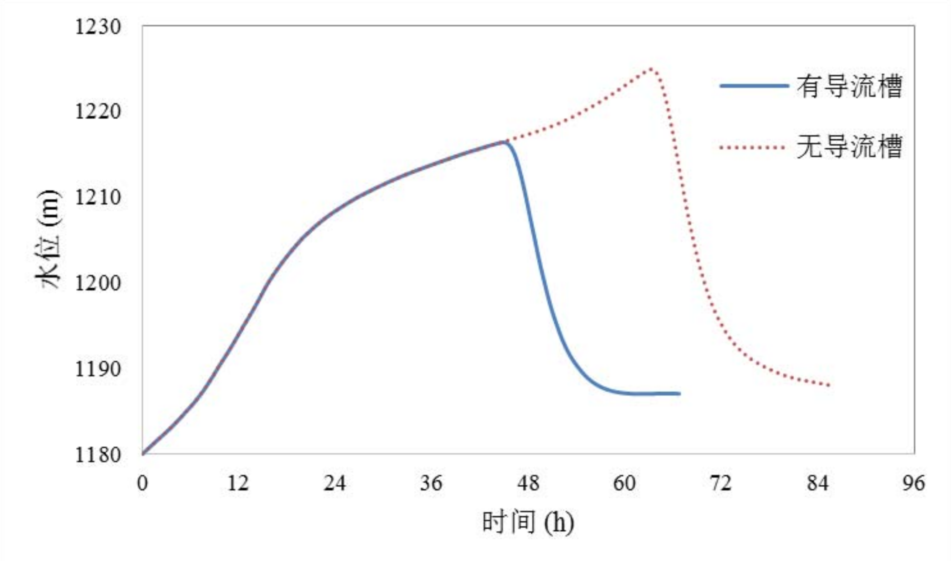
Flood Characteristics of Tianhuaban Reservoir in different floods

*** Means not reach dam crest**

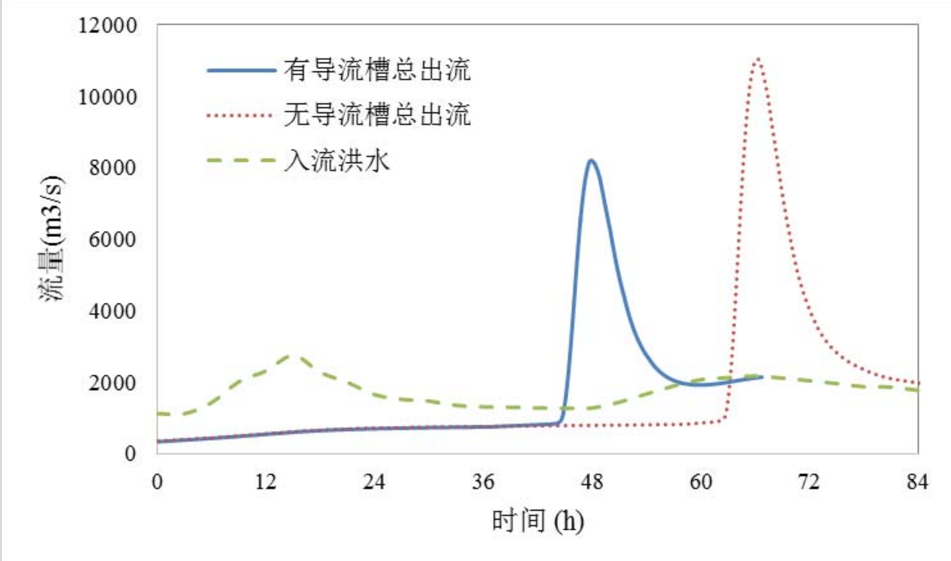
3.3 Flood routing

❑ Comparison of plans with and without diversion channel

Compare the dam breach process for the plans with (8 m depth) and without diversion channel.



Quake lake water stage in 20-year flood for the two plans

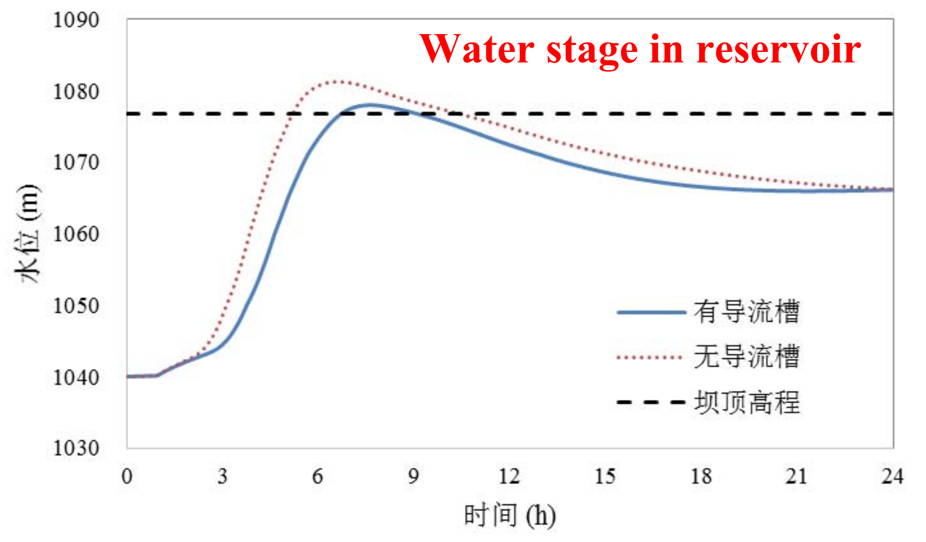


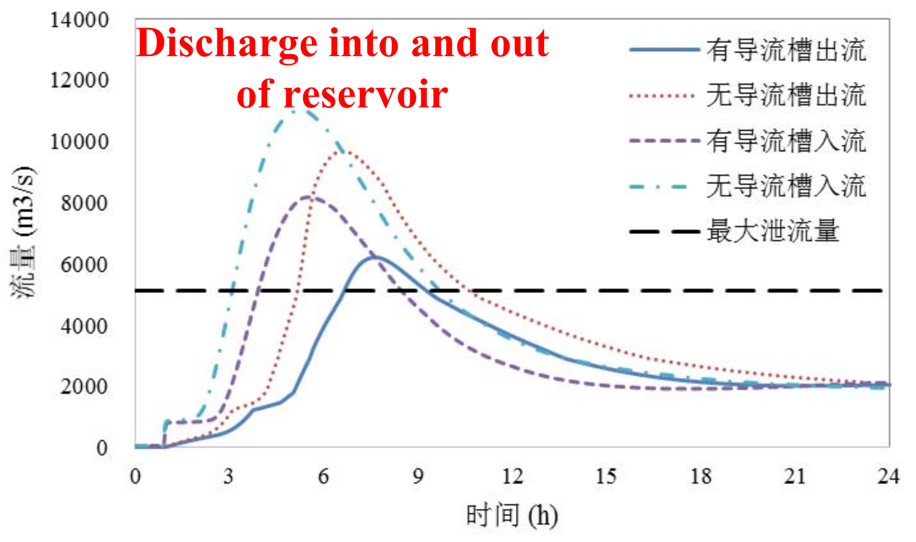
Dam breach discharge in 20-year flood for the two plans

3.3 Flood routing

❑ Comparison of plans with and without diversion channel

Flood routing to the Tianhuaban Reservoir





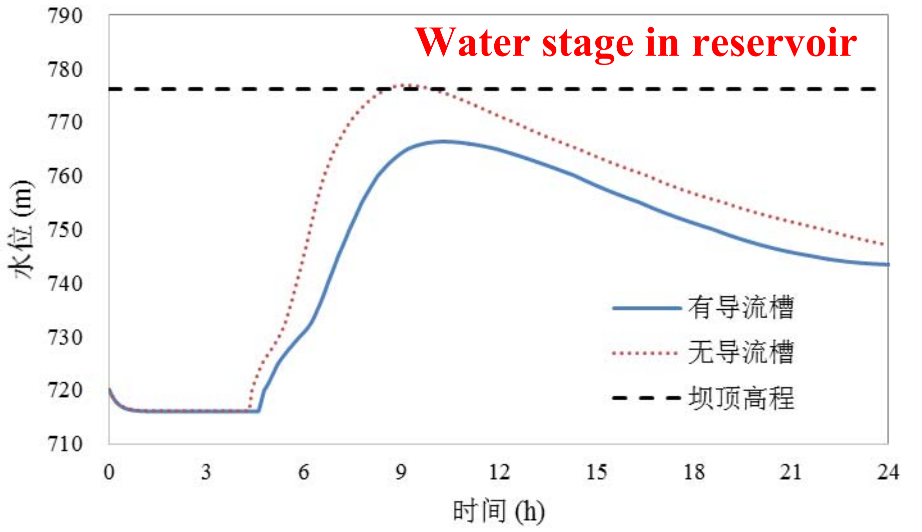
Plan	起调水位 (m)	最高水位/超出坝顶 (m)	最大入库流量 (m^3/s)	最大出库流量 (m^3/s)
with dc	1040	1078.0 / 1.2	8196	6219
without dc	1040	1081.3 / 4.5	11046	9674

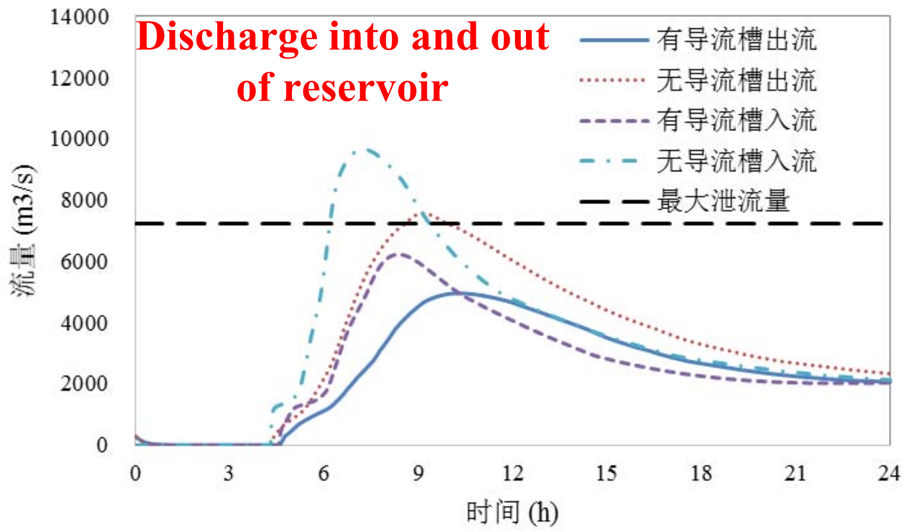
Much severe overtopping when no divert channel

3.3 Flood routing

❑ Comparison of plans with and without divert channel (dc)

Flood routing to the Huangjiaosh Reservoir





Plan	起调水位 (m)	最高水位/超出坝顶 (m)	最大入库流量 (m^3/s)	最大出库流量 (m^3/s)
with dc	720	766.4 / -9.8	6213	4953
without dc	720	776.9 / 0.7	9666	7559

Overtopping may occur without no diversion channel

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Contents

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4. Summary

- The disposal of two barrier dams is presented.
- The major measure of the disposal was to excavate a diversion channel on the dam crest for creating a man-controlled flood.
- Two challenges were addressed: lack of field data and lack of understanding of the failure mechanisms.
- A coupled monitoring and simulation method for flood forecast is promising.
- Although diversion channel works well, reasonable estimation of dam stability subject to overtopping or piping is still desirable.

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Thank you !