An overview of mudflows and consequent risk after the Wenchuan Earthquake

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Outline

- Major mudflow events after the Wenchuan Earthquake
- Initiation mechanism of the post-earthquake mudflows
- Monitoring and early-warning of post-earthquake mudflows
- Numerical modeling and risk assessment of mudflows
- Consequent risk and long-term effect after the Wenchuan Earthquake

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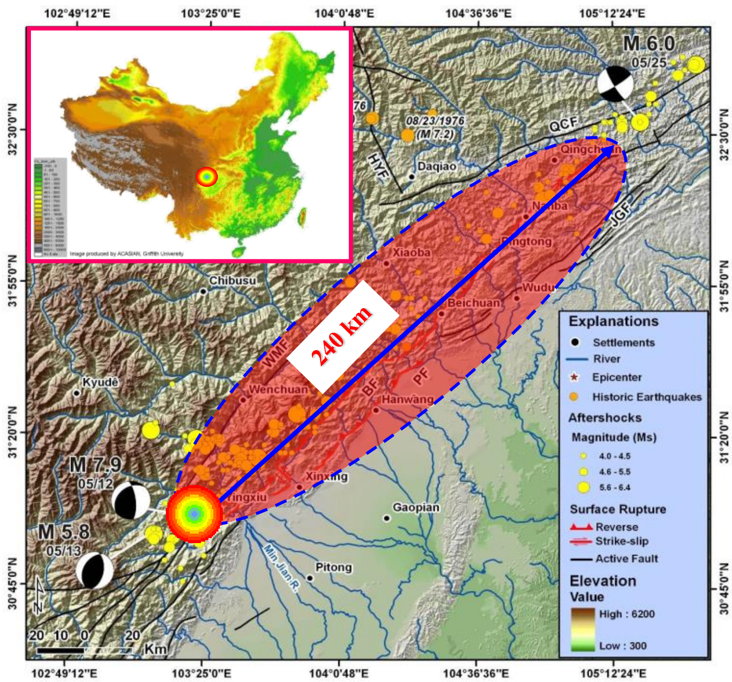
On May 12 2008, Mw 7.9 Wenchuan Earthquake occurred along the Longmen Mountain faults, West of Sichuan Basin, China

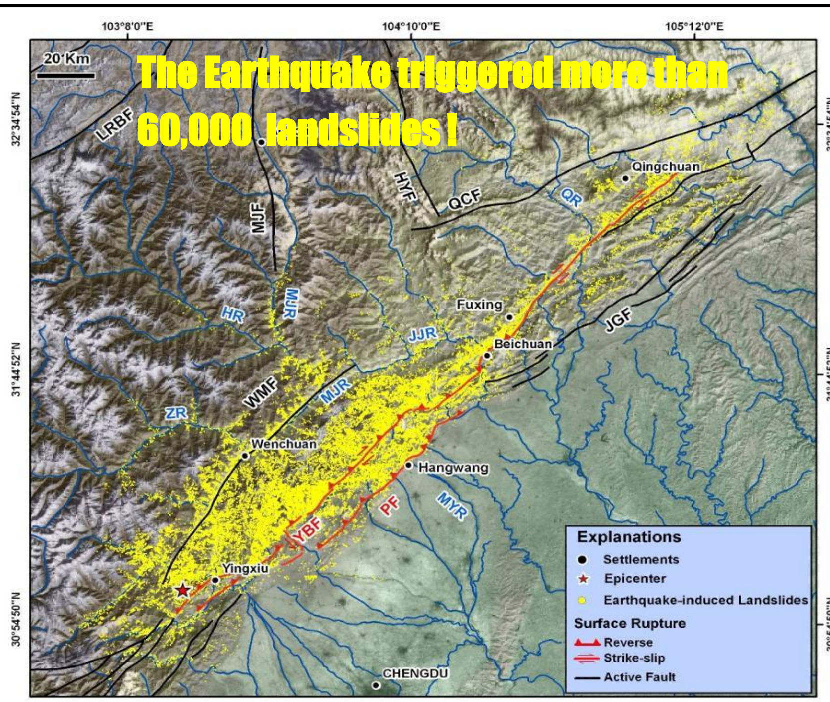
Sources

Surface rupture: Xu et al., 2009;

Epicenter and aftershocks: USGS 2008;

Historic earthquakes: Kirby et al., 2000; Li et al., 2008; Xu et al., 2009





A large number of co-seismic landslide resulted in a huge amount of poorly sorted deposit with volume greater than 10^{10} m^3, which transforming into source material for rainfall-induced mudflows.

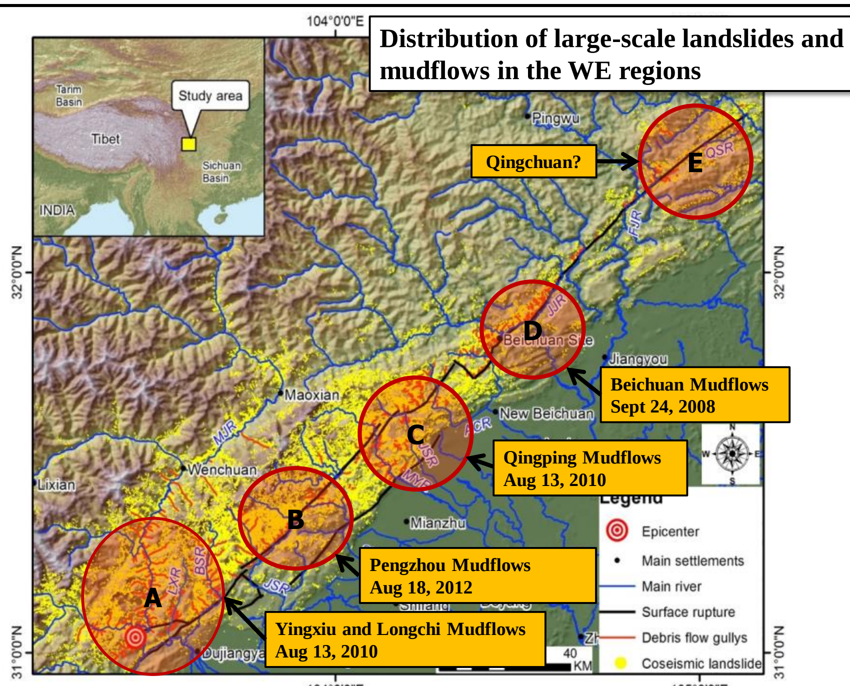
Part I - Major mudflows after the Wenchuan Earthquake

Newly reconstructed Yingxiu town was flooded due to the debris flow dam (Photo taken in August 2010)

Major large-scale mudflows occurred after the Wenchuan Earthquake

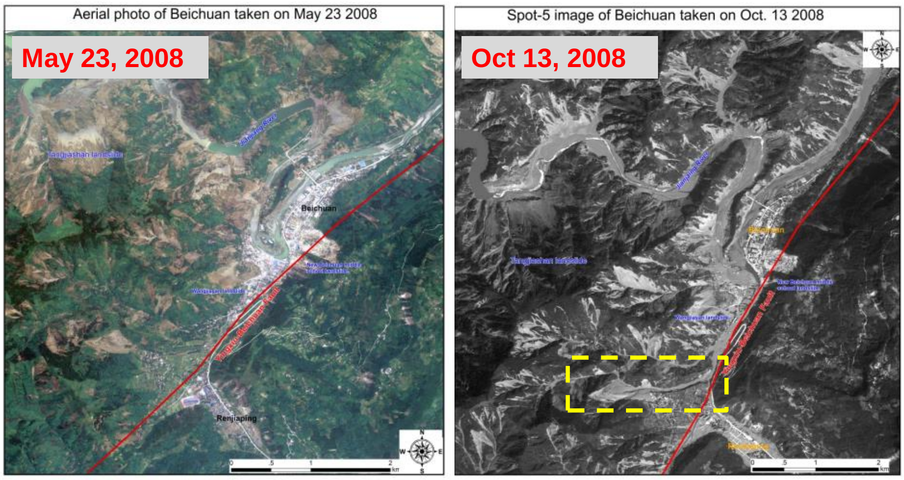
Place and name	Time	Number and the largest individual debris flow	Damage
Mudflows Beichuan County	Sept 28 2008	72 mudflows occurred simultaneously in Beichuan County. The largest one is Wenjia Gully debris flow, with volume more than 1 million m^3	42 people were killed. The old town of Beichuan County was almost completely buried, with a thickness of 6 to 10m.
Mudflows Gaochuan section of the Jushui River in Anxian County	July 18 2009	More than 10 mudflows occurred in the Gaochuan segment of Jushui River; the largest one was more than 3×10^5 m^3	Many houses and roads were damaged
Mudflows Qingping of Mianyuan River basin in Mianzhu County	August 13 2010	Mudflows occurred in the 20 gullies from Qingping to Yibadao segments of Mianyuan River, with a total volume of 10 ×106 m3. The outrush of the largest Wenjiagou debris flow was $4.5\times10^6 m^3$	It caused the deaths of 14 persons, injury of 33 persons and damage of 379 houses, and the direct economic loss 600 million RMB.
Mudflows Yingxiu, Wenchuan County	August 13 2010	Mudflows occurred in the 21 gullies in Yingxiu, with a total volume of 2×106 m3. The largest one was Hongchun debris flow, with a volume of 7.5×10^5 m^3.	32 people were killed. Villages were ruined, and barrier lakes were formed, leading to secondary flood hazards.
Mudflows Longchi, Dujiangyan	August 13 2010	Mudflows occurred in the 44 gullies in Longchi , Dujiangyan, with a total volume of 3×10^6 m^3.	It caused the damage of 161 houses, and the direct economic loss 400 million RMB.
Mudflows Pengzhou	August 18 2012	Mudflows occurred in the 12 gullies in Yinchang, Pengzhou, with a total volume of 6×10^5 m^3.	It caused the deaths of 2 persons, and the direct economic loss 500 million RMB.
Mudflows Mingriver and Wenchuan	July 8-10 2013	Mudflows occurred in the 25 gullies along Muing river. The largest one was Qipangou gully debris flow, with a volume of 8.5×10^5 m^3.	A lot of facilities and villages were ruined, and barrier lakes were formed, leading to secondary flood hazards.

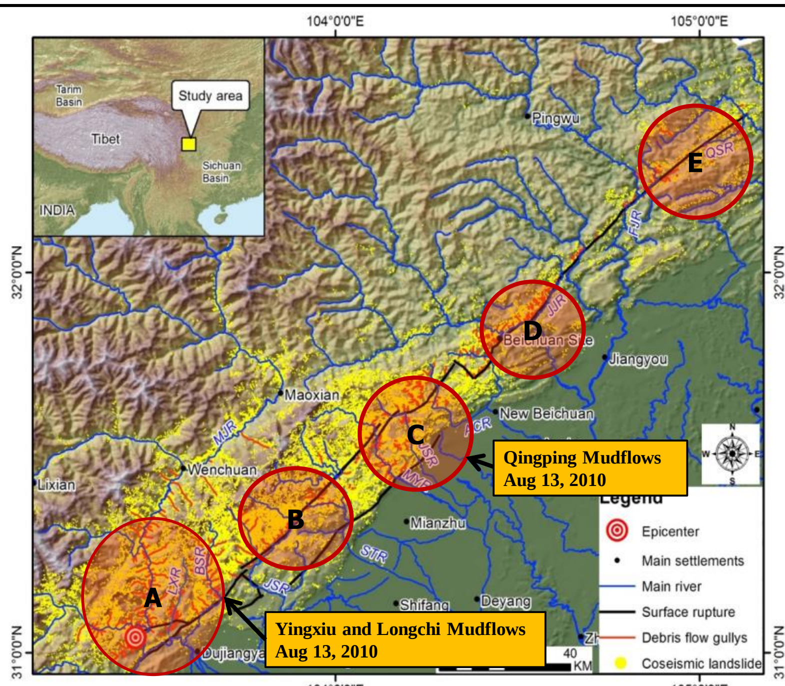
Distribution of large-scale landslides and mudflows in the WE regions



(1) Mudflows in Beichuan town (Sept 24, 2008)

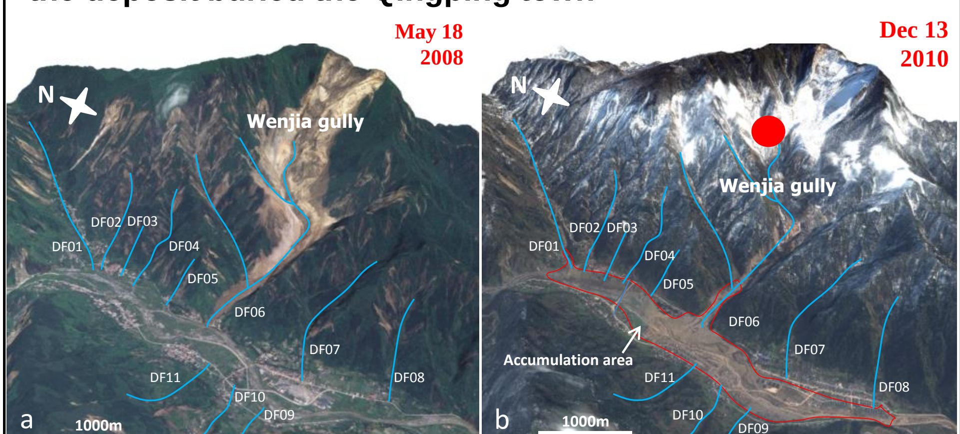
4 month after the Wenchuan Earthquake, 72 mudflows occurred on Sept 24, The old town of Beichuan was almost completely buried with depth of 10 m.



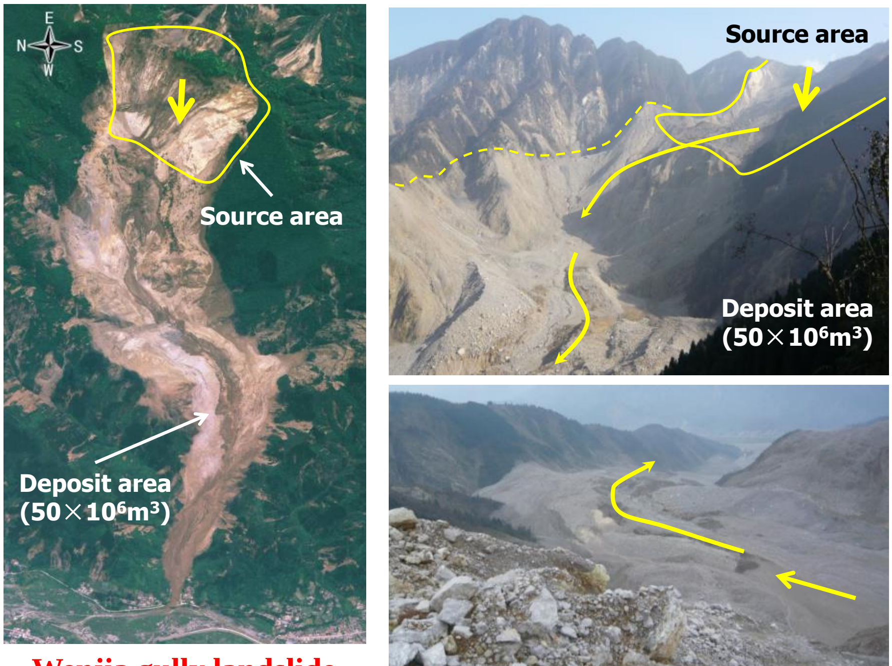


(2) Mudflows in Qingping county (Aug 13, 2010)

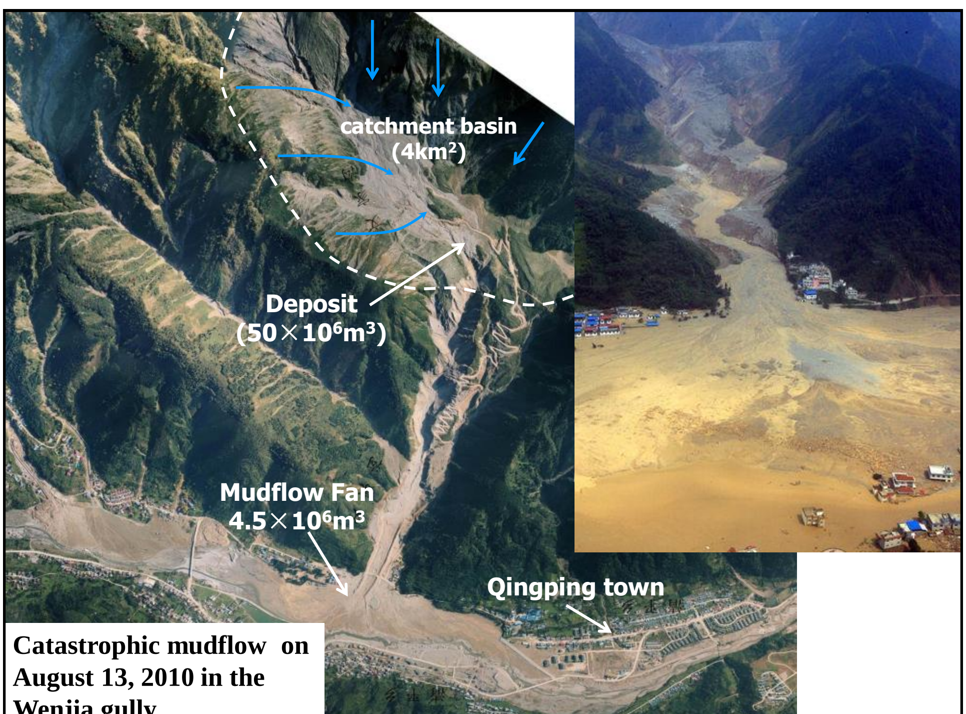
More than 20 mudflows occurred on Aug 13, 2010, of which the deposit buried the Qingping town



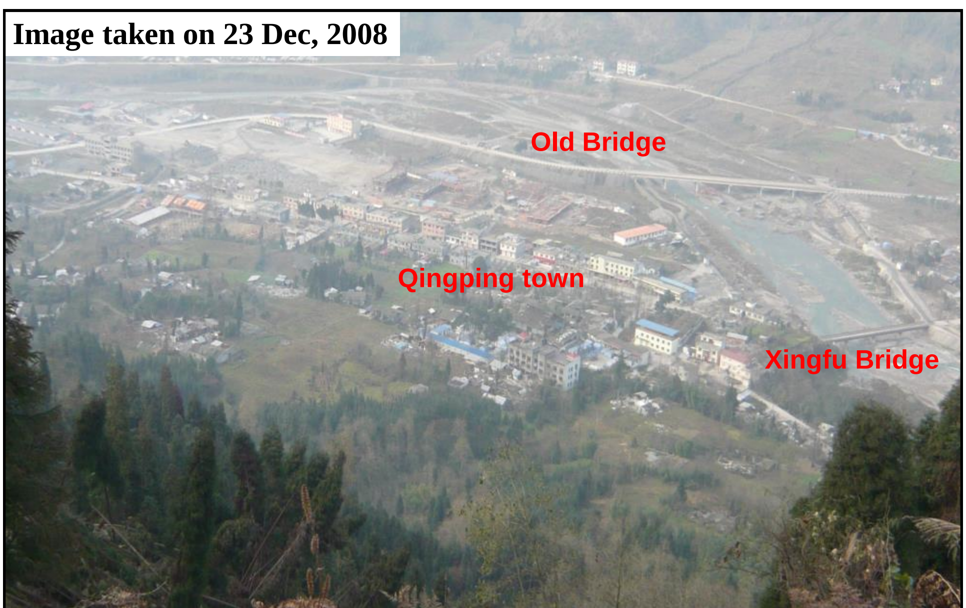
Pre- and post- images of the debris flow event occurred on August 13, 2010 in Qingping Town



Wenjia gully landslide



Catastrophic mudflow on August 13, 2010 in the Wenjia gully

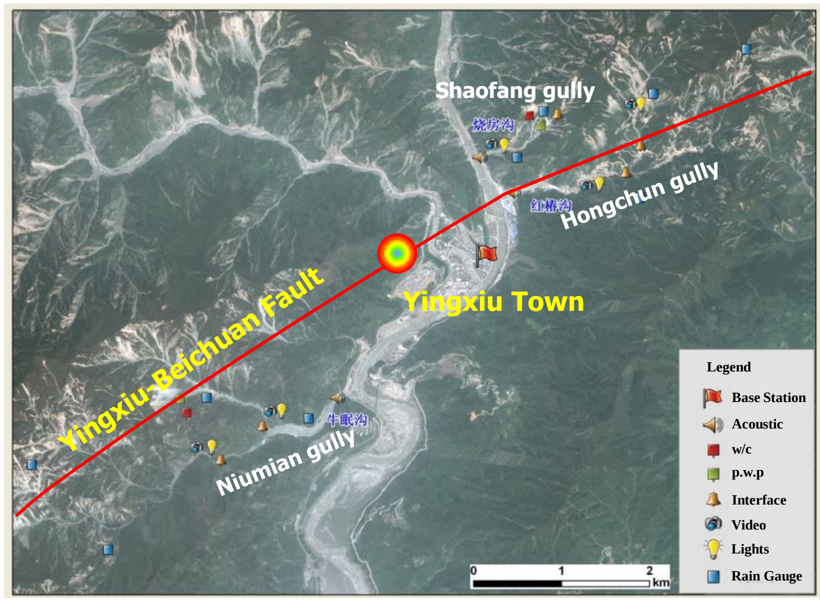


Qingping area prior to the catastrophic mudflow event

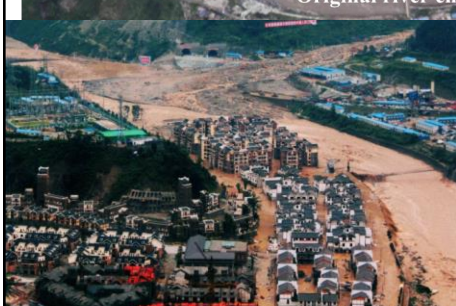
Photo of Qingping county after 8.13 debris

Many rebuilded houses were buried

(3) Mudflows in Yingxiu town (Aug 13, 2010)



(3) Mudflows in Yingxiu town (Aug 13, 2010)



Mudflows in Yingxiu town
August 13, 2010

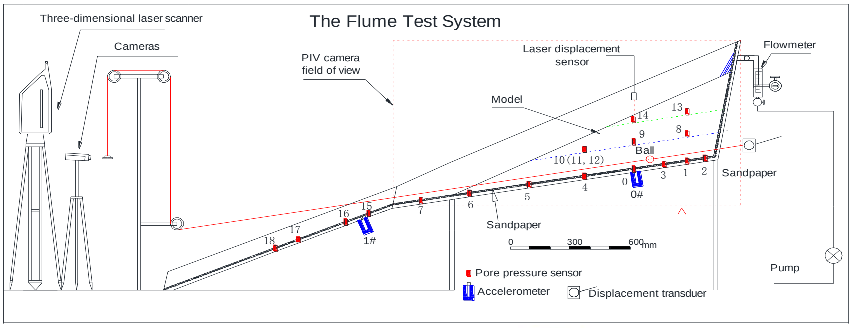
(3) Mudflows in Wenchuan town (July 10, 2013)

On July 10, 2013, a heavy rainstorm at the Wenchuan town induced more than 100 mudflows - 29 people were killed

A giant boulder (dia. > 16 m) was mobilized and travelled for more than 1 km

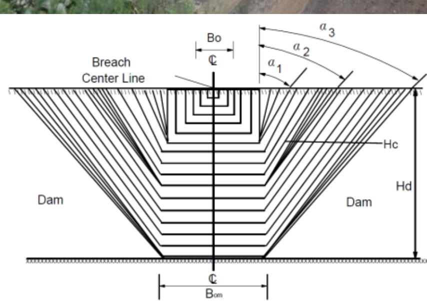
Part II - Initiation mechanism of post-earthquake mudflows

The large volume of loose deposit resulted in the intense channelized erosion and dam-breaching effects

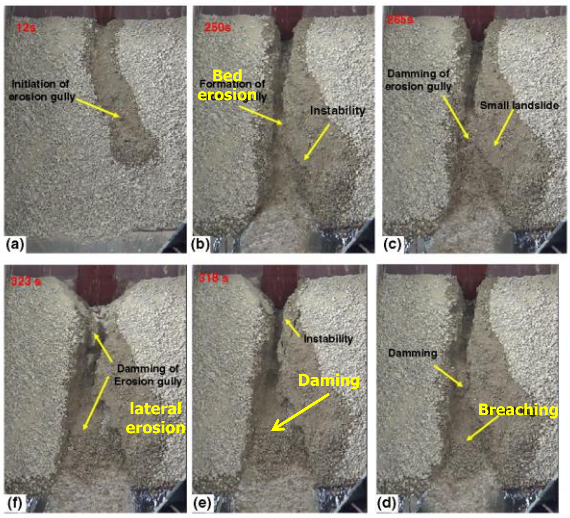


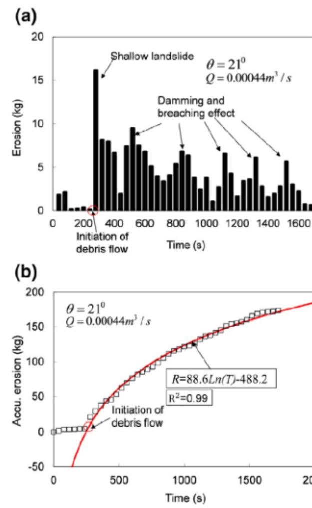
Flow controller and TDR

To study the initiation mechanism, a flume test system was established in SKLGP



The initiation mechanism of mudflow in WE regions is unique, which is similar to dam-breaching process.





Washing out materials

(1) Bed erosion and lateral erosion (shallow landslide) in the deposited materials and initiation of debris flow
(2) Continuous breaching and damming effect and enlargement of the channel

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Diffuse Failure Mechanism

Diffuse failure in loose saturated granular deposits

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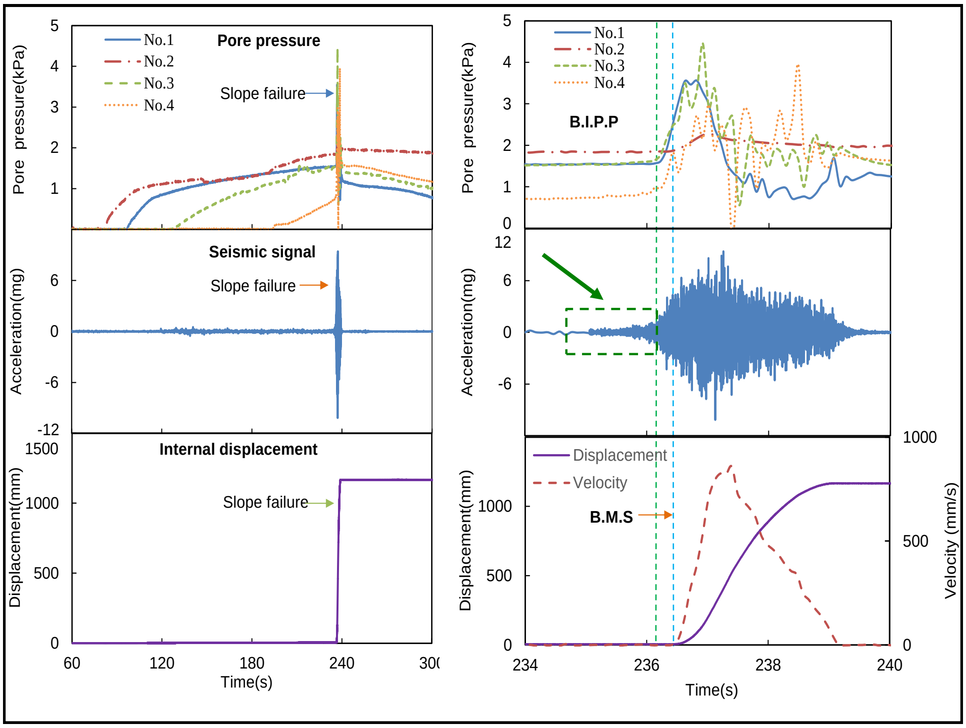
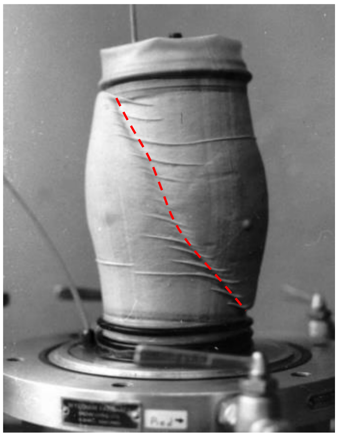
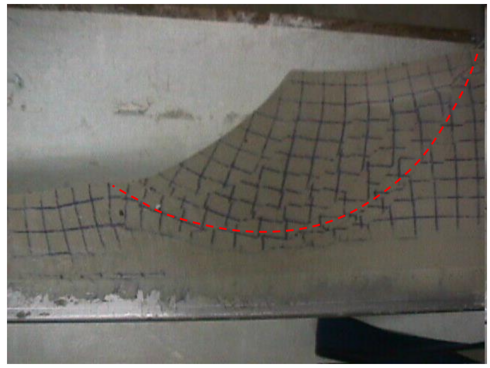


Diffuse Failure Mechanism

Diffuse failure: the abrupt and entire collapse without slip surface (Nicot and Darve, 2011).

Diffuse Failure Mechanism

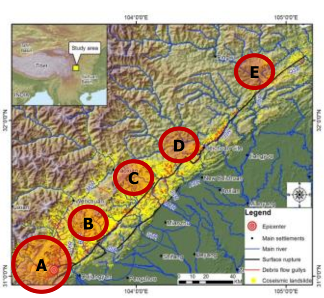


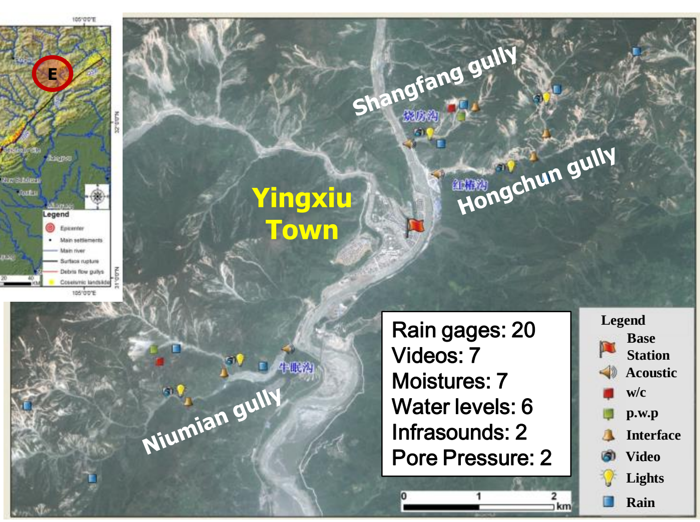


Localized failure

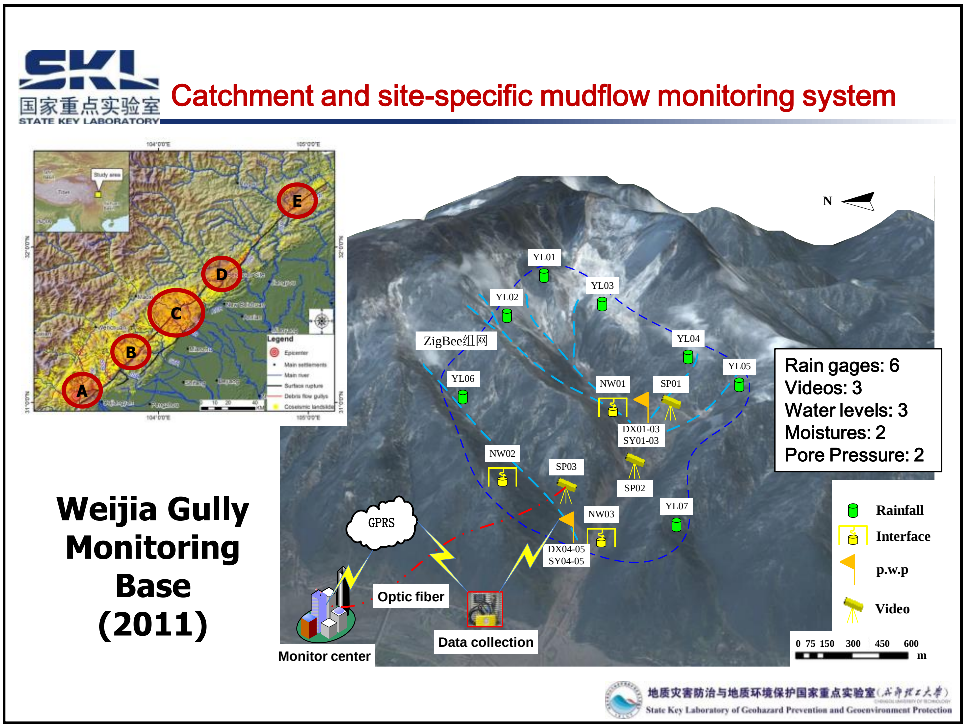
Strains concentrate within thin bands With Load applied , and subsequent failure along this band (Nicot and Darve, 2011).

Part III - Monitoring and pre-warning of post-earthquake mudflows





Yingxiu Monitoring Base (2011)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Catchment and site-specific mudflow monitoring system
Weijia Gully Monitoring Base (2011)
N
YL01
YL02
YL03
YL04
YL05
YL06
YL07
ZigBee组网
NW01
NW02
NW03
SP01
SP02
SP03
DX01-03
SY01-03
DX04-05
SY04-05
GPRS
Optic fiber
Data collection
Monitor center
Rain gages: 6
Videos: 3
Water levels: 3
Moistures: 2
Pore Pressure: 2
Rainfall
Interface
p.w.p
Video
0 75 150 300 450 600
m
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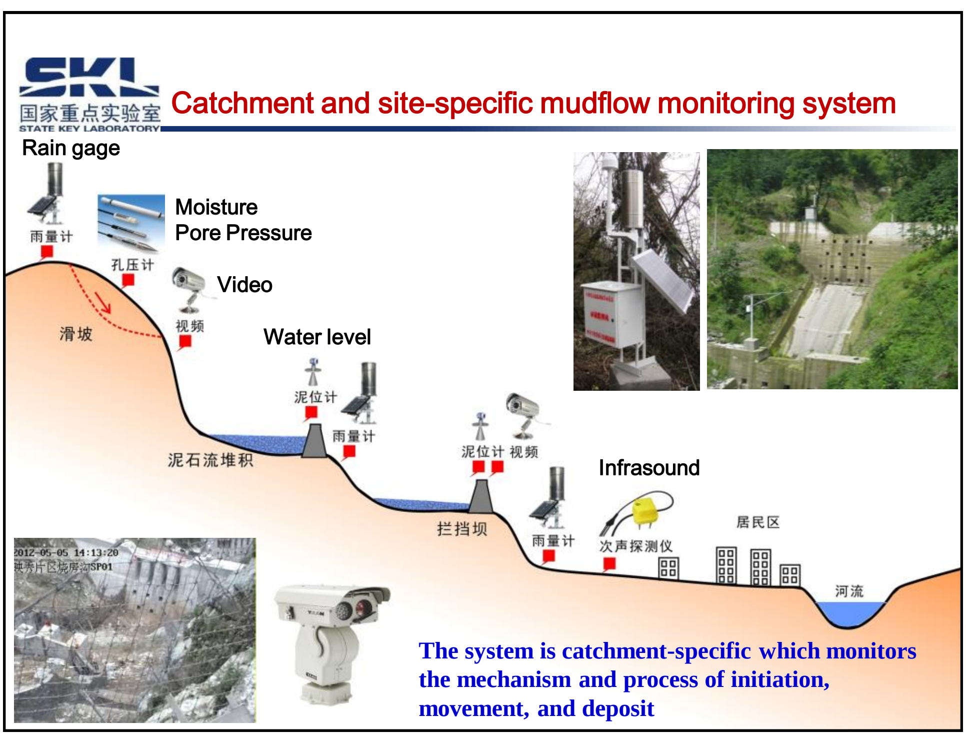
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Catchment and site-specific mudflow monitoring system
Rain gage
雨量计
Moisture
Pore Pressure
孔压计
Video
视频
滑坡
Water level
泥位计
雨量计
泥石流堆积
泥位计 视频
拦挡坝
Infrasound
雨量计
次声探测仪
居民区
河流
2012-05-05 14:13:20
The system is catchment-specific which monitors the mechanism and process of initiation, movement, and deposit

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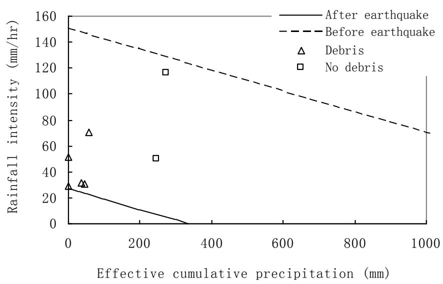
Early warning model of mudflow

Pre- and post-earthquake rainfall thresholds in Beichuan

Before the Earthquake		After the earthquake		Decrease of critical rainfall	
Accumulated rainfall (mm)	Critical intensity (mm/hr)	Accumulated rainfall (mm)	Critical intensity (mm/hr)	Accumulated rainfall (mm)	Critical intensity (mm/hr)
320-350	**55-60**	**272.7**	**41**	**15.0%～22.0%**	**25.0% ～32.0%**



The accumulated rainfall and critical rainfall intensity **were 30% lower** than before the earthquake.

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Early warning model of mudflow

Early warning model considers the aspects of topography, geology, and hydrology (rainfall) for any single mudflow gully

$$P = \frac{RT^{0.2}}{G^{0.5}} \geq Cr$$

P：prediction value

R：rainfall

T：topography

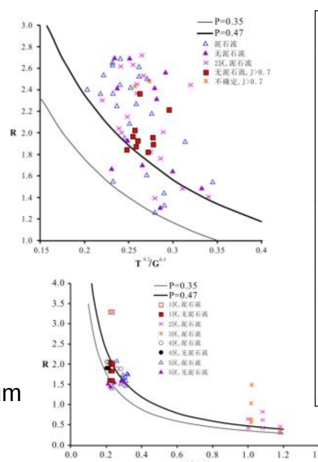
G：geology

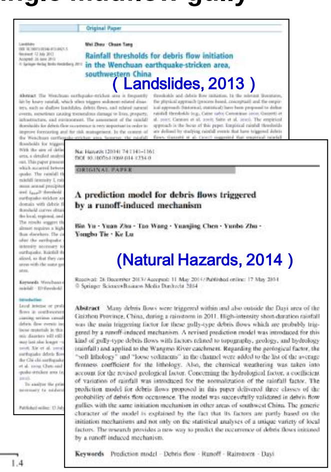
Cr：threshold value

$Cr < 0.35$：low

$0.35 \leq Cr < 0.47$：medium

$Cr \geq 0.47$：high





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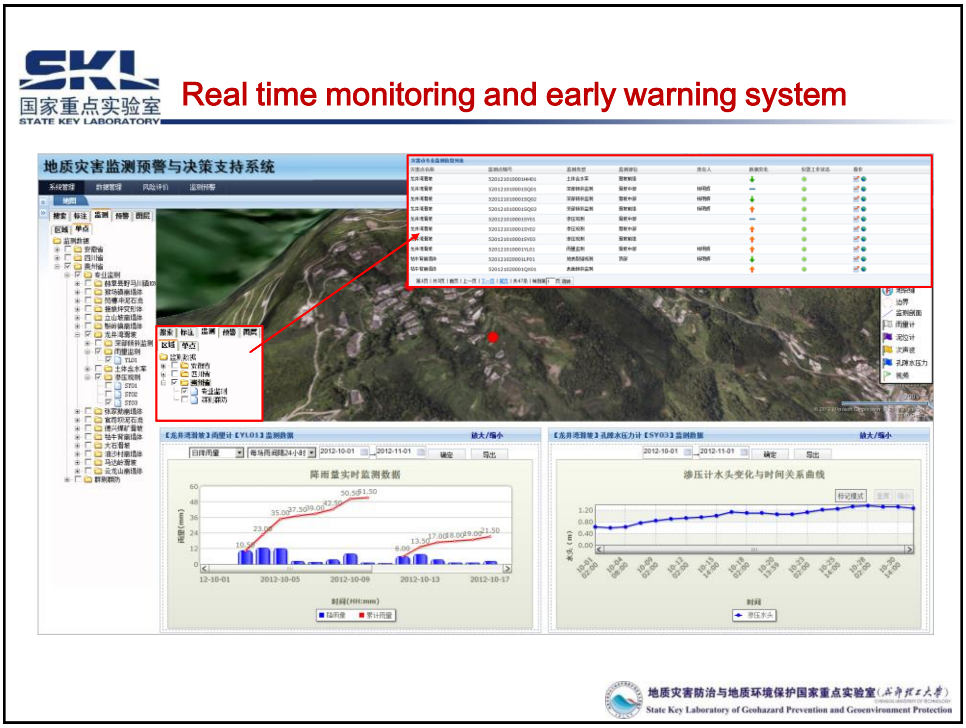
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Real time monitoring and early warning system
地质灾害监测预警与决策支持系统
地质灾害防治与地质环境保护国家重点实验室(成都理工大学)
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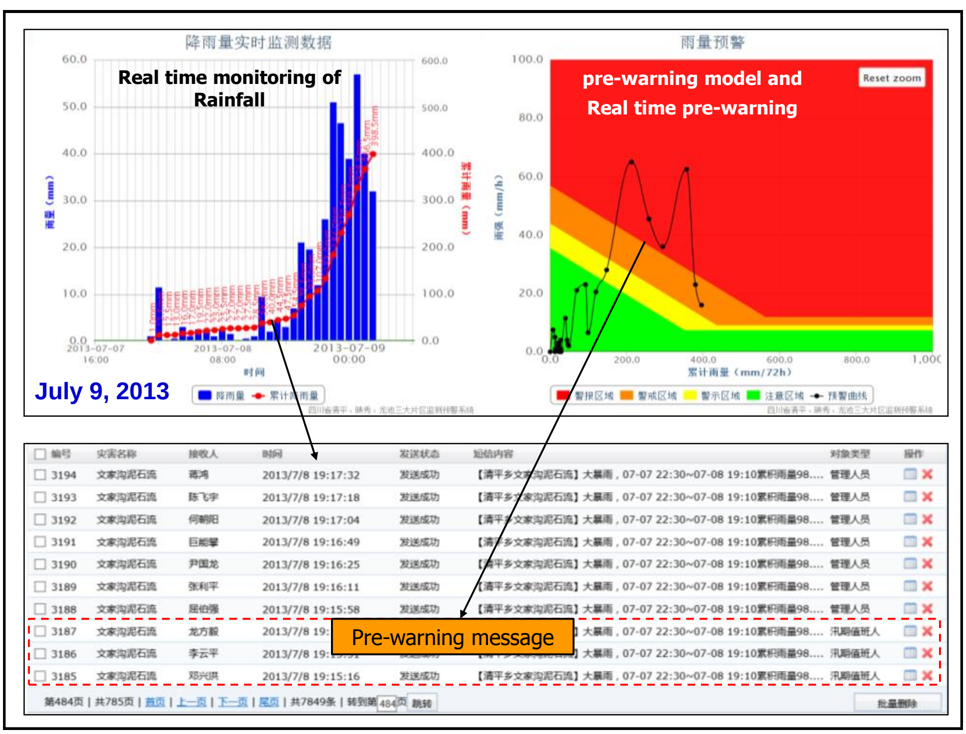
降雨量实时监测数据
Real time monitoring of Rainfall
July 9, 2013
雨量预警
pre-warning model and
Real time pre-warning
Reset zoom
Pre-warning message

Part IV - Numerical modeling and assessment of mudflows

- SPH-based simulation of debris flow
  - ❖ *Key algorithms:*
    - *（1） Solid-water coupled model*
    - *（2） Dynamic erosion model*
    - *（3） Fluid-structure coupled model*

Force of solid to liquid

$$\mathbf{R}^{sf} = n^2 \frac{\rho_f g}{k}(\mathbf{v}^{sf} - \mathbf{v}^f)$$

Force of liquid to solid

$$\mathbf{R}^{fs} = n^2 \frac{\rho_f g}{k}(\mathbf{v}^{fs} - \mathbf{v}^s)$$

Erosion criterion

$$\eta_i = \frac{p_i \cdot \tan(\varphi) + c}{\sqrt{0.5 D_{\Pi}}} < \eta_{\max}$$

The pressure term

$$p_j = H_1 \gamma_w + p_k + \frac{v_k^2}{2g}\gamma_w$$

$$p_i = H_2 \gamma_s + p_i$$

Impact force of fluid to structure:

$$F_s^{f\to s} = -\int_{\Omega_s} p_v \nabla_x W_h(x_s - x_v) d\Omega = -\sum_{v\in\Omega_s} \frac{m_v}{\rho_v} p_v \nabla_x W_h(x_s - x_v)$$

Impact force of structure to fluid:

$$F_f^{s\to f} = -\int_{\Omega_f} p_v \nabla_x W_h(x_f - x_v) d\Omega = -\sum_{v\in\Omega_f} \frac{m_v}{\rho_v} p_v \nabla_x W_h(x_f - x_v)$$

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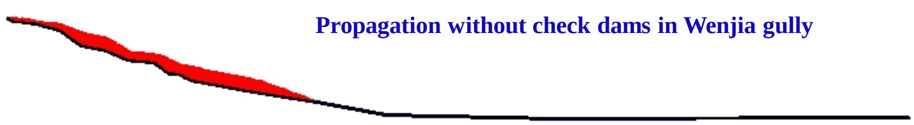
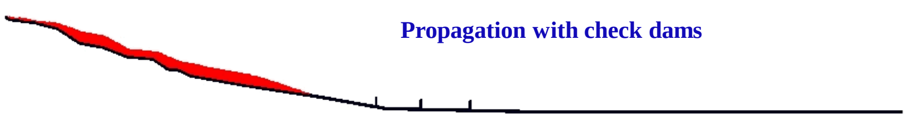
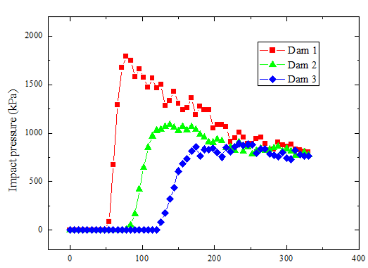
SPH simulation-2D of mudflow in Wenjia gully

Propagation without check dams in Wenjia gully



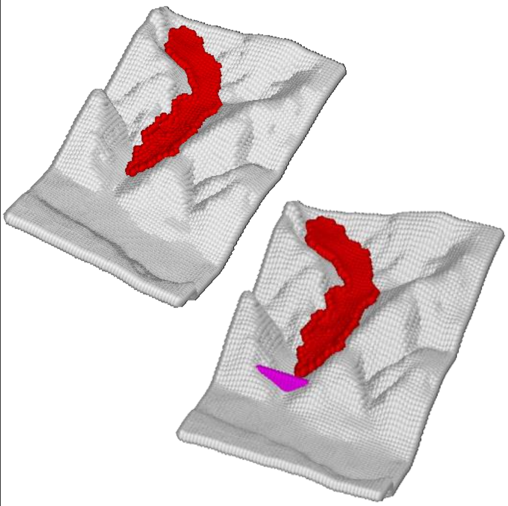
Propagation with check dams

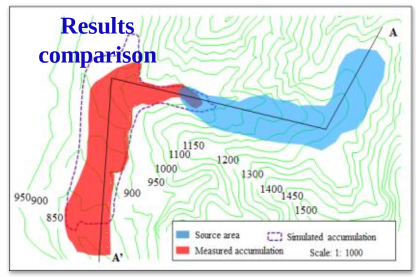


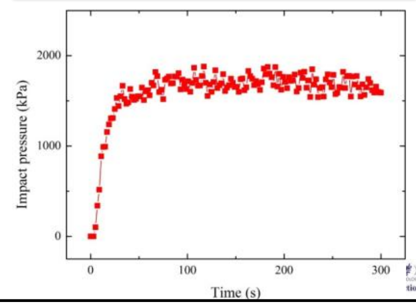


Impact force **exerted by the debris flow on the check dams are investigated using the flow-structure coupled SPH method, the check dams effectively prevented further propagation of debris flow.**

SPH simulation-3D of mudflow in Wenjia gully







The check dams effectively prevented further propagation of mudflow.

Part IV - Numerical modeling and assessment of mudflows

- **FLO 2D based simulation of debris flow**

FLO-2D can simulate flood and mudflows on different surfaces, and then produce the temporal variation of flow depth, flow velocity and affected area.

Governing equations (O'Brien et al. 1993):

Equations of continuity:

$$\frac{\partial H}{\partial t}+\frac{\partial (uH)}{\partial x}=i,$$

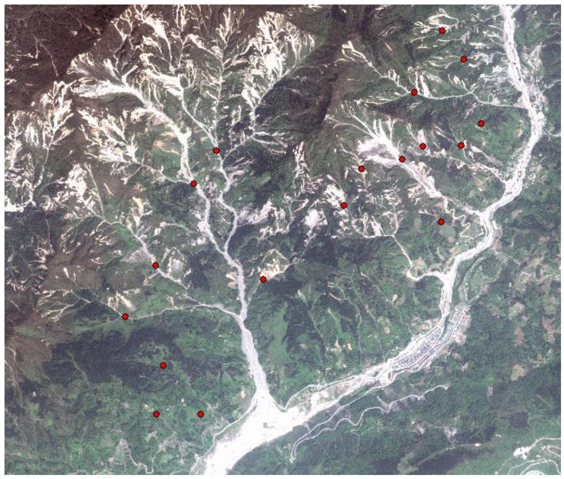
Equations of dynamic wave momentum:

$$S_f = S_o - \frac{\partial H}{\partial x} - \frac{u}{g}\frac{\partial u}{\partial x} - \frac{1}{g}\frac{\partial u}{\partial t}$$

H is flowing depth, u is flowing time, x is spatial variable, t is time, i is rainfall intensity, S_f is bottom friction and S_o is bed slop.

Part IV - Numerical modeling and assessment of mudflows

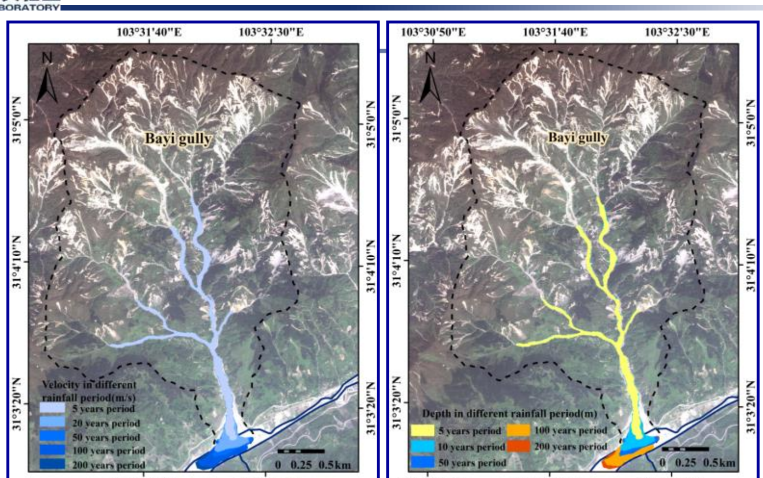
- **FLO 2D** based simulation of debris flow



Mudflows simulated in Longchi

On Aug. 13,2010

Hazard Assessment in Longchi



The result of numerical models in different rainfall return period, which are used for hazard assessment

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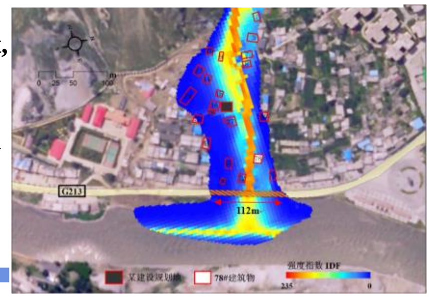
Risk assessment in the Yangling gully mudflow

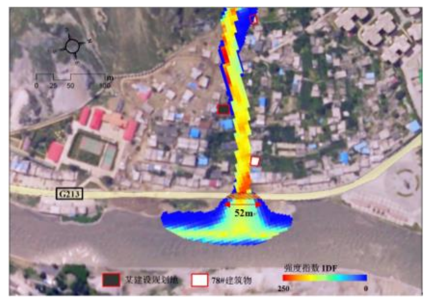
The impact of buildings by mudflows were analyzed by using hazard assessment, which evaluated the hazard susceptibility with different rainfall return period, and thus provided the base for debris flow risk assessment

- Rainfall return period = 10 year

Without mitigation:
21 buildings will be damaged;
Total financial loss: 1.8 million RMB.



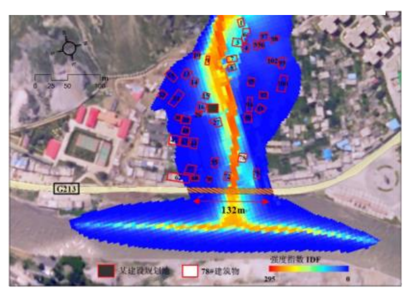
With mitigation:
1 building will be damaged;
Total financial loss: 43.8 thousand RMB.



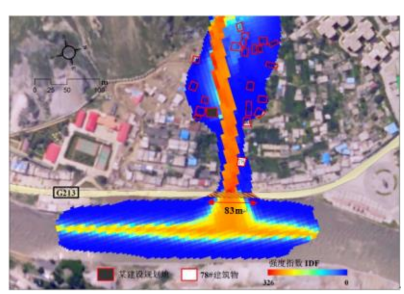
Risk assessment in the Yangling gully mudflow

- Rainfall return period = 100 year

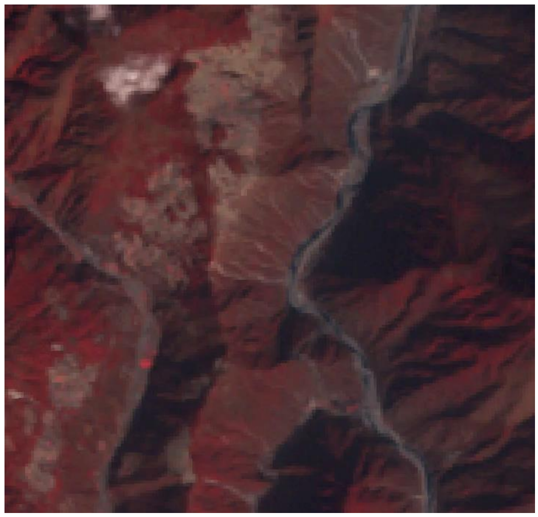
Without mitigation:
43 building will be damaged;
Financial loss: 2.8 million RMB.



With mitigation:
20 building will be damaged;
Financial loss: 1.27 million RMB.



Part V - Consequent risk and long-term effect after the Wenchuan Earthquake



Google Earth time-lapse (2003-2016)

Consequent Risk

Abundant debris were transported from slope into the river and uplifted the riverbed. The average uplift rate of several river courses is over 2m/yr, with average depth of debris over 10 m (max. 30 m). The uplift of riverbed buried the infrastructure and buildings, and resulted in severe flooding.

Buildings were buried by the Jian river in Beichuan

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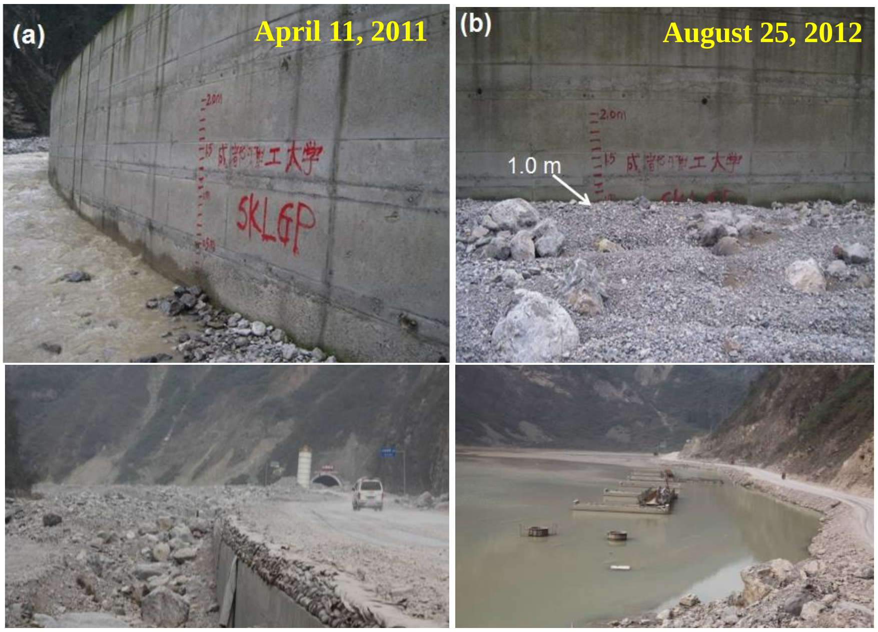
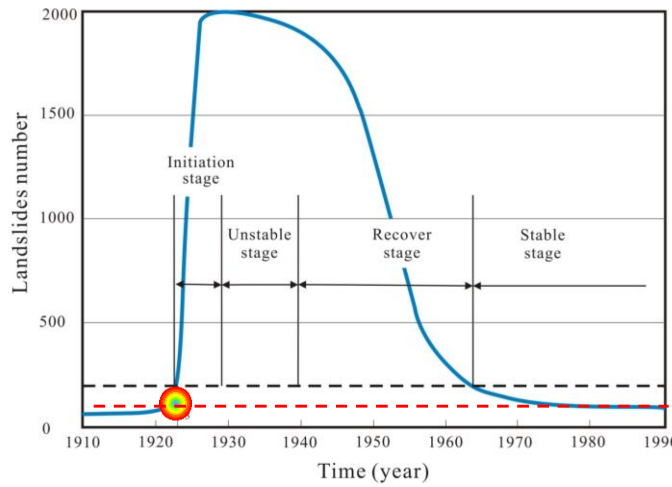


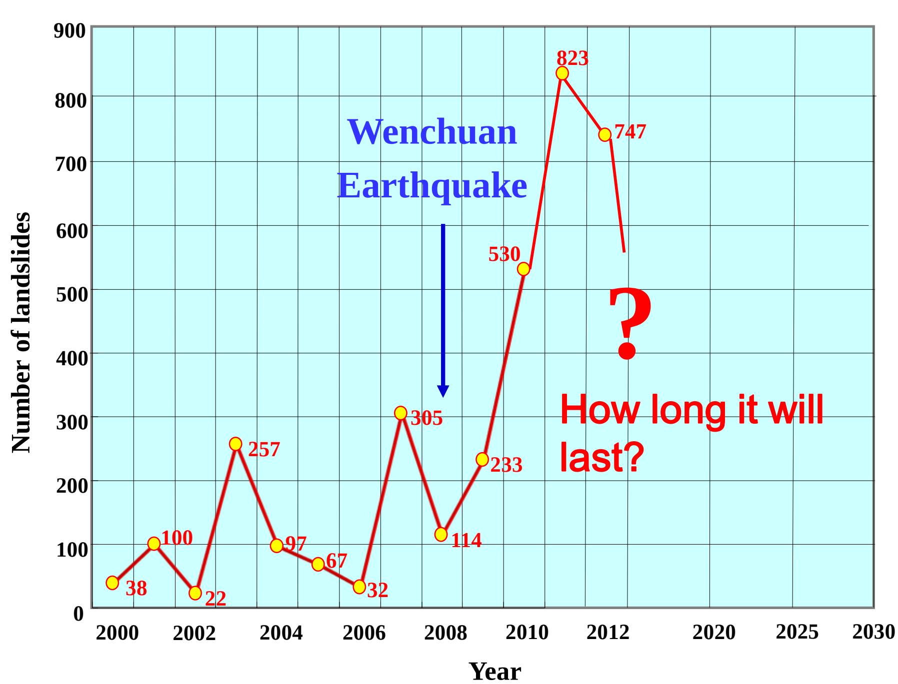
The riverbed was uplifted more than 10 m by the loose materials deposited in the Mianyuan River, which destroyed reconstructed roadways

The uplift of riverbed reduced the cross-section area of the channel, and in turn caused serious flooding

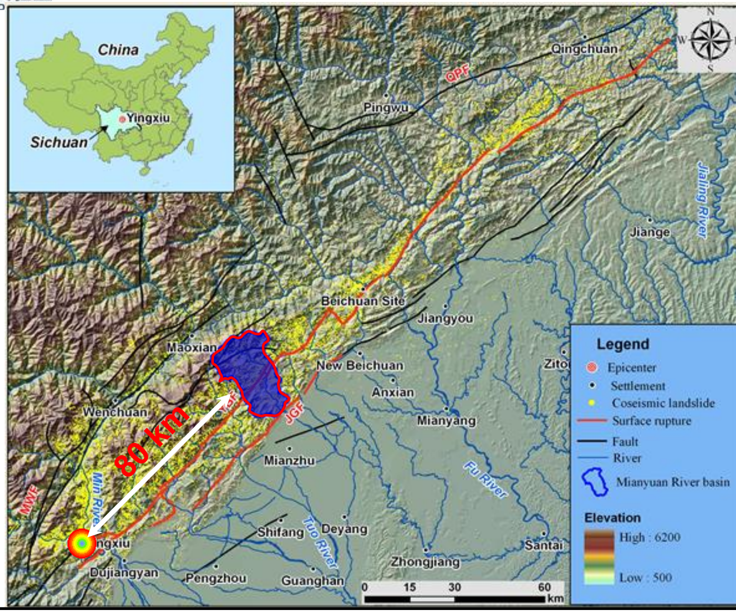
The long-term effect

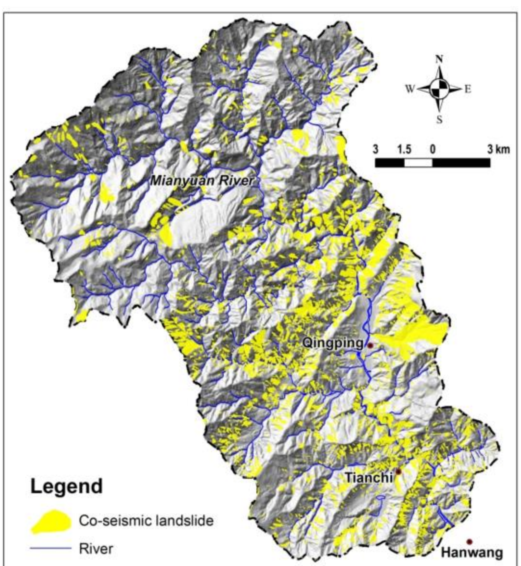


The earthquake Influence lasted more than 60 years in Kantō Earthquake (M_w = 7.9) of 1923 in Japan



A case study in the Mianyuan catchment





The mapped co-seismic landslides in the Mianyuan River basin

- Landslides number: 2259
- Landslide point density: 5.6/km^2.
- Landslides area: 43.1 km^2
- Total volume of landslides (the empirical equation contributed by Parker et al. (2011)):

$$V = 0.106A^{1.388}$$

Where : V: landslide volume (m^3);
A : landslide area (m^2).

- **Total volume : 400.0×10^6 m^3**

How long it will take for the mudflow frequency to return to pre-earthquake level?

- The co-seismic landslides loose deposit is 400×10^6 m^3 in this catchment
- If 15%-30% of the loose materials were transferred from hillslopes to the river system in the form of mudflows. The total volume would be around 60×10^6 - 120×10^6 m^3
- The volume of loose materials transferred to the main river in the past 5 years was 12.7×10^6 m^3
- Preliminary estimation indicates that the mudflows will remain ‘active’ for at least 24 years

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Conclusion

- The frequency of mudflow increased remarkably after the earthquake. Heavy rainfall events have induced more than 640 mudflows, which is 2-5 times greater than the total number observed before the earthquake.
- The accumulated rainfall and critical rainfall intensity for initiating post-earthquake mudflows are 30% of the corresponding value for the pre-earthquake level.
- Catchment and site-specific mudflow monitoring system networks were constructed with early warning system, which established basic automated mudflow prewarning framework.
- The poorly sorted co-seismic landslide deposit will continued to be mobilized from hillslope into the river, and subsequently uplifted the riverbed and increased the flooding risk. It is postulated that such long-term effect will last for at least 20-30 years.

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Outlook

To increase the resilience of communities affected by earthquakes and associated geo-hazards and contribute to economic development and social welfare, the future collaborations between us can focus on:

Further research cooperation

- Monitoring and warning of mudflows and landslides
- Risk assessment of mudflows and landslides
- Control and mitigation of mudflows and landslides

Further academic exchanges

- Joint academic conference
- Joint academic visit
- Joint training for students

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Wenjia Gully Mitigation System


国土 卫士 地矿 铁军 排危 除险 科学 治灾