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
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

The Earthquake triggered more than 60,000 landslides!
A large number of co-seismic landslide resulted in a huge amount of poorly sorted deposit with volume greater than $10^{10} \text{m}^3$, 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

<table>
<thead>
<tr>
<th>Place and name</th>
<th>Time</th>
<th>Number and the largest individual debris flow</th>
<th>Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mudflows Beichuan County</strong></td>
<td>Sept 28 2008</td>
<td>72 mudflows occurred simultaneously in Beichuan County. The largest one is Wenjia Gully debris flow, with volume more than 1 million m³</td>
<td>42 people were killed. The old town of Beichuan County was almost completely buried, with a thickness of 6 to 10m.</td>
</tr>
<tr>
<td><strong>Mudflows Gaocuan section of the Jushui River in Arixian County</strong></td>
<td>July 18 2008</td>
<td>More than 10 mudflows occurred in the Gaocuan segment of Jushui River; the largest one was more than 3×10⁵ m³</td>
<td>Many houses and roads were damaged</td>
</tr>
<tr>
<td><strong>Mudflows Qingping of Mianyuan River basin in Mianzhu County</strong></td>
<td>August 13 2010</td>
<td>Mudflows occurred in the 20 gullies from Qingping to Yibado segments of Mianyuan River, with a total volume of 10×10⁶ m³. The outrush of the largest Wenjiagou debris flow was 4.5×10⁶ m³</td>
<td>It caused the deaths of 14 persons, injury of 33 persons and damage of 379 houses, and the direct economic loss 600 million RMB.</td>
</tr>
<tr>
<td><strong>Mudflows Yingxiu, Wenchuan County</strong></td>
<td>August 13 2010</td>
<td>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 7.5×10⁶ m³</td>
<td>32 people were killed. Villages were ruined, and barrier lakes were formed, leading to secondary flood hazards.</td>
</tr>
<tr>
<td><strong>Mudflows Longchi, Dujiangyan</strong></td>
<td>August 13 2010</td>
<td>Mudflows occurred in the 44 gullies in Longchi, Dujiangyan, with a total volume of 3×10⁷ m³.</td>
<td>It caused the damage of 161 houses, and the direct economic loss 400 million RMB.</td>
</tr>
<tr>
<td><strong>Mudflows Pengzhou</strong></td>
<td>August 18 2012</td>
<td>Mudflows occurred in the 12 gullies in Yinchang, Pengzhou, with a total volume of 6×10⁶ m³.</td>
<td>It caused the deaths of 2 persons, and the direct economic loss 500 million RMB.</td>
</tr>
<tr>
<td><strong>Mudflows Mingriver and Wenchuan</strong></td>
<td>July 8-10 2013</td>
<td>Mudflows occurred in the 25 gullies along Ming river. The largest one was Qipangou gully debris flow, with a volume of 8.5×10⁷ m³</td>
<td>A lot of facilities and villages were ruined, and barrier lakes were formed, leading to secondary flood hazards.</td>
</tr>
</tbody>
</table>

![Distribution of large-scale landslides and mudflows in the WE regions](image-url)
(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
18 Check dams (3-6m)

Blocked dams (8m, 220m)

Headward and channelized erosion

Qingping area prior to the catastrophic mudflow event

Image taken on 23 Dec, 2008
Photo on 14 Aug, 2010

Event volume: $4.5 \times 10^6$ m$^3$

Photo of Qingping county after 8.13 debris

Many rebuilted houses were buried
(3) Mudflows in Yingxiu town (Aug 13, 2010)

The Yingxiu town was flooded
Debris-flow dam
Original river channel

Shaofang gully
Hongchun gully

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

Diffuse Failure Mechanism

Diffuse failure in loose saturated granular deposits
Diffuse Failure Mechanism

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

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

Diffuse Failure Mechanism

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

Yingxiu Monitoring Base (2011)
The system is catchment-specific which monitors the mechanism and process of initiation, movement, and deposit.
**Early warning model of mudflow**

### Pre- and post-earthquake rainfall thresholds in Beichuan

<table>
<thead>
<tr>
<th>Before the Earthquake</th>
<th>After the earthquake</th>
<th>Decrease of critical rainfall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accumulated rainfall (mm)</td>
<td>Critical intensity (mm/hr)</td>
<td>Accumulated rainfall (mm)</td>
</tr>
<tr>
<td>320-350</td>
<td>55-60</td>
<td>272.7</td>
</tr>
</tbody>
</table>

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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*Sources: Landslides, 2013; Natural Hazards, 2014*
Real time monitoring and early warning system

Real time monitoring of Rainfall

Pre-warning message

July 9, 2013
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
\[ R_f^s = n^2 \frac{\rho_f g}{k} (v^f - v') \]

### Force of liquid to solid
\[ R_s^f = n^2 \frac{\rho_s g}{k} (v^s - v') \]

### Erosion criterion
\[ \eta = \frac{p_j \cdot \tan(\phi) + c}{\sqrt{1.5D_{ni}}} < \eta_{\text{max}} \]

### The pressure term
\[ p_i = H^s y^s + p_i \]
\[ p_j = H^f y^f + p_j \]
\[ p_i = H^s y^s + p_i \]

### Impact force of fluid to structure;
\[ F_f^{s} = - \sum_{j=1}^{m} p_i V_j W_j (x_i - x_j) \]

### Impact force of structure to fluid;
\[ F_i^{f} = - \sum_{j=1}^{m} p_j V_i W_i (x_i - x_j) \]

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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.
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:

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

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 slope.
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
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.

➢ 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
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 earthquake influence lasted more than 60 years in the Kantō Earthquake ($M_w = 7.9$) of 1923 in Japan.
A case study in the Mianyuan catchment

- Landslides number: 2259
- Landslide point density: 5.6/km².
- Landslides area: 43.1 km²
- Total volume of landslides (the empirical equation contributed by Parker et al. (2011)):

\[ V = 0.106A^{1.388} \]

Where: \( V \) : landslide volume (m³);
\( A \) : landslide area (m²).

- Total volume: \( 400.0 \times 10^8 \) m³
How long it will take for the mudflow frequency to return to pre-earthquake level?

- The co-seismic landslides loose deposit is $400 \times 10^6$ 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 $60 \times 10^6 - 120 \times 10^6$ m$^3$.
- The volume of loose materials transferred to the main river in the past 5 years was $12.7 \times 10^6$ m$^3$.
- Preliminary estimation indicates that the mudflows will remain ‘active’ for at least 24 years.

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.
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

THANK YOU FOR YOUR ATTENTION!
Wenjia Gully Mitigation System

Check dam 5#

Check dam 4#

Desilting basin

Drainage grid

Flexible drainage channel

Drainage tunnel