Mechanisms and Prediction of Earthquake and Climate Change Induced Cascading Hazards

Xuanmei Fan

State Key Laboratory of Geohazard Prevention and Geoenvironment Protection
Chengdu University of Technology, Chengdu, Sichuan, China
A substantial proportion of the world's largest cities lies in regions with significant seismic risk.

The main reasons for death toll are:
(1) Earthquake-caused collapse of buildings
(2) Earthquake-induced landslides
Earthquake-induced hazards have strong cascading effects

The 2008 Wenchuan earthquake triggered >200,000 landslides

Control works were destroyed

Post-earthquake debris flows

2008 Wenchuan EQ
2009 9.24 debris flows
2010 8.13 debris flows
2011 7.3 debris flows
2013 7.10 debris flows
2020 8.20 debris flows

Caused hundreds of deaths and over 10 billions RMB of economic loss
Main Challenges

Type 1

Earthquake → Coseismic landslides → Landslide dams → Dam-breach flood

- The failure mechanism of earthquake-triggered large landslides is poorly understood;
- There is no models that can accurately predict the coseismic landslides and landslide dams

Type 2

Coseismic landslides → Post-earthquake remobilized landslides → Post-earthquake Debris flows

- Post-earthquake landslides and debris flows have dynamic mechanism, evolving with time
- Early warning of post-earthquake debris flows is challenging
Key Findings

**Finding 1**
Prediction of coseismic landslides and dam-breach flood

**Finding 2**
Mechanisms and prediction of post-seismic landslides and debris flows

**Finding 3**
Early warning model of future chains of geological hazards
Challenges:

How to predict coseismic landslides?

How to predict dam-breach flooding risk?

https://www.hrr.mlit.go.jp/bosai/110920kasenbu/kekkai.html
Coseismic landslide prediction

- Global earthquake-triggered landslide inventory

- 54 historical strong earthquakes
- including more than 400,000 coseismic landslides

Acknowledgment: Hakan Tanyaş and many others who contributed to the inventory

Hakan T et al., JGR: Earth Surface, 2017
Fan et al., Reviews of Geophysics, 2019
Coseismic landslide prediction

Spatial distribution pattern and controls of coseismic landslides

Controlling factors

- **Seismic factors**
  - Distance to fault
  - Fault type
  - Hanging/foot wall effect
  - Locking section effect

- **Terrain factors**
  - Slope; Aspect
  - Internal relief
  - Micro-topography

- **Geological factors**
  - Lithology
  - Geological structure

- **Hydrological factors**
  - Distance to river
  - Stream power index
  - Drainage density

Fault type, distance and hanging wall effect

- Fan XM et al., *Reviews of Geophysics*, 2019
Coseismic landslide prediction

- AI algorithms (CNN, FCN (Fully Convolutional Network), RF......)

Fan XM * et al., *Landslides*, 2018a
Coseismic landslide prediction

Near-real time prediction model of co-seismic landslides

Fan XM * et al., *Landslides*, 2018a
Prediction results were released 2 hours after the EQ

2022 Ms 6.8 Luding earthquake

Wandong region

Wajiao village

Accuracy 83.70%, Kappa coefficient is 0.54
SESSION 6.4: Chengyong Fan, Xuanmei Fan, Xin Wang
 Developed an integrated model for earthquake-induced landslide dam and dam-breach flood hazard chain evaluation

- **Landslide and dam formation simulation**
  - Slope seismic response
  - EQ-triggered landslides
  - EQ-Landslide-Damming

- **Dam breach based on fluid-solid coupling**
  - Reservoir volume
  - Breach time
  - Dam-breach process
  - Hydrograph

- **Dam breach flood simulation**
  - Downstream riverbed morphology based on GIS
  - 1D/2D non-constant flow hydraulic model
  - Flood parameters (Area/depth/velocity...)

Fan XM et al., 2021a,b; 2013; Fan XM et al., *Earth Science Reviews*, 2020 and 2021
Understanding the causes and effects of earthquake-induced landslide dams

Xuanmei Fan
Invited review

The formation and impact of landslide dams – State of the art

Xunxian Fan, Anja Dufresne1, Srikrishna Siva Subramanian2, Alexander Strom, Reginald Herrmann3, Carlo Tacconi Bondesan4, Jeongheui Hyeon5, Ali Z. Yunes6, Stuart Dunziger7, Jaco Coenraads, Martin Greiser6, Benjamin Miller6, Nicola Colborn6, John J. B. James8, Qiang Xu

1 Institute for Water and Environmental Science, Commonwealth Scientific and Industrial Research Organisation (CSIRO),s Water Research Centre, South Yarra, VIC, Australia
2 University of New South Wales (UNSW), Sydney, NSW, Australia
3 Geological Survey of Western Australia (GSWA), Lands and Minerals, Department of Planning, Lands, Water and Environment, Government of Western Australia, Perth, WA 6005, Australia
4 Geologisch-Paläontologisches Institut, Universität Bonn, Endenicher Allee 19a, 53115, Bonn, Germany
5 Northern Territory Department of Environment and Natural Resources (DENDRA), Darwin, NT 0801, Australia
6 Department of Civil Engineering, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208, USA
7 Department of Earth Sciences, University of Cambridge, Pembroke Street, Cambridge CB2 3QZ, United Kingdom
8 Department of Earth Sciences, Imperial College London, Prince Consort Road, London SW7 2BP, United Kingdom
9 Department of Geological Sciences, University of Leicester, University Road, Leicester LE1 7RH, United Kingdom
10 University of Toronto, Ontario, Canada
11 School of Geography, Politics and Environmental Science, Queen’s University, Kingston, ON K7L 3N6, Canada
12 School of Geography, Politics and Environmental Science, Queen’s University, Kingston, ON K7L 3N6, Canada

Abstract

The last decade of our memory has seen numerous reports on landslides and failures that have led to the formation of landslide dams and their impact, particularly in the context of climate change and natural disasters. This review synthesizes the insights and recent advances in the state of the art of landslide dams, and suggests the ways in which they can be better understood and managed. The review is structured around the following themes: (1) the formation of landslide dams; (2) their morphodynamics; (3) the ecological, economic, and social impacts of landslide dams; and (4) future research directions. The review concludes with the need for more comprehensive understanding of landslide dam formation and evolution.
Challenges:

How do post-earthquake landslides and debris flows evolve?
What are the mechanisms and how to simulate?
Evolution of Landslides Over Time After Strong Earthquakes Worldwide

The frequency of landslides increases significantly after earthquakes and then decays within a decade following a power-law to the pre-earthquake level.

Fan XM* et al., *Landslides*, 2018c
Fan XM et al., *Reviews of Geophysics*, 2019
Mechanism of post-earthquake landslides and debris flows

Static liquefaction mechanism

Hydrodynamic force → fine particles migration → pore pressure increase → static liquefaction → slope instability

Controls and mechanisms

Fan XM et al., *Engineering Geology*, 2018, 2023
Prediction of post-seismic hazard chain

- Developed a Numerical Model for Landslides-Debris Flows

Multi-hazard chain scenarios through an integrated numerical modelling approach:
Post-seismic landslides → debris flow → dammed river → outburst flood

Special thanks and memory of Prof. Theo van Asch
Domenech, Fan XM * et al., Engineering Geology, 2019
Yang, Fan XM* et al., Engineering Geology, 2023
Challenges:

How to prevent and early warn post-earthquake debris flows?
Debris flows after the 2008 Wenchuan earthquake

Images after the 20 August 2019 debris flow events

Banzi gully
A database contains >500 post-earthquake debris flows

Fan * et al. Earth Syst. Sci. Data, 2019
The rainfall threshold of debris flows after earthquakes decreases to 1/3 of that before earthquake, and then increases gradually with time.

Jiang, Fan XM * et al., Engineering Geology, 2021
Early warning system of post-earthquake debris flows

Real-time Early Warning System for Landslides and Debris Flows

Successfully early warned more than 220 landslides and debris flows
Climate change-induced cascading hazards in the Tibetan Plateau

Source: Climate Change Service
The Tibetan Plateau is one of the areas with the most complex geological conditions in the world, also called “the Third Pole” of earth.

- Most active tectonic movements
- Largest topographic relief
- Most variable climate
- Most severe glacier retreat
Observed climate and environmental changes in the Tibetan Plateau

TP is the region with the most intense climate change in the world: warming, wetting and greening

Global warming is unprecedented now

TP is warming twice as fast as the global average

Changes of precipitation in TP since 1960

Temporal and spatial distribution of EVI over TP

Average change rate of temperature

0.3-0.4°C warming every 10 years

China blue Book on Climate Change, 2019

(M. Xia et al., 2021)
Global climate change enhances various types of geological hazards

With climate change, glaciers retreat, glacier lakes expand, which induced various types of geohazards in the Tibetan Plateau.

Main hazard types

- Glacier collapses
- Ice-rock avalanches
- Glacier lake outburst floods (GLOFs)
- Glacier-debris flows

(Zhang et al, 2020, ESR)
Yigong landslide and dam-breach flood (4 April to 10 June, 2000)

Cascading hazard: Rockslide→ Mass flow→ Damming river → Dam-breach flood

Height relief: 3000 m

Travel distance: 9.5 km

30 million m$^3$

Pre-outburst flood

Post-outburst flood

50m
Indian Chamoli ice-rock avalanche (7 February, 2021)

On February 7, 2021, an ice-rock avalanche occurred in the Chamoli area of northern India, which triggered flash floods, destroyed 2 hydropower stations, and killed >200 people.

Fan et al. Science of Total Environment, 2022
Indian Chamoli landslide (7 February, 2021)

- The history of fracture expansion before the Chamoli rock-ice avalanche

Fan et al. Science of Total Environment, 2022
Indian Chamoli landslide (7 February, 2021)

- Potentially unstable part
- Displacement curve
Typical Glacier-Related Hazards in Yarlung Tsangpo Grand Canyon
Chains of Hazards in the Zelong-nong Glacier

Namcha Barwa
(7782m)

Zelunglung Glacier in 2023
Credit by Xuanmei Fan

Electrical Resistivity Tomographic (ERT) survey

the glacier is over 140 m thick
Catastrophic chains of geohazard events in the Sedongpu catchment

Cascading hazard: Ice/Rock avalanches → Debris flow → Damming → Dam-breach flood

Past damming events

- 1973.3-1974.11
- 1975.12-1979.4
- 2014.6.1~2014.8.23
- 2017.10.22
- 2017.12.21
- 2018.10.16
- 2018.10.29
- 2021.3.22
- 2023.09.28
- 2023.10.03
Highest erosion rate due to debris flow in Sedongpu Gulley

Frequent debris flow eroded about 500 million m$^3$ of deposits between 2015-2022.
DDA-DF model: Scenario-based prediction of future hazard

**Scenario 1**
- 70 Mm$^3$ source volume

**Scenario 2**
- 210 Mm$^3$ source volume

**Scenario 3**
- 280 Mm$^3$ source volume
Scenario-based prediction of future hazard

- **Height 124 m, Length 3.6 km**
  - 2 times of initial source volume
- **Height 90 m, Length 3.2 km**
  - 1.5 times of initial source volume
- **Height 78 m, Length 1.9 km**
  - 1 times of initial source volume
- **Height 45 m, Length 1.3 km**
  - 0.5 times of initial source volume

Elevation (m) vs. Distance (m)
How Ice Particles Increase Mobility of Rock-Ice Avalanches: Insights From Chute Flows Simulation of Granular Rock-Ice Mixtures by Discrete Element Method
Jiaxi Feng, Xinmei Fan, Qiu, Tao Niu, Ying Fang, Chengjun Zou, Jing Zhang, and Qing Yu

Abstract
Rock-ice avalanches occurring in cold high mountain regions often cause catastrophic disasters due to their extremely high mobility. Rock and ice have different physical properties, such as particle size, density, friction, etc., leading to the segregation of rock and ice in the initiation and improving its mobility. However, how ice affects the mobility of rock-ice avalanches is still poorly understood. A series of numerical experiments were conducted by using the discrete element method to quantify the effect of rock-ice particle size ratio and ice content on the particle segregation and mobility of their mixtures. Results show that rock-ice particle size ratio and volumetric ice content determine the spatial distribution of ice, thereby affecting the mobility of the rock-ice mixture by controlling the rate of particle collision and momentum friction force. In particular, different from conventional understanding, the ice spatial distribution can have a significantly greater influence on the mixture's mobility compared with the volumetric ice content in some scenarios. This study provides insights into the effect of granular ice on the mobility law in the early phase of rock avalanches and has important implications for hazard evaluation.

Plain Language Summary
Rock-ice avalanches are a special type of earth surface process in alpine glacial regions, which has extremely high mobility, complex movement mechanics, and enormous damage potential due to the existence of ice. Understanding how the ice affects the mixture's mobility is essential for assessing and preventing rock-ice avalanches and other related mass movements. In this study, the discrete element method was employed to conduct a series of numerical experiments aimed at investigating the influence of ice on rock-ice avalanches, where the dynamic of granular mixtures was assumed to be composed of rock and ice particles associated with different particle sizes, densities, and friction. We found that the rock particle size ratio and ice volumetric content control the segregation of rock and ice particles. The segregation determines the ice spatial distribution in the mixture, which together with the ice particle size affect the rock-ice mixture's mobility by controlling the rate of particle collision and momentum friction force. The results provide important implications for risk assessment and prevention of glacier-related mass movements.

1. INTRODUCTION
Alpine glacial regions are sensitive and generally respond quickly to climate change (Oerlemans, 2003; Reeh et al., 2006). Franz et al., (2013), Fan et al., (2013), Hambrey, (2007), Yang et al., (2013). With global warming trends, rock-ice avalanches and ice processes chains may significantly increase in frequency and integrate with rock avalanches (Aberle et al., 2013; Fan et al., 2012; Fischer et al., 2013; Haggart, 2008; McPhee, Emmer, et al., 2018; McPhee, Franke, et al., 2018; McPhee et al., 2017, 2020). Since 2014, several rock-ice avalanches and the resulting process chains have occurred in Sadou glacier valley of the Yalong Zangbo basin, Tibet, China, indicating the frequency of hazards is gradually increasing (Wu et al., 2020). On 6 February 2013, a catastrophic rock-ice avalanche disaster caused the destruction of the Rongoud and other villages in Chame, India, destroying two hydro-power projects and causing widespread devastation (Fan et al., 2012; Haggart et al., 2012). The number of casualties, including both facilities and missing individuals, has increased 200 of this incident. Rock-ice avalanches traditionally demonstrate extremely high mobility and catastrophic potential (Franz et al., 2006; Haggart, 2008; McPhee et al., 2018; Scherler, Haggart, et al., 2011; Scherler, Ruckstuhl, et al., 2011; Sebald, 2010; Zhang et al., 2010). Many studies about glacier, glacial debris and their relation to climatic change in Tibet have been published in recent years, which shows the importance of the formation of glaciers and their changes and climate change in the Tibetan Plateau (Z. D. Yao et al., 2012; G. Zhang, Yao, et al., 2013). Many global glacier mapping inventories have been published thanks to the Global Land Ice Mass Survey (GLIMS) project, among these, some addressed the inventory in the Tibetan Plateau (Pfeffer, 2013a, 2013b). More recently, the Tibetan Plateau is considered to be one of the most sensitive regions on Earth to climate change. The major process is glacier retreat and mass loss, which is followed by the Randolph Glacier Inventory (RGI), which has been continued updated till version 6 at the time of writing this study (Hock et al., 2013; Pfeffer et al., 2014). Glaciers and ice sheets are the main components in the Earth’s cryosphere and play an important role in the global climate system.
Conclusions and outlooks

- Undertaking a hazard and risk assessment of the chain of geo-hazards (multiple cascading hazards) caused by large magnitude earthquakes. The challenge is particularly great given the difficulties in quantifying the interaction between hazards.

- The mechanism of the initiation and runout dynamics of geohazards in glacier-covered cold regions is almost unknown, needs more attentions.

- Developing physics-based numerical models for future hazard prediction is crucial for risk reduction;

- The coupling effect of tectonic and climatic forces on geological hazards is not well studied, and it requires multi-disciplinary research in the future.
Thanks to my team and all the collaborators!