ICL Contribution to Landslide Disaster Risk Reduction

Vít Vilímek
Fawu Wang
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Editors

Understanding and Reducing Landslide Disaster Risk

Volume 5 Catastrophic Landslides and Frontiers of Landslide Science

Springer

ICL Contribution to Landslide Disaster Risk Reduction

Series Editor

Kyoji Sassa, The International Consortium on Landslides, ICL, Kyoto, Japan

The ICL Contribution to Landslide Disaster Risk Reduction book-series publishes integrated research on all aspects of landslides. The volumes present summaries on the progress of landslide sciences, disaster mitigation and risk preparation. The contributions include landslide dynamics, mechanisms and processes; volcanic, urban, marine and reservoir landslides; related tsunamis and seiches; hazard assessment and mapping; modeling, monitoring, GIS techniques; remedial or preventive measures; early warning and evacuation and a global landslide database.

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ISSN 2662-1894 ISSN 2662-1908 (electronic)
ICL Contribution to Landslide Disaster Risk Reduction
ISBN 978-3-030-60318-2 ISBN 978-3-030-60319-9 (eBook)
https://doi.org/10.1007/978-3-030-60319-9

Cover illustration: The 2018 Baige landslide in the upper reaches of the Jinsha River, China. Photo was made by A. Strom on April 7, 2019

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

ICL and Springer created a new book series “ICL Contribution to Landslide Disaster Risk Reduction” in 2019 which is registered as ISSN 2662-1894 (print version) and ISSN 2662-1908 (electronic version). The first books in this series are six volume of books “Understanding and Reducing Landslide Disaster Risk” containing the recent progress of landslide science and technologies from 2017 to 2020.

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Foreword by Mami Mizutori

More landslides can be expected as climate change exacerbates rainfall intensity. The long-term trend of the last 40 years has seen the number of major recorded extreme weather events almost double, notably floods, storms, landslides, and wildfires.

Landslides are a serious geological hazard. Among the host of natural triggers are intense rainfall, flooding, earthquakes or volcanic eruption, and coastal erosion caused by storms that are all too often tied to the El Niño phenomenon. Human triggers including deforestation, irrigation or pipe leakage, and mine tailings, or stream and ocean current alteration can also spark landslides. Landslides can also generate tsunamis, as Indonesia experienced in 2018.

Globally, landslides cause significant economic loss and many deaths and injuries each year. Therefore, it is important to understand the science of landslides: why they occur, what factors trigger them, the geology associated with them, and where they are likely to happen.

Landslides with high death tolls are often a result of failures in risk governance, poverty reduction, environmental protection, land use and the implementation of building codes. Understanding the interrelationships between earth surface processes, ecological systems, and human activity is the key to reducing landslide risk.

The Sendai Framework for Disaster Risk Reduction, the global plan to reduce disaster losses adopted in 2015, emphasizes the importance of tackling these risk drivers through improved governance and a better understanding of disaster risk.

One important vehicle for doing that is the Sendai Landslide Partnerships 2015–2025 for global promotion of understanding and reduction of landslide risk facilitated by the International Consortium on Landslides (ICL) and signed by the leaders of 22 global stakeholders, including the UN Office for Disaster Risk Reduction (UNDRR), during the Third UN World Conference on Disaster Risk Reduction in Sendai, Japan.

The Sendai Landslide Partnerships—featured on the Sendai Framework Voluntary Commitments online platform—helps to provide practical solutions and tools, education, and capacity building, to reduce landslide risks.

The work done by the Sendai Partnerships can be of value to many stakeholders including civil protection, planning, development and transportation authorities, utility managers, agricultural and forest agencies, and the scientific community.

UNDRR fully supports the work of the Sendai Landslide Partnerships and ICL and looks forward to an action-oriented outcome from the 5th World Landslide Forum to be held in November 2020 in Kyoto, Japan. Successful efforts to reduce disaster losses are a major contribution to achieving the overall 2030 Agenda for Sustainable Development.

Mami Mizutori
United Nations Special Representative of the
Secretary-General for Disaster Risk Reduction

Foreword by the Assistant Director-General for the Natural Sciences Sector of UNESCO for the Book of the 5th *World Landslide Forum*

As the world slowly recovers from the COVID-19 global pandemic, and looking back at the way this crisis developed, it becomes evident that as a global community we were not prepared for an event of this scale. Although not commonly perceived as such, biological hazards such as epidemics are included in the Sendai Framework for Disaster Risk Reduction 2015–2030. In that sense, the preparedness approach for a pandemic is very similar to that of a geophysical natural hazard such as landslides.

Although natural hazards are naturally occurring phenomena, the likelihood of their occurrence and of associated disasters is rising. Climate change, urban pressure, under-development and poverty and lack of preparedness are increasingly transforming these natural hazards into life-threatening disasters with severe economic impacts. Therefore, Disaster Risk Reduction (DRR) is gaining momentum on the agenda of the UN system of Organizations including UNESCO. While the Sendai Framework for Disaster Risk Reduction 2015–2030 is the roadmap for DRR, other global agendas including the Sustainable Development Goals, the Paris Climate Agreement and the New Urban Agenda have targets which cannot be attained without DRR.

In shaping its contribution to those global agendas, UNESCO is fully committed in supporting its Member States in risk management, between its different mandates and disciplines and with relevant partners. The International Consortium on Landslides (ICL) is UNESCO's key partner in the field of landslide science. The Organization's support to the Consortium is unwavering. Since ICL was established in 2002, the two organizations have a long history of cooperation and partnership and UNESCO has been associated with almost all of ICL activities. I am very glad that ICL and UNESCO are mutually benefitting from their collaboration.

The 5th World Landslide Forum (WLF5) is expected to represent a milestone in the history of landslide science particularly for scientists and practitioners. One of the major outcomes of WLF5 will be the Kyoto 2020 Commitment for global promotion of understanding and reducing landslide disaster risk (KLC2020). This commitment is expected to strengthen and expand the activities of the Sendai Landslide Partnership 2015–2025. With UNESCO already engaged as a partner, the adoption of this international commitment will raise global awareness on landslide risk and mobilize wider partnerships that draw together stakeholders from all levels of society, across different regions, sectors and disciplines.

It is my great pleasure to congratulate the organizers for holding this event and assure you that UNESCO is fully committed in contributing to its success. As part of that contribution, our Organization is proud to host a session on landslides and hazard assessment at UNESCO-designated sites such as natural World Heritage sites, biosphere reserves and UNESCO Global Geoparks. This session aims to assess landslide impacts on our shared cultural and natural heritage, providing the best opportunity to generate public awareness and capacity development for landslide disaster reduction.

I am confident that WLF5 will contribute to further advance the knowledge of both scientists and practitioners regarding landslide disaster risk reduction. This book paves the way for the science, knowledge and know-how which will feature in the deliberations of the Forum. UNESCO commends all of the contributors to this publication. I look forward to an enhanced collaboration between UNESCO and ICL in future activities and undertakings.

Shamila Nair-Bedouelle
Assistant Director-General for Natural Sciences
UNESCO

Preface I

Understanding and Reducing Landslide Disaster Risk

Book Series: ICL Contribution to Landslide Disaster Risk

The International Consortium on Landslides (ICL) was established in pursuance of the 2002 Kyoto Declaration "Establishment of an International Consortium on Landslides," with its Statutes adopted in January 2002. The Statutes define the General Assembly of ICL as follows: in order to report and disseminate the activities and achievements of the Consortium, a General Assembly shall be convened every 3 years by inviting Members of the International Consortium on Landslides, individual members within those organizations, and all levels of cooperating organizations and individual researchers, engineers, and administrators. The General Assembly developed gradually prior to, during and after its first meeting in 2005. In the light of the 2006 Tokyo Action Plan, the Assembly was further facilitated at, and following the First World Landslide Forum held in November 2008. On the occasion of each of its triennial forums, ICL publishes the latest progress of landslide science and technology for the benefit of the whole landslide community including scientists, engineers, and practitioners in an understandable form. Full color photos of landslides and full color maps are readily appreciated by those from different disciplines. We have published full color books on landslides at each forum. In 2019, ICL created a new book series "ICL Contribution to Landslide Disaster Risk Reduction" ISSN 2662-1894 (print version) and ISSN 2662-1908 (electronic version). Six volumes of full color books *Understanding and Reducing Landslide Disaster Risk* will be published in 2020 as the first group of books of this series.

The Letter of Intent 2005 and the First General Assembly 2005

The United Nations World Conference on Disaster Reduction (WCDR) was held in Kobe, Japan, 18–22 January 2005. At this Conference, ICL organized session 3.8 "New international Initiatives for Research and Risk Mitigation of Floods (IFI) and Landslides (IPL)" on 19 January 2005 and adopted a "Letter of Intent" aimed at providing a platform for a holistic approach in research and learning on 'Integrated Earth System Risk Analysis and Sustainable Disaster Management'. This Letter was agreed upon and signed, during the first semester of 2005, by heads of seven global stakeholders including the United Nations Educational, Scientific and Cultural Organization (UNESCO), the World Meteorological Organization (WMO), the Food and Agriculture Organization of the United Nations (FAO), the United Nations International Strategy for Disaster Risk Reduction (UNISDR-currently UNDRR), the United Nations University (UNU), the International Council for Science (ICSU-Currently ISC), and the World Federation of Engineering Organizations (WFEO).

The first General Assembly of ICL was held at the Keck Center of the National Academy of Sciences in Washington D.C., USA, on 12–14 October 2005. It was organized after the aforementioned 2005 World Conference on Disaster Reduction (WCDR). ICL published the first full color book reporting on Consortium activities for the initial 3 years, 2002–2005 titled “Landslides-Risk analysis and sustainable disaster management”. In the preface of this book, the Letter of Intent for Integrated Earth System Risk Analysis and Sustainable Disaster Management was introduced. Results of the initial projects of the International Programme on Landslides (IPL) including IPL C101-1 Landslide investigation in Machu Picchu World Heritage, Cusco, Peru and previous agreements and MoU between UNESCO, ICL and the Disaster Prevention Research Institute of Kyoto University including UNESCO/KU/ICL UNITWIN Cooperation programme were published as well in this book.

The 2006 Tokyo Action Plan and the First World Landslide Forum 2008

Based on the Letter of Intent, the 2006 Tokyo Round-Table Discussion—“Strengthening Research and Learning on Earth System Risk Analysis and Sustainable Disaster Management within UN-ISDR as Regards Landslides”—towards a dynamic global network of the International Programme on Landslides (IPL) was held at the United Nations University, Tokyo, on 18–20 January 2006. The 2006 Tokyo Action Plan—Strengthening research and learning on landslides and related earth system disasters for global risk preparedness—was adopted. The ICL exchanged Memoranda of Understanding (MoUs) concerning strengthening cooperation in research and learning on earth system risk analysis and sustainable disaster management within the framework of the United Nations International Strategy for Disaster Reduction regarding the implementation of the 2006 Tokyo action plan on landslides with UNESCO, WMO, FAO, UNISDR (UNDRR), UNU, ICSU (ISC) and WFEO, respectively in 2006. A set of these MoUs established the International Programme on Landslides (IPL) as a programme of the ICL, the Global Promotion Committee of IPL to manage the IPL, and the triennial World Landslide Forum (WLF), as well as the concept of the World Centres of Excellence on Landslide Risk Reduction (WCoE).

The First World Landslide Forum (WLF1) was held at the Headquarters of the United Nations University, Tokyo, Japan, on 18–21 November 2008. 430 persons from 49 countries/regions/UN entities were in attendance. Both Hans van Ginkel, Under Secretary-General of the United Nations/Rector of UNU who served as chairperson of the Independent Panel of Experts to endorse WCoEs, and Salvano Briceno, Director of UNISDR who served as chairperson of the Global Promotion Committee of IPL, participated in this Forum. The success of WLF1 paved the way to the successful second and third World Landslide Forum held in Italy and China respectively.

The Second World Landslide Forum 2011 and the Third World Landslide Forum 2014

The Second World Landslide Forum (WLF2)—Putting Science into Practice—was held at the Headquarters of the Food and Agriculture Organization of the United Nations (FAO) on 3–9 October 2011. It was jointly organized by the IPL Global Promotion Committee (ICL, UNESCO, WMO, FAO, UNDRR, UNU, ISC, WFEO) and two ICL members from Italy: the Italian Institute for Environmental Protection and Research (ISPRA) and the Earth Science Department of the University of Florence with support from the Government of Italy and many Italian landslide-related organizations. It attracted 864 participants from 63 countries.

The Third World Landslide Forum (WLF3) was held at the China National Convention Center, Beijing, China, on 2–6 June 2014. A high-level panel discussion on an initiative to create a safer geoenvironment towards the UN Third World Conference on Disaster Risk Reduction (WCDRR) in 2015 and forward was moderated by Hans van Ginkel, Chair of Independent Panel of Experts for World Centers of Excellence (WCoE). In a special address to this high-level panel discussion, Irina Bokova, Director-General of UNESCO, underlined that countries should be united to work against natural disasters and expressed commitment that UNESCO would like to further deepen cooperation with ICL. Ms. Bokova awarded certificates to 15 World Centres of Excellence.

The Sendai Landslide Partnerships 2015 and the Fourth World Landslide Forum 2017

The UN Third World Conference on Disaster Risk Reduction (WCDRR) was held in Sendai, Japan, on 14–18 March 2015. ICL organized the Working Session "Underlying Risk Factors" together with UNESCO, the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and other competent organizations. The session adopted ISDR-ICL Sendai Partnerships 2015–2025 (later changed to Sendai Landslide Partnerships) for global promotion of understanding and reducing landslide disaster risk as a Voluntary Commitment to the World Conference on Disaster Risk Reduction, Sendai, Japan, 2015 (later changed to Sendai Framework for Disaster Risk Reduction). After the session on 16 March 2015, the Partnerships was signed by Margareta Wahlström, Special Representative of the UN Secretary-General for Disaster Risk Reduction, Chief of UNISDR (UNDDR), and other representatives from 15 intergovernmental, international, and national organizations. Following the Sendai Landslide Partnerships, the Fourth World Landslide Forum was held in Ljubljana, Slovenia from 29 May to 2 June in 2017. On that occasion, five volumes of full color books were published to disseminate the advances of landslide science and technology. The high-level panel discussion on 30 May and the follow-up round table discussion on 31 May adopted the 2017 Ljubljana Declaration on Landslide Risk Reduction. The Declaration approved the outline of the concept of "Kyoto 2020 Commitment for global promotion of understanding and reducing landslide disaster risk" to be adopted at the Fifth World Landslide Forum in Japan, 2020.

The Fifth World Landslide Forum 2020 and the Kyoto Landslide Commitment 2020

The Fifth World Landslide Forum was planned to be organized on 2–6 November 2020 at the National Kyoto International Conference Center (KICC) and the preparations for this event were successfully ongoing until the COVID-19 pandemic occurred over the world in early 2020. The ICL decided to postpone the actual Forum to 2–6 November 2021 at KICC in Kyoto, Japan. Nevertheless, the publication of six volumes of full color books *Understanding and Reducing Landslide Disaster Risk* including reports on the advances in landslide science and technology from 2017 to 2020 is on schedule. We expect that this book will be useful to the global landslide community.

The Kyoto Landslide Commitment 2020 will be established during the 2020 ICL-IPL Online Conference on 2–6 November 2020 on schedule. Joint signatories of Kyoto Landslide Commitment 2020 are expected to attend a dedicated session of the aforementioned Online Conference, scheduled on 5 November 2020 which will also include and feature the Declaration of the launching of KLC2020. Landslides: Journal of the International Consortium on Landslides is the common platform for KLC2020. All partners may contribute and publish news and reports of their activities such as research, investigation, disaster reduction administration in the category of News/Kyoto Commitment. Online access or/and hard copy of the Journal will be sent to KLC2020 partners to apprise them of the updated information from other partners. As of 21 May 2020, 63 United Nations, International and national organizations have already signed the KLC2020.

Call for Partners of KLC2020

Those who are willing to join KLC2020 and share their achievements related to understanding and reducing landslide disaster risk in their intrinsic missions with other partners are invited to inform the ICL Secretariat, the host of KLC2020 secretariat (secretariat@iclhq.org). The ICL secretariat will send the invitation to the aforementioned meeting of the joint signatories and the declaration of the launching of the KLC2020 on 5 November 2020.

Eligible Organizations to be Partners of the KLC2020

1. ICL member organizations (full members, associate members and supporters)
2. ICL supporting organization from UN, international or national organizations and programmes
3. Government ministries and offices in countries having more than 2 ICL on-going members
4. International associations /societies that contribute to the organization of WLF5 in 2021 and WLF6 in 2023
5. Other organizations having some aspects of activities related to understanding and reducing landslide disaster risk as their intrinsic missions.

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Kyoto, Japan

Appendix: World Landslide Forum Books

WLF	Place/participants	Title	Editors	Publisher/pages
WLF0 (1st General Assembly) 2005	Washington D.C., USA 59 from 17 countries/UNs	Landslides-Risk Analysis and Sustainable Disaster Management	Kyoji Sassa, Hiroshi Fukuoka, Fawu Wang, Goghui Wang	Springer/377 pages ISBN: 978-3-540-2864-6
WLF1 2008	Tokyo, Japan 430 from 49 countries/regions/UNs	Landslides-Disaster Risk Reduction	Kyoji Sassa, Paolo Canuti	Springer/649 pages ISBN: 978-3-540-69966-8
WLF2 2011	Rome, Italy 864 from 63 countries	Landslide Science and Practice Vol. 1 Landslide inventory and Sustainability and Hazard Zoning	Claudia Margottini, Paolo Canuti, Kyoji Sassa	Springer/607 pages ISBN: 978-3-642-31324-0
		Vol. 2 Early Warning, Instrumentation and Monitoring		Springer/685 pages ISBN: 978-3-642-31444-5
		Vol. 3 Spatial Analysis and Modelling		Springer/440 pages ISBN: 978-3-642-31309-7
		Vol. 4 Global Environmental Change		Springer/431 pages ISBN: 978-3-642-31336-3
		Vol. 5 Complex Environment		Springer/354 pages ISBN: 978-3-642-31426-1
		Vol. 6 Risk Assessment, Management and Mitigation		Springer/789 pages ISBN: 978-3-642-31318-9
		Vol. 7 Social and Economic Impact and Policies		Springer/333 pages ISBN: 978-3-642-31312-7
WLF3 2014	Beijing, China 531 from 45 countries/regions/UNs	Landslide Science for a Safer Geoenvironment Vol. 1 The International Programme on Landslides (IPL)	Kyoji Sassa, Paolo Canuti, Yueping Yin	Springer/493 pages ISBN: 978-3-319-04998-4
		Vol. 2 Methods of Landslide Studies		Springer/851 pages ISBN: 978-3-319-05049-2
		Vol. 3 Targeted Landslides		Springer/717 pages ISBN: 978-3-319-04995-3
WLF4 2017	Ljubljana, Slovenia 588 from 59 countries/regions/UNs	Advancing Culture of Living with Landslides Vol. 1 ISDR-ICL Sendai Partnerships 2015-2025	Kyoji Sassa, Matjaž Mikoš, Yueping Yin	Springer/585 pages ISBN: 978-319-53500-5

(continued)

WLF	Place/participants	Title	Editors	Publisher/pages
		Vol. 2 Advances in Landslide Science	Matjaž Mikoš, Binod Tiwari, Yueping Yin, Kyoji Sassa	Springer/1197 pages ISBN: 978-319-53497-8
		Vol. 3 Advances in Landslide Technology	Matjaž Mikoš, Željko Arbanas, Yueping Yin, Kyoji Sassa	Springer/621 pages ISBN: 978-3-319-53486-2
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WLF5	2020 (publication) 2021 (Forum)	Understanding and Reducing Landslide Disaster Risk Vol. 1 Sendai Landslide Partnerships and Kyoto Landslide Commitment	Kyoji Sassa, Matjaž Mikoš, Shinji Sassa, Peter T. Bobrowsky, Kaoru Takara, Khang Dang	Springer In Process
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Preface II

Catastrophic Landslides and Frontiers of Landslide Science

Landslides belong to the most catastrophic of natural phenomena. Their direct and also indirect effects, such as the formation of dammed lakes and outburst floods, have the potential to claim thousands of lives. In order to understand the causes and consequences of landslides it is necessary to study several specific themes, which are discussed in this book and may help in understanding and reducing landslide disaster risk. The papers included in this volume describe various aspects of the causes (e.g. climate change), direct triggers (earthquakes and rainstorms), and the primary and secondary effects of landslides for a better understanding of the process chain: prerequisite—impulse—process—response. These themes are closely interrelated with other aspects of landslide studies discussed in other volumes of the series, “Understanding and Reducing Landslide Disaster Risk”.

Several of the papers presented herein discuss the roles of both global and local long-term processes such as the ongoing climate change, which predetermine the formation of landslides in various parts of the World. Considering the variety of environmental conditions around the globe in which climate, soil and rock weathering lead to significant differences in landslide susceptibility, the authors describe case studies from Europe, Asia, North America, the Pacific region, and even the marine environment (the Norwegian–Greenland Sea). Phenomena such as creep and deep-seated gravitational slope deformations, which often precede catastrophic slope failures, are discussed as well.

Among the direct triggers of large catastrophic landslides, earthquakes and extreme rainfall seem to be the most important factors. Detailed studies of seismically and rainstorm induced landslides help to understand the role of such triggering factors. Almost one third of the papers included in this volume discuss various aspects of the effects of earthquakes on slope stability and on landslide-related phenomena such as liquefaction, which attracted the attention of researchers after the 2018 Palu-Donggala earthquake in Indonesia. Several papers describe the spatial distribution of multiple landslides triggered by the 2012 Hejing earthquake in China the 2015 Gorkha earthquake in Nepal and the 2018 Hokkaido earthquake in Japan. The delayed effects of earthquakes on landslide processes are described by an example from the area affected by the 2008 Wenchuan earthquake in China.

Some of the papers discuss the possible effects of seismic strong motion on the formation of historic and prehistoric landslides in the Greater Caucasus in Russia, in the Swiss and Italian Alps, and in the Carpathians in Romania.

Climate change has long been a hot topic. Its effect on landslides becomes clearer after long-term observation. Recently, more attention has been paid to environmental change in terms of its effect on landslides, and especially in areas undergoing development. This book describes the efforts being made in Hong Kong and cold regions of China, and highlights the importance of considering climate and geoenvironmental changes in landslide disaster reduction.

Landslides are closely associated with other hazards in the sense of causes and response. That is why we need to study the prerequisites, triggers, and regional distribution of catastrophic landslides, as well as their classification. Another important issue discussed in the book is the secondary effects of slope failures such as the formation of natural dams and outburst floods, as well as the effects of slope failure on the banks of existing lakes, which can sometimes be even more catastrophic than the direct effects of slope failure. Such phenomena are analysed through examples from Argentina, Nepal, the Far East of Russia and Iran. In addition, more general aspects of landslide dam hazard assessment are discussed. One paper discusses the possible association of natural processes such as glacial retreat, landslides and volcanic eruptions through an example from British Columbia, Canada.

Innovations have been created throughout the world worldwide in order to help understand the causes and consequences of landslides. The use of Unmanned Aerial Vehicles (UAVs) has developed rapidly in several earth sciences applications, including landslide characterisation and monitoring. UAVs provide strong support for hazard and risk management activities, especially with the introduction of and advances in the miniaturization of traditional and new generation sensors. Through several case studies on landslide investigations, one paper in the book provides an overview of several sensors and techniques using UAVs for landslide detection, characterization and monitoring. Another example is a web-based disaster and risk reduction system (ARAS), which is used to evaluate landslide susceptibility and conduct hazard mapping in the Middle Black Sea region of Turkey and to minimize the undesired consequences of landslides.

We hope this volume will provide readers with new, interesting and useful information that will facilitate further progress in understanding and reducing landslide disaster risks both locally and globally.

Prague, Czech Republic — Vít Vilímek
Shanghai, China — Fawu Wang
Moscow, Russia — Alexander Strom

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Part I

Catastrophic Landslides with Different Triggers

Rock Avalanches: Basic Characteristics and Classification Criteria

Alexander Strom

Abstract

Rock avalanches represent the specific type of flow-like landslides—dry granular flows—that pose major threat to population in mountainous regions and in the adjacent plains. Being extremely mobile, they can affect areas up to dozens of square kilometers, extending sometimes for more than 10 km from the feet of the collapsing slopes. The internal structure of their deposits is characterized by intensive fragmentation of inner parts overlain by much coarser carapace. Such internal structure is typical of the vast majority of large-scale rock slope failures, both long runout and forming compact blockages in narrow river valleys. Therefore, all of them should be classified as rock avalanches, rather than as rock slides. Three additional classification criteria closely related to rock avalanche mobility and allowing more strict definition of a particular rock avalanche are discussed, i.e. the confinement conditions, debris distribution along the rock avalanche path, and directivity of debris motion. Besides providing information on debris motion mechanism(s), these characteristics predetermine the assessment of the exposure of elements at risk that might be affected by rock avalanche. It is demonstrated that transformation from the block slide to granular flow depends somehow on the morphology of the transition-deposition zone and on the mechanical properties of the basal surface, but is independent from the type and mechanical properties of the host rocks.

Keywords

Rock avalanche • Rock slide • Classification • Fragmentation • Internal structure

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Introduction

Classification of any natural phenomena is an important step of its study. It fully relates to landslides or, in broader sense, to slope processes of various types. Their clear and logical definitions help researchers, besides better understanding of landslides' nature, to "talk one language" using the same terms when describing similar features or phenomena. This paper is focused on the definition and classification of rock avalanches—one of the most dangerous type of landslides, leaving aside other landslide types listed in (Hungr et al. 2014). Features that can and should be classified as rock avalanches are often described in the literature either as "rock avalanche" or as "rock slide" ("rockslide"), thus it seems to be important to propose more strict definition of these terms and their usage.

One more problem to which this article is addressed is that none of the landslide classifications commonly used worldwide (Varnes 1954, 1978; Hutchinson 1968, 1988; Cruden and Varnes 1996), including the latest one (Hungr et al. 2014), differentiate landslide types characterizing initiation of slope failure and those characterizing further motion of a landslide. However, their kinematics and motion mechanism at these stages, on which classification proposed in (Hungr et al. 2014) is based, could change drastically. Such transformation fully relates to rock avalanches.

Hungr and his co-authors (2014) divide all "landslides" (slope processes), at the first level, in six groups: fall, topple, slide, spread, flow and slope deformation (see column 1 of their final Table No 5). It should be noticed that the last type —"slope deformation"—does not provide any strict mechanical meaning, unlike the five other types.

Such characteristics as fall, slide, flow, and spread can be applied to many landslides starting from their motion initiation and up to final stabilization, when they reach slope foot and stop. Topples often convert into slides (Nichol et al. 2002), but may remain as topples for a very long time—up to centuries and even millennia. However, when we deal

V. Vilímek et al. (eds.), *Understanding and Reducing Landslide Disaster Risk*,
ICL Contribution to Landslide Disaster Risk Reduction,
https://doi.org/10.1007/978-3-030-60319-9_1

with flow slides in rock ("rock avalanches" according to Hungr et al. 2014), the situation changes significantly. It seems that none of them really initiates as a dry granular flow—large-scale rock slope failure always starts as a slide of any type, and, to become real rock avalanche, its mechanics should change from slide to flow. Since "type of movement" is the primary classification criterion (Hungr et al. 2014), such motion type evolution must be somehow considered in the rock avalanche classification system.

Processes preceding rapid motion of a rock mass downslope, such as primary, secondary and tertiary creep (see, e.g. Qin et al. 2006), are left aside in the following analysis to avoid excessive complexity.

The special classification of flow slides based on characteristics of the affected material was proposed in (Hungr et al. 2001). They strictly differentiate "debris avalanches" defined as "*a very rapid to extremely rapid shallow flow of partially or fully saturated debris on a steep slope, without confinement in an established channel*" from "rock avalanches" that originate in bedrock. It should be noticed, however, that the term "debris avalanche" is also used commonly by researchers studying large-scale sectoral collapses on volcanoes (Schuster and Crandell 1984; Capra 2011) whose size and motion mechanism(s) are closer to those of rock avalanches rather than of debris avalanches within the meaning of these terms after (Hungr et al. 2001).

Study of numerous non-volcanic rock avalanches, from the Central Asia region mainly (Strom and Abdrakhmatov 2018), though not exclusively, demonstrate significant variability of their deposits' shape: some moved strictly ahead producing narrow tongues of fragmented debris, some form wider fan-shape bodies, while other turn up to right angle affecting areas that otherwise could be considered as safe, etc. Such variability, on the one hand, provides information on debris motion mechanism(s), and, on the other hand, predetermines the exposure of elements at risk that might be affected.

All the above-mentioned problems are interrelated: type of rock avalanche depend on its motion mechanism and, vise-versa, the latter can be derived from the shape of rock avalanche deposits and their internal structure. All these could and should be reflected somehow in the rock avalanches classification.

General Characteristic Features of Rock Avalanches

Hungr and his co-authors (2014) defined rock avalanche as an "*extremely rapid, massive, flow-like motion of fragmented rock from a large rock slide or rock fall*". I have to argue that failure of more than one million cubic meters of rock (the commonly accepted lower limit of such phenomenon, though descriptions of rock avalanches with smaller volume can be found in the literature) quite rarely occur as a fall and that vast majority of rock avalanches originate just as rock slides. Role of volume in differentiation of the phenomena starting as rock falls and as rock slides was mentioned in Hungr et al. (2001).

It is important that this definition does not imply long runout. It is just noticed that rock avalanches are "*extremely rapid*". High speed of motion due to significant momentum gained during the initial descend can result, however, in quite variable effects, depending, first, on the confinement conditions.

It can be illustrated by large slope failures of the approximately same size (about 1.5–2 km^3 in volume) that occurred in unconfined and in frontally confined conditions. The first one—the Koman rock avalanche (Kurdiukov 1950, 1964; Strom 2014; Robinson et al. 2015; Reznichenko and Davies 2015; Reznichenko et al. 2017) moved across wide Alai intermountain depression (39.54°N, 72.69°E) and had total runout of about 34 km that is impossible for slowly moving landslide (Fig. 1). This feature would be classified as rock avalanche univocally.

However, other rock slope failures of the same size that blocked narrow and deep valleys by rather compact natural dams have been called "rockslides" in most of publications.

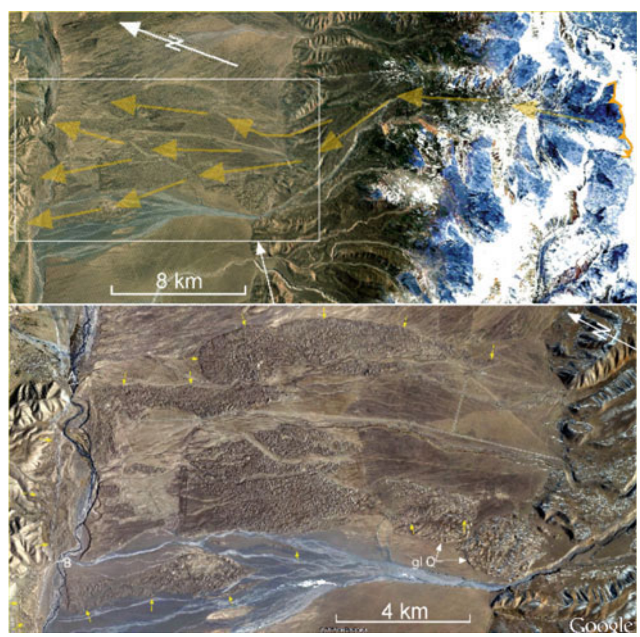

Fig. 1 The Koman rock avalanche. Above—general view. Orange line—assumed headscarp; transparent arrows show direction of debris motion. Below—closer space view of the deposits, whose original lateral limits are marked by yellow arrows; glQ—pre-slide glacial deposits; **A** and **B** sites where the internal structure of the deposits can be observed in details. Google Earth images (after Strom and Abdrakhmatov 2018, with permission of Elsevier)

Such term was used for the breached Late Pleistocene blockage in the Kokomeren River valley, Central Tien Shan (Figs. 2, 3, 41.93°N, 74.22°E) (Strom 1994; Abdrakhmatov and Strom 2006; Hartvich et al. 2008; Strom and Abdrakhmatov 2018). Same term was used by Strom and Abdrakhmatov (2018) for the Big Dragon landslide dam in Eastern Tien Shan (42.6°N, 82.4°E, China that had crossed deep valley and had runout of ca. 4 km only, but with 370 m high runup (Fig. 4). In the latter case term "rock avalanche" was applied to describe just part of its body that had moved 4.3 km downstream. But was it correct?

No, it was incorrect! Much more correct is classifying both of them as rock avalanches in frontally confined conditions. Both compact landslides (the term "landslide" is used as a general term related to any type of slope failures) moved at a very high speed—in the Kokomeren case it is not so obvious, but in the Big Dragon case the extreme velocity of ca. 300 km/h can be derived from the distinct 370 m high runup. Besides, rock avalanche definition proposed in Hungr et al. (2014) points out "*massive, flow-like motion of fragmented rock*" as a characteristic feature of rock avalanche that fully corresponds to what can be observed in the completely dissected body of the Kokomeren landslide. Various lithologies that can be distinguished in its headscarp area due to their different color (Fig. 2) remain in the same mutual positions in the deposits, despite being intensively fragmented (Fig. 3).

Similar characteristic features of the deposits' interiors were observed at numerous other Central Asian landslides that originated on high rocky slopes (Abdrakhmatov and Strom 2006; Strom and Abdrakhmatov 2018), in the Alps (Dufresne et al. 2018), in the Caucasus (Strom 2004, 2006), in the Karakoram and Himalaya (Hewitt 2002, 2006; Weidinger et al. 2014), in New Zealand (McSaveney and Davies 2006). Similar features were found in Tibet in the narrow and deep valleys of the Jinsha River (Fig. 5) and of its tributaries where collapsing rock masses could not move far away due to the well pronounced confinement.

Since direct assessment of the prehistoric landslides motion velocity is not always possible, the critically important characteristic features allowing strict distinguishing between "rock slides" and "rock avalanches" are those indicating "*massive, flow-like motion of fragmented rock*" that can be derived from the study of the internal structure and grain-size composition of the deposits.

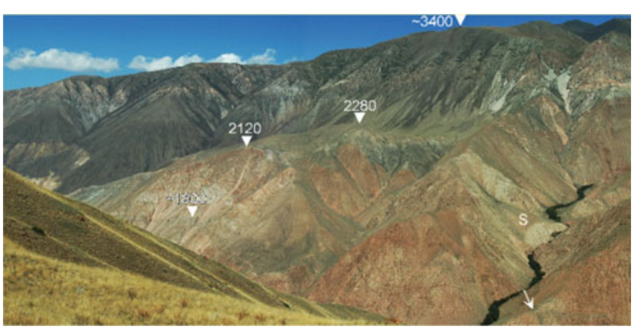

Fig. 2 Overview of the Kokomeren rockslide. White arrow at the lower right part of the photo marks active fault that, presumably, could trigger this slope failure. Base of the deposits is at ~1800 m a.s.l. S—much smaller "satellite" rockslide (after Strom and Abdrakhmatov 2018, with permission of Elsevier)

Fig. 3 Right-bank remnant of the Kokomeren rock avalanche deposits. Grain size composition of the blocky carapace and of the internal comminuted part of the deposits can be seen in the insets. Well-expressed varicolored badland is composed of the heavily comminuted granite (pink pyramids) and metasediments (gray and whitish pyramids) (modified after Strom and Abdrakhmatov 2018, with permission of Elsevier)

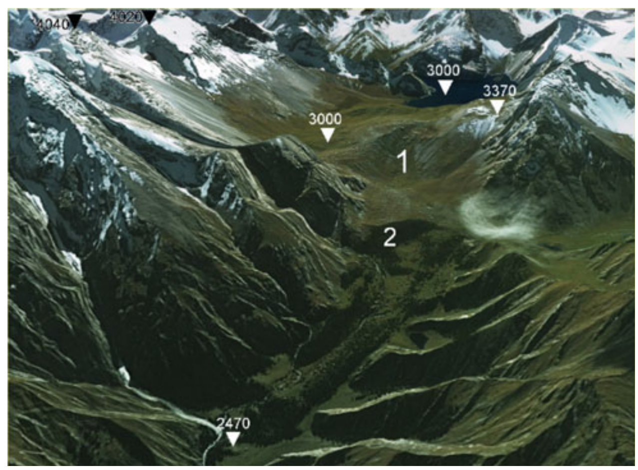

Fig. 4 The Big Dragon Lake rock avalanche dam with 370 m run-up of its frontal part accompanied by the 4.3 km long deflected secondary rock avalanche that originated from the secondary scar 1 and moved up to 2470 m a.s.l. with an intermediate secondary scar 2. 3D Google Earth view (after Strom and Abdrakhmatov 2018, with permission of Elsevier)