Extreme hazards in mountain communities:

selected examples and applied risk management

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Managing Extreme Hazard Events in Mountain Regions:
A booklet for Politicians and Decision Makers

Extreme events in mountainous areas can occur suddenly or develop gradually over extended periods. When these hazards impact settlements and traffic infrastructures, effective management is essential, as the crisis can be unpredictable and prolonged and pose significant challenges to mountain populations. Smaller communities may lack the expertise to handle extreme hazards, while larger communities with substantial seasonal tourism can experience severe impacts, attracting high media attention.

From November 3rd to 6th, 2024, the Residency Living Lab in Courmayeur, Aosta Valley, Italy, brought together a team of international scientists and experts to discuss the management of mountain hazard events. This booklet compiles 20 representative hazard scenarios, ranging from large deep-seated landslides to severe avalanche winters, and include cases from the European Alps, the Rocky Mountains, and the Himalayas.

The purpose of this booklet is to provide a concise overview of possible extreme events, and the management measures implemented. It is designed for politicians and decision-makers responsible for managing hazards in mountain communities. Key contacts of those who managed the listed cases are included, enabling decision-makers to quickly access relevant experiences and expertise when new problems arise. This resource helps in filling a critical gap, as decision-makers often lack the time to consult scientific literature to support their choices.

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Residency Living Lab: Courmayeur, 3-6 November 2024

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SECTION 1:

GLACIER COLLAPSE

Grandes Jorasses serac/ Taconnaz hanging glacier

TYPE OF HAZARD

Glacier collapse

AREA

Mont Blanc Massif, Italy, France

KEYWORDS

ice avalanches, glacier destabilization, monitoring plan, climate change

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PROBLEM DESCRIPTION

Hanging glaciers are a possible threat for the inhabitants of alpine valleys because of periodic (es: Grandes Jorasses, Weisshorn) or single events of collapse (es: Altels gletscher) and subsequent ice-avalanche. If the majority of victims of serac falls are climbers, in some cases ice falls from the higher alpine areas can reach the lowlands. We present two case studies, comprising a site on the Italian side of Mont Blanc (Grande Jorasses serac, GJS) which is under monitoring for the periodic gravity driven collapses, while on the French side a large glacier, Taconnaz Glacier (TG), is undergoing a transition from a cold to a temperate base because of present climatic evolution, inducing possible ice avalanche much larger than the current seracs. In the medium term (i.e. next 2-3 decades) both glaciers are going into a similar fate and further research involving field measures and modeling are needed in order to better understand the process and to plan future safety measures and land use planning.

MEASURES APPLIED

Monitoring and Characterization

- Englacial Temperature measures, ice thickness measures, ice surface velocity, deformation analysis, modelling of the thermal regime in the future;
- For the TG, the aim of this monitoring and modelling is to better characterize the maximum volume of breakup that can be expected in the future, and to estimate when it might begin to occur.

Early warning system

- GB-InSAR deformation monitoring, doppler radar system (GJ). No early warning system at play for TG.

Response Planning

- Traffic line closure, Evacuations (GJ).

Mitigation

- Integrated risk management;
- Process modeling and analysis of temperature evolution at the glacier beds.

COMMUNICATION

In Italy, the National Civil Protection has created a specific working group that is working on the management of glacially related risks. Two subgroups are working on specific topics: the technical group is focusing on strategies for the monitoring of glacial hazard situations, while the other group is focused in developing a communication strategy for the general public at a national level in order to increase the awareness of the population on climate change and hazards originating in glaciated terrain and high-altitude areas. This is work in progress and there is no specific action taken yet.

In France, there is not yet a communication aimed at the general public for this specific case. A steering committee has been set up, bringing together scientists, ONF-RTM, government departments and local authorities to share the new knowledges in term of observation and modelling.

LESSONS LEARNED/FUTURE PERSPECTIVES

The changing conditions of the alpine cryosphere, pose an important challenge for the management of cryospheric risks in the Alps. Processes still lack knowledge and understanding, and are difficult to measure with continuity because of the extreme environment. Under these conditions, it is very important that research initiatives are supported and promoted in order to have data and elements for a possible strategy of future management of this type of risk.

Much research remains to be done to improve our ability to manage this risk. How important is the role of water percolation in crevasses in warming the glacier? How much of the glacier could collapse in the future, and when?

Aerial image of the Ice Avalanche from the Whymper Serac on the 1st of June 1998

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Potential ice avalanche from the Planpincieux Glacier

TYPE OF HAZARD

Glacier collapse

AREA

Courmayeur, Aosta Valley, Italy

KEYWORDS

glacier break-off, evacuation, near real-time monitoring, traffic line interruption, tourism

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PROBLEM DESCRIPTION

In the past century, break-offs and floods from the Planpincieux Glacier occurred and, on a few occasions, the small bridge of the Montitaz Torrent was damaged. In such cases, the involved ice volume was unknown. In late August 2017, a 60'000 m3 ice chunk detached from the Montitaz Lobe of the glacier, and the ice avalanche stopped 800 m upstream of the bridge. Starting from 2019, in summer, a wide transversal crevasse isolated the lower portion of the Montitaz Lobe from the main glacier body, which began to accelerate rapidly. The estimated volume ranged between 250'000 and 500'000 m3, based on georadar measurements and experts' image analysis. Based on past events, ice avalanche run-out numerical simulations were conducted in 2013 and 2020 by the SLF of Davos with different hypothetical volumes involved. These simulations showed that volumes greater than 250'000 m3 would reach the underlying Planpincieux hamlet, potentially damaging buildings and the valley's access road.
The Planpincieux Glacier faces toward the Val Ferret, which is one the most visited sites of the region of Aosta Valley by tourists. Therefore, without counter measures, the risk of people involvement is high, but the possibility to allow public access to the valley is crucial for the local economic activities that are sustained by tourism. A compromise between these contrasting necessities must be found.

MEASURES APPLIED

The emergency has been faced following different groups of measures: i) monitoring of the hazard; ii) definition of an alert protocol; iii) mitigation measures.

Monitoring of the hazard

After the crisis of 2019, the existent monitoring network was strengthened with the addition of many survey systems that allowed real-time monitoring and data redundancy. A time-lapse camera provided a clear interpretation of the processes in action; a ground-based interferometry radar measuring the glacier velocity was adopted for early warning; a Doppler radar detected ice avalanches and triggered traffic lights in case of occurrence to close the valley road. Besides, more scientific investigations were conducted.

Definition of an alert protocol

Different elements that can be predisposing to ice avalanches were identified and included into an alert protocol that was delivered to the local authorities on a periodic basis (from monthly to daily, depending on the season). Such protocol reduced the subjectivity in the interpretation of the monitoring data and facilitated understanding by – usually non-expert – decision makers.

Mitigation measures

Based on the outcomes of the alert bulletin, different measures aimed at reducing the exposure of the population to the risk of ice avalanche could be put in action: from the closure of specific sectors of valley roads, to the evacuation of the inhabitants from the buildings more sensitive to ice collapses.

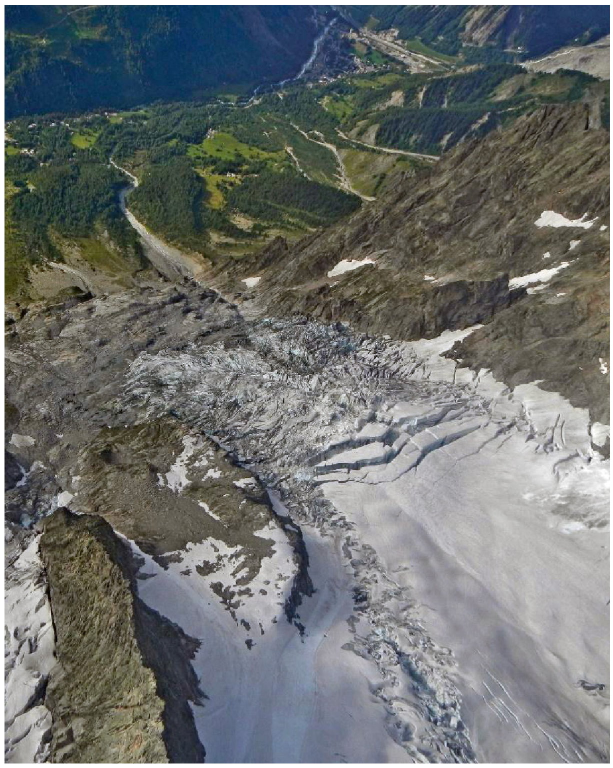
COMMUNICATION

The communication of the risk has been a crucial part of the management of the emergency, mostly because of the understanding reticence of the population against the evacuation of their homes and economic activities and against the closure of the access to the valley that caused financial loss. Therefore, meetings with the population have been organized to illustrate the potential risks with the support of scientific entities.

Besides, simple and clear update bulletins, reporting the state of activity of the glacier by means of infographics, were disseminated on a regular basis (depending on the season) to inform the population.

LESSONS LEARNED/FUTURE PERSPECTIVES

The anomalous morphological and dynamical behavior of the Planpincieux Glacier was observed in 2019 thanks to an existent photographic survey system that was arranged in 2013 to monitor the glacier evolution using a low-cost solution. After the identification of an actual risk, more sophisticated apparatuses were acquired for early-warning. Similar approaches could be followed in other contexts, where explorative low-cost monitoring can be initially adopted and subsequently integrated with other systems in case of necessity. A complementary/alternative option is the analysis of glacier velocity using free remote sensing products, which offer regional-scale data, but are less suitable for detailed investigations.



Aerial image acquired in summer 2014 of the Planpincieux Glacier. On the right side is the Montitaz Lobe and below it is the glacial fan where the ice avalanches fall and travel downward. At the valley bottom, buildings and roads are visible. Credits: Daniele Giordan

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SECTION 2:

GLACIAL LAKE OUTBURST FLOOD (GLOFs)

Artificial drainage of a proglacial lake

TYPE OF HAZARD

Glacial Lake Outburst Flood (GLOFs)

AREA

Chamonix Mont-Blanc,
Auvergne-Rhône-Alpes Region, France

KEYWORDS

proglacial lake, GLOFs, artificial drainage

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PROBLEM DESCRIPTION

A proglacial lake started to form since 2015 on the right side at the front of the Bossons Glacier (French Mont Blanc Alps). Given this lake was dammed by the glacier on its left bank, it has expanded and deepened over time. Radar measurements were performed in 2021 and confirmed that the slope of the bed was favorable to the formation of a subglacial channel. Such subglacial drainage is known to conduct to unpredictable and very fast drainage with high peak discharge. From debris flows simulations, it was estimated that the Bossons village would be impacted by such a sudden drainage for a lake volume around 20 000 m3. Four bathymetries of the lake were performed between 2021 and 2023 and confirmed that the lake volume stayed under this threshold.

MEASURES APPLIED

In 2022, an emergency action was taken by decreasing the level by 1.25 m by digging the natural outlet of the lake. At the same time, we started thinking to more definitive solutions, such as digging a channel at the surface of the glacier to start an artificial overflow. This solution was inspired by the Rochemelon (2005, France) and Plaine Morte (2019, Switzerland) experiences. Simulations of overflow drainage showed that there was no induced risk of flood induced by an uncontrolled increase in water flow in the channel. The only "risk" was that the drainage was unachieved because the water flow in the channel was too low to incise the ice. From 10 to 31 July 2023, two spider excavators have dug a 100 m long channel, excavating approximately 4 000m3 of ice. The 1st of August 2023, the channel was impounded. The lake totally drained in less than a week, incising a 7 m deep ice channel at a mean rate of 1m/d. It was estimated that the lake volume represented only 5% of the water flowing within the channel, 95% being the water entering the lake from the glacier stream. The water is now directed in the most left outlet stream flowing through the Bossons village. Since then, the lake has not appeared anymore.

COMMUNICATION

During winter 2023, a public meeting was organized by the mayor of Chamonix in order to explain to the inhabitants the work that will be carried out during summer to drain the lake. It was also explained the necessity to unbuild two, too small, bridges in the Bossons village to account for the future increase of water flow in this stream. In July, journalists were invited to visit the work site and it gives a number of local but also national news.

During the work, the access to the place was forbidden and a number of pedagogical panels were deployed to explain the raisons the paths were closed. This communication was more in direction of the number of tourists around Chamonix during summer. At the start of the drainage, inhabitants were informed and ready to evacuate in case something went wrong. It was also checked that nobody was walking in the vicinity of the Bossons stream.

LESSONS LEARNED/FUTURE PERSPECTIVES

Just before the start of the work, the ice dam was only few meters higher than the lake level, such that the overflow would have happen naturally in 2023 or at max in 2024. It was nevertheless decided to perform the channel digging in order to control the exact date of the start of the drainage. Lake Bossons was an ideal case, at relatively low altitude (1700m) and easy to access from the Chamonix Valley. We took this opportunity to deploy a number of instruments during the whole drainage week in order to better calibrate the breach discharge model, that has since been used on other applications.

Much research remains to be done to improve our ability to manage this risk. For example, how predictable is the formation and growth of a subglacial or intraglacial channel? Also, the predictability of incision rate in an overflow channel and the ice melt at the bottom of a lake could be improved by combining observations and physical modelling.

Credit Bruno Jourdain (IGE)

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Outburst floods from Mendenhall Glacier Alaska

TYPE OF HAZARD

Glacial Lake Outburst Flood (GLOFs)

AREA

Southeastern Alaska U.S.A.

KEYWORDS

glaciers, outburst flood, flooding, melt, ice-dammed lake, glacier retreat, climate change

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PROBLEM DESCRIPTION

The cyclical advance and retreat of glaciers results in the creation and disappearance of ice-dammed basins, which allow water to temporarily accumulate. These basins tend to fill with water during the onset of summer and then release it in sudden, devastating floods, endangering local populations and infrastructure (Taylor et al., 2023). In southeastern Alaska, near the city of Juneau, the Mendenhall Glacier has been the source of such glacial lake outburst floods (GLOFs), particularly from Suicide Basin, an over deepened side basin where an ephemeral ice-dammed lake forms and releases catastrophically (Kienholz et al., 2020). Since 2011, Suicide Basin has experienced nearly annual GLOFs, with the most significant events occurring in 2023 and 2024.

During August 4-6, 2023, an outburst from Suicide Basin led to the Mendenhall River cresting at a record 4.56 meters, surpassing previous flood records and causing substantial damage to nearby communities. The event released approximately 49.2 million cubic meters of water, leading to a flood discharge exceeding 700 cubic meters per second, far greater than any previously recorded outburst.

The following year, on 6 August, 2024, another outburst occurred, releasing approximately 55.3 million cubic meters of water from Suicide Basin. This event caused the Mendenhall River to crest at 4.87 meters, setting a new record. The peak discharge during this flood exceeded 930 cubic meters per second, surpassing the previous year's historic levels.

These consecutive record-breaking floods highlight the dynamics of the Mendenhall Glacier system and the increasing hazard posed by GLOFs in the Juneau area. The rapid melting of glaciers, influenced by ongoing changes in climate, contributes to the formation and expansion of glacial lakes like Suicide Basin, increasing the potential for such outburst events. Efforts are underway to monitor the ice-dammed lake, develop better predictive tools for estimating the stored water volume and possible discharge, develop glacier evolution models to understand potential future ice-dammed lake locations, and develop strategies to mitigate the risks associated with future GLOFs.

MEASURES APPLIED

In response to the increasing threat of glacier outburst floods from Mendenhall Glacier, scientists and policymakers are pursuing targeted research, mitigation, and community engagement efforts to mitigate future flood risks:

Advanced Hazard Modeling & Prediction

Recent funding by the National Science Foundation and U.S. Geological Survey (USGS) will allow studies by the University of Alaska and Carnegie Mellon University that aim to integrate field data, remote sensing, and modeling to predict future flood hazards and improve regional assessments.

Long-Term Mitigation Planning

The U.S. Army Corps of Engineers, backed by American Relief Act funding, has launched a comprehensive investigation into sustainable flood mitigation solutions for the Mendenhall River floodplain.

Enhanced Monitoring & Early Warnings

The National Weather Service (NWS), and USGS have expanded hydrological monitoring in Suicide Basin, deploying sensors and cameras to improve early flood detection.

Community-Based Resilience & Infrastructure Protection

A partnership among the City of Juneau, the U.S. Forest Service, and the Central Council of the Tlingit and Haida Indian Tribes is exploring long-term strategies to safeguard homes, infrastructure, and cultural resources.

COMMUNICATION

A multi-faceted system is used to mitigate glacier outburst flood risk in Juneau. The warning of glacier outburst and response to rapid flooding relies on real-time monitoring, rapid alerts, and coordinated emergency action by local, state, and federal entities. The University of Alaska Southeast, USGS and NWS track ice-dammed lake level using in situ sensors and cameras and aerial and satellite imagery, triggering flood alerts through NOAA Weather Radio, Wireless Emergency Alerts, and the Juneau Alert System. The City and Borough of Juneau (CBJ), Capital City Fire/Rescue, and Juneau Police coordinate evacuations and public safety efforts, while the Emergency Operations Center manages crisis response. Residents are informed of evacuation routes and receive preparedness information through outreach programs. This integrated approach blends science, technology, and local action to protect the community from sudden glacier outburst floods.

LESSONS LEARNED/FUTURE PERSPECTIVES

The escalating outburst floods from Mendenhall Glacier underscore critical lessons about climate-driven hazards and the need for adaptive strategies. The record floods of 2023 and 2024 signal a possible shift to a more dynamic glacier system, which is outpacing current prediction capability and challenging emergency response efforts. As ice-dammed lakes in the Mendenhall Glacier system evolve, infrastructure along the Mendenhall River will continue to be at risk, demanding long-term mitigation such as revised zoning, engineered defenses, or property buyouts. Community preparedness and real-time monitoring remain vital, but with the glacier's retreat altering the region's hydrology, future risks may evolve in unpredictable ways. Proactive planning, advanced forecasting, and local resilience efforts will be key to navigating this shifting landscape.

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The Tête Rousse water cavity

TYPE OF HAZARD

Glacial Lake Outburst Flood (GLOFs)

AREA

Saint-Gervais-les-Bains,
Auvergne-Rhône-Alpes Region, France

KEYWORDS

subglacial lake, GLOFs, artificial drainage

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PROBLEM DESCRIPTION

The Tête Rousse glacier is famous for the disaster of July 11, 1892, which claimed 175 lives. That night, the glacier released 100'000 m3 of water plus the equivalent in ice, causing a huge flood that deposited around 800'000 m3 of sediment. In 2010, a new cavity was discovered in the glacier based on the analysis of various geophysical methods carried out since 2007: ground penetrating radar (GPR), surface nuclear magnetic resonance imaging (SNMR), boreholes, ice temperature, pressure and sonar measurements. Temperature and creep modelling enabled us to estimate that the cavity had expanded over the decades prior to its discovery. From temperature measurements and modelling, it was established that the cavity has formed due to a thermal barrier, i.e. the front of the glacier was cold whereas the upper part was temperate. As the quantity of water was slightly the same as in 1892 (55,000 +/- 10,000 m3), but many more people were living downstream, it was decided to pump the water out urgently.

MEASURES APPLIED

Once the volume and precise location of the cavity had been confirmed, it was decided to pump water from the surface using bottom pumps placed in the cavity by surface drilling. The risk of collapse of the cavity roof was estimated and deemed low enough to continue drilling from the glacier surface. In autumn 2010, a total of 47,728 m3 of water was pumped from the cavity. Over the following winter, the cavity partially closed by creep, then began to fill up in early spring. A smaller volume was pumped again in 2011 (16,162 m3) and again in 2012 (8,682 m3). It was then decided that the volume of the cavity was low enough to stop pumping the following year. n 2012, after the third pumping operation, the roof of the cavity partially collapsed on the right bank of the glacier. In 2016, taking advantage of the fact that the water level was close to the surface at this point, an overflow channel 6 meters deep was dug in the ice. The objective was to control the maximum water pressure (level) within the cavity. This channel completely closed in less than two years, due to snow accumulation and water refreezing. Today (2025), the original cavity is no longer fed by surface or subglacial runoff. A second reservoir has formed in the upper part of the glacier, within the rimaye crevasse. The glacier is still under survey, with the objective of measuring where and how much water is stored within the glacier.

COMMUNICATION

Since the discovery of the cavity in 2010, a warning system has been deployed at the glacier front. It consists of cables that would be cut in the event of a GLOF, linked to an alarm system in the valley. Inhabitants are informed of the measures to be taken when the alarm sounds. This system is still in place today. Public meetings were organized to explain to residents the risk created by the water stored in the glacier. All work on the glacier was well covered by the local and national media. On the scientific front, several articles have been published as part of the study of the Tête Rousse cavity, and research is still ongoing on the glacier in addition to the annual operational study.

LESSONS LEARNED/FUTURE PERSPECTIVES

The Tête Rousse glacier is a very complicated site in terms of risk management, as there is no solution for permanently draining the subglacial cavity and the hydraulic connections within the glacier are constantly evolving. Fifteen years after the discovery of the cavity, the same total volume of water is now stored in the glacier, but in different places and not necessarily in the form of continuous pockets of water. As there is no way of detecting such a cavity from surface observations, modelling is essential to locate glaciers likely to be subject to a thermal barrier. This work is currently underway at the IGE. In addition, GPR and SNMR measurements have proven their effectiveness in locating and estimating the volume of these subglacial cavities. But they must be complemented by drillings and pumping tests to qualify the water connectivity within the glacier. Regarding the warning system, maintaining such a system in a mountain environment over a such a long period is a difficult task, especially if one wants to avoid at maximum false alarm.

Much research remains to be done to improve our ability to manage this risk. For example, how predictable is the formation and growth of an intra or sub-glacial channel?

Credit Olivier Gagliardini (IGE) – 2010 pumping of the cavity

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SECTION 3:

ROCK-ICE AVALANCHE

The 7th Feb 2021 Chamoli Rock Ice Avalanche in the Indian Himalayas

TYPE OF HAZARD

Rock-Ice Avalanche

AREA

Chamoli District, Uttarakhand State, India

KEYWORDS

chamoli, rock ice avalanche, tapovan hydropower

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PROBLEM DESCRIPTION

About 27 million cubic meters of rock and ice detached from the Rontigad peak on 7 Feb 2021 and initiated as a rock ice avalanche, which later transitioned into a debris flow and a flash flood. It destroyed 2 hydropower projects, killed about 200 people, and caused severe damage to the environment. The impact of this event was observed up to 150 km from the initiation. The huge entrainment and water saturation exacerbated this event during flow.

MEASURES APPLIED

- A comprehensive investigation by the National Disaster Management Authority (NDMA);
- Release area identification by the USDMA, NTPC and DTRL;
- Monitoring of the river discharge by NTPC Tapovan.

COMMUNICATION

The first reporting of this event came to the highlight when the debris flow destroyed the Tapovan Hydropower project and rushed through the desiltation chamber where approximately 200 workers were on duty.
Local administration communicated to USDMA through the District Disaster Management Authority (DDMA).
USDMA reported to NDMA and also involved lined departments of the State.
NDMA deployed a Central Team involving National Institutions of significance to assess day-to-day situation and PDNA.
Press media also played an important role during the whole process.

LESSONS LEARNED/FUTURE PERSPECTIVES

- Hazard-Vulnerability-Risk mapping of high-altitude regions susceptible to avalanches/other mass movement processes;
- Large Scale Hazard Indication Mapping should be carried out

on a regular basis considering the potential release zones and worst possible scenarios using a user-friendly, and simple numerical model;

- Remote sensing-based mapping & Monitoring preferably through SAR Interferometry for possible identification of release zones.

Release Zone of the 7th February 2021 Chamoli Rock Ice Avalanche

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SECTION 4:

SNOW AVALANCHE

Avalanche on Passo Foscagno 2024

TYPE OF HAZARD

Snow Avalanche

AREA

Livigno, Lombardy, Italy

KEYWORDS

avalanche forecasting, road management, traffic management

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PROBLEM DESCRIPTION

Livigno is a municipality situated in the central Italian Alps, near the borders with Switzerland and South Tyrol. It is one of Italy's most popular ski resorts, attracting more than one million tourists each winter. The permanent population is approximately 7'000 people, supplemented by around 4'000 seasonal workers, and the resort area can simultaneously accommodate up to 20'000 tourists. The main valley floor of Livigno is located at an elevation of approximately 1800 meters above sea level. The area is influenced by 41 major avalanche paths that expose infrastructure to avalanche hazards, including the main village, isolated houses, and roadways. Livigno is connected externally through three mountain passes: Forcola, Passo Foscagno, and Passo del Gallo. Forcola Pass remains closed throughout the winter season, while Passo Foscagno and Passo del Gallo are vulnerable to avalanches and may occasionally be closed during critical periods, resulting in the isolation of Livigno. In the past decade, avalanche hazards have led to the isolation of the village for approximately 2-4 days each year. On the Passo Foscagno road, five major avalanche paths have been identified as particularly problematic, although several smaller avalanche sites can also impact the road directly.

During Easter 2024, a period characterized by a high influx of tourists, including many day visitors, heavy snowfall occurred. From 27 March to 31 March, over 100 cm of snow accumulated in Livigno, with approximately 25 cm falling specifically on Easter day (31 March). On the afternoon of Easter Sunday, Passo Foscagno had to be temporarily closed due to vehicles becoming stranded and difficulty in maintaining road clearance. Given the forecast for an additional 70 cm of snow accompanied by strong winds overnight, the avalanche forecaster, in agreement with civil protection authorities, prioritized clearing the road to briefly re-establish circulation, scheduling a new closure for 9:00 PM that evening. The primary concerns were potential avalanche occurrences impacting the road and extreme weather conditions compromising safe travel. While no specific high-risk sites were identified, widespread avalanche interference was considered likely. Nonetheless, emergency vehicle access was preserved throughout the night, as Passo Foscagno provides the sole winter connection between Livigno and the rest of Italy.

An assessment for potential reopening was scheduled for 9:00 AM on 1 April. However, at 8:00 AM, an avalanche released from the northern slopes of Monte Foscagno near the summit area of the pass, crossing a relatively flat area of approximately 370 meters, reaching the road located slightly uphill on the opposite side. The avalanche narrowly missed a nearby hotel, impacted two vehicles parked in its immediate proximity, and damaged three medium-voltage power line pylons—critical infrastructure supplying electricity to the entire municipality. The avalanche exceeded the known historical maximum avalanche runout distances recorded in the regional avalanche database by approximately 350 meters. Fortunately, one of the power line cables remained functional, resulting in only a 15 minutes disruption of electrical service in the town.

Due to continued avalanche risk, authorities delayed reopening the pass until the evening of 1 April. On 2 April, a temporary road closure between 10:00 and 11:00 AM allowed avalanche control activities using helicopter and Daisy Bell systems targeting slopes that had not yet spontaneously been released. These preventive measures produced no additional significant avalanche activity, indicating a substantial improvement in snowpack stability.

MEASURES APPLIED

Monitoring and Characterization:

The Livigno Avalanche Center operates daily throughout the winter season with up to four dedicated staff members continuously monitoring snow and weather conditions. In addition to traditional snowpack observations, the center benefits from regular feedback provided by local mountain guides. Data is collected from ten automated weather stations strategically positioned at various altitudes and locations to capture specific microclimatic conditions.

For these stations and an additional ten monitoring points, forecasters use the SNOWPACK model combined with numerical weather models, providing real-time (nowcasting) snowpack evolution data and forecasts extending up to 14 days.

Satellite-based SAR image analysis algorithms have been developed to detect avalanche activity, identify wet snow conditions, and provide insights on snow depth. Avalanche occurrences are also systematically recorded through manual observations. Combining simulated snowpack stability data, digital terrain models, and avalanche dynamic modeling enables avalanche forecasters to generate daily scenarios predicting potential avalanche activity within the monitored area.

View of the Monte delle Mine Rock Glacier and the exposed valley

Early warning system

- Meteorological forecast models are crucial tools for providing advance assessments; however, the complexity of alpine terrain often reduces their reliability;
- Real-time monitoring systems detecting spontaneous avalanche activity can offer immediate predictive insights into imminent events.

Response Planning

- Road closures;
- Artificial avalanche releases;
- Emergency protocols.

Mitigation

- Temporary road closures;
- Artificial avalanche triggering to secure unstable slopes;
- Structural avalanche protection (barriers, dams, etc.);
- Burial of exposed electrical power line segments to reduce avalanche risks.

COMMUNICATION

Road closure information is disseminated via Livigno Municipality's official social media channels (Telegram, Facebook, Instagram), direct communications with tourism operators and their respective associations, and institutional websites. Variable message boards positioned strategically along key road networks are also utilized.

LESSONS LEARNED/FUTURE PERSPECTIVES

Avalanche hazards cannot always be precisely anticipated. Exceptional snow and weather conditions can lead to unprecedented and unexpected avalanche events. Although exact predictions are challenging, context-based information can help anticipate otherwise unpredictable phenomena. However, this approach remains complex and not always feasible.

Electrical power lines should also be considered critical infrastructure and their exposure to avalanche hazards must be factored into municipal emergency planning. An avalanche-induced power outage affecting approximately 30'000 people in an alpine community during winter conditions poses severe management challenges. Additionally, continuous medical services are crucial for highly populated, isolated areas. Relying predominantly on helicopter transport for emergency response can become problematic during poor flight conditions, and maintaining road access for emergency vehicles can significantly increase the risk to rescue personnel.

In preparation for the 2026 Winter Olympics, monitoring systems (geophones and infrasonic arrays) will be implemented for real-time avalanche activity detection, enhancing the data available to forecasters. Predictive modeling data on snowpack stability, in both snowcasting and forecasting, provide valuable support for avalanche prediction efforts.

Collecting satellite-derived avalanche activity data and snowpack conditions, despite their delayed nature, is crucial for better understanding, recording, and studying territorial snowpack dynamics.

Having on-site avalanche forecasters continuously tracking conditions throughout the winter season remains essential to addressing unforeseen scenarios, even when leveraging advanced informational resources.

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Avalanche winter 1999

TYPE OF HAZARD

Snow avalanche

AREA

Switzerland, Austria, France

KEYWORDS

snow avalanche, extreme events, traffic line interruption, avalanche victims, evacuation

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PROBLEM DESCRIPTION

The winter of 1999 was marked by a catastrophic series of avalanches in Switzerland and Austria, resulting in significant loss of life and extensive infrastructural damage. In Switzerland alone, the winter claimed 17 lives and caused damages exceeding CHF 600 million, while in Austria, particularly in the village of Galtür in Tirol, 31 fatalities were reported due to a massive avalanche that buried several buildings. In France, the worst avalanche accident occurred in the winter of 1999 near Chamonix. The Montroc Avalanche destroyed part of a village and killed 12 people. The avalanche events were unprecedented, with over 1200 avalanches causing damage in the Swiss Alps, severely disrupting transportation and isolating communities, which had a profound impact on the tourism sector. The avalanches were attributed to a combination of meteorological conditions, including heavy snowfall on 29 January, 9 February and 22 February and unstable snowpack, which prompted a reevaluation of avalanche risk management strategies in the three countries. In response to the disaster, initiatives were launched in Switzerland to enhance organizational measures for avalanche risk management, including the further development of hazard maps and improved communication systems between authorities and safety services. This shift towards a more integrated risk management approach was driven by the recognition of the need for better forecasting and preparedness to mitigate future avalanche-related disasters The lessons learned from the winter of 1999 have since informed policies and practices aimed at reducing avalanche risks, emphasizing the critical role of scientific research and community preparedness in safeguarding lives and infrastructure in alpine region.

MEASURES APPLIED

Monitoring and Characterization

- Aerial imagery acquisition by swisstopo
- Manual mapping of avalanche extents

Early warning system

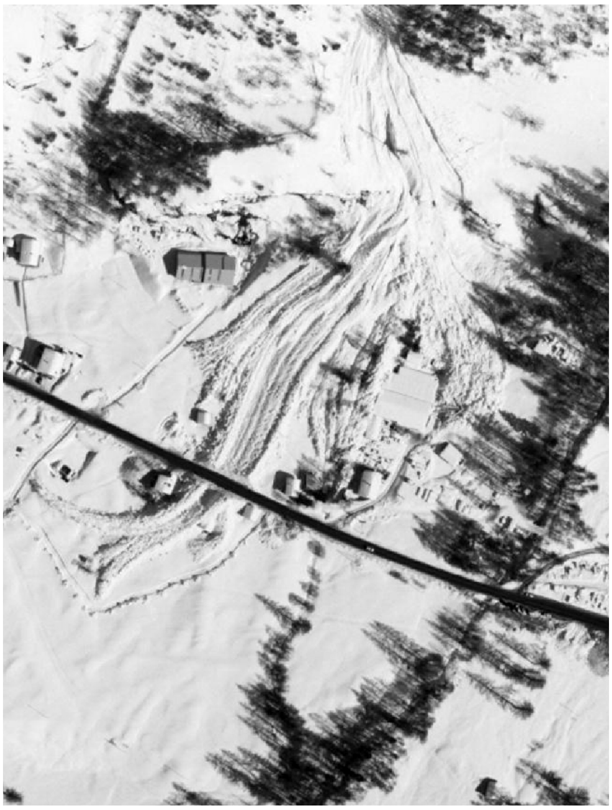
- Avalanche warning SLF

Response Planning

- Traffic line closure
- Evacuations

Mitigation

- Reevaluation of hazard maps and the mapping procedures
- Review of the effectiveness of mitigation measures and refinement of the design approach
- Integrated risk management



Aerial imagery 26 February 1999 in Evolène, canton of Valais (ch.swisstopo.lubis-luftbilder_schwarzweiss)

COMMUNICATION

The avalanche danger is constantly evaluated by the avalanche warning services in Switzerland (SLF) and other Alpine countries. These warnings are communicated to the public by numerous channels (Radio, Web, TV, social media etc.). The warning services also keep a constant communication channel with national, regional and local authorities. In Switzerland the GIN network is now active for that (https://www.info.gin.admin.ch/bafu_gin/en/home.html) as successor platform for IFKIS.

LESSONS LEARNED/FUTURE PERSPECTIVES

The constant evolution of infrastructure and tourism in mountain regions is increasing the vulnerability. A next extreme avalanche winter, maybe also triggered by more intense extreme precipitation events due to climate change, might have even larger impacts than 1999. Therefore, an integrated risk management strategy combining different sets of measures is crucial. The hazard mapping started after the avalanche winter 1951 in Switzerland demonstrated it effectiveness hindering the building of infrastructure in endangered areas. The different parts starting with operational avalanche warning, organizational measures such as evacuation plans, planning measures such as hazard mapping, technical measures such has snow supporting structures or avalanche dams as well as silvicultural measures need to be coordinated to achieve an enhanced effect to avalanche hazards. The future trend is moving more towards enhanced temporary measures such as remote-controlled blasting systems, avalanche radars and automatic avalanche detection systems. Temporary measures can be more easily adapted to changing conditions due to global warming.

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Proactive actions for avalanche risk management on infrastructure

TYPE OF HAZARD

Snow Avalanche

AREA

Autonomous Region of Aosta Valley, Italy

KEYWORDS

avalanche, roads, town, traffic, tunnel, avalanche prevention works, artificial detachment

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PROBLEM DESCRIPTION

Operational solutions to manage avalanche events that can interact with the road system, the only one access to villages or economic and accommodation facilities located upstream of the avalanche basin.

Over the years, several active and passive works have been carried out to mitigate the risk of avalanches on road axes, however, these works are not always sufficient to manage the avalanche risk. The causes are various: extreme weather events, particular avalanche dynamics, under sizing of the works. Or lack of active or passive works whose construction is not sustainable due to the orographic characteristics of the basin or because avalanche events are rare.

Proactive management is therefore necessary in conjunction with or in the absence of avalanche prevention works to mitigate avalanche risk. Below, some of the basins in the Aosta Valley are analyzed.

The basins with proactive management in integration with active or passive works are: in the Lys Valley the Bounitzon basin, in Morgex the Lavancher basin.

In the Bounitzon basin there is a 139 m long avalanche barrier gallery, built in 1979 to protect the SS 44, in critical situations, the avalanche flowing through the gallery also affected the road system, repeatedly obstructing it. This recently occurred in the winter seasons 2008-2009 and 2023-2024.

In the Lavancher basin, however, there are 4.350 meters of protective defense structures (linear snow bridges) of a height varying between Dk=4metres and Dk=3 meters have been installed in the start zone, as have about 40 ‘upside down tree-shaped’ wind-breaking deflecting devices positioned along 350 linear meters of the crest. Yet, for example in the 2009-2010 season, the avalanche repeatedly fell, creating preferential flow channels, grazing and putting at risk the village of Dailey.

The basins with exclusive proactive management are: the Rochefort basin (Ferret Valley), the Zerbion basin (Ayas Valley), the Cresta Fort du Bard – Chanavey bacin (Rhêmes Valley), the Tzasetze basin (Cogne Valley).

Specifically, for the Rochefort basin the high altitude of the release area, the innumerable points of possible accumulation by the wind and therefore of detachment of the avalanche, the steep slope and sliding area, mean that it is not possible to create and make effective an active work, much less a passive work due to the dynamics and magnitude of the spontaneous event. Furthermore, the creation of such a work would impoverish the natural environment of the valley. In the other basins the return times of the event are rare and sporadic and the cost of creating the work does not find economic justification.

MEASURES APPLIED

Over the years, the solutions adopted for the proactive management of avalanche risk are:

- use of artificial detachment with explosive charges, Snyper, Vassale or Gaz-ex;
- remodeling of the avalanche flow and accumulation zone.

Artificial detachment

In the Rochefort and Zerbion basins, the PIDAV (Intervention Plan for Artificial Avalanche Detachment) have been created. In particular, for the Rocherfort Basin, in 2017 an Operational Plan for the Management of Avalanche Danger (POGPV) was drawn up and includes the PIDAV, aimed at reducing the risk of avalanches through preventive measures and artificial detachment interventions. The plan is based on historical data and technical reports for effective management and is a dynamic document that evolves based on experiences and detachment techniques. Commissioned by the municipal administration and managed by the local avalanche commission, its implementation has been regularly and successfully applied since 2019. Up to January 2025, approximately 12 interventions have allowed the closure of Val Ferret to be limited.

Currently, Sniper charges are used, dropped by helicopter at the shooting points defined by the operational plan, at altitudes between 2900 m and 3670 m with slopes between 30 and 50 degrees and based on quantitative definitions of accumulation. The choice of shooting sites is dictated by the morphological characteristics and snow accumulation and adapted from time to time to contain the magnitude of the event caused.

The objective is to cause repeated medium/large events while avoiding the very large/extreme event capable of reaching the valley floor.

The document also contains the clivometric map with the areas predisposed to natural release. The sludge map showing the distribution of stress in the soil and snowpack, with concave areas more subject to avalanches. The nivometeorological monitoring plan using nivological data, periodic surveys, observations of snow height, wind snow accumulation, temperature and characteristics of the snowpack, attention and alert thresholds.

As well as the safety and management procedures for the artificial detachment of avalanches.

A PIDAV has also been created in the Rhêmes and Tzasetze basins, but in this case the proactive management uses a fixed system installed on site with Gaz-ex exploders, in these basins, the shooting points are fixed and do not require a repeated site-specific assessment. In this case the release area does not exceed 2600 m of altitude.

Remodeling avalanche

Proactive avalanche remodeling management is instead implemented in the flow and accumulation zone when several avalanche events can overlap in the same season. This is the case of the Bounitzon and Morgex basins.

The action is implemented when a seasonal event renders the effectiveness of the work useless and therefore there is a high probability that each subsequent event will find a “preferential flow”, channeling onto the road network or near a residential area.

Specifically, the characteristics of these basins allow, in the accumulation zone and partially in the flow zone, to use snow groomers (normally used in ski areas to groom the slopes) or vehicles such as

bulldozers/excavators, to mobilize the snow accumulations of the avalanche in order to create banks to channel and contain subsequent flows towards open areas, protecting the infrastructure.
This type of management, as it is extraordinary, is managed and evaluated by the Autonomous Region of Aosta Valley using the technicians of the Department of Civil Protection and Fire Brigade Operational Interventions, in synergy with the technicians of the avalanche office and the competent avalanche commission for the territory. From 2008 to 2025, five remodeling interventions have been carried out throughout the regional territory.

COMMUNICATION

For all proactive management methodologies, the communication implemented prohibits access to the area to be managed and there is constant monitoring during the operations.
For Val Ferret, the POGPV includes preventive measures and procedures for closing and reopening the municipal road in case of danger and outlines the monitoring and suspension procedures for traffic to ensure public safety.
The Mayor, in collaboration with the Director of Operations, manages the temporary closure of the municipal road in case of avalanche danger.
The detachment operations are carried out by helicopter, following rigorous safety and communication procedures. The area concerned is always closed to the public and must be monitored to ensure safety during operations. Below an extract of communication adopted over the years:
"The procedures include the activation of the Operational Plan for the management of avalanche danger from 7:30 am until the end of operations, which consist of the evacuation of the towns of Meyen and Pont-Pailler; from 07.30 am the ban on access, circulation and parking in the area subject to reclamation (Marbrée, Rochefort, Praz de Moulin); from 07.30 am the ban on access, circulation and parking for vehicles and pedestrians along the Val Ferret road between the locality of La Palud and Planpincieux."

LESSONS LEARNED/FUTURE PERSPECTIVES

Active and passive works are not always sufficient to manage avalanche risk.
The works do not eliminate the risk, there is always a residual risk due to extreme events or events with particular dynamics or sometimes the works are undersized or it was not possible to realize them in relation to economic reasons.
Implementing proactive management measures allows to overcome such situations, allows to contain costs, intervene quickly and effectively also to protect the local economy.
On the other hand, it requires an operational plan and requires specialized and competent management.

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Snow and avalanche emergency of December 2008 in the western and south-western Italian Alps, Piedmont Region

TYPE OF HAZARD

Snow Avalanche

AREA

Province of Cuneo, Italy
Province of Torino, Italy

KEYWORDS

extreme events, snow emergency, avalanche risk management, road safety, civil protection plans

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PROBLEM DESCRIPTION

After several days of bad weather with significant early snowfalls recorded between 9 to 12 December 2008, starting from the morning of Sunday 14 December to the night of Wednesday 17, Piedmont was affected by intense and widespread precipitations that caused critical conditions linked to heavy snowfalls and avalanches on the Alpine valleys, landslides on hills, and flood in plains. During the event, exceptional snowfalls were recorded; the total amount of new snow fallen in four days (14-17/12/2008) was between two to three times the average of total new snow for December measured in Piedmont mountains over the previous 40 years. Duration and intensity of precipitations determined a very high avalanche risk on all the Piedmont alpine sectors, Grade 5, the highest value of the European avalanche danger scale. During snowfalls and in the subsequent days numerous natural loose and slab avalanches, frequently of large size, were released: 52 Municipalities were affected by avalanche phenomena and in some cases avalanches directly affected residential buildings, fortunately with no casualties; 68 villages were isolated for several days; 33 preventive evacuations were performed; 243 Municipalities were affected by road and rail interruptions; electricity supply interruptions occurred to about 173 Municipalities [1]. The emergency phase lasted one day before Christmas Eve. The damage costs to the public property caused by the 14–17 December 2008 snowfalls have been estimated by regional authorities to be about 470 million of euros [2], giving evidence of the real emergency dimension and impact of the event.

MEASURES APPLIED

The Regional Directorate of Public Works, Soil Protection, Mountain Economy and Forests of Piedmont Region during the emergency operated in close contact with the Local Avalanche Commissions

(CLV), to continuously verify and update the situation on a local scale. The air support activated by the mentioned Regional Directorate from three helicopter bases was fundamental for the CLV institutional activities (monitoring of avalanche activity and planning of prevention actions). The helicopters' operation was coordinated on ground by the personnel of the State Forestry Corps and the heli-bombing activities were coordinated by the Regional Operational Room of Civil Protection with technical assistance of a snow expert from ARPA, which provided support to the emergency management during all the crisis phases. The main activities of ARPA were: the elaboration of updated target forecasts, the snow and weather real-time data delivery, the on-line Agency Avalanche Information System sharing, the coordination of the avalanche and damage reporting to get a regional updating framework of critical situations, the support to the avalanche and snowpack survey and to artificial triggering. In the southern sectors, operations were coordinated by the Unified Avalanche Commission for the Province of Cuneo, constantly assisted by an ARPA snow expert in support of the Civil Protection crisis room of the province.

COMMUNICATION

Communication during the event was managed from three point of view:

- The institutional communication to the public was managed by the Communication Sector of the Piedmont Region, through press releases issued twice a day.
- The operational communication for the management of the emergency was coordinated, due to its severity, by staff of the national Civil Protection Department from the regional operating room to the municipalities, mountain communities and road services of the provinces concerned.
- The Local Avalanche Commissions transmitted daily to the Mayors and the Regional Operating Room a report on the avalanche situation in the Piedmont valleys, with indications for the adoption of preventive measures for public safety.

In addition, in order to support the planning and execution of CLV activities on the field, ARPA prepared and daily transmitted to all CLV's a specific bulletin with main meteorological and snow-cover parameters for all Alpine sectors.

View of the Monte delle Mine Rock Glacier and the exposed valley

LESSONS LEARNED/FUTURE PERSPECTIVES

The December 2008 avalanche crisis highlighted the importance of well defined and shared standards, acknowledged and accepted prevention actions suited to minimize the heavy snowfall effects, with particular attention to the road conditions and to the school system opening/closing.
The "emergency preparedness" at different institutional levels, including stakeholders and population, came out as a key factor to minimize negative impacts.

Main lessons learnt are as follows:

- prompt involvement of local actors.
- improving the management of road and motorways closing and opening.
- providing the media, authorities and people with univocal, official and timely information.
- standardize the operational procedures for CLV, including artificial avalanche releases operations.
- improving the people preparedness.

After the December 2008 crisis, many actions were undertaken, either at regional or local level, to upgrade the overall system:
(a) Mid-scale regional avalanche mapping (known as SIVA – Sistema Informativo Valanghe) published online in 2001 on GIS public platform, (https://webgis.arpa.piemonte.it/portale-valanghe/) was updated with important new information about avalanches even with secular time of recurrence and laid the basis for the new regional avalanche Cadastre.
(b) Operational Guidelines for Local Avalanche Commission were established and set in practice [3].
(c) Regional and local authorities were partners of several European research projects aimed to improve methods and tools for avalanche prevention and preparedness (e.g. STRADA Strategic Project, co-funded by Interreg I-CH 2007-2013, PITEM RISK and PITER Terres Monviso, co-funded by ALCOTRA 2014-2020 I-F European Cross-border Cooperation Programs).
(d) New budget lines were established by regional authorities to sustain the CLV activity with new snow instruments and training activities.

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Brienz/Brinzauls landslide

TYPE OF HAZARD

Rock Avalanche

AREA

Community of Albula/Alvra,
Canton of Grisons, Switzerland

KEYWORDS

landslide, monitoring, early warning, evacuation

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PROBLEM DESCRIPTION

The slope where the village of Brienz/Brinzauls is located experienced slope instability since the retreat of glaciers around 13'000 years ago. The geological and geomorphological settings predispose the slope to a variety of complex processes, which affect the uppermost regions with rock falls, debris slides and rock avalanches, while the lower portions are dominated by deep seated deformation reaching up to the Albula river. The instability is not only threatening the village but also important road connections, a railway and a power line. In 1877 the north-eastern part of the slope accelerated, with approx. 13 million m3 (Igl Rutsch) moving with a few meters per day over several weeks and stopping before reaching the village. Since spring 2023 a strong acceleration of the north-central part (Insel) was observed and the village (approx. 100 inhabitants) was evacuated a first time on 12 May 2023. On 15 June 2023, part of the Insel failed catastrophically with about 1.2 to 1.7 million m3 rock mass and debris flowing down rapidly during the night, reaching the cantonal road and stopping about 40 meters before the houses. After this event, a deceleration of the rock slope was observed, and the people were allowed to return to their houses. However, the depression of the Insel release filled again with debris from the rock walls above and started to accelerate again in November 2024, with peak velocities up to 40 centimeters per day. As the unstable materials react quickly after snowmelt and/or heavy rainfall, prompt warning before a potential catastrophic failure is difficult and thus the village has been evacuated again and is still uninhabited today.

MEASURES APPLIED

Monitoring and Characterization

- Instrumented boreholes, geophysical investigations;
- Hydrogeological characterization and Geological modelling;

- Satellite radar interferometry (InSAR);
- Regular LiDAR and photogrammetric elevation model acquisitions;
- High resolution webcams with DIC (digital image correlation) (Gepraevent AG und Monitron AG).

Early warning system

- Ground Based InSAR (Geopraevent);
- GNSS stations (HMQ AG und Grünenfelder AG);
- Total station with mirrors (HMQ AG).

Response Planning

- Runout Modeling for different scenarios using RAMMS, DAN3D and MPM;
- Risk phases (green, yellow, red and blue) communicated to the public;
- Evacuation plans;
- Planning for relocation of the village.

Mitigation

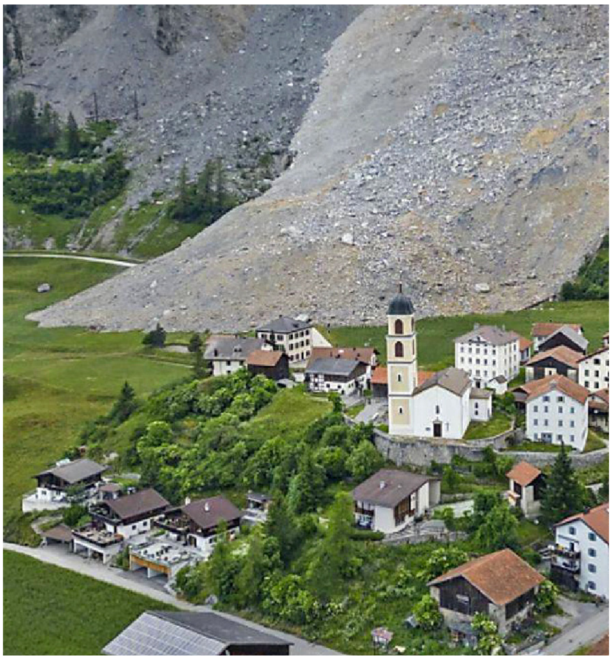
- Tunnel for dewatering;
- Road closure with traffic light coupled to a doppler radar to detect rockfall;
- Evacuation.

COMMUNICATION

As many people are affected by this hazard, a professional expert, Christian Gartmann (https://www.gartmann.biz) was employed to lead the official communication of the community of Albula. Regular bulletins are issued to the public (https://www.albula-alvra.ch/infobrienzerrutsch). Official meetings have been initiated to inform and discuss with the local population and streamed online as livestream. The communication setup is a crucial part of the management of the Brienz/Brienzauls landslide management. Also, different national TV formats have been produced on this hazard (e.g. Einstein www.srf.ch/play/tv/sendung/einstein) as well many national and international news reports.

LESSONS LEARNED/FUTURE PERSPECTIVES

Deep seated landslides moving slowly over many decades can suddenly accelerate initiation a big crisis for the population as well as critical infrastructure (power lines, buildings, roads and railways). In such a situation, an efficient and accurate early warning system as well as a sophisticated communication strategy are crucial. Combination of different instruments and methods such as a ground-based radar, GNSS and total station point measurements, as well as numerical modelling to evaluate potential runout scenarios help decision making. Frequent and transparent communication of the situation to the local population using different channels, in collaboration with professional communication experts, enables a reliable and trustworthy inclusion of the affected population.



Archive image - Keystone/Michael Buholzer

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Spitze Stei rock slope instability

TYPE OF HAZARD

Rock Avalanche

AREA

Community of Kandersteg,
Canton of Bern, Switzerland

KEYWORDS

monitoring, runout simulation,
early warning

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PROBLEM DESCRIPTION

Given its critical geological predisposition, the region around Kandersteg was affected by several prehistoric, multi-million cubic meter large rock slope failures. Kandersteg is built on the deposition of the Fisistock rock slope failure, the largest event with a volume of almost 1000 mio. m3. During the 2010s, a remaining section of the original Fisistock instability in the so called 'Spitze Stei' area reactivated, involving a volume of about 16 mio. m3. The reactivation was accompanied by permafrost thaw or warming and increased water infiltrations into the slope. This caused a weakening of Marl layers, which act as sliding plane. Seasonally varying water pressures in the slope controlling the current displacement velocities and cause a distinct acceleration during snow melt. Displacement rates range between 1.5 m/year for the deep-seated sliding process up to several meters per year for a superimposed debris slide. In the current phase of the instability, ductile behavior of the ice saturated marl layers is assumed to prevent a further acceleration and failure of the slope.

A future failure of the slope is nevertheless considered as likely. The primary rock avalanche would affect an area used heavily by tourists. Although direct damage to infrastructure would be limited to a small road, a ski piste and possibly a few buildings, the risk of human casualties is significant. The municipality has therefore established a flexible restricted area adjusting to the hazard situation.

The remobilisation of rock avalanche deposits by debris flows poses a significantly greater hazard potential. Debris flows could reach the village centre and cause major damage here. A retention dam was built on the edge of the village to protect it. In addition, a planning zone including a temporary construction ban applies to large parts of the village. On the process side, the situation is exacerbated by the fact that the deposits of the rock avalanche could potentially bury the spring outlets of the underground drainage of

Lake Oeschinen. This could lead to the rapid saturation of the deposit and favour debris flows. This is particularly the case if there are major subsequent rock falls that affect the deposit of the first event.

MEASURES APPLIED

Monitoring and Characterization

Regular LiDAR and photogrammetric elevation model acquisitions; Temperature, deformation and water pressure measurements in boreholes; Electrical resistivity tomography (ERT), Geotechnical laboratory tests; Analysis of historical aerial images; Hydrogeological, geological and kinematical model; Webcams; Lidar and Radar gauges.

Early warning system

- Ground Based InSAR (Geopraevent);
- GNSS stations;
- Total station with mirrors.

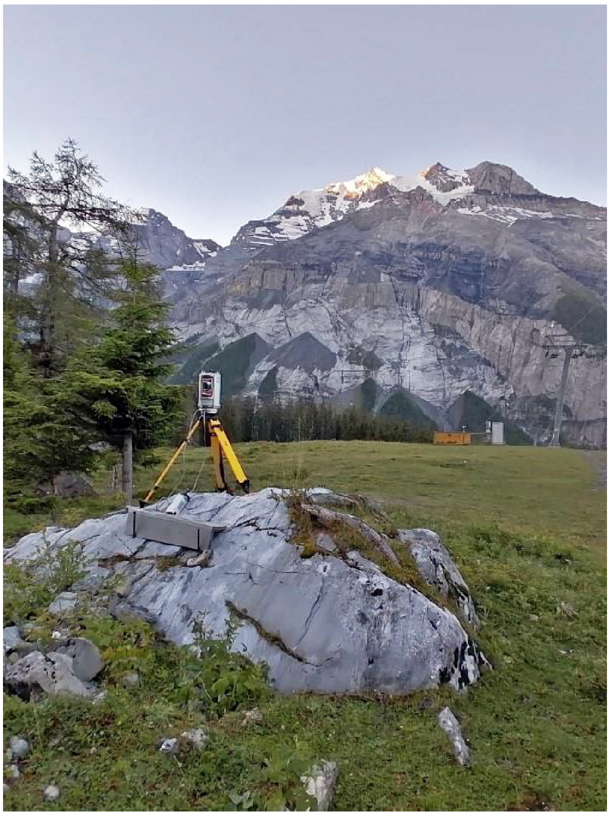

Image: Robert Kenner, SLF

Response Planning

- Runout Modeling for different scenarios using RAMMS and MPM;
- Flexible restricted area;
- Risk phases (green, yellow, red and blue) communicated to the public;
- Evacuation plans.

Mitigation

- Retention dam;
- Measures against flooding in the village;
- Evacuation plans.

COMMUNICATION

Frequent communication of findings and hazard situation to the public via website of the community and informative meeting. Swiss TV production (SRF DOK & Einstein) as well many national and international news reports.

Official information website of the community Kandersteg with frequent updates (in German): *https://www.gemeindekandersteg.ch/spitze-stei*

All reports and hazard assessments are openly available on this website (Fachunterlagen).

LESSONS LEARNED/FUTURE PERSPECTIVES

Permafrost thaw can cause the activation/reactivation of water driven rock slope instabilities. Phases of uniform ductile slope creep can last for years and can pose a considerable burden for the communities affected, as they can lead to long-lasting restrictions on community life and local development.
Even if primary rock fall does not threaten a village, the management of sediments, mobilised by secondary debris flow activity constitutes a major challenge. Fast remobilisation of large volumes by the impacts of subsequent failures must be considered. The intense monitoring is ongoing.

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Turtle Mountain rock avalanche

TYPE OF HAZARD

Rock Avalanche

AREA

Crowsnest Pass, Rocky Mountains, Alberta, Canada

KEYWORDS

rock avalanche, rockslide, geological monitoring, risk management

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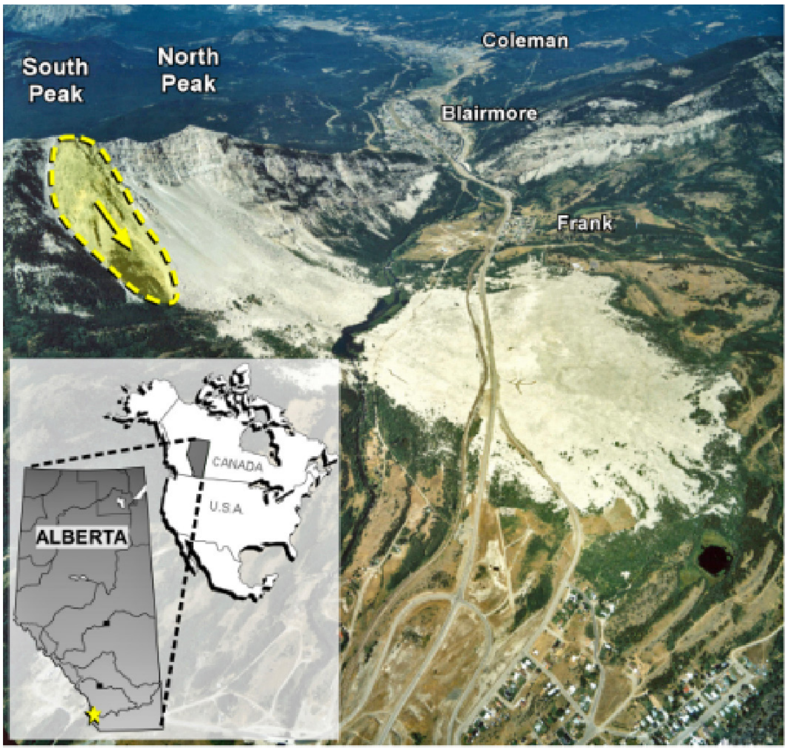
PROBLEM DESCRIPTION

In mountainous regions, there are often large rock slope instabilities than can move slowly over time and rapidly accelerate and have sufficient energy to flow and impact on large areas in the valley bottoms.

In 1903 a large rock avalanche in the Western Canadian Rocky Mountains buried part of a mining town, killing over 80 people. Following this event studies highlighted an additional unstable mass on the eastern flank of the mountain that could impact on populations and infrastructure in the valley bottom. This to an evolving approach to risk management over the next 120 years driven by utilizing updated technologies and understanding of the mountain that have allowed decision makers to better understand the risk and support informed decision making.



MEASURES APPLIED

Hazard avoidance: Following the 1903 rock avalanche, the remaining portion of the Town of Frank were re-located as to not be in the path of future rock slope failures originating from the eastern flank of Turtle Mountain.

Land Planning

In the 1930's, the identification of an additional unstable mass (estimated at 5x106 m3) led to the development of an empirically based estimate of potential impacted areas for which future development was discouraged but not formally implemented.

Characterization

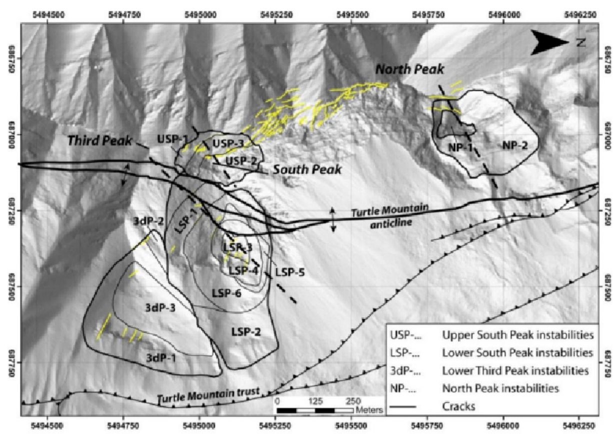
In the early 1980's there was an initial campaign implemented to install a series of points on the mountain that could be utilized to characterize displacement patterns and rates but there was no long-term support for these studies. In the mid-2000's, following the implementation of different monitoring technologies on the

COMMUNICATION

A formal emergency response protocol was developed for the project in collaboration with the provincial emergency management agency and the municipality. Annual table top exercises were undertaken to confirm understanding of roles, responsibilities and actions and annual updates on the mountain were provided in municipal meetings. All results of the annual monitoring were also published on the Alberta Geological Survey websites (www.ags.aer.ca).

LESSONS LEARNED/FUTURE PERSPECTIVES

While in 2003, the government of Alberta had good intentions by allocating funding and resources to implement a near real-time warning system over a short time period, there had not been sufficient studies to understand how the mountain was moving and whether this approach to risk management was appropriate. While significant effort was allocated to installation of sensors on the mountain in the early 2000's, it was not until the late 2000's where studies were undertaken to refine the understanding of the hazard and it was determined that the movements were sufficiently slow and the volumes lesser than anticipated. This led to moving away from relying on short term warning to a renewed focus on tracking movements over longer time periods using remote monitoring technologies and committing to applying land use guidelines to minimize downslope impacts.



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Veslemannen Rock Slope Hazard

TYPE OF HAZARD

Rock Avalanche

AREA

Møre og Romsdal County,
Western Norway

KEYWORDS

rock avalanche, rock slope management, early warning system, emergency response plan

AUTHORS

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PROBLEM DESCRIPTION

As part of the national rock slope management program a high-risk rock slope object was identified on the mountain Mannen, in Møre and Romsdal county, western Norway. Two scenarios, ranging in volume between 2 million m3 and 20 million m3 were identified which could impact on downslope inhabitants, a regional road and regional railway line, and the river at the base of the valley could be dammed and cause flooding upstream of the slide.
Veslemannen was a small (estimated up to 120.000 m3), but very active section of the larger scenarios, discovered from the displacement measurements in 2014. The hazard zones from this section only affected four inhabited houses. Veslemannen failed in 2019 after a series of evacuations of the residents.

MEASURES APPLIED

Monitoring and Characterization

Drill holes, geophysical investigations and surface mapping were undertaken to better understand the nature of the rock mass. Surface and remote monitoring systems were set up to understand and monitor movement trends in an early warning system.

Runout Modeling and Risk Zonation

For both the large scenarios and Veslemannen, the potential downslope extents of a failure runout were modelled, and zones were determined based on the likelihood of potential scenarios.

Early Warning and Response Planning

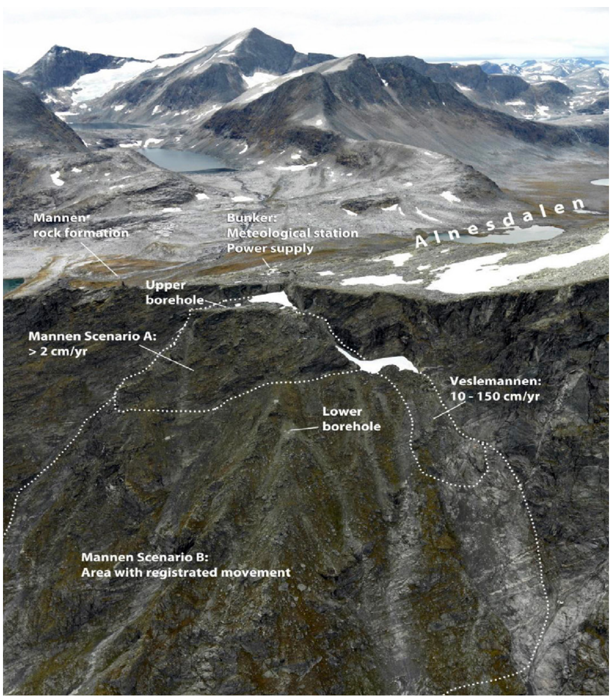
Based on the learnings from the monitoring program, multi-staged displacement thresholds were developed for the Veslemannen scenario corresponding to color-coded hazard levels. Following the national plan for emergency preparedness for rock slope failures in Norway, routines were implemented for geological and technical control, communication and response planning with the municipality, county, railway and road officials (see below).

COMMUNICATION

The nature of the hazard and risks were communicated to the municipality, county, road and rail officials and an emergency response plan was developed. From 2014 there were significant accelerations of the displacements for the smaller mass that led to threshold exceedances and execution of the emergency response plans, which included evacuation of residents and restrictions on road and rail traffic. The trend accelerated in particular in 2018 and 2019 up to the September 2019 failure of the Veslemannen section, which led to several evacuations of the inhabitants in the hazard zone.

LESSONS LEARNED/FUTURE PERSPECTIVES

There were a total of 15 warnings of the top (red) hazard level and evacuation over a span of six years where no collapse occurred. The slope movements were strongly affected by precipitation events that caused the velocity thresholds to be exceeded repeatedly, though the thresholds were evaluated and set higher every year. When the slope collapse did occur in September 2019, the volume (54.000 m3) and runout were smaller than the evacuation zone, which was a "worse case" conservative scenario. Some of the key lessons learned were the difficulty in predicting how and when a rock mass may fail, in particular when a slope is highly affected by external forcing such as precipitation events. Run-out zones are difficult to model accurately and evacuation zones need to be conservative to ensure no fatalities from a failure. In similar situations, where unstable volumes are small, other methods to manage the risk like building of debris diversion structures) could be considered as an alternative for 24/7 monitoring. Repeated "false" alarms can lead to a significant burden and uncertainty for the inhabitants and a lack of trust to the decision making.



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SECTION 6:

LANDSLIDE

The Mont de La Saxe landslide: monitoring and management

TYPE OF HAZARD

Landslide

AREA

Courmayeur, Aosta Valley, Italy

KEYWORDS

landslide monitoring, risk mitigation, geotechnical engineering, early warning system, infrastructure protection, drainage systems, civil protection

AUTHOR

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PROBLEM DESCRIPTION

The Mont de La Saxe landslide area spans 150,000 m^2 with an estimated volume of 8.5 million m^3, threatening critical infrastructure and the local community. The landslide exhibits complex kinematic behavior, with multiple active sliding planes ranging from shallow depths (20-30m) to deeper layers (50-90m). The instability affects residential areas, luxury hotels, and critical infrastructure such as the Mont Blanc Tunnel, whose closure could result in economic losses of approximately €2 million per day. Conventional protective measures have proven insufficient for large-scale collapses, necessitating active mitigation strategies to slow down the evolution of the landslide.

MEASURES APPLIED

Monitoring History

- 2002-2007: Initial geomorphological analysis and installation of first topographic and borehole surveys confirming the active nature of the landslide;
- 2008: Establishment of the first continuous monitoring network for real-time movement tracking;
- 2010: Increased monitoring frequency following observed acceleration of slope movement;
- 2012: Expansion of monitoring system with additional sensors to enhance data precision and coverage;
- 2013: Exceeding of alert thresholds, prompting the implementation of mitigation and civil protection measures;
- 2014-Present: Ongoing monitoring and continuous adaptation of risk mitigation strategies, integrating a “technology watch” approach.

Multi-Technology Monitoring System

Real-Time Monitoring Infrastructure

- 44 RTS topographic targets;

- 8 GNSS continuous receivers;
- 6 multiparametric DMS probes;
- 1 GB-InSAR unit;
- 1 high-resolution rockfall detection system.

Investment and Maintenance

- Initial investment: ~€2 million;
- Annual maintenance cost: ~€150.000.

Risk Mitigation Measures

Drainage System

- Implementation of drainage boreholes (2013-2015, expanded in 2018);
- Discharge capacity varies seasonally between 3,500 m^3/day and 8,500 m^3/day;
- Landslide velocity reduced by a factor of four.

Early Warning and Decision-Making Strategy

- Alert system based on movement data, piezometric conditions, and meteorological forecasts;
- Four alert levels (Green, Yellow, Orange, Red) trigger different civil protection responses, including evacuation and road closures.

COMMUNICATION

Institutional communication: continuous updates provided by the regional authorities.

Public and stakeholder communication:

- Reports and alerts issued to local municipalities and civil protection units;
- Real-time data sharing with decision-makers;
- Media briefings to keep the public informed of evolving risks and necessary precautionary measures.

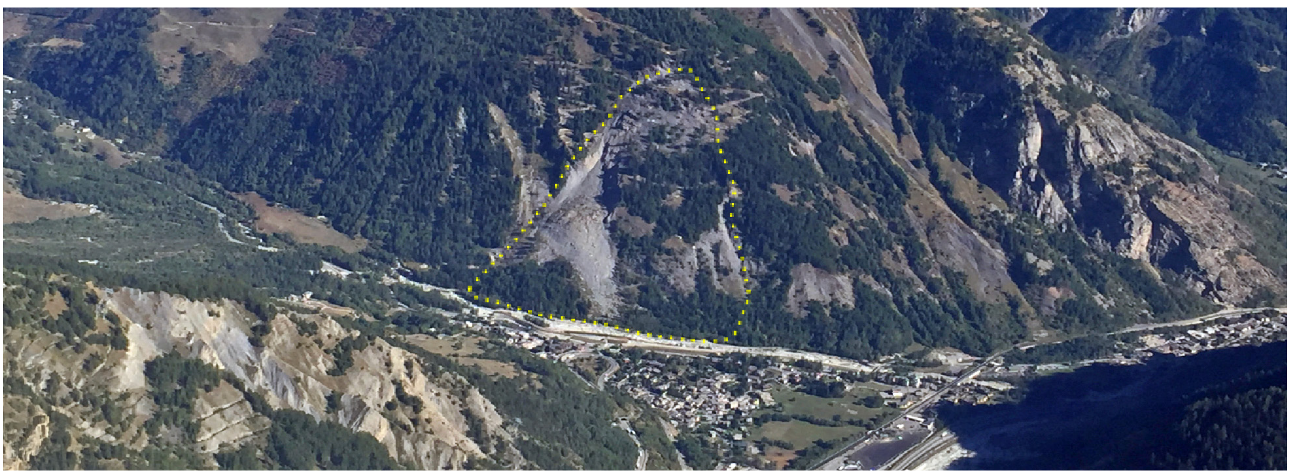
LESSONS LEARNED/FUTURE PERSPECTIVES

Technological Integration

- AI and machine learning applications to enhance predictive modeling of groundwater variations and landslide evolution;
- Continuous improvement of real-time monitoring capabilities.

Resilience and Adaptation

- Strengthening cooperation with local authorities and civil protection agencies;
- Optimizing mitigation techniques for long-term stability and risk reduction;
- Further advancements in remote sensing for improved hazard assessment.



Aerial photo taken from helicopter at about 3700 m a.s.l. on Oct 1st, 2016, showing the 400.000 m3 collapsed sector (2014). The dashed line marks the unstable active slope of the landslide (photo: D. Bertolo).

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SECTION 7:

DEBRIS FLOW

Rock glacier collapse, Livigno 2024

TYPE OF HAZARD

Debris flow

AREA

Livigno, Lombardy, Italy

KEYWORDS

landslide monitoring, integrated monitoring system, cost-effective solutions

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PROBLEM DESCRIPTION

In recent decades, the Alpine climate has undergone significant changes, with a marked increase in average annual temperatures. This has led to imbalances in glacial systems, accelerating glacier retreat and compromising permafrost stability. Rock glaciers, ice-rich landforms covered by debris, are also affected by climate change, resulting in geomorphological and hydrological impacts. Between 2022 and 2024, the rock glacier on the northwestern slope of Monte delle Mine (Livigno, Italy), at an elevation between 2650 m and 2850 m a.s.l., experienced accelerated melting. Initially, this process manifested as a depression at the center of the deposit. Since July 2024, instability has further developed, leading to the formation of an erosional scarp in the central part of the glacier front, directly exposing ice embedded within fine sediments.

This phenomenon has triggered increased differential erosion and debris mobilization, resulting in repeated debris flow events along the Rin da Clüs stream and a significant rise in fine sediment transport in the Spöl River, the main watercourse of Livigno Valley. The presence of residential and industrial infrastructure downstream, along with water intake structures for artificial snowmaking, has necessitated urgent mitigation measures and further investigation into the causes of this phenomenon.

In July 2024, as the situation worsened, an emergency evacuation order was issued for a residence on the slopes of Monte delle Mine, and access to the affected area was restricted. To mitigate debris flow risks and enable a safe return for residents, a diversion barrier was constructed as an emergency measure, and a geomorphological study of the landslide was initiated.

MEASURES APPLIED

Additional diversion barriers will be constructed along the valley floor to control debris flows, along with the development of a sedimentation basin to reduce solid transport into the Spöl River. Furthermore, a detention basin is planned to regulate water turbidity for artificial snowmaking purposes.

Monitoring and Characterization:

The initial analysis focused on delineating the spatial extent of the instability using image correlation techniques applied to optical satellite imagery with a 3 meters resolution. The analysis, conducted on two sets of three images, revealed that between July and August 2024, not only did the rock glacier undergo accelerated erosion, but an entire section of the slope moved downslope, with displacement reaching up to 8 meters in one month. Some ridge sections of the slope were also affected, indicating the potential reactivation of deep-seated gravitational movements.

The severity of the phenomenon required continuous monitoring and the implementation of long-term mitigation strategies, including:

- Real-time GNSS monitoring: Deployment of a GNSS station network for continuous measurement of slope displacement;
- Interferometric SAR observation: Installation of corner reflectors for satellite-based monitoring and expansion of control points using InSAR techniques;
- Image correlation observation: Assessment of slope movements using optical satellite imagery;
- Microclimatic and hydrological monitoring: Installation of sensors to measure soil temperature and humidity, snow cover thickness, and relevant nivometeorological parameters to correlate permafrost degradation with slope instability. Additionally, monitoring of the chemical variation of spring water is included;
- Geophysical investigations: Geophysical surveys planned for summer 2025 to map interstitial ice presence and determine the depth of the affected gravitational instability zone;
- Visual monitoring: Installation of webcams for real-time visual assessment of unstable areas.

Early warning system:

Data collected from GNSS stations will support the activation of alert protocols in case of accelerated

View of the Monte delle Mine Rock Glacier and the exposed valley

slope movement, potentially leading to the evacuation of exposed areas. Simultaneously, nivometeorological data acquired from predictive models and in situ measurements, combined with water chemistry monitoring, will contribute to pre-warning model development and help identify potential correlations between atmospheric conditions and slope dynamics.

Response Planning

- Evacuations in case of extreme instability.

Mitigation

- Integrated risk management;
- Design and construction of a debris flow diversion barrier;
- Development of a sedimentation basin to reduce solid transport in stream water.

The integration of satellite data (InSAR and image correlation) will allow for extensive
monitoring of slope instability evolution. Geophysical investigations will provide more accurate estimates of unstable volumes, helping to define precise hazard scenarios and integrate findings into the local civil protection plan.

COMMUNICATION

Road closure information is disseminated via Livigno Municipality's official social media channels (Telegram, Facebook, Instagram), direct communications with tourism operators and their respective associations, and institutional websites. Variable message boards positioned strategically along key road networks are also utilized.

LESSONS LEARNED/FUTURE PERSPECTIVES

Ongoing climate evolution has caused and will continue to cause instability issues in periglacial zones. Many of these processes are not yet fully understood. It is increasingly important to focus on studying such issues to guide professionals in their assessment and management, ensuring the implementation of appropriate measures and actions. Various tools are now available to establish a comprehensive analysis, management, and mitigation system for natural hazards. Depending on the severity of the situation, progressive actions and cost-effective monitoring solutions can be implemented accordingly. The integration of multidisciplinary approaches remains a key resource for effective hazard management.

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30th July 2024 debris flow at Wayanad, Kerala, India

TYPE OF HAZARD

Debris Flow

AREA

Wayanad district, Kerala, India

KEYWORDS

debris flow, wayanad, chooralmala, western ghat, landslide dam

AUTHORS

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PROBLEM DESCRIPTION

On 30 July 2024, a deadly debris flow occurred at the Wayanad district of Kerala state, India, which severely affected four villages downstream, namely Punchirmattam, Mundakai, Vellarimala and Chooralmala. The runout was approximately 8 km, and it destroyed many houses, infrastructure and bridges on its way. More than 300 people lost their lives due to this event.

Rainfall was the major triggering factor of this debris flow, and the huge entrainment along its path enhanced its mobility.

MEASURES APPLIED

Post Disaster Need Assessment (PDNA) was carried out by a high-level committee constituted by the National Disaster Management Authority (NDMA), Government of India in association with Kerala State Disaster Management Authority (KSDMA).

Demarcation of Go and No-Go Zones

Drones' studies, LiDAR-based mapping, satellite-based studies, and Geotechnical investigations were performed by different Institutes and Organizations of Gov. of India to decode the formation, mobilization and impact of this event.

Field based observations were made and numerical simulation through debris flow modeling is being attempted to validate the near real-field scenario. This will enhance the understanding of debris flow dynamics and process in the Western Ghats region of India.

It is also recommended by NDMA to preserve this event site as Wayanad Natural Living Disaster Lab to introspect on this disaster of such scale and impact and also to look forward for a disaster resilient society. The disaster caused extensive loss of life and infrastructure, highlighting the vulnerabilities in the region's current settlement pattern. The concept for the new township shall include and revolve around addressing the issues of Climate change, social inclusivity, vulnerability of the existing ecosystem which will help in developing a sustainable and resilient township.

COMMUNICATION

The Indian Meteorological Department issues orange alert on 29 July 2024, 1 pm in the District Level Rainfall Forecast for Kerala and Lakshadweep. Landslide alert was issued by the State and Wayanad district Emergency Operation Centre and appropriate anticipatory evacuation was carried out by Revenue and local self-Government in various Panchayat.

On 29 July 2024, a local resident reported about the heavy rainfall to the District Panchayat President (also Co-Chairman of the District Disaster Management Authority). He visited multiple places with the local police, revenue and fire and rescue services as well as local representatives. People from the vulnerable locations were evacuated and camp was started in Chooralmala area.

NDMA committee found that an Apada Mitra observed muddy water and tree trunks downstream side of the release zone at 11.45 pm on 29 July 2024.

LESSONS LEARNED/FUTURE PERSPECTIVES

- Debris Flow Susceptibility-Hazard-Vulnerability-Risk Zonation in the potential debris flow regions;
- Identification & Assessment of Future Possible Release Areas for Debris Flow;
- Scenario-based Debris Flow Run-out Simulation and Hazard-Risk Assessment;
- Relocation & Reconstruction for Resilient Township;
- Community-centric Awareness & Capacity Building;
- Rainfall should be considered as a warning of debris flow events in high and very high debris flow susceptibility and hazard zones.

Wayanad Debris flow (The Hindu 2024)

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SECTION 8:

ROCKFALL

The Gallivaggio rockfall management case study

TYPE OF HAZARD

Rockfall

AREA

Gallivaggio, Lombardy, Italy

KEYWORDS

rockfall risk management, monitoring

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PROBLEM DESCRIPTION

The Gallivaggio rockfall is a gravitational instability phenomenon affecting a mountainous slope in Valchiavenna, Lombardy. The event has manifested through progressive movements and sudden accelerations, posing a threat to the viability of State Road 36 and surrounding infrastructure, including the Gallivaggio Sanctuary. The primary causes of the rockfall are linked to geological, tectonic, and climatic factors, including the presence of structural discontinuities in the rock, erosion processes, and water infiltration from precipitation. Monitoring has revealed significant volumes of moving material, with the risk of sudden collapses that could endanger the safety of the population and local infrastructure.

MEASURES APPLIED

Monitoring of the hazard

Various monitoring and intervention measures have been implemented to mitigate the risk associated with the Gallivaggio landslide. Geotechnical and geomatic monitoring systems, including interferometric ground-based radars and extensometers, have been installed to track the evolution of the movement.

Definition of an alert protocol

The alert protocol defined for the Gallivaggio landslide is similar to the one in place for all early warning systems managed by ARPA Lombardy. Through a specific modeling process, event scenarios and trigger thresholds for the landslide phenomenon were defined. When one of the threshold values is exceeded, technicians carry out a series of verification activities aimed at confirming the accuracy of the data and the significance of the event. Once this confirmation is obtained, a communication is sent to the Civil Protection, which proceeds to notify all parties involved in the necessary activities to ensure the safety of the population.

Mitigation measures

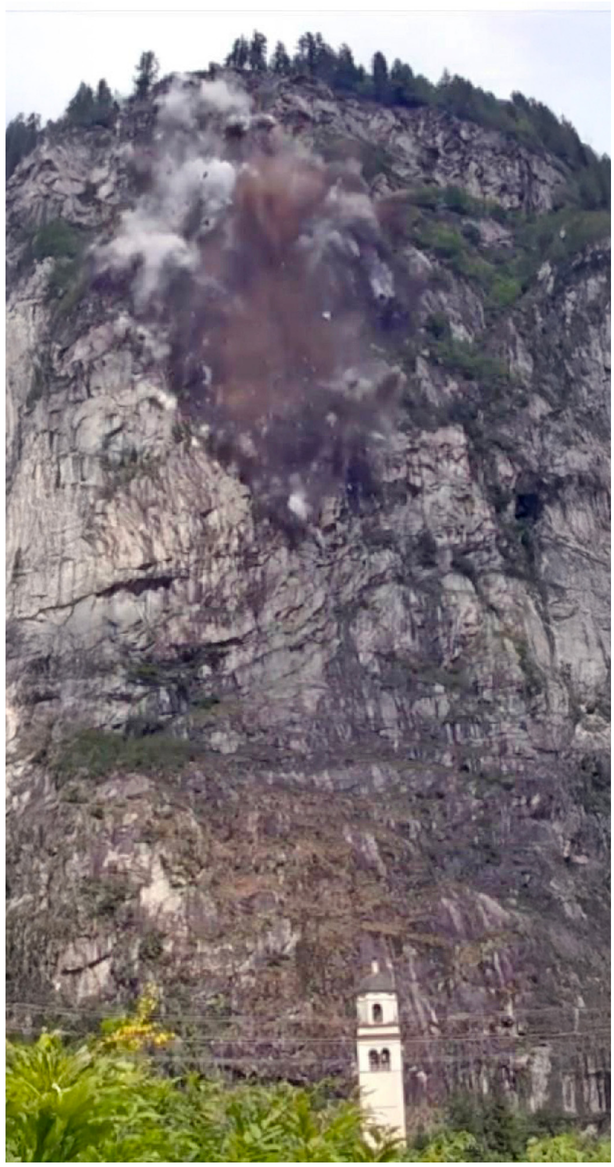
Stabilization interventions such as rockfall nets, dynamic barriers, and controlled scaling have been carried out to reduce the volume of unstable material. At the infrastructural level, protective measures have been adopted along the roadway, including road diversions and temporary closures in case of alerts. Mitigation strategies have been complemented by continuous planning and communication with local authorities and the population to ensure effective risk management.

COMMUNICATION

Effective communication is a crucial aspect of risk management for landslides. Specifically, for the Gallivaggio landslide, the main information regarding the configuration of the monitoring network and the analysis of movements or acceleration situations is disseminated on the ARPA Lombardy website, in local newspapers, and on video channels. It should be noted that, before the Gallivaggio landslide of May 29, 2018, public meetings were also held to improve communication with the resident population.

LESSONS LEARNED/FUTURE PERSPECTIVES

In 1987, after the massive Val Pola landslide, the governing body of the Lombardy Region decided that civil protection was of the greatest importance and thus established an effective monitored slope. The aim, given the impossibility of preventing these large landslides, is to preserve human lives by evacuating or restricting access to areas affected by potential collapses. Currently, the monitoring service, managed by the Regional Agency for Environmental Protection, is active on 45 large landslides across the regional territory. Future prospects involve making the forecasting process related to landslide events increasingly effective.



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SECTION 9:

LAND SUBSIDENCE

The ground subsidence of January 2023 at Joshimath, Indian Himalayas

TYPE OF HAZARD

Land Subsidence

AREA

Chamoli District, Uttarakhand State, India

KEYWORDS

joshimath, ground subsidence, damage assessment, PDNA, reconstruction, relocation

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PROBLEM DESCRIPTION

On 2 January 2023, outburst of muddy water observed in Jaypee Colony (a place at the toe of the subsided slope in the Joshimath Township) with a discharge of 600 lpm was observed.
Between 3-8 January 2023, major subsidence was observed which resulted in the form of ground cracks, cracks on the walls and floors of the buildings and ground movement.
Situated on an ancient landslide made up of weathered big un-settled boulders in a loose matrix of fine sandy and clayey material.
Risk to land subsidence highlighted in Mishra Committee Report (1976).
There is a history of creeping and occasional subsidence in the region.
The disturbance of aquifers and the hydro-geological environment in the region seems to be the main cause for the sinking of soft-geological strata.
Subsidence gets accelerated by heavy rains and snow melt.

MEASURES APPLIED

Immediately after the first information received about this issue, the National Disaster Management Authority (NDMA) with Uttarakhand State Disaster Management (USDMA) and different Indian institutes (CSIR-CBRI, CSIR-NGRI, WIHG, IIRS, Geological Survey of India (GSI), etc.) started ground verification of the land subsidence affected zones.
Two vulnerable multi-storey hotels and a number of residential buildings that were posing risk to the surroundings were demolished.
Damage and vulnerability assessment of 2364 buildings spread over nine administrative zones and risk assessment of the affected area were carried out by CSIR-CBRI.
Buildings falling under the highly vulnerable zones were vacated and temporary shelters to affected people were provided by local administration.

Relocation sites were identified in the near vicinity and demo buildings for reconstruction were erected at these sites by CSIR-CBRI.

Post disaster need assessment (PDNA) was carried out by NDMA and USDMA for funding from the Central Government.

The fund based on PDNA has been allocated to the Uttarakhand State Government and reconstruction of the affected Joshimath Township is under progress.

COMMUNICATION

- Initial communication was made by the local public to the Joshimath local administration;
- Local administration communicated to USDMA through District Disaster Management Authority (DDMA);
- USDMA reported to NDMA and also involved lined departments of the State;
- NDMA deployed Central Team involving National Institutions of significance to assess day-to-day situation and PDNA;
- Press media also played an important role during the whole process.

LESSONS LEARNED/FUTURE PERSPECTIVES

- Is the scientific community putting the recommendation in the right perspective for administration?;
- Need of bridging the gap between scientific communication and administrative decision;
- Inadequate/absence of drainage system on hill slopes may lead to such events which may further exacerbated by the loads due to the increasing infrastructures;
- The scenario-based vulnerability-risk leading to damage assessment of the infrastructure is an urgent need in the growing urbanization in hills;
- Instrumentation and Monitoring of vulnerable townships in hills must help in disaster preparedness and risk reduction;
- Mitigation plans need to be implemented at the right time once reported by the stakeholders for effective disaster risk reduction and management;
- In the mountains, techno-legal regime needs a greater attention in formulating and implementing regulations and building bylaws.

Release Zone of the 7th February 2021 Chamoli Rock Ice Avalanche

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SECTION 10:

MULTI-HAZARD

Precipitation-induced multi-hazard event in Haines Alaska

TYPE OF HAZARD

Multi-hazard

AREA

Haines, Alaska, U.S.A.

KEYWORDS

precipitation, atmospheric river, rain, snow, landslide, avalanche, infrastructure, rain-on-snow, climate change

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PROBLEM DESCRIPTION

An intense atmospheric river unleashed a torrent of snow and rain across southeastern Alaska on 2 December, 2020, triggering numerous snow avalanches and landslides. The devastation included a catastrophic landslide on Beach Road in Haines, where multiple homes were destroyed, and two lives were tragically lost.

The primary trigger for the landslide was extreme precipitation associated with a one-in-500-year atmospheric river event, which resulted in significant rain-on-snow conditions. This led to rapid snowmelt and excessive runoff, saturating the soil and increasing pore water pressure, which ultimately destabilized the slope. According to Darrow et al. (2022), the underlying ultramafic bedrock contained structural weaknesses that contributed to slope failure. Pre-existing geomorphic features, including evidence of past landslides and displaced rock masses, further indicate that the area had a history of instability.

The landslide caused extensive destruction, including the loss of homes, infrastructure damage, and fatalities. The event also led to widespread evacuations and significant emotional distress within the community. Geologists monitoring the site have concluded that while the area is currently stable, future landslides remain a possibility, particularly given climate change projections that predict more frequent and intense atmospheric river events.

The Beach Road Landslide underscores the need for improved landslide risk assessments and early warning systems in regions susceptible to extreme precipitation. With climate change expected to increase the frequency of extreme weather events, proactive mitigation measures will be critical in reducing future risks to communities in landslide-prone regions.

MEASURES APPLIED

Following the 2 December, 2020, Beach Road Landslide in Haines, Alaska, significant scientific and applied responses have been undertaken to analyze the event, improve hazard assessment, and enhance community resilience.

Scientific Responses

- Landslide Mechanism Analysis: Darrow et al. (2022) conducted an in-depth geomorphological study, identifying weak ultramafic bedrock, pre-existing landslide features, and extreme precipitation as key factors contributing to slope failure. Their research emphasizes the need for integrating geological and meteorological data in hazard assessments;
- Acquisition of High-Resolution Topographic Data: Zechmann et al. (2024) conducted and extensive aerial lidar survey that has resulted in a high-resolution digital terrain model used for geologic mapping and modeling geologic hazards;
- Landslide and Snow Avalanche Hazard Susceptibility Mapping: The Alaska Division of Geological & Geophysical Surveys (DGGS) developed landslide susceptibility maps to inform future planning and risk mitigation (Nicolazzo and Larsen, 2025). These maps incorporate historical landslide data and geophysical analyses. Large-scale snow avalanche indication maps are also being developed for area;
- Community Data Collection & Research Collaboration: Ongoing studies involve community input, lidar surveys, and field investigations to refine hazard models and improve predictive capabilities;
- Applied Responses;
- Geotechnical Assessments & Mitigation Planning: The Alaska Department of Transportation, alongside R&M Consultants, conducted site investigations to assess ongoing slope stability and develop mitigation strategies.

Long-Term Recovery & Support

Organizations like the Long-Term Recovery Group and the Chilkoot Indian Association have provided assistance to displaced residents, addressing immediate needs and long-term recovery efforts.

Enhanced Monitoring & Preparedness

State agencies are implementing improved monitoring techniques and developing early warning systems, integrating atmospheric river forecasting with landslide risk models to mitigate future hazards.

COMMUNICATION

Atmospheric rivers produce intense precipitation and can significantly impact snowpack growth or rapid melt, potentially leading to multiple geologic hazards, including flooding, avalanches, and landslides. Knowledge of where such hazards can occur is critically important. Following the disaster resulting from the December 2020 atmospheric river event, Haines now benefits from close communication with a state and federal inter-agency geohazards group and a broader community of scientists, rightsholders and stakeholders working together to share information and promote preparedness with respect to landslide hazard in Southeast Alaska. This collaboration is fueling the development of a local landslide warning systems, designed to proactively monitor hazardous weather and ground conditions and provide warnings. Bolstering these efforts, a 2024 federal bill proposes establishing an atmospheric river forecasting program, complete with at least one Alaskan observatory. This initiative promises improved data collection, modeling, and risk communication, ultimately strengthening the state's capacity to anticipate and respond to landslide-triggering extreme weather. These combined strategies empower residents in Haines and elsewhere in Southeast Alaska to make informed decisions and take necessary precautions when hazardous conditions arise.

LESSONS LEARNED/FUTURE PERSPECTIVES

Haines, Alaska leverages multiple channels to keep residents informed about potential geologic hazards, particularly landslide and avalanche dangers stemming from intense precipitation or atmospheric rivers. The community of Haines is in contact with forecasters from the National Weather Service and receive alerts about potential extreme weather. Locally, the community uses a Nixle alert system to deliver real-time notifications via text and email, while the Haines Borough, Haines Avalanche Center, and the Alaska Geological & Geophysical Surveys host webpages dedicated to educating citizens on avalanche conditions, recognizing landslide warning signs, and encouraging vigilance, especially during heavy precipitation events.

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