Rock slope and gravity - 2025

Forecasting and Modelling Large Rock Slope Failures in a Changing Mountain Environment

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Blatten by Swisstopo

Index of the authors

Session 1:

Large rock slope instability characterization in the context of climate changes

Permafrost degradation in high mountain rock slopes and its role in the Blatten disaster

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(Abstract to come)

Knowns and unknowns in assessing the impacts of climate change on rock slope failures in the Norwegian Arctic and sub-Arctic and implications for hazard assessment

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Over the past 50 years, seven known large rock slope failures (>100,000 m³ — large enough to generate rock avalanches) have occurred in Norway. Six occurred in Arctic Norway and one in a southern glacial setting. Five originated on slopes with relief contrasts exceeding 200 m, and three events failed as rock avalanches and two as rock creep flows. The remaining two, lower-relief slopes failed as rapid to very rapid rotational rockslides. Comparison with modelled permafrost maps (Magnin et al., 2019) and local temperature data shows that all failures occurred within or near areas (<100 m) of sporadic to continuous permafrost. Currently, unstable rock slopes threatening settlements or water bodies with adjacent communities are hazard-classified following a standardized workflow (Hermanns et al., 2012; Oppikofer et al., 2017). This approach assesses morphology, structure, and activity but assumes all slopes fail as rock avalanches. Runout distances are estimated using global H/L–volume relationships, and displacement wave run-up is evaluated with the empirical SPLASH model (Oppikofer et al., 2018). This last tends to overestimate the impacted area and is used today for susceptibility mapping. Recent observations challenge these assumptions by revealing (1) additional failure types such as rock creep flows, and rotational slides, and (2) the influence of degrading permafrost, neither of which are considered in the existing workflow. Non-rock avalanche failures typically have shorter runouts and lower velocities, reducing their capacity to generate displacement waves and thus leading to overestimated hazard zones. In addition, neglecting permafrost conditions may result in underestimated failure likelihoods under a changing climate. To address these challenges, the Geological Survey of Norway and the Norwegian Water and Energy Directorate, together with an expert board, are developing a revised classification system that incorporates both failure type and likelihood, with potential integration of climate-sensitive parameters. Discussion continues on whether to integrate climate-related parameters, as the links between climate change and rock slope stability are not entirely understood and permafrost data are scarce in Norway. Preliminary tests— using failures with known pre-failure conditions at Piz Cengalo, Switzerland (2017), Elliot Creek, Canada (2020), Forkastningsfjellet, Norway (2022), and Kleines Nesthorn, Switzerland (2025)—suggests the revised system may be an effective tool for assessing slopes approaching critical stability.

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Permafrost and large unstable rock slopes: Controls on Displacement Rates in Norway

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(Abstract to come)

Increased glacial lake outburst flood hazard in Iceland, in the light of ongoing climate changes

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Keywords: GLOF, proglacial lakes, climate changes, mass movements.

Over the last 140 years, or from the maximum extent of glaciers during the Little Ice Age, it is estimated that Icelandic glaciers lost over 16% of their mass. During this time interval temperatures have been fluctuating, with exceptionally warm period in the 1920s and 1930s followed by slightly colder interval until beginning of the 1980s. During this time outlet glaciers retreated considerably and in front of several of them proglacial lakes began to form. From around 1970 to 1995 outlet glaciers readvanced, and in some instances proglacial lakes were filled up with ice again. At the end of the 20th century another turning point occurred, with higher temperatures and exceptional rapid retreat of outlet glaciers. Existing proglacial lakes have expanded, and many new ones formed. In some cases, catastrophic break up has occurred, as recent break up at the Heinabergsjökull outlet glacier in SE Iceland.

These glacial fluctuations have and are affecting the slope stability above these retreating outlet glaciers, resulting in various types of mass movements onto outlet glaciers and formation of fractures. The frequency of mass movements on outlet glaciers has increased, from the turn of the century compared to the last 4 decades of the 20th century. New discoveries of unstable slopes above outlet glaciers have also increased since 2000.

The largest mass movement fallen onto an outlet glacier in Iceland occurred in 1967 when a large rockslide fell onto the Steinsholtsjökull outlet glacier in South Iceland and into its proglacial lake, causing a glacial lake outburst flood (GLOF). The GLOF entirely overprinted the pre-existing proglacial landscape in the valley.

Over the last few years several proglacial lakes have been mapped with multibeam sonar scanner, revealing the lake bathymetry for the first time. The lake bathymetry, coupled with radio-echo sound survey of subglacial topography of these outlet glaciers, makes it possible to study the glacial retreat rate and formation of proglacial lakes in light of climate fluctuations and the depth distribution in the lake basins. It also gives possibilities to estimate future lake development and retreat rate.

The potential for mass movement triggered GLOFs in areas where proglacial lakes have formed has increased considerably over the last decades. Many of these areas both attract tourists year-round and have seen recent related infrastructure development in their vicinities. This development raises serious concerns and stresses an urgent need to study and monitor these environmental hazards.

Rainfall-induced rock slope failure controlling factors in deglaciated mountain settings

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Rock slides triggered by heavy rainfall storms can pose significant hazards to mountain communities and infrastructure. The large volumes of rock and water involved often result in high mobility rock avalanches and debris flows with destructive consequences. In deglaciated valleys, steep slopes and current or former paraglacial conditions, which may induce rock damage and progressive failure, contribute to landslide-prone conditions. Meanwhile, intense rainfall events appear to be increasing in frequency due to global climate change. In this paper, we review case studies in the Americas Pacific regions, from the Patagonian Andes (2017 Santa Lucia and 2020 Termas El Amarillo landslides) and western Canada (2021 Seabird Island landslide), where large (10^5-10^7 m^3), catastrophic rock avalanche-debris flows were generated in the last decade during atmospheric river events. Numerical models based on field and remote sensing data identified several combined conditioning and triggering controls on the slope failures, including deglaciation-induced stress changes and rock damage, structural and kinematic controls, rock weathering and alteration, and the effects of single or combined rainfall events. The results highlight the challenges of including multiple factors for the assessment of hazards in these complex mountain settings.

Acceleration of landscape change in the Southern Alps of New Zealand during the past decade

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The elevation and position of landscape features, and changes over time, can be defined by photogrammetry and repeated high-resolution digital elevation models. A new change detection system (MAP23D – see posters) uses a semi-automated pipeline to build high-resolution digital surface models (DSM) from satellite or aerial imagery, and/or LiDAR elevation models (DEM). Automated surface processing enables precision and accuracy sufficient to define sub-meter scale changes in models of difference (DoD). Displacement of features over time is quantified through a feature-tracking algorithm using multiple hillshade models. Operational rapid response to natural events is possible whenever cloud-free stereo-imagery can be obtained. Topographic changes in Aoraki-Mt Cook region of New Zealand have been quantified with MAP23D products spanning epochs between 2008 and 2022. Dramatic snowfield retreat and glacier down wasting is revealed by these data, along with smaller scale rockfall and landslides. A GIS map of landforms and inventory of 920 landslides has been constructed, including previously unnoticed collapses >105m3, and numerous deep-seated slope failures (reaching 2.1Gm3 in Murchison valley). There are 119 slow-moving slope failures and 536 rapid rock avalanches, toppling or debris flow events. Attributes pertaining to source volume, slope susceptibility, runout and deposit thickness provide information on the magnitude, frequency, and spatial reach of landslide-related hazards. The region's productivity of hazardous collapses shows a near fourfold increase from 57 during 2009-2012 (n=57) to 2013-2017 (n=295) and 2018-2023 (n=208). Although potentially enhanced by dynamic stress and increased moment from large South Island earthquakes, many small-moderate (102-104m3) collapses appear directly linked to areas of slope creep or de-buttressing induced by glacial recession. Intense precipitation events, snowfield melting, and glacier down wasting are now prevalent due to our changing climate. Modelling is beginning to elucidate the role of multiple factors in the susceptibility of slopes and style of failure and collapse. Regardless of direct cause or effect, the central Southern Alps is clearly destabilized, and rates of landscape change accelerated, locally elevating the level of hazard.

Forecasting Challenges in Snowmelt-Driven Rock Slope Instability: Insights from Indre Nordnes, Northern Norway

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Monitoring of unstable rock slopes is a key tool for enabling early warning and evacuation ahead of potential rockslide failures. While idealized models often show a steady acceleration phase prior to failure, many slopes exhibit more complex deformation patterns, even though the overall trend is acceleration. This complexity poses significant challenges for reliable forecasting without too many false alarms. One such example is the high-risk rock slope at Indre Nordnes in Northern Norway, which has been continuously monitored by the Norwegian Water Resources and Energy Directorate (NVE) since 2010. The site displays a clear seasonal movement pattern, strongly correlated with snowmelt intensity. The velocity increases in June, particularly in years with high snow accumulation followed by rapid snowmelt due to high temperatures. These periods of increased velocity coincide with the appearance of temporary water springs at the landslide toe. Movement typically ceases by mid-summer. Since 2020, displacement rates have increased substantially. In addition to the seasonal trend, the slope has evolved to become more sensitive to snowmelt, with higher velocities triggered by less intense melt events. This complicates early warning efforts, especially at the onset of seasonal movement, when it remains uncertain whether the slope will stabilize or continue accelerating. This uncertainty increases the risk of false alarms and is comparable to the Veslemannen rockslide in western-Norway. A deeper understanding of the evolving behavior and threshold conditions of such slopes is essential for improving forecasting models and enhancing risk management strategies in rockslide-prone areas.

Session 2:

Large rock slope instability characterization case study and hazard assessment

Detection and evaluation of possible catastrophic landslides

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Keywords: Prediction, catastrophic landslides, earthquake, rain

Catastrophic landslides, which are deep-seated, extremely rapid and highly mobile, must be predicted and evaluated for their occurrence possibility. This paper is a summary of our experience of catastrophic landslides for their prediction and hazard evaluation. Hazard evaluation would be made for potential landslides, so the prediction of landslide sites or areas need to be made first. Predictive methodology is dependent on the triggers of landslides, such as rainstorms and earthquakes. Some landslides have no specific triggers, but they are very rare. Our recent experience tells that rainfall-induced catastrophic landslides could be predicted pin-point by using high-resolution DEMs obtained by LiDAR, which became popular in the landslide community since 2000s. Most of the rain-induced catastrophic landslides are preceded by some type of deep-seated gravitational slope deformation (DGSD), which is represented by minor displacements with eyebrow scarps and/or smooth slope surfaces with few gullies. Undercutting of the deformed slopes is an additional factor to be considered as a prediction criterion. Most important geological structure for rain-induced catastrophic landslide has been found a downslope dipping fault with brittle crush zone, which is weak and likely become a sliding zone. Brittle crush zone with gouge is impermeable and impedes water drain to cause pressure build up. When the faults dip into the mountain within the flexurally toppled rock mass, pore pressure builds up behind the fault increasing the weight of the slope to trigger a landslide. Earthquake-induced catastrophic landslides have several preparatory processes: preceding gravitational slope deformations are similar to the rain-induced landslides and the topographic features could be used as a criterion for the prediction. A cataclinal slope that is cut at its foot is unstable against shaking and likely to slide when fragile beds like porous tuff are intercalated. First-time landslides of this type are rather difficult to predict, but the geometrical relationships between the bedding and slopes could give a clue. On the other hand, pyroclastic fall deposits, soft mudstone, and carbonate rocks are weathered and become susceptible to earthquake shaking without any topographic features, so their presence should be taken into account and landslide prediction would be made according to the areal distributions of the materials. Pumice layers with mantle bedding on slopes are very susceptible to earthquake shaking, particularly when a clay mineral halloysite is made in the depths by weathering. Mudstone in the dissolved zone, which is made by weathering, is porous and weak and susceptible to earthquake shaking. Carbonate rocks are dissolved by groundwater to have many voids and become susceptible to shaking.

Spatial and temporal dimensions of the slow to fast transition of large rock slope failures

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(Abstract to come)

Is PS Interferometry the right tool for early detection of slope acceleration? Insights from the Swiss Alps and the Himalaya

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Anticipating the onset of slope acceleration is one of the most pressing challenges in landslide hazard assessment. Since early 2000' satellite-borne Persistent Scatterer Interferometry (PSI) has enabled more and more accurate observations, however, although significant advances have been made in data quality, resolution, and processing techniques, the use of SAR remained relatively limited until the launch of the European Space Agency's Copernicus Sentinel-1 mission. This program marked a turning point by providing systematic, global, and openly accessible radar data. Since then, additional missions from both public space agencies and commercial operators have further expanded the potential of SAR, supporting not only retrospective analyses and regional surveys but also operational monitoring and early-warning applications. In this presentation, I will explore whether PSI is the right tool for the early detection of slope acceleration towards potential failure. Drawing from recent experiences in the Swiss Alps such as Moosfluh, Brienz/Brinzauls and Kleines Nesthorn, and case studies in the Himalaya, I will discuss both the capabilities and the limitations of PS interferometry in this context.

Landslide Hazards in the Himalaya of Bhutan

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Keywords: Landslide Hazards, Road Cut Failures, Bhutan Himalaya

Bhutan is a developing country similar in size to Switzerland but with only 10% of its population. As in other neighbouring Himalayan countries, landslides cause heavy economic losses and casualties every year, but the hazards posed by landslides have never been systematically analysed at a national level. Only a few foreign geologists have worked in Bhutan since Heim and Gansser, due to strict controls and high administrative hurdles. We have been fortunate to be able to work in Bhutan for over 10 years in partnership with the Royal University and the Ministry of Energy and Natural Resources. Our research has focused on regional landslide patterns and predisposing factors, long-term landslide activity, and its relation to landscape evolution. We have also studied landslide hazards along important traffic corridors. An additional component of our collaboration with the Bhutanese government is knowledge transfer and capacity building, with the aim of making life safer in one of the world's most active orogens.

As a landlocked country, the first national access roads ('highways') to India were built around 1960. These roads cross the frontal range of the Himalayas along steeply incised north-south-oriented trunk river channels with very high discharge rates and topographic gradients. In the 1980s, a west-east-oriented national road was built connecting Bhutan's main cities, which are located in a flatter section of the trunk rivers (the Inner Valleys), and crossing several 4,000-metre-high passes. The few single-lane national 'highways' built between 1960 and 1980 have been partially widened into two-lane roads over the last 15 years and are complemented by a large number of unpaved farm roads.

Landslide hazards and risks along these national traffic corridors are very high and are mainly manmade. During the monsoon season, around 1,000 roadblocks occur every year along these few national highways. We will systematically discuss the causes and hazards of these roadblocks and compare them with natural landslide hazards along the same roads. We demonstrate how man-made road-cut failures and hazards strongly depend on the age and type of highway construction, and how geology, rainfall and weathering control the spatial distribution of natural landslides and their hazards.

Large-Scale Landslides on Surprisingly Gentle Slopes: Lessons from Recent Earthquakes in Japan

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Keywords: Large-scale landslide, long travel, earthquake, gentle slope, localized liquefaction, ground water level

Recent large earthquakes in Japan have revealed that catastrophic landslides can occur even on surprisingly gentle slopes, challenging the traditional view that steep gradients are necessary for large-scale failure. This presentation examines two representative cases: the Aratozawa landslide triggered by the 2008 Iwate–Miyagi Nairiku Earthquake (Mw 7.2) and the Horonai landslide induced by the 2018 Hokkaido Eastern Iburi Earthquake (Mw 6.7).

The Aratozawa landslide displaced about 67 million m³ of material from a prehistoric landslide deposit along an ultra-gentle sliding surface of only 0–2°. The enormous mass enabled a long runout, generating a 6 m wave in an adjacent reservoir. Field investigations, MASW and microtremor surveys, and laboratory shear tests revealed a saturated, highly liquefiable sandy layer at the base. Newmark analysis using seismic records and ring shear test results showed that strong shaking and high groundwater levels were both essential for triggering failure on such an ultra-gentle slope.

The Horonai landslide was a deep-seated, dip-type rockslide that occurred along a gently dipping (~6°) bed plane. It displaced about 15 million m³ of materials with the main sliding body being about 80 m thick. Field drill revealed that the sliding surface was developed within the coarser tuffaceous sandstone layer with the exitance of sand boil laying above the sliding surface. Laboratory tests confirmed that liquefaction could occur within the saturated sandy strata, and dynamic ring-shear experiments successfully reproduced accelerating movement under strong seismic loading, demonstrating how transient pore-pressure rise can promote rapid failure and long runout.

Comparison of these cases shows that large-scale landslides on gentle slopes require the coincidence of weak saturated layers, strong ground motion, and mass-related mobility effects. These findings emphasize the need to incorporate subsurface hydro-mechanical properties and site-specific seismic response into hazard assessments, since even gentle terrain may host devastating coseismic landslides when conditions align.

Towards a national overview for rock avalanche potential

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Several rock avalanches with significant consequences have occurred in Norway over the past centuries, leading to high societal awareness of this natural hazard. Consequently, a national program for mapping unstable rock slopes was initiated in 2006. Since then, several high-risk sites have been investigated in detail and are now continuously monitored. To date, five out of eleven Norwegian counties have been systematically analyzed for unstable rock slopes. Identified slopes are assessed using a hazard and risk classification system established in 2012 (Hermanns et al., 2012). This process is time-consuming, and ongoing mapping activities may not always target the slopes requiring the most urgent follow-up. National susceptibility maps exist for all other landslide processes in Norway and are essential tools for land-use planning and decision-making in construction projects. However, producing similar susceptibility maps for large rock slope failures is currently impossible, as such failures may occur on slopes that do not yet show clear signs of gravitational deformation. The lack of a national overview of unstable rock slopes—and the extended lag time between initial detection and final classification—has created challenges for major infrastructure and development projects. To address this, the Geological Survey of Norway has finalized a national mapping project aimed at establishing a complete overview of potentially unstable rock slopes and their associated indicative hazard and consequence potential. This approach enables a more effective prioritization of high-risk sites than the existing county-bycounty framework. The project is structured in three main steps: Systematic analysis of remote sensing data (e.g., detailed DEMs, orthophotos, and InSAR data) to identify potential unstable rock slopes. Simplified ranking based on indicators of slope activity and stage of development. Assessment of potential consequences, including automated volume estimation, semi-automated run-out modeling, and empirical assessments of displacement wave run-up heights (Oppikofer et al., 2018; Tonnel et al., 2023). To optimize Step 1, known unstable slopes have been assessed against various criteria to define and target areas likely to contain additional unstable slopes. The results indicate that the study area can be limited—based on relief, population presence, and proximity to fjords and lakes—to roughly one third of Norway's total land area. Step 3 is designed to efficiently process a large number of slopes (>1000). By combining the results from the relative instability ranking and the consequence assessment, a national priority list of unstable rock slopes is produced. This list will guide future mapping, monitoring, and mitigation efforts and serve as a reference for prioritizing work related to other natural hazards in Norway. Moreover, the improved understanding of potential impact zones and consequences (both primary and secondary) will support more sustainable land-use planning and help prevent the development of new critical infrastructure in high-risk areas.

A new national inventory of past rock avalanches in Norway

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More than a thousand large unstable rock slopes are known across Norway, some of which threaten society through potential failure as rock avalanches – extremely rapid (granular) flows of fragmented rock. Since historical cases are rare and thus offer limited guidance for prediction, the geological record becomes crucial for constraining the spatial distribution, controls, and runout extent of Norwegian rock avalanches. We report the outcomes of a national, systematic mapping effort to detect and classify rock avalanche deposits and their former source areas. Deposits were mapped where diagnostic flow-type morphologies were evident, including blocky carapaces, transverse pressure ridges, longitudinal furrows, run-up/overspill features, and valley-spanning tongues. Our inventory comprises ~300 onshore rock avalanche deposits distributed throughout the country, but with higher densities in over-steepened fjord and inland valley systems of the southwest (Møre og Romsdal, Vestland) and the north (Nordland, Troms). Numerous additional deposits terminate partly or wholly within fjords and will be a focus of future work integrating onshore mapping with marine bathymetric and/or seismic datasets. Onshore deposits are classified according to runout-path morphology (open-slope/unobstructed, channelized, valley-spanning), mobility (H/L; reach angle), source-area lithology, and the substrate encountered along the runout path. The volumes of ~200 deposits were calculated using detailed DEM-based approaches (e.g., Sloping Local Base Level, polynomial surface fitting, and reconstruction of pre-event contours for DEM-differencing), tailored to the corresponding runout-path morphology. Where detailed reconstructions were not possible (~100 deposits), we used simple empirical estimates to derive a magnitude class. Reconstructed deposit volumes span a range of ~10^5–10^8 m^3, with a median volume ~106 m^3. Between 45 and 55% of deposits have volumes <106 m^3, which is often considered a lower volumetric threshold for rock avalanche behaviour. This finding illustrates that past rock avalanche mobility in Norway was influenced not solely by volume, but that confinement, substrate conditions, and other factors, likely also played an important role. Finally, we evaluate runout-length variability across the main path morphologies and compare volume–mobility relations (H/L) with cases worldwide.

Uncertainties in displacement data and failure surface properties for large rock slope hazard characterization

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Keywords: rock slope hazard, remote sensing, InSAR, lidar, failure surface, large-scale roughness.

Understanding the hazard from large rock slope failures in mountainous regions is important because, although uncommon, they have the potential to result in extremely rapidly moving and spatially extensive landslides. Various classification systems for initial hazard characterization have been developed to identify and prioritize potentially unstable rock slopes (e.g., Jaboyedoff et al. 2012; Hermanns et al. 2012; Oppikofer et al. 2018; Porter et al. 2023). In most cases, subsurface and/or long-term monitoring information are not available, thus the inputs for initial rock slope hazard assessments contain many sources of uncertainty. The main sources of uncertainties in rock slope hazard classification include 1) surface displacement estimates, 2) failure surface orientation and geomechanical properties, 3) failure surface depth.

Present-day rock slope displacement rates are the most important factor in most rock slope hazard classification methods. Although direct rock slope instrumentation provides the most reliable displacement information, it can commonly be costly to acquire and has a long lead time for the design, installation, commissioning, and calibration before reliable data are available. Satellite-based Interferometric Synthetic Aperture Radar (InSAR) can provide preliminary displacement information for use in initial rock slope hazard classifications. InSAR data at the national and continental scale have been available in Europe since 2020 (Crosetto et al. 2020). Free and publicly available InSAR displacement data from Natural Resource Canada (2025) and NASA (2025) recently became available for most of Canada. This new information provides improved understanding of slope processes and is being used by infrastructure operators, local governments, consultants, and researchers to update landslide inventories and hazard characterizations. Nonetheless, the InSAR technique has limitations (e.g., Wu and Madson, 2024) and hazard characterization needs to consider the impact of radar wavelength, stack depth, processing algorithm, topography, vegetation, snow cover, satellite line-of-sight relative to slope movement, and rate of surface displacement.

The failure surface orientation and geomechanical characteristics are essential for rock slope hazard classifications (Hermanns et al. 2012; Oppikofer et al. 2018), rock slope stability (Bar and Barton, 2025), and rock slope post-failure velocity estimates (Glastonbury and Fell, 2008). Estimating an equivalent effective friction angle along a failure surface is often challenging because in an actively deforming slope, the geometry and geomechanical attributes of the failure surface are unknown. The geomechanical properties along the failure surface may also vary on seasonal, multi-year, or decadal scales due to groundwater fluctuation. A range of remote-sensing techniques have been developed to capture the three-dimensional geometry of discontinuities from scales of 0.001 to 10s metres (Fatolahzadeh and Sepúlveda, 2025) and from 10s to 100s metres (Wolter et al. 2014; Stead et al. 2019). Reviews of high-resolution terrestrial lidar data of past rock slope failures have shown that they can have significant topography, including structurally controlled steps. Advancements in both existing (Grasselli, 2006) and novel techniques are being developed to capture the multi-scale three-dimensional roughness along discontinuities. This will contribute to our understanding of how roughness varies across scales, and which scale of roughness is important for large rock slope failures.

The depth and shape characteristics of a failure surface also represent important sources of uncertainty in the initial assessment of rock slope hazard because the volume (along with the velocity) is a measure of the intensity (destructive potential) of a landslide. Analytical methods based on landslide geometry and the surrounding topography (Jaboyedoff et al. 2020; Prajapati and Jaboyedoff, 2022; Singh and Sepúlveda, 2025) or surface velocity data (Booth et al. 2013; Borgatti et al. 2025) have been proposed. To reduce the uncertainty, the calculated failure surface depth obtained from these methods should be compared to the conceptual model of the structures controlling the rock slope movement.

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Pico Poster

7 minutes

An inventory of historical and geological rock avalanches in the canton of Vaud, Switzerland

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Keywords: Rock avalanche, Inventory, Vaud canton.

The eastern part of the canton of Vaud, in Switzerland, corresponds to the transition between the Prealps and the Alps with elevation ranging from 400 to 3000 m asl. Due to the contrast with the neighbouring Valais canton, which boasts a full alpine panorama, rock avalanches have been poorly documented in the area. In the cantonal inventory of Vaud, only six rockslide events of less than 500 m^3 have been registered between 1973 and 2024. Here we aim to compile an inventory of large events (> 100'000 m^3), both in historical (A.D.) and geological (Quaternary) timescales, which has not been previously done. Rock avalanches are characterized by their rapid disintegration, flow-like movement and a high degree of mobility (Hungr et al., 2014), and are easily identifiable by their deposits, due to the presence of large boulders and a hilly topography located far from the source area, and which has often-times been undercut by streams over time. Several large rock avalanches ("éboulements" in French) have been identified in the canton of Vaud, both near the Rhône valley and in high mountain areas. Events in the Rhône valley tend to be historically documented or studied, such as the Ovaille 1584 (Revue historique vaudoise, 1929) rockslide or the Chiètres deposit (Parriaux et al., 2017). While the ones in high mountain areas have not yet been studied or have been previously misinterpreted as glacial sediments. In contrast, large events in Valais such as Dérborence (1714, 1749 – Spiro et al., 1956) and Blatten (2025) are easily identifiable and have been well documented, even in remote valleys. A total of 9 rock avalanche deposits have been identified here, using both topographical data and historical documents, for which volumes and reach angles have been estimated when unknown. We show here that although these types of events are uncommon, they have occurred in the past and will keep occurring in the future, where volumes and triggering mechanisms should remain relatively unchanged, while a slight increase in frequency can be expected due to climate change.

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Towards anticipating permafrost rock slides – From laboratory tests to slope-scale mechanical models

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Slope failures in high-altitude permafrost rock have received growing attention as their cascading impacts can threaten infrastructure and communities several kilometers away. Yet, the processes that prepare and trigger rock slides remain complex and often failures occur without prior notice. Laboratory tests show that frozen rock exhibits stronger mechanical properties - such as higher shear and tensile strength - compared to unfrozen rock. Here, we investigate whether these laboratory findings can be upscaled to the slope scale using distinct element modeling. In parallel, we integrate observed cryospheric changes - such as surface ice loss, increased water availability, and enhanced rockfall activity - into the stability analyses, which were conducted for recent cases in the Alps – such as Bliggspitze, Fluchthorn, Vernagtferner, AT. We found that combined mechanism prepare and trigger larger volumes in the shorter period, while water availabilty plays a central role in destabilizing the rock slope. By emphasizing a rock mechanical perspective, we aim to unravel the mechanisms driving permafrost rock slides and to identify critical scenarios guiding future monitoring efforts.

Structural Analysis and 3D Modeling of the Unstable Rock Slope Area Berrføtlene, Sogndal Municipality, Norway

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Berrføtlene is an unstable rock slope located on the eastern side of Fjærlandsfjorden in Sogndal, Vestland County, Norway. The slope was mapped by the Geological Survey of Norway (NGU), which recorded little to no movement and preliminarily classified it as low risk. More recent InSAR data have detected movements of about 3 cm per year, in a lower part of the slope not previously mapped. As a result, the slope has been instrumented with satellite reflectors and is under periodic monitoring by the Norwegian Water Resources and Energy Directorate (NVE, 2022). These findings indicate that the risk may be higher than previously assumed, making an updated assessment necessary.

Our work aims to identify which geological structures define the unstable part of the slope. It investigates what these structures, combined with movement data, reveal about the direction of movement, potential scenarios, and the possible volume of a future landslide. The results should lead to a geological model of Berrføtlene, which can support NGU in a revised and updated risk classification of the unstable rock slope.

The methods include detailed field mapping, structural analysis, ground- and satellite radar, drone surveys, and 3D modelling in order to identify boundaries, potential glide planes, and possible landslide volumes. Preliminary results show that the bedrock consists of granitic orthogneiss, mylonite, and dioritic orthogneiss, with no sharp lithological boundaries. The surrounding area displays a consistently oriented metamorphic foliation that can be mapped within the sliding blocks. The foliation is most likely not a controlling structure, although it is a useful indicator of rotation in certain actively sliding blocks. Our preliminary structural analysis indicates two main fracture sets are present and that the potential glide plane is complex. The failure mechanism could be planar, wedge-shaped, toppling, stepped, or a combination of these.

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Unveiling the role of seepage forces in the acceleration of landslide creep

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Integrating Remote Sensing and Geomorphological Approaches for Identifying, Mapping and reconstructing Ancient Landslide in and around Joshimath town, Chamoli, Uttarakhand Himalayas, India

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Keywords: Deep-seated gravitational slope deformations (DSDGD's), Rock avalanche (RA), run-up, landslide dam,

Deep-seated gravitational slope deformations (DSDGDs) are slow, large-scale mass movements that shape mountain belts globally, particularly in tectonically active, uplifting, incised, and formerly glaciated terrains (Panek & Klimes 2016). Evolving over centuries to millennia, DSDGDs produce characteristic morpho-structures like multiple-crested ridges, ridge depressions, sagging, and toe bulging that progressively destabilize slopes. This progressive deformation may localize along deep slip surfaces into deep-seated landslides (DSLs; >50 m failure surface depth), which are typically slow but can accelerate (Chigira et al. 2011). Although rare, DSDGDs may also transition to catastrophic rock avalanches (RAs), causing rapid slope failure, river damming, infrastructure loss, and hazard to corridors. While timing the transition from slow deformation to catastrophic RAs remains elusive, the identification of susceptible slopes is essential for mitigation (Strom & Singh 2022).

The town of Joshimath and its neighbourhood in the NW Himalaya exemplifies DSDGD's hazard as it lies atop extensive paleo-landslide fabric on the footwall of an active Himalayan thrust fault. Rapid unplanned urbanisation, deforestation, population growth and intense rainfall events further exacerbate this hazard. Highly hazard prone it has recorded historic events including 2021 RA and cascading debris-flows, 2013 GLOF, 1970 flash flood and river damming, 1830 earthquake and ongoing surface movements and infrastructure damages. Additionally, the slopes display paleo-slips, scarps, cracks and river-damming features typical of DSDGD's (Heim & Gansser 1939; Pant et al. 1975; Strom & Singh 2022). Yet almost no systematic monitoring and comprehensive studies on DSDGDs, DSLs and RAs in Joshimath exist. High-resolution DEM-derived hillshade mapping was hence utilised to identify and map major diagnostic DSDGD features namely: i) Major large-scale landslides-RA deposits and DSLs, ii) their run-ups on opposing slopes, iii) deformation cracks and iv) other landslide scars-scarps. The output map was validated with available literature-based evidence, Google Earth images and field observations. Next river-thalweg (x-z) analysis was conducted to identify potential landslide dam locations-major landslide events by detecting knick points in river thalweg profile by fitting equilibrium river profile using a power-law stream model implemented using MATLAB. The landslide dam locations were correlated with literature, Google Earth, and field-based landslide dam records and supporting evidence. Finally, a schematic 2D reconstruction of source-zone topography and failure surfaces was developed based on bedrock dip, slope geometry. This reconstruction was then compared with Sloping Local Base Level (SLBL)-simulated failure surfaces and pre-failure topographies (Jaboyedoff et al., 2004, 2020) for validation, addressing critical gaps in hazard assessment for the Joshimath region.

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Machine Learning Analysis of Controlling Parameters in Rock Avalanche Propagation

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Keywords: Rock avalanche propagation; Travel distance; Parameters analysis; Machine learning; XGBoost model

Rock avalanches are highly destructive events that occur in mountainous regions, leading to damage and casualties. The Study of rock avalanche mechanisms is crucial for understanding their propagation and control parameters, providing more effective risk mitigation strategies. However, the prediction of rock avalanche propagation is still challenging that requires more detailed analysis. In our study, we used an inventory of rock avalanches from Central Asia, covering 6 countries. Considering several input parameters, the machine learning-based approach of extreme gradient boosting (XGBoost) with grid search optimization was proposed. These parameters included headscarp height, mean slope angle of headscrap, headscarp length and width of its base, source volume, confinement type, and maximal height drop. The XGBoost-based model can multi-output the distance of propagation L and the total impacted area, which outperformed by comparison with other machine learning models. To verify the applicability of the proposed XGBoost-based method for predictions with limited databases, eleven rock avalanche events in Uzbekistan were analyzed. The importance analysis of main parameters was conducted based on the SHapley Additive exPlanations model. The results showed the importance of each parameter and it revealed that failed volume had the most impact on propagation among the input variables. Controlling parameters sensitivity analysis results showed that increase of maximal height drop and source volume tend to increase the travel distance and total impacted area at most. Confinement also affect these parameters at a large extent. Future work will explore the impact of terrain features along the path on the performance of the model, e.g. topography, lithology, and substrate etc.

Innovative Segmented Multi-Temporal InSAR for Enhanced Monitoring of Deep-Seated Gravitational Slope Deformation: What We Learnt from the 2016 Hongye Landslide in Taiwan

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Deep-seated gravitational slope deformation (DSGSD) poses significant challenges for monitoring in complex mountainous terrain, particularly when catastrophic failures lead to severe radar decorrelation, sparse valid scatterers, and unreliable deformation measurements. Taiwan's unique geodynamic setting, characterized by active tectonic uplift, steep topography, and frequent high-intensity, short-duration rainfall events (such as typhoons), often triggers rapid and large-scale slope failures. This contrasts sharply with many European regions where landslide mechanisms are typically driven by snowmelt or prolonged rainfall, resulting in slower deformation rates. The 2016 Hongye landslide in southeastern Taiwan, located in a region of highly fractured metamorphic rocks and high precipitation, exemplifies the challenges of monitoring such dynamic slope processes. This study addresses these limitations by proposing an innovative segmented Multi-Temporal InSAR (MT-InSAR) processing strategy. This approach partitions long-term radar sequences into "pre-failure" and "post-failure" intervals, based on the landslide event timing, to maintain stable phase connections and enhance coherence. The 2016 Hongye landslide serves as a compelling case study, analyzed using ALOS-2 PALSAR-2 imagery acquired from 2015 to 2020. Additionally, multi-temporal airborne Light Detection and Ranging (LiDAR) data from 2012 and 2020 were integrated to delineate geomorphological features. Compared to conventional unsegmented methods, the segmented MT-InSAR approach significantly improved coherence and yielded a denser distribution of valid scatterers. Results revealed continuous downslope movement for up to eight months before the failure, followed by a gradual stabilization process post-event. Integration of LiDAR data enabled the delineation of geomorphological features, including secondary scarps, erosion gullies, and accumulation zones, estimating a total collapse volumes of approximately 3.6×10^5 m^3. This study demonstrates how pre-failure deformation signals can be effectively identified, providing critical insights into the temporal evolution of slope instability. This research demonstrates the critical importance of tailoring interferometric processing to local deformation characteristics, restoring coherence in decorrelated terrain, and enhancing the detection of residual instability zones. The proposed methodology strongly aligns with RSG2025's theme of "gravity-driven slope deformation monitoring" and provides a globally applicable framework for improving landslide early-warning systems and post-failure assessments in complex mountain environments. Beyond addressing Taiwan's specific geological and climatic challenges, its adaptability offers valuable insights for global landslide monitoring and hazard mitigation in regions with similar rapid and dynamic mass wasting processes.

Integrated InSAR and Multi-Temporal LiDAR for Slope Hazard Forecasting: Lessons from the 2024 Hualien Earthquake and Pathways to Resilience in the Taroko Area, Taiwan

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Keywords: Multi-temporal LiDAR, DEM of Difference, InSAR Surface deformation, Geohazard Assessment, Corridor-scale Hazard

Extreme events, such as earthquakes and typhoons, frequently trigger extensive landslides and rockfalls in Taiwan, posing significant risks to critical transportation infrastructure and public safety. The April 3, 2024, Hualien Earthquake (ML 7.2) caused widespread slope failures along the Taiwan Railways Administration (TRA) North-Link Line and within the Taroko area. Eastern Taiwan, where the study area is located, is characterized by steep slopes, active fault systems, and high seismicity. Frequent typhoon impacts, combined with tectonic uplift, result in rapid erosion and sediment transport rates that far exceed those observed in many European regions (e.g., the Swiss Alps), where slower processes like snowmelt or weathering primarily drive mass wasting. These unique geomorphic conditions highlight the need for region-specific monitoring frameworks tailored to Taiwan's highly dynamic slope processes. To develop rapid and quantitative decision support for disaster response, this study develops an integrated monitoring–analysis–forecasting framework that combines Interferometric Synthetic Aperture Radar (InSAR) and multi-temporal Light Detection and Ranging (LiDAR) to quantify slope activity and topographic volume changes during the pre-, co-, and post-event stages. We processed pre-seismic (2015–2022) ALOS-2 and co-seismic (March 28–April 8, 2024) Sentinel-1 InSAR datasets to calculate the Slope Unit Activity Index (SUAI) and Differential Interferometric Pixel Amplitude (DIPA). Multi-temporal LiDAR datasets—including 2015 and 2022 airborne LiDAR, 2024 April 30 UAV LiDAR (5 cm resolution), and post-remediation airborne LiDAR acquired in 2025—were used to construct high-resolution Digital Elevation Models (DEMs) and conduct DEM of Difference (DoD) analysis. This framework identified seven highly active slopes post-earthquake. At K51, the volumetric evolution displayed a clear three-stage sequence characterized by initial incision in the source area, rapid debris mobilization following the seismic event, and subsequent stabilization after engineering remediation. From 2022 to April 30, 2024 (post-seismic), an initial loss of approximately 1,350 m³ was observed, driven by source area incision and minor toe accumulation. From April 30 to August 2, 2024 (post-typhoon), the volume rapidly increased to 13,544 m³ as upper slope failures mobilized downslope along gullies, forming a large depositional wedge near the corridor and bridge. From August 2, 2024 to March 29, 2025 (post-remediation), an additional 15,526 m³ change occurred as debris was removed and the slope reshaped, resulting in a flattened engineered surface.The DoD analysis revealed clear spatiotemporal patterns of landslide material migration and redistribution, capturing a 'head scarp retreat–gully-channelized sediment transport–toe aggradation–engineered stabilization' sequence. This top-down process aligns closely with the spatial pattern of InSAR activity escalation, highlighting the value of integrating InSAR and LiDAR for rapid hazard assessment and engineering decision support. Future work will focus on integrating high-resolution topography and derived debris parameters into rockfall trajectory and impact energy simulations, providing quantitative assessments of movement paths, kinetic energy, and hazard zones. In addition, simulating post-engineering scenarios such as slope reshaping and protective measures (e.g., rockfall nets, retaining structures, sheds, and drainage improvements) will enable the estimation of reactivation probabilities and the evaluation of mitigation

effectiveness. This integrated monitoring–analysis–forecasting framework demonstrates how integrating InSAR and LiDAR can support not only rapid hazard assessment but also long-term recovery planning, offering a pathway to resilience for disaster-affected regions such as the Taroko area. It provides a globally applicable blueprint for transportation corridors exposed to similar high-dynamic hazards and offers valuable insights for adapting the framework to slower-moving hazards worldwide.

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Towards improved estimation of the energy line angle for runout prediction of rock mass movements

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Unified Flow Rule of Undeveloped and Fully Developed Dense Granular Flows down Rough Inclines

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Based on laboratory experiments, Pouliquen (1999) uncovered a universal scaling law for the average velocity v of homogeneous flows of spherical grains down rough inclines [1]: v/(gh)(1/2)~h/hs (θ), where g is the gravitational acceleration, h the flow thickness, and hs (θ) the thickness below which the flow stops depending on the inclination angle θ. Today, this so-called "flow rule" is well established in the field and has served as a critical test for continuum granular flow models [2]. However, based on more accurate measurements for granular materials composed of either spherical or non-spherical grains, Börzsönyi and Ecke (2007) found v/(gh)(1/2)~(tanθ/μr)2 h/hs (θ), with μr the dynamic friction coefficient, and pointed out that this revised flow rule was predicted by a two-dimensional granular kinetic theory [3, 4]. In addition, for non-spherical grains, they noticed deviations from this rule at large h/hs (θ). Both Pouliquen and Börzsönyi and Ecke assumed that the granular flows in their experiments were steady. Here, we report on chute measurements of the free-surface velocity v in dense flows of spheres and diverse sands and spheres-sand mixtures down rough inclines. These and previous measurements [1, 2] are inconsistent with standard flow rules, in which the Froude number v/(gh)(1/2) scales linearly with h/hs (θ) or (tanθ/μr)2h/hs (θ). This is because the characteristic length L a flow needs to fully develop can exceed the chute or travel length l and because neither rule is universal for fully-developed flows across granular materials. We use a dimensional analysis motivated by a recent unification of sediment transport to derive a flow rule that solves both problems in accordance with our and previous measurements: v=v∞[1-exp(-l/L)](1/2), with v∞∝μr(3/2)[(tanθ-μr)h](4/3) and L∝μr3[(tanθ-μr)h](5/3)h.

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From Brienz to Blatten: Depth-Averaged Particle Modeling of Alpine Mass Flows

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Large-scale rock, ice, and debris avalanches in alpine terrain present significant challenges for hazard modeling due to their complex flow behavior and the need for computationally efficient simulation tools. The depth-averaged material point method (DAMPM) offers a promising approach by combining the scalability of depth-averaged models with the flexibility of a particle-based solution strategy capable of handling large deformations and time-dependent material behavior.

This poster showcases recent developments and applications of DAMPM to simulate gravity-driven mass movements, with a particular focus on the 2025 Blatten VS rock–ice avalanche. We briefly outline the model framework, and validate its performance against numerical benchmark cases. The simulations of the Brienz GR landslide and the Blatten avalanche illustrate the model's ability to reproduce observed deposit extents and flow paths, capturing key dynamics of runout and terrain interaction. For each event, we present both final deposition states and flow behavior visually. The Blatten case is discussed in greater detail, highlighting the model's capacity to handle complex topography. These results demonstrate how DAMPM can support hazard assessment by bridging the gap between classical depth-averaged models and three-dimensional elastoplastic models, offering a scalable and adaptable tool for hazard assessment.

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Advancing the Predictive Capability of Landslide Simulations Using the High-Resolution Three-Dimensional Material Point Method

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Keywords: Material Point Method, High-performance computing, Failure surface modelling, Apparent basal friction coefficient, Apparent residual friction angle, Parametric analysis, Runout prediction

The high-speed, large-deformation following slope failure makes the prediction of landslide motion and deposition a key aspect of hazard mitigation. The Material Point Method (MPM) naturally handles large deformations, yet its practical application remains limited by uncertainties in failure surface reconstruction, material strength degradation, and the trade-off between model resolution and computational cost. Using the 2011 deep-seated Akatani landslide in Japan as a case study, this work reconstructs the actual failure surface with the Sloping Local Base Level (SLBL) method constrained by pre- and post-event DEM datasets, and develops three SLBL-based predictive scenarios derived solely from pre-event topography. A total of 56 high-resolution 3D MPM simulations were performed by varying the apparent basal friction coefficient (μ_b^{app}) and the material residual friction angle (φ_{res}). Specifically, μ_b^{app} was inferred from the empirical Fahrböschung angle ($\Delta H/L$) -volume relation, and φ_{res} was taken either from experiments (φ_{res}^{lab}) or inferred from the same relation as an apparent value (φ_{res}^{app}). Spatial variability in initial shear strength was represented using random fields. Model performance was evaluated using the Precision-Recall-F1 framework to quantify the agreement between simulated and observed deposit contours, supported by analyses of deposit thickness, kinematic profiles, shear band development, and velocity indicators. Results show that the maximum volume defined by the SLBL-constrained failure surface enables the MPM model to reproduce the observed deposition pattern with high fidelity. When φ_{res}^{app} based on the $\Delta H/L$ value at a 50% runout exceedance probability was used, the simulated runout front matched field observations more accurately than simulations using φ_{res}^{lab}. The simulated peak center-of-mass velocity ranges from 22 to 28 m/s, consistent with seismic-derived estimates. This study establishes a transferable three-dimensional high-resolution MPM modeling and computational workflow applicable under data-limited conditions, improving runout prediction capability and supporting quantitative landslide risk assessment.

Session 3:

Failure and modelling of large rock slope prone to trigger rock avalanches

Modelling Large Landslides

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Keywords: Modelling, Landslides, numerical Methods.

Modelling large landslides is a challenge.

The objective of the talk is not to propose a whole methodology on the subject but to draw attention to some points that are often neglected or unrecognized.

The following topics will be covered

Why get into modelling? Is it an absolute necessity today? What is the aim?

Conceptual Model before Modelling

Is 3D a necessity and, in case of 2D modelling, is plane strains always obvious?

Boundary conditions.

Initial state of stress or how to build the least bad scenario.

Continuous/discontinuous modelling

Fractures network

Mechanical properties of rock mass.

The role of anisotropy on failure

Geological Modeling and Hazard Assessment for the Spitze Stei Rock Slope Instability in Kandersteg, Switzerland

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The Spitze Stei rock slope above Kandersteg, Switzerland, is a complex periglacial system of rock and debris compartments that exhibit heterogeneous movement patterns and varying degrees of acceleration. Owing to its potential hazard to the nearby village of Kandersteg, the large instability, covering an area of 0.5 km² and comprising more than 16 million cubic meters of material, has been continuously monitored since its reactivation in 2018. The resulting dataset offers significant opportunities to improve the understanding of the slope's kinematics and to support the development of realistic hazard scenarios. A detailed 3D geological model was developed by reconstructing the basal slip surfaces of the different compartments using geomorphological observations and monitoring data including 3D feature-tracking. For each compartment, the kinematics and potential failure mechanisms and scenarios were evaluated qualitatively. As the geotechnical parameterization of such a complex, partly permafrost-affected slope presents significant challenges, we adopted a simplified stability analysis to assess potential interactions among compartments. To this end, the factor of safety was calculated for different scenarios using a limit-equilibrium approach for (1) the present-day topography and (2) different partial-failure configurations. The relative differences in safety factors between scenarios were then used to evaluate interactions among compartments. The resulting insights into compartment coupling support ongoing hazard assessment. This approach provides a framework for characterizing the spatial variability of instability, refining volume estimates, and informing risk management for the Spitze Stei rock slope.

Session 4:

Characterizing the high mobility rock, ice, debris avalanches

Rock avalanche mobility – what is its optimal characteristics?

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Keywords: Rock avalanche, Angle of reach, Runout, Affected area, Energy, Confinement.

Rock avalanches (RA) – one of the most hazardous types of slope processes in mountainous regions, are characterized by an abnormally high mobility. Physically it can be described in terms of velocity (v) that, according to very few direct measurements and to the numerous data on the RA debris runup (h) on the opposite slope of a valley ($v=(2gh)^{0.5}$) could reach 300-400 km/hour. Traditionally, since pioneering works of Albert Heim, RA mobility is characterized by angle of reach – ration of height drop and runout (H/L), where H is the elevation difference between headscarp crown and the deposits tip, and L – the horizontal projection of the distance between these two points along the RA travel pass. It was found that H/L value decreases drastically with increasing volume of failure (V).

However, as it was demonstrated by F. Legros (2002), statistically the correlation coefficient of the relationship between V and just L is higher than that of the relationship between V and H/L. Same conclusions were made based on the Central Asian RA database (Strom, Abdrakhmatov, 2018; Strom et al., 2019). Thus, runout prediction of the slope failure of the given volume should be more accurate than that of the H/L.

Besides, the geometric characteristics of the mobility can be not only the runout, but also the affected area. An important parameter required for risk assessment is the exposure of elements at risk, which depends, foremost, on the area, either total (A_{total} = source area +travel area + depositional area), or just on the area, covered by RA deposits (A_{dep}). And R^2 coefficients of the ($A_{total,\ dep}$ – V) relationships appear to be higher than those of the (L – V) relationships. It should be pointed out that producing such statistical correlations we must consider the confinement conditions of RA motion. Indeed, it is meaningless to compare geometric parameters (L, A) of the unconfined RA that move over the free, unbounded surface of wide neotectonic depression where debris can spread both forward and sidewise, with such parameters of the RA moving just down-valley and confined by valley slopes, or with frontally confined RA that either collides with steep opposite slope or climbs on it, overcoming the gravity force. ($A_{total,\ dep}$ – V) relationships derived for these three main types of confinement conditions have much higher R^2 coefficients than those for (L – V).

The highest R^2 coefficients have the relationships between the geometrical mobility parameters (L, A_{total}, A_{dep}) and the V×H product that is somehow proportional to the potential energy released during rock avalanche emplacement (Strom, Abdrakhmatov, 2018; Strom et al., 2019; Strom, 2024). It is evident that the mobility is governed by the kinetic energy, which main, if not the only source is the potential energy and it is really surprising that such relationships have been quite rarely analyzed before.

One more problem that deserves to be discussed, is the selection of parameters that should be used to derive relationships suitable for prediction of the runout or the affected area of the events that are just anticipated. Such assumption means that we can roughly assess possible failure volume V. But values of the vertical and horizontal distanced between headscarp crown and the deposits tip (H, L) are unknown until the event occurs. Thus, for the predictive purpose it is logical to use the height of the unstable slope (H_s) instead of H and to compare L, A_{total}, and A_{dep} with the V×H_s product (Strom, 2024). The variability range of the parameters used to derive the empirical relationships should be considered as well.

Rapid deep-seated slope failures in different paleoclimate: coseismic or rainfall induced? Insights from the Outer Western Carpathians

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Rapid deep-seated rockslides that transformed into rock avalanches and mudflows are one of the most dangerous features of mountainous regions. In the flysch belt of the Outer Western Carpathians along the border between the Czech Republic and Slovakia, high-resolution LiDAR digital terrain models revealed more than 2.5 thousand of clustered half-ellipsoidal scars of prehistoric depleted source zones belonging to such highly mobile deep-seated rockslides. These depleted source zones occur mostly in mudstone-dominated rock at generally gentle slopes ranging from 8 to 20° and they are up to forty meters deep and up to 500 m long. The released landslide masses travelled for a distance of up to 1-2 km, while being transformed to debris flows, mudflows and rock avalanches.

We conducted conventional radiometric techniques such as radiocarbon dating (^{14}C) and optically stimulated luminescence (OSL) applied to datable sediments, and rock surface cosmogenic radionuclide exposure (CRE) Beryllium-10 dating at depleted source zones scars of those rockslides across the region. They grouped at discrete time periods of ~1.6-1.7 ka b2k, ~2.5-2.8 ka b2k, ~7.4 ka b2k, ~8.5 ka b2k, ~13.6-

13.7 ka b2k, ~23 ka b2k, ~45 ka b2k and even ~90 ka b2k, corresponding mostly to the humid and warm climate of the Holocene, but also cold and dry periods of the Weichselian glacial period. Therefore, the climatic control seems not to be the only plausible factor of their origin.

In order to better infer their triggering mechanism, we implemented an integrated approach combining morphometric analysis, velocity-dependent friction laws (VDFL) from rotary shear experiments with Newmark Displacement Analysis (NDA), and numerical modeling to constrain possible earthquake parameters from a model case-study landslide characteristics. Firstly, we conducted a detailed structural analysis to characterize the failure surface and intersecting joints within an overturned anticline. Laboratory experiments of the host rock revealed that friction dropped dramatically during rapid slip, enabling catastrophic landslide acceleration under seismic loading of undrained saturated material. The undrained fully saturated conditions, however, could not lead to the failure alone. NDA incorporating VDFL identified a critical nearby earthquake magnitude threshold between Mw 7.1-7.3 necessary to trigger such a huge and hypermobile landslide. Additionally, discrete element modeling (PFC3D) successfully reproduced the long-runout distance and formation of a landslide dam in the flat valley floor known from the geological evidence.

For a coseismic triggering speaks also the local geological evidence of other sedimentary structures in the vicinity including injected sand and flame structures within fluviolacustrine sediments, or large angular boulders in riverbed fluvial sediments documented in a trench.

Besides, we also inferred the coseismic origin for a number of individual cases across the orogen. Based on their morphometric characteristics, their Index of Potential Dynamic Trigger - I_{PT} ranged between

0.32 and 0.75 providing another evidence for possible coseismic origin of those highly mobile slope failures. The convergence of complete source evacuation, extreme mobility, and structural controls demonstrate seismic rather than climatic triggering as well. These findings challenge existing views of seismic hazard in Central Europe and demonstrate that regions previously considered stable based on short historical catalogs may still face significant earthquake potential with millennial-scale recurrence intervals.

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The hypermobility of rock avalanche, insights from experimental study

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(Abstract to come)

Friction behaviour of giant rockslides considering temperature effects

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Giant rockslides occurring in high-elevation mountainous regions can evolve into highly mobile and channelised rock avalanches, posing severe risk to local communities. The basal friction behaviour plays a critical role in governing their mobility throughout the runout process. In this study, we conducted two types of laboratory mechanical tests, the high-speed rock friction test and the undrained ring-shear test, to investigate the possible frictional mechanisms that exist from the rockslide initiation to the runout of the resulting avalanche. Results from the high-speed rock friction tests show that the generation of rock powder is a key factor responsible for frictional weakening, while its subsequent expulsion and recrystallisation can lock the rock interface again. These findings explain the frictional processes occurring at rock interfaces during the early stage of failure. For the shearing behaviour of granular materials during avalanche runout, ring-shear tests under different drainage conditions demonstrate that both normal stress and shear displacement are positively correlated with the generated temperature, whereas shear rate shows little effect. Under undrained condition, the temperature increase is approximately 35% of that observed in the drained case, accompanied by a complete loss of strength. Moreover, friction weakening effect was further studied in ring-shear tests with impact loading, which show that a liquefied basal layer can form near instantaneously when the substrate is loose and weakly consolidated. To sum up, these results highlight the complicated effects of thermal, mechanical, and hydraulic processes, which jointly contribute to the evolution and mobility of catastrophic landslide hazards, underscoring the need for further investigation.

Volume amplification in debris avalanches induced by rainfall

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Keywords: propagation, entrainment, spreading, forecasting, consolidation, mobility

Debris avalanches propagate along open slope with large bed entrainment during the propagation stage. This is combined often with significant lateral spreading. As a result, impressive landslide scenarios are observed in the field, with volume amplification factors of some tens, from a small source zone to an overall large/dramatic propagation/deposition zone. This poses a challenge towards the correct classification of such phenomena (in terms of volume), and for their correct forecasting. A small triggering zone could the ideal target for active mitigation works, while passive mitigation works could be profitably applied inside the propagation zones. Indeed, both intervention strategies presuppose the very precise forecasting of the source, amplification and propagation zones. However, during propagation of debris avalanches strong consolidation of the moving material occurs – favoured by the combined effects of bed entrainment on the front and spreading on the lateral sides –. Thus, lateral spreading is controlled by flow velocity and mobility of debris avalanches in the piedmont zones is usually much shorter than flows of analogous/similar materials moving along channels. It means that forecasting could be: unconservative for the design of prevention/protection works (in the source/propagation zones) and too safe in terms of propagation (in the piedmont zones). Nowadays, various models are available to consider the combined effect of all the processes mentioned before. But still site-specific calibration and validation of the models are required, as a fundamental step.

From lab bench to smart slopes: an interdisciplinary journey studying Rock Avalanches and their impacts

Irene Manzella

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(Abstract to come)

Session 5:

Modelling large rock, ice, debris avalanches

New insights into the failure and runout of rock slopes derived from field observations and numerical modelling

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Flow-like landslides in rock are among the most damaging landslide types, as they can impact people and property over large spatial areas. Since these events can emplace in a matter of minutes, managing their risk requires forecasts of catastrophic failure probability and runout extent, which can inform land-use planning and emergency scenarios. Numerical models are one tool that can be used to make these forecasts, however, the selection of appropriate input parameters has made their application challenging in practice. In this talk, we first provide an overview of the diversity of behavior that can occur during the failure and runout of rock slopes. Next, we combine high quality field data with GPU-accelerated numerical modelling to show how site-specific factors can explain some of the variability between events. We partially validate these findings using the results of LiDAR scanners installed in-situ, which collect field data of moving flow-like landslides at a frequency of 10 frames per second. We further show how GPU computing enables regional-scale calibration and prediction using mechanistic numerical models. We then present a probabilistic prediction framework, and show how forecasts of catastrophic rock slope failures can be parameterized. These forecasts have substantial variability due to unknown site-specific factors, such as soil saturation, which are accounted for by running hundreds to thousands of simulations per event. We conclude with a discussion of the most important remaining uncertainties, as well as promising directions for future work.

Towards a predictive 3D model for alpine mass movements: Insights from recent events in the Swiss Alps

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Keywords: modelling, MPM, Material Point Method, 3D, Blatten, Brienz, rock-ice avalanche, landslides.

We present a newly developed numerical model [1,2] designed to address the practical needs of engineers evaluating risks related to alpine mass movements. Based on the Material Point Method (MPM) and finite-strain elasto(visco)plasticity, our model can incorporate various material models representing snow, ice, rock, and water. This enables detailed simulations of a wide range of materials under different flow regimes. Rate-dependent cohesive Drucker–Prager and Modified Cam Clay models, which both recover the liquid $\mu(I)$ granular rheology under flow conditions, have been implemented and validated. Key features of the model include: 1) physical input data that can be derived from classical geotechnical or field experiments; 2) explicit simulation of bed entrainment; and 3) the ability to simulate interactions with complex terrain and mitigation structures at very high resolution, achieving scales as fine as decimeters and evaluating the resulting impacts. The model is designed with practical applications in mind, integrating seamlessly with GIS tools to automate the visualization and interpretation of results in three-dimensional terrain [3]. Validation against well-documented cases demonstrates our model's potential to replicate and predict real-world phenomena with high fidelity. Notably, its successful application to the 2023 Brienz rock avalanche and the 2025 Blatten rock–ice avalanche has shown good runout predictions, while in the Blatten case, discrepancies in deposit distribution and seismic signals highlighted limitations of the single-phase frictional model. These observations suggested potential liquefaction and the need for additional physical ingredients, which were effectively captured phenomenologically by adopting a $\mu(I)$-type rheology, though future two-phase formulations are expected to provide further improvements [4]. Additionally, its application to future potentially catastrophic rock avalanche events and to dam overflow analysis highlights its capacity for supporting predictions and simulation-guided recommendations for the design and optimization of mitigation measures. As a tool for hazard assessment and engineering design, our model represents a promising step forward in modeling alpine mass movements, enabling tailored simulations and providing practical, versatile solutions for engineers.

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Thermo-hydro-mechanics of multi-phase rock-ice avalanche

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Keywords: multi-phase mass flows; thermo-hydro-mechanical model; rock-ice avalanche; ice-melting; advection-diffusion of heat - temperature equation; frictional-weakening, melt-rate-weakening, flow mobility

I propose a novel physically-based multi-phase thermo-hydro-mechanical model for rock-ice avalanches. It considers rock, ice and fluid; and includes the mechanism of ice-melting and a dynamically changing general temperature equation for the avalanching mass, the first of its kind. It explains advection-diffusion of heat including heat exchange across the rock-ice avalanche body, basal heat conduction, production and loss of heat due to frictional shearing and changing temperature, a general formulation of the ice-melting rate and enhancement of temperature due to basal entrainment. The temperature equation includes a coupled dynamics, considering the rates of change of thermal conductivity and temperature. Ice melt intensity determines these rates as mixture conductivity evolves, characterizing distinctive thermo-hydro-mechanical processes. Fast ice melting results in substantial change in temperature. I formally derive the melting efficiency-dependent general fluid production rate. As properly described with the unified, multi-phase thermo-hydro-mechanical rock-ice avalanche model, a complex interplay between the frictional-weakening and the melt-rate-weakening is revealed determining the net flow mobility. The model includes internal mass and momentum exchanges between the phases and mass and momentum productions due to entrainment. The latter significantly changes the state of temperature; yet, the former exclusively characterizes the rock-ice avalanche. Temperature changes are rapid when heat entrainment across the avalanche boundary is substantial. The new model offers the first-ever complete dynamical solution for simulating rock-ice avalanche with changing temperature. This offers a fundamentally novel understanding of the complex process of rock-ice avalanche, flashing the deep insights into the underlying dynamics. I present the first multi-phase thermo-hydro-mechanical simulation of the 2021 Chamoli rock-ice avalanche event with the comprehensive simulation tool r.avaflow, https://www.avaflow.org.

Efficient Multiphase Modeling of Large-Scale Landslides on Complex 3D Terrains

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Keywords: Material Point Method, Multiphase Modeling, Large Deformation, 3D Complex Terrains

Modeling the dynamics of solid–fluid mixtures over complex 3D terrains is crucial for understanding and predicting large-scale landslides. The material point method (MPM), a hybrid Lagrangian–Eulerian approach (Sulsky et al., 1994), has proven effective for simulating such multiphase systems under large deformations. However, extending MPM to large-scale 3D problems remains computationally challenging, particularly when solving for the incompressible fluid phase. The coupled solid–fluid formulation often leads to large, ill-conditioned linear systems that limit efficiency and scalability. In this talk, we present an efficient MPM formulation for simulating multiphase landslide dynamics in three dimensions. The proposed approach adopts a staggered-grid discretization for the fluid phase. This staggered-grid discretization yields a symmetric sparse system with a narrow bandwidth that can be efficiently solved using a standard conjugate gradient method. By implementing this solution strategy into a recently developed GPU-based MPM framework (Zhao et al., 2025), the method enables fast and robust simulation of complex solid–fluid interactions on realistic terrains. This development represents a step toward practical, high-fidelity modeling of large-scale landslide processes.

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Measuring the unmeasurable? Geotechnical and remote sensing investigations of landslides

Hervé Vicari[1], Franziska Bründl[1], Yves Bühler[2], Andreas Stoffel[2], Ralf Herzog[3], Daniel Farinotti[3], Jiahui Kang[4], Fabian Walter[4], Jordan Aaron[3], Brian McArdell[4], Johan Gaume[1]

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The dynamics of landslides is strongly governed by their material composition and boundary conditions. The fine fraction can markedly alter permeability—both within the flowing mass and in the underlying bed material—so that when soil sediments mix with water, it strongly influences the generation and persistence of excess pore pressures and, consequently, shear strength. While new two-phase continuum models are increasingly capable of capturing these coupled hydro-geomechanical processes, a key challenge remains: can we reasonably measure the field material properties required to parameterize such models? Field sites are often steep, heterogeneous, and difficult to access, complicating in-situ characterization. To address this challenge, we conducted a systematic geotechnical investigation of ten debris flow channels across Switzerland. Soil samples were collected to determine grain size distributions, revealing significant variability in fine content among sites. Higher fine contents were found to reduce sediment permeability, quantified using in-situ dual-head infiltrometer tests. Complementary drone surveys provided high-resolution erosion and deposition patterns, allowing us to relate observed geomorphic changes to both channel and catchment morphology and sediment properties. Simple correlations suggest that higher fine contents correspond to enhanced erosion and more frequent debris flow activity, though these relationships are also strongly modulated by channel geometry and sediment availability. Combining geotechnical and geomorphological parameters enable us to classify the investigated channels into distinct behavioral groups. The methods developed and trained through this study proved invaluable for the investigation of the 28 May 2025 Blatten landslide. Granular flow modeling results indicated that a substantial frictional reduction was required to explain the extreme mobility of this event, implicating transient excess pore pressures as a likely mechanism. Geotechnical analyses of the landslide material revealed low permeability and high fine content, suggesting that excess pore pressure dissipation times may have greatly exceeded the event duration if even a 1 m flow layer became liquefied. Our results highlight the importance of integrating geotechnical measurements with remote sensing to constrain key parameters for next generation two-phase numerical models.

How to use seismic waves to get information on landslide characteristics (Online presentation)

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(Abstract to come)

Modeling the Collapse of Birch Glacier Using Damage Mechanics

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Keywords: Damage Mechanics, Glacier collapse, Rock–ice avalanche

On 28 May 2025, Birch Glacier in Switzerland collapsed due to heavy due from a landslide, triggering a major rock–ice avalanche that destroyed the village of Blatten located downstream. Here, we use a two-dimensional model based on continuum damage mechanics to investigate the mechanisms that led to the collapse of Birch Glacier. While ice dynamics is modeled using a standard non-Newtonian rheology, the fracturation of the ice is described through the introduction of an isotropic damage variable. The rock loading induces high stresses that initiate ice damaging, which in turn causes ice softening, which further accelerates the damaging process. Once calibrated, the model reproduces the progressive acceleration of Birch Glacier leading up to its collapse. This modeling framework provides a valuable tool for understanding—and potentially anticipating—similar catastrophic events in the future.

How to deal with rock avalanches models to predict hazard zone: the case of Blatten as a back-analysis

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Keywords: Rock avalanche back-analysis, Blatten event, scenario of propagation, runout distance

Rock avalanches (RA), characterized by rapid, high-energy flows of fragmented rock, pose significant hazards and risks in mountainous regions. Anticipating the potential run-out distance of RA resulting for the collapse of slope instability is a critical stage of hazard assessment and risk management, to make the right decisions at the right moment, notably about the zones to be evacuated. This task is however complex due to the variety of parameters influencing the propagation of the flow. Two main approaches, empirical and numerical, are commonly employed for this purpose, based on landslide inventories and back-analysis of former RA events. Wolff et al. (2025) propose a multi-method approach for estimating the maximum run-out distance and the run-up height on the opposite valley flank in the case of frontally confined RA. The selection of the most probable maximum distance represents a compromise between the different outcomes obtained with the various methods, numerical and empirical. This approach was first developed to describe scenarios of propagation linked to potential future scenarios of rupture at Cima del Simano (Wolff et al. 2023), in the case where the topography frontally limits the flow propagation.

The RA event of Blatten in May 2025, triggered by the collapse of the Nesthorn summit, shows similar frontal confinement and thus presents a good opportunity to put the method to the test. Firstly, and based only on the knowledge of the location of the fracture involved in the collapse, the volume of rupture was re-estimated with the Slope Local Based method (SLBL, Jaboyedoff et al. 2020). Then the most probable runout distance is delineated by applying the method developed in Wolff et al. (2025) and compared with the real maximum runout distance of the event. The method gives relatively good results: In front of the Kleines Nesthorn, it corresponds to a Fahrböschung angle f of 23°, very close to the real maximum f of 24°.

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Session 6:

Monitoring techniques and risk assessment

Seismic monitoring of large rock instabilities

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(Abstract to come)

DMS® multi-parametric columns for subsurface monitoring

Mario Lovisolo

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(Abstract to come)

Rockslide monitoring in Norway: technical status, key challenges and future opportunities

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The Norwegian Water Resources and Energy Directorate (NVE) is responsible for monitoring high-risk unstable rock slopes across Norway. Unlike many countries, NVE operates a dedicated technical section for maintaining, upgrading, and expanding field instrumentation. This presentation provides an overview of the monitoring technologies we employ—such as ground-based radar, GNSS, and robotic total stations—and the solutions we use to ensure power supply and communication in remote areas. We will discuss challenges related to harsh weather, technical reliability, and data quality, and present ongoing efforts to renew and expand our monitoring network. Finally, we highlight future opportunities for improved monitoring and outline key research needs.

Airdrop sensors - a concept for in situ monitoring of highly active, hazardous slopes

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Failure of large unstable rock slopes poses a significant risk to human livelihood and infrastructure in mountainous regions. This risk can be mitigated by early warning systems utilizing in situ sensors in the unstable slope requiring prior knowledge of the instability and installation well before failure. Recent cases from Blatten (Switzerland) and Skarfjellet (Norway) have, however, shown the challenges associated with slopes that are not part of an already existing early warning system. Installing in situ instruments on such highly active slopes poses an extreme danger to the life of the worker tasked with the installation and will in many cases not be possible at all. The instrument itself will most likely only survive a very short time. To overcome these challenge, we present a rugged sensor design that can be dropped over a slope via helicopter or drone and upon impact provide in situ motion data. Originally developed for the study of glacial hydrology our sensors have successfully been dropped on rock and water surfaces from up to 100 m height. They are equipped with high accuracy GNSS receivers in addition to an inertial measurement unit and a long range radio module for data transfer. Paired with a GNSS base station this enables high accuracy tracking of both absolute and relative motion in three dimensions. Our system design presents a possible tool to manage the last phase of a large rock slope failure with in situ slope information.

Warning and alarming system at the Simplon Pass

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The Simplon pass culminates at 2006 m over sea and is one of the principal alpine roads crossing the Alps in the North-South direction. It is extremely important for intra-European goods transportation, as it is open over the winter and is only protected by avalanche galleries and does not cross a tunnel, so that dangerous goods like chemicals can be transported safely all year round on this road. On the 29th of June 2024 at ca. 4.30 PM, following a few days of high intensity precipitation, several massive debris flows originating from the region of the Hübschhorn rock glacier entered the Engi gallery that is normally protecting the road from avalanches in winter and deposited a layer of more than one meter debris over several tens of meters, causing the closure of the road. The Hübschhorn rock glacier had been melting substantially over the last decade so that a combination of high temperature and important cumulative precipitation could mobilize the debris. The road had to be reopened as rapidly as possible and the debris flow channel had to be raised to avoid new damages to the road in case of events, but this meant performing construction works in a region with frequent rockfall and high debris flow risk. The Federal Roads Office mandated Geoprevent to rapidly install both a monitoring system to provide some information about the state of the rock glacier and a multi-component alarm system to detect debris flows and rockfall, close the road and trigger a local alarm on the construction site in case of detections. This works introduces the different components of these complex monitoring and alarming systems and presents some insights about the challenges faced during their installation and operation.

Advantages and limitations of SAR interferometry for large rock instabilities

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Keywords: SAR interferometry, landslide monitoring, remote sensing.

Long-term, wide-area monitoring of slope movement is essential for understanding landslide dynamics and evolution. Satellite SAR interferometry is a key technology for this, now entering an advanced operational stage due to the increased availability of satellite data. Its ability to cover large areas with high spatial resolution and detect sub-millimeter deformations, using an archive of data that goes back years, has made it a widely used tool for detecting and monitoring large, slow-moving alpine rock instabilities. However, this technique also faces inherent challenges in alpine terrain. These include (i) no data for steep, complex slopes where the satellite's view is obstructed, (ii) reduced or complete loss of displacement information over vegetated areas and during periods of snow cover, (iii) difficulty detecting ground movement that occurs along a north-south direction, and (iv) a satellite revisit time that is often too slow to capture the rapid acceleration of a slope just before it fails. To reduce these limitations, we can combine radar data from different satellite frequencies and platforms and use complemenary processing approaches. This integrated approach enhances performance, particularly in vegetated areas and for faster-moving landslides. In order to review potential and limitations of current satellite SAR data for the assessment of the state of activity of slow-moving landslide, we exemplary present results over large alpine rock alpine slope instabilities in Switzerland and Italy (e.g., Moosfluh, Kleines Nesthorn, Monte Mater, Val Canaria, Brienz/Brienzauls). Our presentation will conclude with an outlook on recent advances, including the use of terrestrial platforms, very-high resolution data, and mid-inclination satellite orbits to enhance the monitoring capabilities.

From Norway to the World: Expanding Ground Motion InSAR for Landslide Hazard Assessment

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Keywords: InSAR, landslides, early warning, Sentinel-1, Copernicus, Keywords list.

In Norway, systematic use of satellite-based ground-motion monitoring has transformed our ability to detect, track, and respond to unstable rock slopes. Through integration of interferometric SAR (InSAR), field investigations, and numerical modelling, national authorities have established operational early-warning systems that protect communities from catastrophic landslides. The national InSAR Norway service, launched in 2018, delivers free, nationwide deformation maps derived from Sentinel-1 data and has become an operational component of landslide hazard management. Its success has relied on close collaboration between the Geological Survey of Norway (NGU), the Norwegian Water and Energy Directorate (NVE), the Norwegian Space Agency, and NORCE Norwegian Research Centre, who developed the processing systems and software that form the backbone of the service. These institutions together operate the system on a powerful high-performance computing cluster (HPCC) that ensures national-scale processing capacity and reliability.

Building on this experience, Norway has contributed to the development and implementation of the European Ground Motion Service (EGMS) under the Copernicus Land Monitoring Service, the first continental-scale InSAR programme. EGMS provides harmonized, GNSS-calibrated displacement products covering all participating European states, enabling cross-border analysis of slope deformation and subsidence with millimetre precision. The methods and operational models refined through InSAR Norway informed many aspects of the EGMS, alongside the contributions of numerous European partners, demonstrating how coordinated processing, validation, and open dissemination can be achieved on a continental scale.

Looking beyond Europe, the next challenge is to ensure that these proven methods benefit regions most exposed to large rock-slope failures yet lacking reliable deformation data. A Global Ground Motion Service could provide accessible, standardized, and freely available monitoring products by building on existing Sentinel and commercial SAR missions, high-performance computing infrastructures, and open-data policies. Such a service would empower local authorities and scientists in developing and mountainous countries to detect precursory motion, prioritize field mapping, and enhance resilience to climate-driven slope instability.

Achieving this vision will require cooperation between remote-sensing specialists, modellers, and hazard managers—the same communities represented at RSG 2025. By linking physical understanding of rock-mass behaviour with large-scale InSAR observation, we can move toward global, evidence-based forecasting of slope failures in a changing mountain environment.

The OMIV Legacy: Two Decades of Multi-Instrumental Insights into Large Landslide Kinematics

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(Abstract to come)

Two decades of examples and cases of long-term natural hazards GBInSAR monitoring under climate change

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Since 2003, Ellegi srl has been conducting GBInSAR monitoring campaigns of landslides, particularly in the Alpine region, and some of these have been monitored consecutively for very long periods, up to 20 years. Furthermore, over the past five years, monitoring activities in the Alpine region have highlighted a new and interesting trend: the increased demand for GBInSAR measurement campaigns at sites above 3,000 m above sea level. In addition to being particularly challenging logistically, these sites are particularly interesting due to the simultaneous presence of areas characterized by activity typical of periglacial structures, with very rapid dynamics, coupled with slower gravitational movements. For some of these phenomena, the evolution of the movements detected by the GBInSAR radar will be presented, attempting to relate them to multiannual variations in rainfall and temperature.

Remote-sensed detection and characterization of the St. Cyr Rockslide, British Columbia, Canada

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Keywords: Rockslide, InSAR, lidar, characterization, remote sensing.

In 2020, ALOS-2 Fine SAR data was first collected and processed to provide the first L-Band InSAR data set an existing hydroelectric reservoir in the Canadian Selkirk Mountains. This data highlighted a large active mass adjacent to St. Cyr creek whose extents had not been previously characterized. Subsequent acquisition of airborne lidar and field reconnaissance was utilized to characterize the morphology of the slope and additional two-dimensional analysis of two-dimensional C-Band InSAR data was utilized to determine that the rock slide mass likely ranged from 1.3 x 10^7 *m3 to 1.9 x* 10^9 *m3 with a rupture zone likely up to 200 meters below the ground surface. Two boreholes advanced in 2022 confirmed the existence of shear zone located up to 250 m below the ground surface (mbgs) along the highway near the edge of the reservoir, indicating that the rockslide toe is located within the reservoir. Additional coarse and fine SAR data dating back to 2014 indicates that the slide has been moving at velocities ranging from 20 mm/year to 30 mm/year over the past decade.*

Session 7:

Risk management and crisis management

Monitoring of the Kleines Nesthorn with radar and camera systems

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On Monday, 19th of May 2025, the village of Blatten in the Lötschental (VS, Switzerland) was completely evacuated because of alpine mass movements detected on the Kleines Nesthorn. On the same day, Geoprevent installed an interferometric radar that provided data on which the local authorities relied to manage the crisis related to the collapse of the Birch glacier. During the crisis and afterwards, Geoprevent was mandated to install a comprehensive multi-component monitoring system of the Kleines Nesthorn, Birch and Nest glaciers. Altogether, an interferometric radar, two high-resolution camera systems, one pan-tilt-zoom camera and several GPS systems were installed. The data gathered provided key and unique insights of the processes happening before and after the collapse of the Birch glacier. The data is currently being post-processed and prepared to be made available for the scientific community.

The catastrophic 2025 landslide in Blatten (Switzerland) from an integrated risk management point of view

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(Abstract to come)

History, status and future development of monitoring and risk reduction related to unstable rockslopes in Norway

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As the national authority responsible for landslides risk management, the Norwegian Water Resources and Energy Directorate (NVE) has responsibility for hazard mapping and operative monitoring and warning of catastrophic rock avalanches and related secondary effects. Large rock-slope failures are common events in the inner fjord areas of Norway and represent a serious risk. Historically such events have generated catastrophic displacement waves and during the last 100 years more than 170 people have lost their lives in western Norway.

The risk management of these specific risks have of course been influenced by the dramatic historical events, but for the last 30 years even more by the knowledge through observations and documentation of unstable slopes at the end of the last century and beginning of the 20th century. The implementation of a national hazard mapping and risk classification project based on a standardized methodology has given a more systematic approach to the prioritization of monitored sites. The monitoring systems now include a relatively wide spectre of technical systems both on site and remote.

The history of how we have coped with these treats will be seen in context to a hazard management process in terms of residual risk, technological development and future societal needs.

From Monitoring to Decision Making: Integrated Management of the Mont de La Saxe Landslide (Courmayeur, Italy)

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Keywords: Landslide monitoring; Decision support; Early warning; Risk management; Mont de La Saxe; Civil protection; Alpine hazards.

The Mont de La Saxe landslide (Courmayeur, Western Italian Alps) is one of the most instrumented and studied slope instabilities in Europe. Since 2009, a multi-sensor monitoring system—combining ground-based InSAR, GNSS, inclinometers, piezometers, and meteorological data—has continuously tracked its evolution. Beyond the technical aspects, the key challenge lies in converting monitoring data into effective, transparent decisions during critical phases. A structured decision-support framework was developed to integrate quantitative indicators with qualitative field observations, providing adaptive alert levels for civil protection. The experience gained during the 2013–2014 emergency and subsequent applications to other Alpine sites demonstrates how long-term monitoring, coupled with clear decision logic, can enhance risk management and public trust in complex mountain environments.

Do we monitor the most critical slopes? Recent Norwegian cases and response

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Keywords: Monitoring, crisis management, emergency preparedness

Recent small rock avalanches in Norway have occurred from slopes without previously mapped instabilities, fortunately without any casualties. As the national authority responsible for landslides risk management, the Norwegian Water Resources and Energy Directorate (NVE) must consider how to efficiently prevent related future fatalities.

A large effort has been put into systematic mapping and risk classifying unstable slopes with potential to fail catastrophically. Until now 1144 unstable slopes have been identified, of which 122 have been hazard and risk classified in detail. The remaining slopes have been assigned a preliminary hazard and risk score to help prioritize the mapping efforts. The inventory is believed to include almost all visible large unstable slopes in Norway. The most critical slopes are monitored continuously (10) or periodically (21). In parallel, another project has mapped the source areas and deposits of 423 historic and prehistoric rock avalanches. This inventory is believed to be complete where the event occurred on land while probably incomplete where the failures went fjords and lakes. The Geological survey of Norway (NGU) compiled both the database of unstable slopes and the past rock avalanche events.

There is a clear discrepancy when comparing the mapped or monitored unstable slopes to the historic or prehistoric rock avalanches. Most obvious is that past failures statistically tend to originate on steeper slopes whereas most of the mapped instabilities are on gentler slopes. This suggests that steep slopes may fail rapidly with limited geomorphic precursors such as back scarps that typically develop over longer timescales. Consequently, there may be a bias in monitoring priorities, potentially overlooking steep slopes with limited visible deformation. NVE is concerned that the hazard from instabilities on steep slopes gets underestimated or not identified at all. This could be the largest residual risk of fatalities from rock slope failures. To address this, NVE strategy so far is:

- *Develop tools for identifying changes in movements from satellite InSAR data within the framework of InSAR Norway (work in progress)*
- *To see if we can use repeated airborne LiDAR scans to identify movements*
- *Encouraging municipalities and citizens to report rockfalls and increased activity, which may precede larger failures, and follow up reports with investigation on available online data and in the field*
- *To have a "emergency monitoring instrument kit" available for fast deployment, and preparedness for rapid assessment of hazard zones to be used in case evacuations are required*
- *Toolboxes for rapid volume estimation and hazard zones delineation for evolving situations*

In conclusion, we believe that preventing fatalities from large rock avalanches requires both a sustained mapping effort and a dynamic approach to identify the unstable slopes, particularly those that only become apparent close to the time of failure.

Regional scale susceptibility map for rock avalanches and consequences-based prioritization for follow-up activities

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Keywords: Rock avalanche, susceptibility, volume, propagation, integrated risk management.

Large rock slope instabilities that might cause rock avalanches pose a serious threat to communities in mountainous environments; the 2025 rock-ice avalanche from Kleines Nesthorn that destroyed the Swiss village of Blatten is a remarkable recent example. Knowing the location of such rock slope instabilities, the area that could be impacted by rock avalanches and their potential consequences is the key element for the integrated risk management. Here, we present the methodology and results for the rock avalanche susceptibility map in the canton of Vaud (Switzerland), the consequences assessment and prioritization for follow-up activities. The workflow is inspired by the systematic mapping of unstable rock slopes in Norway (Hermanns et al. 2014, 2020) to which the lead author of this study contributed to implement.

The canton of Vaud is characterized by four main geographic regions, the Jura Mountains, the Plateau, the Prealps and the Alps. Past legendary rock avalanches mainly occurred in the Alps, but rock avalanche deposits were also found in the Prealps and the Jura Mountains. The first step for the rock avalanche susceptibility map consists in creating an exhaustive inventory of large rock slope instabilities for the whole canton (total area of approximately 900 km²). This inventory is based on visual recognition of morphostructural signs of post-glacial gravitational deformations visible on hillshades of the DEM, orthophotos and other GIS data at a scale of 1:5000 or better. Characteristic morphostructures are back-scarps, open fractures, scarps, counterscarps, depressions, sliding surfaces etc. (Agliardi et al. 2001, Jaboyedoff et al. 2012, Oppikofer et al. 2015). In total, 243 instabilities are recorded, whereof 122 in the Prealps, 78 in the Alps, 37 in the Jura Mountains and 6 on the Plateau.

The characterization of each instability includes an assessment of signs of activity (rockfall activity, past rock avalanches in the vicinity, InSAR displacement rates), the development stage and the potential volume. The development stage expresses the level of certainty of observations on hillshades and orthophotos, as well as the development of morphostructures of the potential instability. As first approximation, the potential maximum volume of an instability is computed using a simple geometric equation, leading to volume classes ranging from large rockfalls with less than 10,000 m³ to small rock avalanches with 10,000 to 100,000 m³, medium-size rock avalanches with 100,000 to 1 million m³, and large rock avalanches of more than one million m³. In total, 145 potential instabilities have a volume greater than 10,000 m³ and a potential, proven or advanced development stage and is considered for the rock avalanche susceptibility map. The failure of instabilities with volumes smaller than 10,000 m³ will not propagate as rock avalanches and their runout areas are already covered by existing rockfall susceptibility maps, also made by Terranum.

The second phase for the rock avalanche susceptibility map includes a more detailed volume computation (only for instabilities larger than 100,000 m³) and the modelling of the rock avalanche runout area. The detailed volume estimates use the Sloping Local Base Level technique (Jaboyedoff et al. 2004, 2020), a simple numerical model that can be used to model the minimum, probable and maximum volume of each potential instability (Oppikofer et al. 2016). These volumes are then used in refined empirical relationships linking the volume of the instability to the travel angle (or Fahrböschung) observed for rock avalanches in the Alps (e.g.

Heim 1932, Scheidegger 1973, Corominas 1996, De Blasio 2011). Propagation modelling is carried out using Flow-R software (Horton et al. 2013), which has been adapted to consider the inertia of rock-avalanche-type propagations. Two impact zones are created for each potential instability: the probable runout zone is based on the probable volume of the instability combined with the average travel angle, while the conservative runout zone is based on the maximum volume of the instability combined with the pessimistic travel angle. Finally, these probable and conservative runout zones are combined with the development stage of potential instabilities to produce the rock avalanche susceptibility map with different levels of susceptibility.

The third step consists in the semi-quantitative analysis of the potential consequences in the runout areas of rock avalanches. This consequence analysis considers the number of people and estimates the value of infrastructure exposed within the runout areas. Secondary effects such as displacement waves and damming of rivers are highlighted but are not explicitly included in the consequences assessment.

Finally, the prioritization of follow-up activities is assessed based on a matrix combining the potential consequences with the development state of the rock slope instability. Out of the 145 inventoried instabilities in the canton of Vaud, fourteen instabilities were classified as first priority and second priority for local investigations and field mapping, thus focusing on the most critical sites ; in addition, 53 were classified as third and fourth priority for remote reconnaissance from helicopter or drone.

This entire process, from remote GIS source detection to semi-quantitative risk prioritization, led us to manage a previously underestimated and hidden risk over an entire territory and target critical sites for detailed investigations. These investigations allow to confirm the presence of a rock slope instability, to define potential failure scenarios, to qualitatively assess the likelihood of failure and to propose appropriate monitoring and mitigation strategies as further follow-up activities as part of the integrated risk management.

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