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# Alpine rock slope failures, rockfalls and debris flows in a changing climate and their anticipation

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## Introduction

Climate change effects on rock slope failures, rockfalls and debris flows have been commonly postulated but there is still restricted evidence on the processual coupling. Climate warming in mountains occurs ca. 2 times faster than in lowlands and affects temperature patterns, precipitations patterns, snow cover and duration, permafrost and glacier retreat. This directly conditions weathering rates, hydro- and cryostatic forcing as well as rock-ice mechanical destabilization and glacial unloading/debutressing. Indirect effects include enhanced river incision rates, altered vegetation dynamics and release of organic acids, altered hydrological pathways and conditions etc. This talk reports contributes to the understanding of processual couplings of rock slope failures, rockfalls and debris flows to climate change effects and shows future chances for their anticipation.

## Permafrost-affected rock slope failures

In a benchmark mechanical concept [Krautblatter et al., 2013], we developed a model that relates the destabilisation of thawing permafrost rock slopes to temperature-related effects on both, rock- and ice-mechanics; and laboratory testing of key assumptions has been performed. The destabilisation of permafrost rocks had before been purely attributed to changes in ice-mechanical properties. The effect of thawing on mechanical properties of bedrock and its mechanical relevance for friction and brittle fracture propagation had not been considered yet. This effect is significant since compressive and tensile strength as well as fracture toughness of intact rock are reduced by up to 50 % and more when intact rock thaws. Based on literature and experiments, a modified Mohr-Coulomb failure criterion has been developed for an ice-filled rock fracture that takes into account (i) fracturing of cohesive rock bridges, (ii) friction of rough fracture surfaces, (iii) ductile creep of ice and (iv) a representation of rock-ice interfaces. The model implies that warming-related changes in rock-mechanical properties may significantly influence early stages of the destabilisation and also explains high-magnitude failures in permafrost rock slopes irrespective of the presence of ice in fractures. Only after the deformation accelerates to a certain velocity level, where significant strain is applied to ice-filled fractures, ice-mechanical properties outbalance the importance of rock-mechanical components. Rock-mechanical properties become more important for higher normal stress, i.e. higher magnitudes of rock slope failure.

The applicability of the model has been proven and developed in field, lab and modelling studies. In the laboratory, we measured p-wave velocities of 22 decimetre-large low porosity metamorphic, magmatic and sedimentary rock samples from permafrost sites with a natural texture (>100 micro-fissures) in 0.3 C increments close to the freezing point to prove significant changes in elastic properties in unfreezing rocks and developed a modified Timur's two phase-equation implementing changes in matrix velocity in freezing low porosity bedrock [Draebing and Krautblatter, 2012; Krautblatter and Draebing, 2014]. Fatigue, critical and subcritical fracture propagation under relevant conditions were assessed [Jia et al., 2017; Jia et al., 2015; Voigtländer et al., 2018].

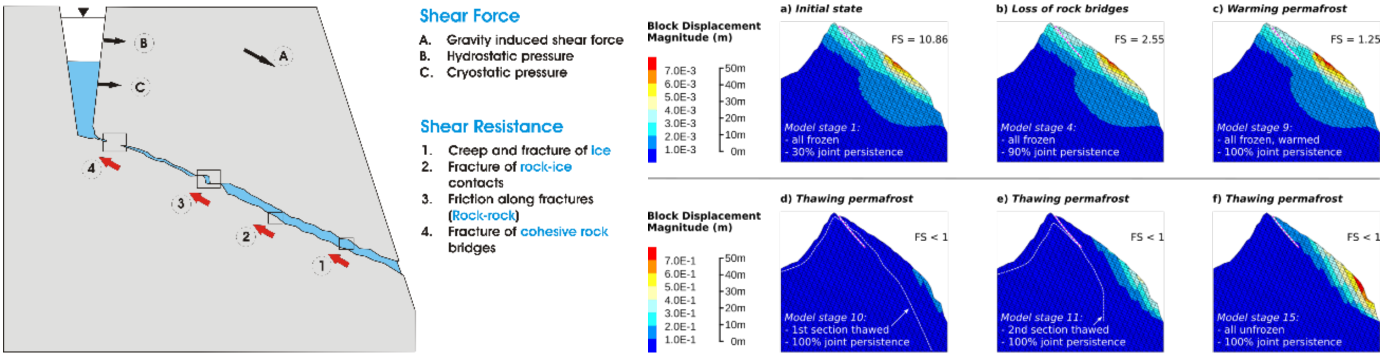

Fig. 1: Components of the Rock-Ice Mechanical model (left) and its implementation into a UDEC model fro an instable rock mass at the Zugspitze (right).

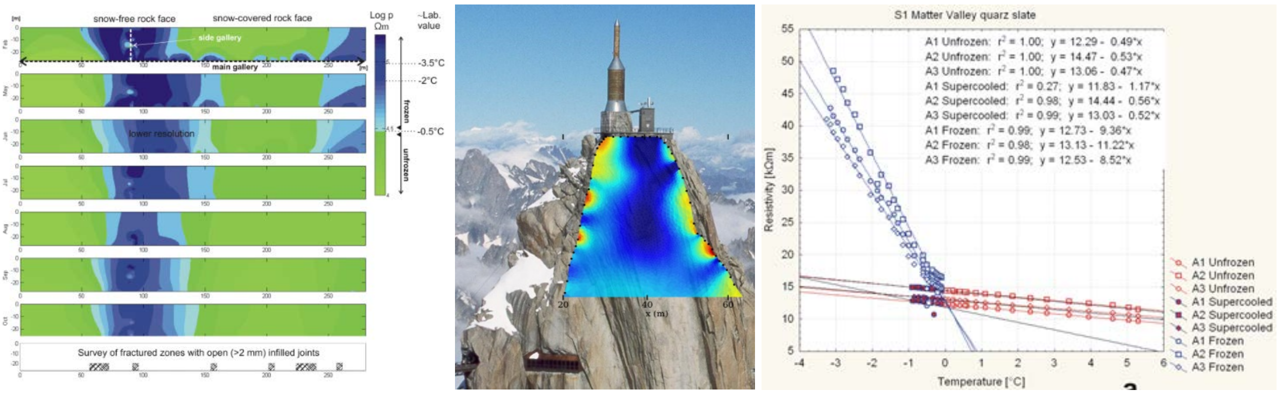

Fig. 2: Monthly distribution of frozen rock at the Zugspitze derived from ERT (left), ERT under the summit of the Aiguille du Midi showing the frozen part in blue/turquoise (mid) and lab-calibration of electrical resistivities with frozen/unfrozen rock temperature for and water-saturated quartz slate (right).

We performed experiments for the least known mechanical component, the rock ice-interfaces under relevant permafrost stress and temperature conditions, yielding a novel, temperature-dependent Mohr-Coulomb failure criterion for rock-ice interfaces [Mamot et al., 2019]. Summarising these findings, we could develop the 1st mechanical model that can anticipate the mechanical destabilisation of warming permafrost rocks [Mamot et al., 2021]. This article also generalises the susceptibility of permafrost rock walls according to lithology, fracture orientation and steepness – a starting point for generalising the susceptibility of permafrost rock walls to future failure.

## Quantitative geophysics to constrain state of permafrost and mechanical degradation of rock slopes

The application of near surface geophysics in permafrost-affected loose material with significant ice content became popular subsequent to 2000. However, bedrock was not commonly tested since resistivity and p-wave velocity gradients for frozen bedrock were believed to be too small for reliable detection. In an extensive field monitoring program 2005-2007 in a permafrost affected rock ridge (Matter Valley), we could demonstrate for the 1st time that Electrical resistivity tomography (ERT) is capable of detecting and monitoring permafrost extend in bedrock, i.e. rock slopes [Krautblatter and Hauck, 2007]. Performing laboratory test on the electrical resistivity of fully water-saturated frozen rock specimen with different lithologies, we derived a bilinear temperature-resistivity relationship for unfrozen and frozen bedrock with average gradients of 2.9(±0.3) %/°C (unfrozen, known before) and a tenfold 29.8 ±10.6 %/°C frozen gradient [Krautblatter, 2009]. Using accurate laboratory-calibration, we could publish a quantitative temperature-calibrated ERT time series of permafrost bedrock along a gallery at the Zugspitze (see above) [Krautblatter et al., 2010]. P-wave velocities of 22 decimetre-large low porosity metamorphic, magmatic and sedimentary rock samples show significant changes in p-wave velocity and developed a modified Timur's two phase-equation implementing changes in matrix velocity in freezing low porosity bedrock [Draebing and Krautblatter, 2012]. Refraction seismic tomography can equally be applied for permafrost monitoring in frozen bedrock [Krautblatter and Draebing, 2014].

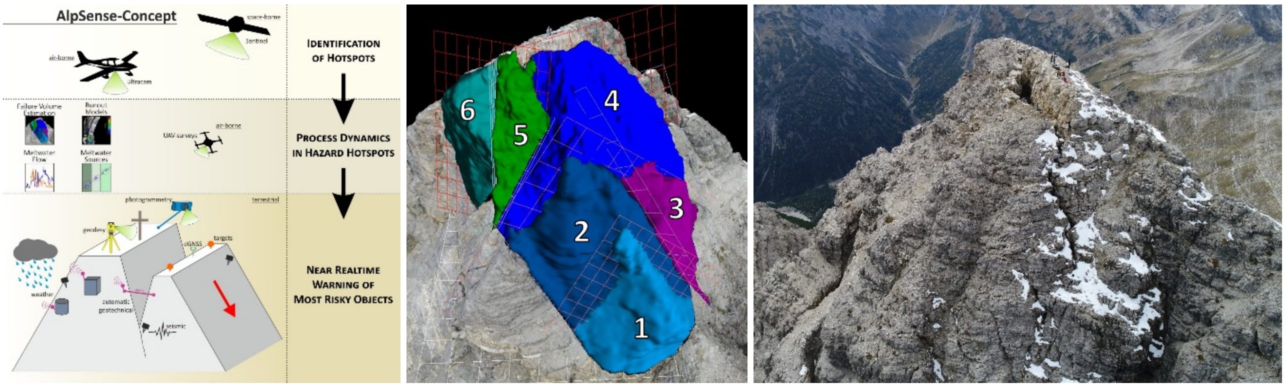

Fig. 3: Early warning strategy at the Hochvogel (D/A, left), potential compartments of future failures comprising altogether 260000 m³ (mid) and the Hochvogel with the visible decameter deep crack (right, persons for scale)

Fig. 4: Debris flow layers in a short core from the Plansee (left), the drill rig (mid) and lake bathymetry showing underwater debris flow deposits (right).

These methods and especially temperature-calibrated ERT have since been successfully adopted for applications ranging from extreme Alpine rock slopes to Arctic environments [Magnin et al., 2015; Siewert et al., 2012]. T-calibrated ERT has also been modified for the applied usage in early warning systems for alpine cable cars [Keuschnig et al., 2016].

A 900-day freezing laboratory study in Sussex, UK, shows that temperature-resistivity behavior over 25 subsequent freezing cycles in 6 highly-equipped large rock samples with galvanic and capacitive EIT monitoring [Murton et al., 2016]. Recently, we have further developed this method to 4D-applications of quantitative bedrock permafrost monitoring over a decade; the 1st method that can measure volumetric permafrost loss in rock slopes [Scandroglio et al., 2021].

## Anticipating and modelling rock slope failure and hazardous landslides (in a changing climate)

In 2007, we developed a suggestion for a universal model for rockfall activity and rock wall retreat based on geological, geotechnical and ambient parameters [Krautblatter and Dikau, 2007]. Based on direct measurement of 140 t of rockfall deposition, we suggested a nonlinear rainfall intensity – rockfall model spanning 6 magnitudes of rockfall intensity [Krautblatter and Moser, 2009]. This was complemented with an assessment of the proportional contribution of different magnitudes of rockfalls and rock slope failure [Krautblatter et al., 2012].

The rock-ice mechanical model that explains the weakening of rock slopes in degrading permafrost due to rock and ice mechanics, the mechanics at the rock-ice interface and hydrostatic and cryostatic pressures [Krautblatter et al., 2013] was conceptually combined with the effects of stress changes in deglaciating valleys [Krautblatter and Leith, 2015] and nonlinear spatial and temporal effects [Krautblatter and Moore, 2014]. Further studies added relevant mechanical understanding of path-dependent fracture propagation [Jia et al., 2017], subcritical fracture propagation [Voigtländer et al., 2018], stress corrosion [Voigtländer et al., 2020] and the efficacy of frost weathering [Draebing and Krautblatter, 2019]. A validation of long-term effects has recently been published in a multiyear observation by a co-supervised PhD of rockfall activity in deglaciating cirques [Hartmeyer et al., 2020]. Enhanced mechanical understanding was transformed into multi-phase models of rock-ice avalanches [Pudasaini and Krautblatter, 2014], a cyclic fatigue model [Jia et al., 2015], lahar models for glacier-capped volcanoes [Frimberger et al., 2021], a comprehensive model for permafrost rock slope destabilisation [Mamot et al., 2021] and erosive landslide mobility [Pudasaini and Krautblatter, accepted].

A systematic assessment of the kinematic forecasting potential of well-documented rock slope failures has been undertaken by Saettele et al. [2016]. Since 2018 we instrumented 5 alpine sites in the projects AlpSenseBench and AlpSenseRely to develop cutting edge landslide prediction at instrumented benchmark sites with latest satellite-based, air-based, geotechnical and geophysical instrumentation. Hereby we hypothesize that electric, seismic, acoustic and gravimetrical geophysical signals [Dietze et al., 2021] can support anticipation of future failures prior to kinematic signals and enlarge the forecasting window [Hermle et al., 2021; Leinauer et al., 2023].

## Debris flows in a changing climate and environment

Aerial photography and geophysical analysis of Lateglacial/Holoce debris cone volumes since 1947 at the Plansee (A) indicates that debris flow activity since the 1980s has increased 3 times in comparison to the 3 decades before and 2 times in comparison to the entire Lateglacial/Holoce debris cone deposition rate [Dietrich and Krautblatter, 2017; 2019]. Comparing recent debris flow rates to a 4000 year record of lake sediments in the Plansee, yieded evidence that debris flow activity in the last hundred years is >10 times higher than in the 4000 years before [Kiefer et al., 2021]. This coincides with evidence from the Reintal (D) where debris flow rates in the 20th/21st century were >5 times higher than in the 19th century [Sass et al., 2007]. Recent debris flow rates are seemingly increasing in many Alpine Environments worldwide and can feature massive sediment redistribution rates in high alpine catchments often modifying stream bed heights by several meters [Barbosa et al., 2024]. Such hyperconcentrated flows can be massively erosive even in bedrock channels and pose massive threat in environments that have not before experienced debris/hyperconcentrated flow activity [Stammberger et al., 2024].

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