Towards a benchmark mechanical model for warming permafrost rock slopes

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This paper discusses mechanical modelling strategies for instable permafrost bedrock. Modelling instable permafrost bedrock is a key requirement to anticipate magnitudes and frequency of rock slope failures in a changing climate but also to forecast the stability of high-alpine infrastructure throughout its lifetime.

High-alpine rock faces witness the past and present mechanical limit equilibrium. Rock segments where driving forces exceed resisting forces fall of the cliff often leaving a rock face behind which is just above the limit equilibrium. All significant changes in rock mechanical properties or significant changes in the state of stress will evoke rock instability which often occurs with response times of years to 1000 years. Degrading permafrost will act to alter (i) rock mechanical properties such as compressive and tensile strength, fracture toughness and most likely rock friction, (ii) warming subzero conditions will weaken ice and rock-ice interfaces and (iii) increased cryo- and (iv) hydrostatic pressures are expected. We have performed hundreds of laboratory experiments on different types of rock that show that thawing and warming significantly decreases both, rock and ice-mechanical strength between -5°C and -0.0°C. Approaches to calculate cryostatic pressure (ad iii) have been published and are experimentally confirmed. However, the importance and dimension of extreme hydrostatic forces (ad iv) due to perched water above permafrost-affected rocks has been assumed but has not yet been quantitatively recorded.

This paper presents data and strategies how to obtain relevant (i) rock mechanical parameters (compressive and tensile strength and fracture toughness, lab), (ii) ice- and rock-ice interface mechanical parameters (lab), (iii) cryostatic forces in low-porosity alpine bedrock (lab and field) and (iv) hydrostatic forces in perched water-filled fractures above permafrost (field).

We demonstrate mechanical models that base on the conceptual assumption of the rock ice mechanical model (Krautblatter et al. 2013) and rely on frozen/unfrozen parameter testing in the lab and field. Continuum mechanical models (no discontinuities) can be used to demonstrate permafrost rock wall destabilization on a valley scale over longer time scales, as exemplified by progressive fjord rock slope failure in the Lateglacial and Holocene. Discontinuum mechanical models including rock fracture patterns can display rock instability induced by permafrost.
degradation on a singular slope scale, as exemplified for recent ice-supported 10,000 m³ preparing rock at the Zugspitze (D). Discontinuum mechanical models also have capabilities to link permafrost slope stability to structural loading induced by high-alpine infrastructure such as cable cars and mountains huts, as exemplified for the Kitzsteinhorn Cable Car and its anchoring in permafrost rocks (A).

Over longer time scales, the polycyclicity of hydro- and cryostatic forcing as well as material fatigue play an important role. We also introduce a mechanical approach to quantify cryo-forcing related rock-fatigue. This paper shows benchmark approaches to develop mechanical models based on a rock-ice mechanical model for degrading permafrost rock slopes.