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A thermo-mechanically coupled failure model for degrading permafrost rock slopes based on laboratory and field data

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Instability and failure of permafrost-affected rock slopes have significantly increased coincident to rising air temperature in the last decades. Most of the observed failures in permafrost-affected rock walls are likely triggered by the mechanical destabilisation of warming bedrock permafrost including ice-filled joints. To anticipate failure in a warming climate, we need to better understand how rock-ice mechanical processes affect rock slope destabilisation and failure with temperatures increasing close to 0 °C. Warming permafrost in rock slopes decreases the shear resistance along rock joints (considering ice or soil infillings and cohesive rock bridges) as well as the compressive and tensile strength of saturated intact bedrock (Krautblatter et al., 2013).
For the first time, we mechanically model the weakening of a degrading permafrost rock slope considering a change from the frozen to the unfrozen state. For this, we combine the temperature distribution in a rock slope with a temperature-dependent mechanical failure model.
We calibrate this model with a shallow, ice-supported rockslide of approximately 10.000 m^3 at the permafrost-affected Zugspitze summit crestline (2885 m a.s.l.), Germany, using frozen and unfrozen rock-ice-mechanical parameters. For this, we performed a set of laboratory studies on a broad spectrum of mechanical properties of thawing bedrock and rock joints with Wetterstein limestone from the Zugspitze. The tested mechanical properties of the intact bedrock contain the uniaxial compressive strength (σc), the tensile strength (σt) and the Young′s modulus (E). Investigated rock joint properties involve the shear strength of rock joints filled with ice and rock joints without infilling (Mamot et al., 2018). A temperature-dependent strength reduction could be shown for all investigated parameters.
Tomographies of electrical resistivity (ERT) and seismic refraction (SRT) of the Zugspitze summit crest were used to identify the spatial distribution of permafrost within the rock slope.
Modelling is performed with the two-dimensional Universal Distinct Element Code (UDEC) which simulates and represents the mechanical behaviour of discontinuous media – an assemblage of discrete rock blocks separated from each other by discontinuities. The model shows a decreasing factor of safety and higher displacement rates as soon as thawing sets in.
The combination of thermal and mechanical information as input data for numerical failure models helps scientists and engineers to anticipate for the first time the strength reduction of degrading permafrost rock slopes.

Krautblatter, M., Funk, D., Günzel, F. K. (2013). Why permafrost rocks become unstable: a rock-ice-mechanical model in time and space. Earth Surface Processes and Landforms 38: 876-887.
Mamot, P., Weber, S., Schröder, T. and Krautblatter, M. (2018): A temperature- and stress-controlled failure criterion for ice-filled permafrost rock joints. The Cryosphere 12: 3333-3353.