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Why thawing permafrost rocks become unstable

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The destabilisation of permafrost rocks is commonly attributed to changes in ice-mechanical properties (Davies et al. 2001). The effect of low temperatures on intact rock strength and its mechanical relevance for friction and critical/subcritical fracture propagation has not been considered yet. However, mechanical strength such as compressive and tensile strength are reduced by up to 50% and more when intact rock thaws (Mellor, 1973). Here we show, that the reduction of the shear resistance of rock-rock contacts in discontinuities may play a key role for the onset of larger instabilities in thawing permafrost rocks.

The presence of permafrost can increase shear stress due to altered hydrostatic pressure (i.e. by perched water) and cryostatic pressure (i.e. by ice segregation). The shear resistance of ice-filled fractures responds to four different mechanical processes acting individually, in succession or in combination: (i) friction/fracture along rock-rock contacts, (ii) friction/fracture along rock-ice contacts, (iii) fracture/deformation of ice in fractures and if present (iv) deformation of frozen fill-material.

Based on a Mohr-Coulomb assumption, we defined a failure criterion of an ice-filled rock fracture, with cohesive rock bridges, contact of rough fracture surfaces, ductile creep of ice and with a representation of rock-ice "failure" mechanisms along the surface and inside the ice body. The synoptic models are based on the principle of superposition, i.e. that shear stress "absorbed" by one component reduces the amount of shear stress applied to the other components. To test the importance of reduced friction, we conducted shearing tests on homogeneous fine-grained limestone specimen taken from a permafrost site (Zugspitze, Germany). In a temperature-controlled shearing box, we repeatedly tested mechanical properties of sand-blasted surfaces between +5° and –7°C.

Failure along existing sliding planes can be explained by the impact of temperature on shear stress uptake by creep deformation of ice, the increased propensity of failure along rock-ice fractures and reduced total friction along rough rock-rock contacts. This model may account for the rapid response of rockslides to warming occurring along existing planes of weakness (reaction time). In the long term, brittle fracture propagation is initialised. Warming reduces the shear stress uptake by total friction and decreases the subcritical/critical fracture toughness along rock bridges. The latter model accounts for slow destabilisation of former permafrost rock slopes over decades to millennia, subsequent to the warming impulse (relaxation time). Both models underline the importance of reduced total friction for the onset of the destabilisation. We could show for the first time, that the shear resistance of ice-free smoothened rock-rock surfaces decreases significantly subsequent to thawing. This occurred even after enhanced fracture smoothing due to repeated shearing experiments.

Thawing-related changes in rock-mechanical properties may significantly influence early stages of the destabilisation of larger thawing permafrost rocks irrespective of the presence of ice in the system. The models imply that only after the deformation accelerates to a certain velocity level (where significant strain is applied to ice-filled discontinuities) ice-mechanical properties outbalance the importance of rock-mechanical components. We present two models that relate the destabilisation of thawing permafrost rocks to temperature-related effects on rock- and ice-mechanics.