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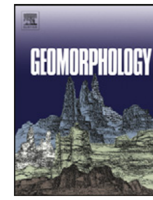

Interaction of thermal and mechanical processes in steep permafrost rock walls: A conceptual approach

D. Draebing [a,*], M. Krautblatter [b], R. Dikau [a]

[a] University of Bonn, Department of Geography, Meckenheimer Allee 166, 53111 Bonn, Germany
[b] Technische Universität München, Monitoring, Analysis and Early Warning of Landslides, Arcisstr. 21, 80333 München Germany

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ABSTRACT

Degradation of permafrost rock wall decreases stability and can initiate rock slope instability of all magnitudes. Rock instability is controlled by the balance of shear forces and shear resistances. The sensitivity of slope stability to warming results from a complex interplay of shear forces and resistances. Conductive, convective and advective heat transport processes act to warm, degrade and thaw permafrost in rock walls. On a seasonal scale, snow cover changes are a poorly understood key control of the timing and extent of thawing and permafrost degradation. We identified two potential critical time windows where shear forces might exceed shear resistances of the rock. In early summer combined hydrostatic and cryostatic pressure can cause a peak in shear force exceeding high frozen shear resistance and in autumn fast increasing shear forces can exceed slower increasing shear resistance. On a multiannual system scale, shear resistances change from predominantly rock-mechanically to ice-mechanically controlled. Progressive rock bridge failure results in an increase of sensitivity to warming. Climate change alters snow cover and duration and, hereby, thermal and mechanical processes in the rock wall. Amplified thawing of permafrost will result in higher rock slope instability and rock fall activity. We present a holistic conceptual approach connecting thermal and mechanical processes, validate parts of the model with geophysical and kinematic data and develop future scenarios to enhance understanding on system scale.

1. Introduction

Permafrost is a thermally defined phenomenon for underground material remaining under 0 °C for at least two consecutive years (NRC-Permafrost-Subcommitee, 1988; Muller, 2008). In rocks, freezing point depression caused by solutes, pressure, pore diameter or pore material can lead to a mobile supercooled unfrozen water content down to temperatures of −10 °C (Mellor, 1970; Lock, 2005). Thermal conditions influence rock instability on different temporal scales, e.g. on a multiannual scale like the observed increase of regional rock fall activity (Fischer, 2010; Ravanel and Deline, 2010) or on a seasonal scale like hot summers like 2003 (Gruber et al., 2004a). Field evidences of ice in rock scarps and rock fall talus slopes indicate that permafrost is involved in these processes (Dramis et al., 1995; Pirulli, 2009; Fischer et al., 2010; Ravanel and Deline, 2010; Kenner et al., 2011). Rock slope failures can be classified according to volume (Whalley, 1974, 1984) and size (Heim, 1932). Numerous case studies focus on permafrost influence on rock-ice avalanches with magnitudes $>1 \times 10^7$ m^3 or cliff fall events (magnitudes 10^4–10^6 m^3) (Bottino et al., 2002; Haeberli et al., 2004; Huggel et al., 2005, 2008; Fischer et al., 2006; Geertsema et al., 2006; Lipovsky et al., 2008; Sosio et al., 2008). Other studies show higher activities of fall processes of different magnitudes (cliff falls 10^4–10^6 m^3, block falls 10^2–10^4 m^3, boulder falls 10^1–10^2 m^3 and debris falls <10 m^3) in permafrost-influenced rock walls (Sass, 2005a; Fischer et al., 2007; Krautblatter and Dikau, 2007; Rabatel et al., 2008; Deline, 2009; Ravanel and Deline, 2010; Ravanel et al., 2010). Recently, Krautblatter et al. (2013) introduced a comprehensive rock- and ice-mechanical model to explain why permafrost rocks become unstable on different temporal and spatial scales. The authors identify and quantify rock- and ice-mechanical properties responsible for decreasing stability in degrading permafrost-affected rock slopes. In this article, we add relevant heat transfer processes and the timing of these processes.

The thermal influence on rock walls can be subdivided into three different processes: conduction, convection and advection. Conduction is heat diffusion in a solid or static fluid as a result of a temperature gradient based on the principles of thermodynamics. Convection is a heat current in combination with particle transport, where the energy is transported by liquid or gaseous particles in a discrete way. Advective heat transport is a continual heat transport through a moving fluid. Gruber and Haeberli (2007) describe the degree of material fracturing, the ice and snow cover of the surface and the availability of water as the thermal key controls on rock walls. Fracturing affects infiltration capacity and water content. Ice and snow cover controls rock temperature

* Corresponding author. Tel.: +49 228 73 5896; fax: +49 228 73 9099.
E-mail address: daniel.draebing@giub.uni-bonn.de (D. Draebing).

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and water availability. Water availability affects the advective heat transport, rock weathering and turbulent exchange of latent energy at the rock surface.

Snow cover changes the energy balance of the surface by increasing albedo, long-wave emissivity and absorptivity, and by decreasing thermal conductivity in comparison to rock surfaces (Zhang, 2005). Due to latent heat processes, snow melt is an energy sink. As a result of its properties snow cover possesses an insulation effect which influences the ground thermal regime. This influence of snow cover on permafrost strongly depends on the spatial and temporal snow distribution (Luetschg et al., 2008) and could be identified on flat terrain, rock glaciers and gentle slopes (Keller and Gubler, 1993; Keller, 1994; Phillips, 2000; Ishikawa, 2003; Luetschg et al., 2003, 2004; Luetschg and Haeberli, 2005). The spatial distribution of snow cover on steep rock walls is highly variable caused by interactions between wind processes and slope morphometry (Wirz et al., 2011). These interactions result in preferentially snow accumulation behind ridges, in small gullies or at the toe of slopes (Wirz et al., 2011). During the period of snow accumulation morphometric factors are more important than during snow depletion (Schmidt, 2009).

Previous research focussed on either rock stability, snow cover influence or permafrost distribution. However, previous studies have not assessed the influence of snow cover on thermal and mechanical processes in steep permafrost rock walls. Here we present (1) our conceptual model which connects thermal and mechanical processes on a seasonal scale and establishes a framework for joint thermo-hydro-mechanical forcing, (2) geophysical and kinematic data to validate parts of our model, and (3) future scenarios to enhance understanding on system scale.

2. The model approach

In Section 2, we discuss Fig. 1 from the top (A: homogeneous rock wall) to the middle (B: heterogenic rock model) and then to the bottom (C: dynamic rock model with snow cover). Our approach is based on the factor of safety (*FS*) model:

$$FS = \frac{shear\ strength}{shear\ stress} \quad (1)$$

relating the sum of resisting forces (shear strength) to the sum of driving forces (shear stress). For this, we adopt the rock-ice mechanical model developed by Krautblatter et al. (2013). The model includes a mechanical representation of the fracture toughness of rock bridges, friction of rough rock-rock contacts in fractures, the deformability of ice in fractures and the performance of rock-ice interfaces in fractures. In our model, the rock wall is represented by a cubic body with vertically inclined slopes. To simplify the model, rock material is assumed to be homogeneous and no influences of topography, aspect, snow cover and spatial variability on permafrost thaw are incorporated (Gruber et al., 2004a,b; Wirz et al., 2011). This provides us with a model with the three components: rock mass, rock discontinuities and snow cover (Fig. 1).

2.1. Homogeneous rock walls

Intact rock contains air-, water- or ice-filled pores and material as well pores determine thermal properties. Heat transfer occurs primarily in a conductive way. Thermal conductivity (k) of metamorphic and igneous rocks approaches 1.5–3.5 W m^{-1} K^{-1}, while sedimentary rocks approach 2–4 W m^{-1} K^{-1} (Vosteen and Schellschmidt, 2003). If a

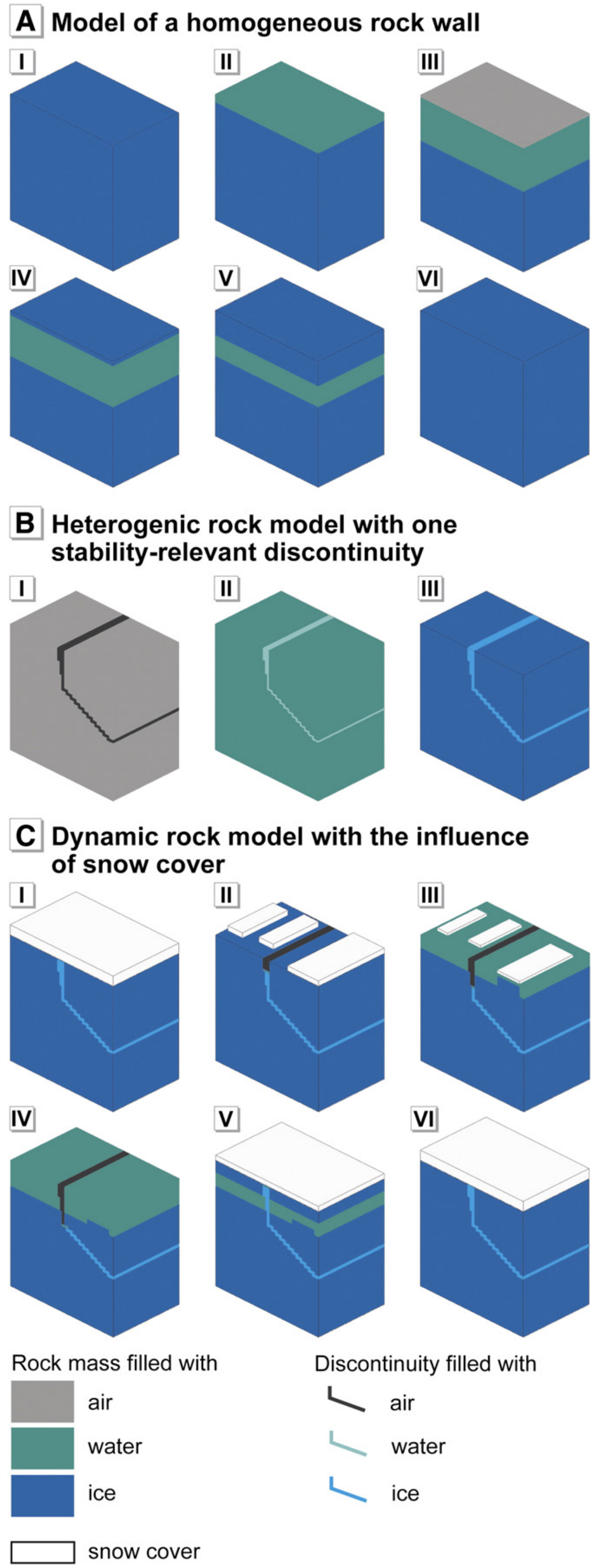

Fig. 1. Graphical representation of the three model components in different periods of temporal development. A) Temporal permafrost development in a homogeneous rock mass. B) Heterogenic rock mass with a rock discontinuity (fracture) filled with air (I), water (II) and ice (III). C) Temporal development of a rock mass and of rock discontinuity influenced by snow cover.