Stability Analysis of a Temperature-Dependent Jointed Rock Mass

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Abstract. Permafrost degradation is a critical factor to consider when examining the destabilization of rock slopes in cold regions. This study focuses on the numerical analysis of the Zugspitze summit-crest in Germany, utilizing a temperature-dependent mechanical model. Material properties and degradation parameters were measured by an independent research group who conducted various geomechanical and geotechnical laboratory tests, as well as field study. The analysis covers the effects of temperature on the mechanical properties of the rock mass, and the results indicate that the slope's stability is affected by temperature changes in the model. The model demonstrates a positive correlation between increasing temperatures due to climate change and the likelihood of rock slope instability and failure. The model presented in this study can aid in managing the risks associated with permafrost degradation and rock slope instability.

Keywords: Slope Stability · Thermal Dependent Material · Jointed rock · DFN

1 Introduction

Permafrost degradation due to climate change has significant implications for infrastructure, ecosystems, and human safety, and with the observed trend of rising temperatures, the likelihood of rock slope failures has been increasing. One of the major concerns associated with the stability of rock slopes is the presence of discontinuities as they can lead to destabilized permafrost thaws, and failures commonly occur at ice-filled joints since they act as slipping surfaces and detachment planes. Additionally, the increase in temperature alters the mechanical properties of rock and ice, such as the ductile temperature-dependent and stress-dependent creep of ice and ice-rich soils.

Rock slope instability in permafrost conditions is highly sensitive to temperature changes since higher temperatures reduce the overall shear resistance along the rock joints, which reduces the fracture toughness of cohesive rock bridges and lowers the friction along the rock-rock contacts. Mamot et al. [1] proposed a new failure criterion that considers the effects of temperature and normal stress on the mechanical behavior of rock fractures in permafrost environments, and it takes into account the loss of ice friction and cohesion that occurs as temperatures rise and ice melts.

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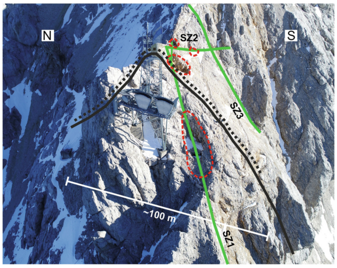

Fig. 1. A view from the top of the Zugspitze summit [1]

There were limitations in past attempts to study the impact of warming on the mechanical response of rock slopes. One study by Davies et al. [2] simulated the warming of a rock slope in a laboratory centrifuge model, which estimated the factors of safety of unfrozen and ice-filled joints at temperatures close to the melting point. Numerical modeling is employed to assess rock slope stability and analyze the spatial distribution and evolution of permafrost, but no temperature-dependent mechanical numerical model has been developed. The mechanical part of the numerical model needs to implement the deformation and strength reduction of permafrost bedrock and ice-filled discontinuities upon warming and thawing. To accurately assess the factor of safety in a warming climate, a better understanding of how the mechanical components of rock and ice, control rock slope destabilization and how failure is required, along with finding a method to mechanically express the warming and thawing of the permafrost in models.

Mamot et.al. [1] developed the first temperature-dependent numerical model, capable of assessing the stability of degrading permafrost rock slopes, which exemplifies the Zugspitze summit. Zugspitze is among the highest peaks of the Northern Calcareous Alps located in the Eastern Alps (Fig. 1). In this research, we used RS3 (Rocscience 3D finite element package) to analyze the stability of the summit by updating the material properties of rock mass under the temperature rise. The program is capable of modeling a large number of discontinuities and calculate the factor of safety.

2 Model Setup and Numerical Analysis

The mechanical model was composed of a sequence of six subsurface layers of varying thicknesses and rock types, with a parallel orientation to the derived permafrost boundary, as shown in Fig. 2. The temperature-dependence aspect of the model accounted for a stronger warming signal coming from the south slope, hence the stepwise warming from the slope surface to the core of the crest. When the model was initially prepared, the entire geometry was assumed to be frozen with an average temperature of -4 °C, and the temperature of each layer was incrementally increased over the course of fifteen stages until all layers were unfrozen.

The rock mass has a profile consisting of three fully persistent rock slopes (Joint sets 1–3), along with a dominant shear zone (SZ), shown in Fig. 3, and more detail on the orientation of the joint sets is provided in Table 1.

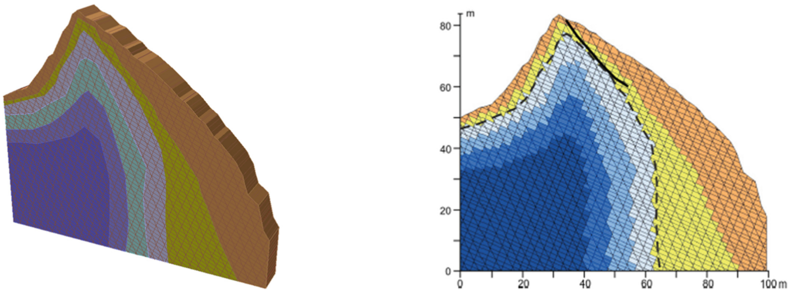

Fig. 2. Profile of the layers in (a) 3D model in RS3 and (b) 2D section of the model analyzed by Mamot. et.al [1].

Based on the formulation from the report [1], the changes in the temperature affected the properties of both, the rock and the joints. Accordingly, the model was prepared with that paper's results of the lab tests and data calibrations. Please note, in this study, we are ignoring the effect of thermal expansion and only material degradation is considered.

In Table 2, the stiffness of each joint-sets is provided. According to the report [1], the normal and shear stiffness of the joint was dropped, only when the thawing happens. In this research, we assumed that all strength related properties for joints inside of each layer are identical and it changes when the temperature changes. The complete list of these property updates is given in Table 3. From stages 1 to 4, while the temperature of each layer is -4 °C, we are assuming the persistence between joints are increasing from 30% to 90%. This has been modeled by reducing the cohesion and the friction angle of each sets of joint network. At stage 5, the persistence of joint sets is 100% and we

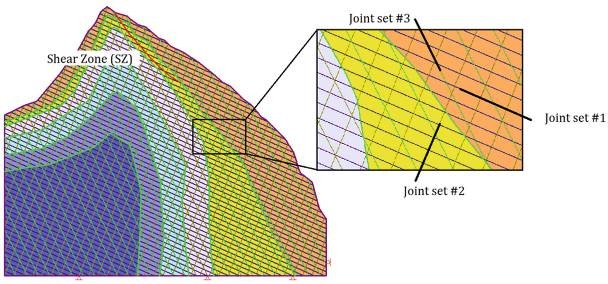

Fig. 3. Distribution of joint network

Table 1. Joint set orientation

	Spacing	Angel with x-axis
Joint Set #1	1.35 m	-24^{o}
Joint Set #2	2.7 m	69^{o}
Joint Set #3	3.15 m	-64^{o}

Table 2. Variation of joint stiffness by stage (All units are in MPa)

	Joint set#1	**Joint Set#2**	**Joint Set#3**	**SZ**
Stage 1–9	Ks = 10,000 Kn = 26,000	Ks = 5,000 Kn = 13,000	Ks = 4,300 Kn = 11,100	Ks = 5,000 Kn = 13,000
Stage 10–15 (for unfrozen Layers)	Ks = 9,900 Kn = 25,300	Ks = 4,200 Kn = 10,800	Ks = 4,900 Kn = 12,600	Ks = 4,900 Kn = 12,600

assume the ice fully fills the joints, therefore a small increase in cohesion is observed (based on lab tests [1]). From stage 6 to the end of the analysis, the rise in temperature leads to a reduction of cohesion, however, the friction angle would increase while the thawing happens.

Table 3. Variation of joint strength at each stage

	Layer 1	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**	**Layer 6**
Stage 1	C=2.7 $\phi = 42.1$	C=2.7 $\phi = 42.1$	C=2.7 $\phi = 42.1$	C=2.7 $\phi = 42.1$	C=2.7 $\phi = 42.1$	C=2.7 $\phi = 42.1$
Stage 2	C=2.0 $\phi = 40.8$	C=2.0 $\phi = 40.8$	C=2.0 $\phi = 40.8$	C=2.0 $\phi = 40.8$	C=2.0 $\phi = 40.8$	C=2.0 $\phi = 40.8$
Stage 3	C=1.2 $\phi = 39.5$	C=1.2 $\phi = 39.5$	C=1.2 $\phi = 39.5$	C=1.2 $\phi = 39.5$	C=1.2 $\phi = 39.5$	C=1.2 $\phi = 39.5$
Stage 4	C=0.4 $\phi = 38.2$	C=0.4 $\phi = 38.2$	C=0.4 $\phi = 38.2$	C=0.4 $\phi = 38.2$	C=0.4 $\phi = 38.2$	C=0.4 $\phi = 38.2$
Stage 5	C=0.7 $\phi = 30.5$	C=0.7 $\phi = 30.5$	C=0.7 $\phi = 30.5$	C=0.7 $\phi = 30.5$	C=0.7 $\phi = 30.5$	C=0.7 $\phi = 30.5$
Stage 6	C=0.5 $\phi = 26.4$	C=2.7 $\phi = 42.1$	C=2.7 $\phi = 42.1$	C=2.7 $\phi = 42.1$	C=2.7 $\phi = 42.1$	C=2.7 $\phi = 42.1$
Stage 7	C=0.4 $\phi = 22$	C=0.5 $\phi = 26.4$	C=2.7 $\phi = 42.1$	C=2.7 $\phi = 42.1$	C=2.7 $\phi = 42.1$	C=2.7 $\phi = 42.1$
Stage 8	C=0.3 $\phi = 16.8$	C=0.4 $\phi = 22$	C=0.5 $\phi = 26.4$	C=2.7 $\phi = 42.1$	C=2.7 $\phi = 42.1$	C=2.7 $\phi = 42.1$
Stage 9	C=0.2 $\phi = 13.5$	C=0.3 $\phi = 16.8$	C=0.4 $\phi = 22$	C=0.5 $\phi = 26.4$	C=2.7 $\phi = 42.1$	C=2.7 $\phi = 42.1$
Stage 10	C=0.0 $\phi = 29.2$	C=0.2 $\phi = 13.5$	C=0.3 $\phi = 16.8$	C=0.4 $\phi = 22$	C=0.5 $\phi = 26.4$	C=2.7 $\phi = 42.1$
Stage 11	C=0.0 $\phi = 29.2$	C=0.0 $\phi = 29.2$	C=0.2 $\phi = 13.5$	C=0.3 $\phi = 16.8$	C=0.4 $\phi = 22$	C=0.5 $\phi = 26.4$
Stage 12	C=0.0 $\phi = 29.2$	C=0.0 $\phi = 29.2$	C=0.0 $\phi = 29.2$	C=0.2 $\phi = 13.5$	C=0.3 $\phi = 16.8$	C=0.4 $\phi = 22$
Stage 13	C=0.0 $\phi = 29.2$	C=0.0 $\phi = 29.2$	C=0.0 $\phi = 29.2$	C=0.0 $\phi = 29.2$	C=0.2 $\phi = 13.5$	C=0.3 $\phi = 16.8$
Stage 14	C=0.0 $\phi = 29.2$	C=0.0 $\phi = 29.2$	C=0.0 $\phi = 29.2$	C=0.0 $\phi = 29.2$	C=0.0 $\phi = 29.2$	C=0.2 $\phi = 13.5$
Stage 15	C=0.0 $\phi = 29.2$	C=0.0 $\phi = 29.2$	C=0.0 $\phi = 29.2$	C=0.0 $\phi = 29.2$	C=0.0 $\phi = 29.2$	C=0.0 $\phi = 29.2$

*Note: The unit for Cohesion is MPa

Table 4. Variation of joint strength at each stage

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
Stage 1-9	E = 24750 C = 3.9 ϕ = 44 T = 0.9	E = 24750 C = 3.9 ϕ = 44 T = 0.9	E = 24750 C = 3.9 ϕ = 44 T = 0.9	E = 24750 C = 3.9 ϕ = 44 T = 0.9	E = 24750 C = 3.9 ϕ = 44 T = 0.9	E = 24750 C = 3.9 ϕ = 44 T = 0.9
Stage 10	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 24750 C = 3.9 ϕ = 44 T = 0.9	E = 24750 C = 3.9 ϕ = 44 T = 0.9	E = 24750 C = 3.9 ϕ = 44 T = 0.9	E = 24750 C = 3.9 ϕ = 44 T = 0.9	E = 24750 C = 3.9 ϕ = 44 T = 0.9
Stage 11	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 24750 C = 3.9 ϕ = 44 T = 0.9	E = 24750 C = 3.9 ϕ = 44 T = 0.9	E = 24750 C = 3.9 ϕ = 44 T = 0.9	E = 24750 C = 3.9 ϕ = 44 T = 0.9
Stage 12	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 24750 C = 3.9 ϕ = 44 T = 0.9	E = 24750 C = 3.9 ϕ = 44 T = 0.9	E = 24750 C = 3.9 ϕ = 44 T = 0.9
Stage 13	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 24750 C = 3.9 ϕ = 44 T = 0.9	E = 24750 C = 3.9 ϕ = 44 T = 0.9
Stage 14	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 24750 C = 3.9 ϕ = 44 T = 0.9
Stage 15	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 22620 C = 3.3 ϕ = 44 T = 0.7	E = 22620 C = 3.3 ϕ = 44 T = 0.7

*Note: The units for module of elasticity, cohesion and tensile strength are MPa

For the analysis, the unit weight of the rock was set to be 27 kPa and the Poisson ratio was assumed to be 0.3. The module of elasticity and also the strength parameters variation is given in Table 4.

3 Numerical Results

In order to capture the stability of the Zugspitze summit crest, we perform numerical analysis on RS3. This program uses the shear strength reduction method [3], in which, the strength parameters of both rock and joints will be reduced by a certain factor (SRF) and the stability of the slope will be examined. This process for MC material can be summarized here:

$$C_{srf} = \frac{C_{original}}{SRF};\ \tan(\phi_{srf}) = \frac{\tan(\phi_{original})}{SRF};\ T_{srf} = \frac{T_{original}}{SRF}$$

where C is the cohesion and ϕ is the angle of friction, The value of SRF will be updated until convergence won't be reached. The associated SRF value will be considered the critical SRF for the model.

The model was discretized by around 1.2 million 4-noded tetrahedral linear elements and the density of the mesh can be seen in Fig. 4-a. It's noteworthy to mention that the joint network was created with the DFN tool in the program which is under development and will be available in the commercial version very soon for all customers. This tool lets the user define the complex joint network in three dimensions and assign it to their model for numerical analysis.

In Fig. 4-(b-d), you can see the total displacement at the critical SRF value which can indicate the failure pattern in the slope. At the early stages, when the rock mass is fully frozen and the persistence of the joint network is less than 100%, a higher SRF value is expected. This has been confirmed in our analysis where the SRF at the second stage is 9.6. While the temperature is slowly rising, the strength of the rock and especially the joints would reduce (Table 2). When the ice is filled in the joints, the cohesion, and the friction angle would reduce, and a lower factor of safety is expected. In our analysis, we got a critical SRF of 3.6 in stage 6 (Fig. 4-c). This image demonstrates that the failure zone is approaching the outer surface, where the warming process occurs first, and where the joints have lower strength. Also, it can be seen that the initiation of shear failure started from the discrete joint (SZ), located on top of the crest. The warming

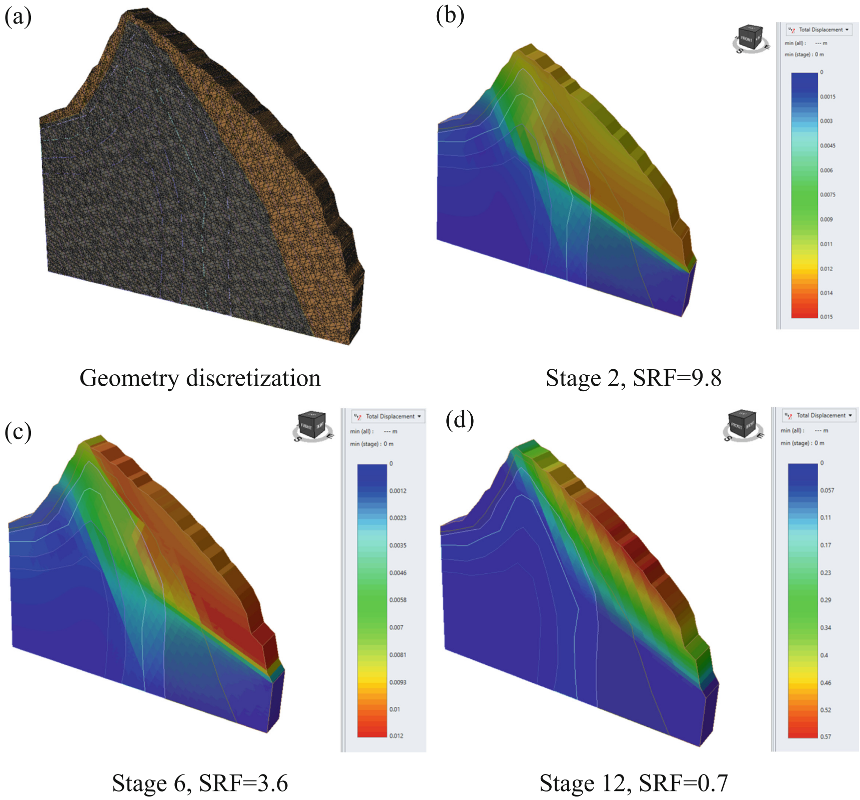

Fig. 4. Calculation of critical SRF for Zugspitze summit

process continues until the entire thawing progress has affected all layers. Based on our simulation, the factor of safety keeps reducing, while at stage 10, the critical SRF drops under 1.0 (SRF = 0.7) which indicates a safety hazard for the slope. As it is shown in Fig. 4-d, the failure is localized around the surface of the first layer. It is worth noting that, for all stages after stage 10, the factor of safety remains unchanged and the failure occurs on the third joint set, connected to the surface. In the end, we repeated the same analysis in RS2 and compared our results. The critical SRF and total displacement after the failure are presented for both programs, which shows a very close agreement between the calculated results (Fig. 5).

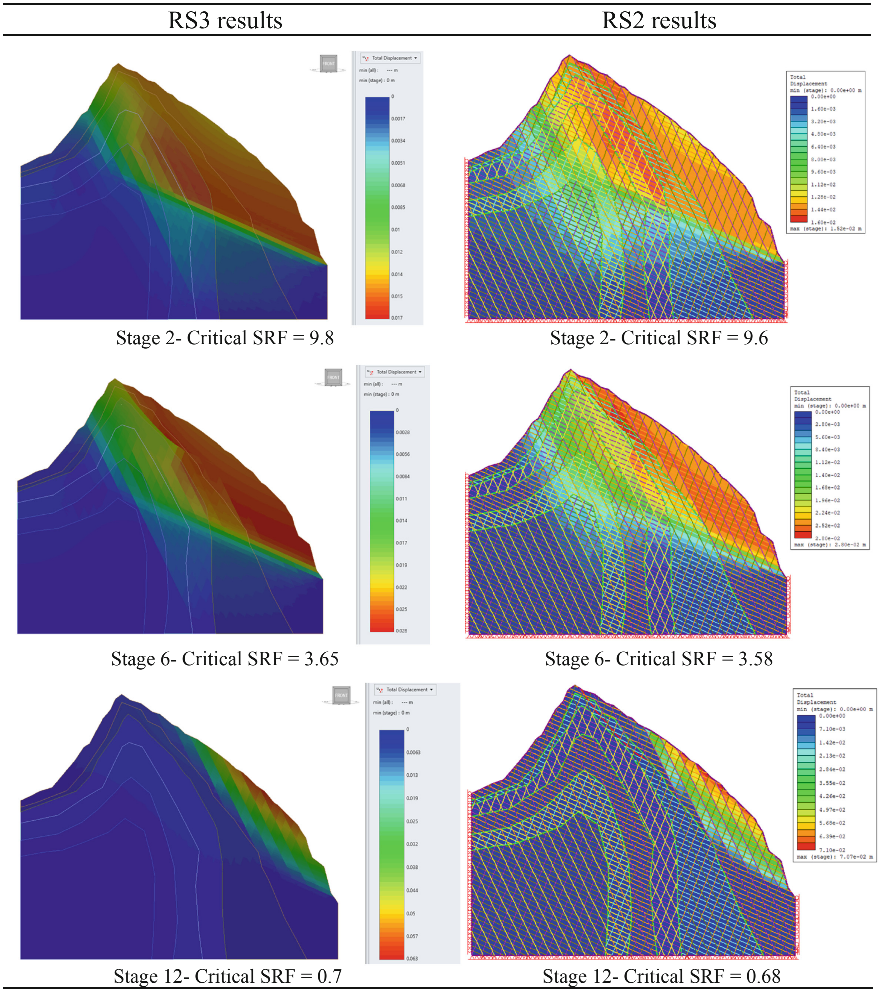

Fig. 5. Comparison of RS3 and Rs2 results

4 Summary and Concluding Remarks

This research involved an examination of the stability of the Zugspitze slope, utilizing RS3 to consider the effects of temperature on the rock mass. The slope's degradation was simulated by adjusting the rock strength properties and modifying the cohesion and frictional angle of the joints. In the first five stages of the analysis, the persistence of the joints was increased by reducing the strength of the joint sets. From stage 6 to stage 9, the warming process began, and the temperature of the outer layers gradually increased until thawing occurred, resulting in a low factor of safety. Very similar results and failure patterns have been observed from RS2 simulations.

References

1. Mamot, P.; Weber, S.; Eppinger, S.; Krautblatter, M. A temperature-dependent mechanical model to assess the stability of degrading permafrost rock slopes. *Earth Surf. Dyn.* **2021**, *9*, 1125–1151
2. Davies, M.C.; Hamza, O.; Hariss, C. The effect of rise in mean annual temperature on the stability of rock slopes containing ice-filled discontinuities. *Permafrost Periglac.***2001**, 12, 137-144
3. Hammah, R.E.; Yacoub, T.E.; Corkum, B.C.; and Curran, J.H. The shear strength reduction method for the generalized Hoek–Brown criterion. *American Rock Mechanics Association*, **2005**