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Thermal sensitivity of the residual shear strength: effect on slope stability

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ABSTRACT: Understanding and modelling the Soil-Vegetation-Atmosphere (SVA) continuum is challenging owing to the complex couplings among the mechanical, hydraulic, thermal, chemical, and biological domains. Our research examines the temperature dependence of the residual shear strength of the soil component, aiming to establish a foundational understanding in which bio-mediated interactions can be more accurately integrated. Our findings demonstrate a significant sensitivity of the residual shear strength of fine-grained soils to changes in temperature. This suggests that the factor of safety along pre-existing slip surfaces, especially at shallow depths, may vary seasonally and in the long term, responding with a temporal lag to surface temperature trends. Vegetation, through both its foliage and root systems, modulates this thermo-mechanical behaviour by affecting heat and moisture fluxes, as well as modifying the soil's intrinsic parameters. In alignment with the aims of the RootS network, our efforts will aim to quantify the influence of vegetation on thermally induced changes in soil strength, ultimately enhancing slope stability models within the broader SVA framework.

Keywords: thermo-hydro-mechanical coupling; slope stability; shear strength; temperature; clay

1 INTRODUCTION

The interaction between thermal, hydraulic, and mechanical processes in the shallow subsurface plays a key role in shaping the behaviour and stability of natural slopes and engineered earth systems. Rainfall, pore water pressure, and mechanical loading are well-recognised drivers of slope response, while the effect of temperature variations on soil behaviour has received less attention, particularly outside permafrost or wildfire conditions (Baillarget and Scaringi, 2025; Scaringi and Loche, 2022). Changes in temperature can modify the soil's hydro-mechanical parameters, including the residual shear strength. This is especially true in clay-rich materials, where temperature alters interparticle forces and pore fluid viscosity. Understanding thermo-hydro-mechanical (THM) coupling is becoming increasingly relevant as climate change alters ground thermal regimes and hydrological cycles, potentially modifying the stability and deformation patterns of near-surface materials. Knowledge of THM coupling is also essential for describing the complex interactions within the soil–vegetation–atmosphere (SVA) continuum. Vegetation introduces multiple feedback mechanisms: roots enhance soil strength and modify its structure; evapotranspiration regulates soil moisture and pore water pressures; and vegetation cover influences the soil's hydraulic conductivity, heat capacity, and thermal conductivity (Cecconi et al., 2025). These coupled effects govern the exchange of water and energy between the ground and the atmosphere, ultimately controlling the mechanical response of the shallow subsurface. Capturing such processes typically demands advanced, fully coupled frameworks that explicitly account for temperature-dependent hydraulic and mechanical behaviours, as well as chemical and biological effects (not addressed herein).

Here, we summarise an investigation of the dependence of the residual shear strength on temperature and its effect on slope-scale stability. The analysis is based on a model slope representing the Dubičná landslide in Czechia, an example of a clayey, slow-moving landslide in a temperate climate. Building on laboratory evidence, we carried out finite-element simulations to (i) assess the role of thermal sensitivity in slope response, (ii) explore the long-term implications of progressive warming, and (iii) evaluate the interaction between temperature-driven strength variations and groundwater fluctuations. These analyses provided a preliminary understanding of the slope response to temperature changes, which will be integrated into a thorough investigation of the SVA continuum in future research.

2 MATERIALS

A soil sample was taken from the shear zone of the Dubičná landslide in Czechia. The soil is plastic (PI = 39%) and rich in clay minerals (CF = 37%, mainly smectite + illite). The residual shear strength was investigated through temperature-controlled ring-shear tests conducted in a modified Bromhead apparatus that allowed control of the water bath's temperature (Dhakal et al., 2025; Loche and Scaringi, 2023). Experiments were performed on saturated specimens under constant normal stress and various rates of shearing. Two procedures were adopted. The first entailed separate tests at fixed temperatures (20, 70 °C) to determine the frictional strength at steady thermal conditions (Fig. 1). The second monitored the evolution of shear resistance within a single test, under slow shearing (v = 0.018 mm/min, ensuring drained conditions), while temperature was gradually varied, thus isolating the direct effect of temperature on the residual state (Kadlíček et al., 2025).

Results indicated an increase in strength with temperature. Linear interpolation of the experimental data yielded a relative rise in the residual friction angle of +0.2%/°C. This thermal sensitivity (α) was used in numerical simulations. Under low shear rates (v < 0.100 mm/min), heating-induced weakening is seen in clay-poor soils, while heating-induced strengthening is the usual response of smectite-rich soils (Shibasaki et al., 2017). Thus, alongside Dubičná soil, two materials with high α were considered for modelling. These display either thermally induced weakening or strengthening and define the observed limits for α (Table 1).

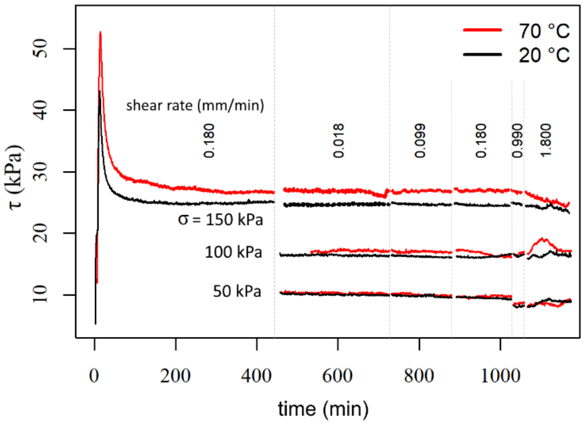


Figure 1. Effect of temperature on the residual shear strength of Dubičná marls: shear stress as a function of time and shear rate for two specimens, one tested at 20 °C and one at 70 °C

Table 1. Residual friction angle at T = 20 °C ($\varphi'_{res,0}$) and values of the thermal sensitivity parameter (α) of the selected soils (Kadlíček et al., 2025)

Soil	$\boldsymbol{\varphi'_{res,0}}$ **(°)**	$\boldsymbol{\alpha}$ **(%/°C)**
Dubičná marls	9.08	+0.2
Thermal strengthening soil*	3.38	+1.7
Thermal weakening soil*	12.24	-0.2

** from Shibasaki et al. (2017).*

3 MODELLING

Stability analyses were performed for the 1960s, the 2020–2023 period, and the 2060s. The evolution of ground temperature was simulated as follows.

i) For the 1960s, the surface thermal boundary condition was set as the average temperature of the 1960–1969 decade (8.2 °C). A geothermal gradient of 29 °C/km was given (Dědeček et al., 2022). The model was initialised by running it for thirty years until stable seasonal temperature oscillations were achieved (Fig. 2).

ii) Subsequently, the model was fed historical monthly temperatures until 2023. A one-year simulation was then performed using monthly average temperatures averaged over the 2020–2023 period, representative of present-day analyses.

iii) Finally, monthly average temperatures were simulated until 2060, using a trend of warming based on exponential extrapolation of historical data (1961–2023).

Ground surface warming at the site is substantial: from 8.2 °C in the 1960s to the current 10.5 °C, with a projected increase to >13 °C in the 2060s.

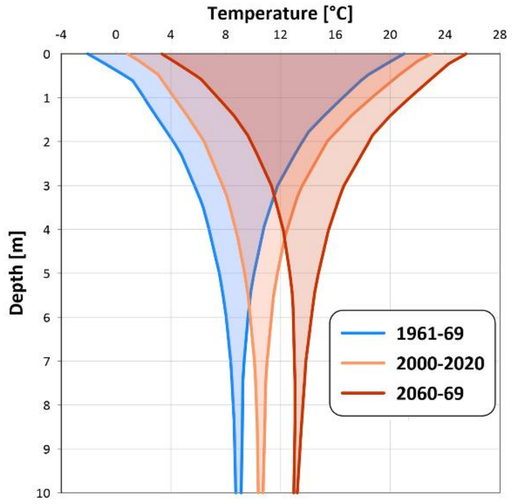


Figure 2. Impact of climate change on ground temperature profiles (envelopes of monthly-averaged values)

Thermal conductivity (λ_s) and specific heat capacity (c_s) were back-calculated to capture heat propagation and temperature changes with depth and time. Note that actual field conditions (partially saturated topsoil over saturated layers) were approximated by assuming constant λ_s and c_s with depth, a reasonable assumption for Dubičná soil. Constant values reproduced observed temperature profiles well (Fig. 3). Calculated ground temperatures for various λ_s values were compared with measurements (Fig. 3) to find a best fit.

An idealised slope was modelled in PLAXIS 2D (Fig. 4). The geometry reproduced the main features of the Dubičná landslide, with an inclination of 7.6° and a shear zone parallel to the ground surface at a depth of 5 m. Variants with deeper (7 m) and shallower (3 m) shear zones were also considered. Both the landslide body and substrate were treated as linear elastic materials, while the shear zone was represented by a user-defined temperature-dependent Mohr–Coulomb model, where $\varphi'_{res,0}$ varied linearly with temperature via the thermal sensitivity coefficient α, allowing simulation of both thermal strengthening (α > 0) and weakening (α < 0) (Table 1). Stability analyses were performed with the strength reduction method for three time windows (the 1960s, 2020–2023, and 2060s). Monthly average temperatures were imposed as boundary conditions at the surface to simulate seasonal and long-term temperature fluctuations. The factor of safety (FS) was computed for each month, and solver settings were refined to ensure numerical convergence and capture subtle temperature-driven variations in FS.

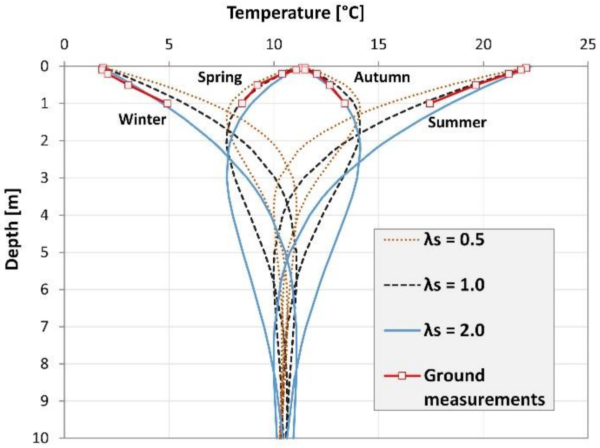
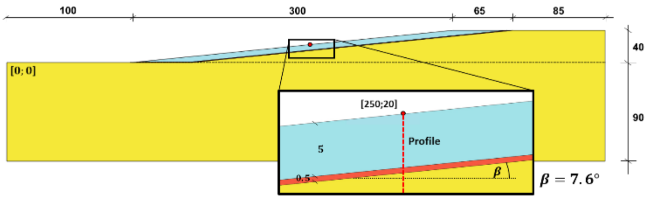


Figure 3. Comparison of model predictions of ground temperature profiles for three values of thermal conductivity λ_s (W/(m·K)) and one value of heat capacity c_s = 800 kJ/(m^3·K) vs. ground measurements at a nearby meteorological station for the period 2000–2020



Layer	γ (kNm^{-3})	G (kNm^{-2})	υ (-)	$\varphi'_{res,0}$ (°)	c (kPa)	ψ (-)
Landslide	18.0	11.49·10^3	0.2	-	-	-
Substrate	18.0	120·10^3	0.2	-	-	-
Shear zone	18.0	5.32·10^3	0.2	9.0	0.0	0.0
Shear zone toe	18.0	5.32·10^3	0.2	9.0	5.0	0.0

Figure 4. Slope geometry (units: m) and material parameters

4 RESULTS

A representative numerical result is shown in Fig. 5 for α = +1.7%/°C. This value refers to the response of very active, smectitic clays under slow shearing (Shibasaki et al., 2017). It is worth noting that, in order to compute a value of FS close to 1, the residual friction angle of the Dubičná soil (~9°; Table 1) was used in all simulations regardless of the chosen α.

The analysis shows a significant increase in stability regardless of the shear zone depth. In particular, the trend in Fig. 5 corresponds to a landslide initially exhibiting seasonal reactivation (represented numerically by the FS periodically dropping below 1) and then transitioning to year-long stability (FS > 1 year-long) because of ground warming. Stability envelopes for soil exhibiting less thermal strengthening (Dubičná soil) or even weakening are displayed in Fig. 6. Note that these analyses assume no changes in the slope's hydraulic regime.

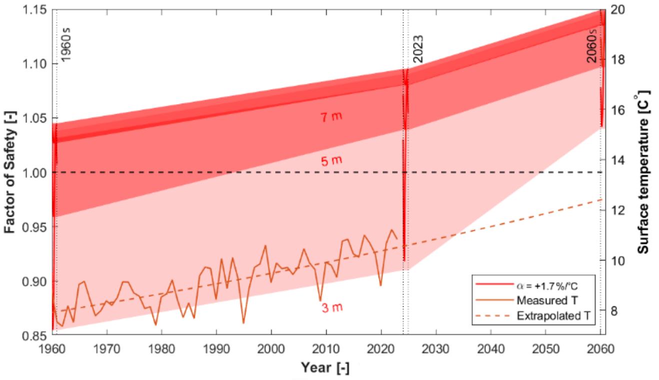


Figure 5. Envelopes of FS for the 1960s, 2020–2023, and 2060s for α = +1.7%/°C and shear zone depths of 3, 5, and 7 m. Measured air temperature fluctuations (monthly-averaged) are given for reference

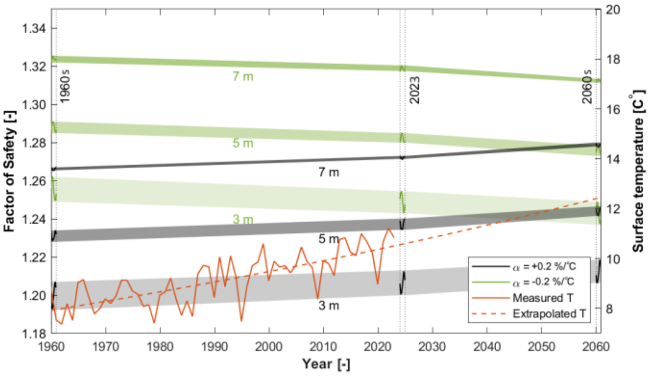


Figure 6. Same as in Fig. 5 but with α = ±0.2 %/°C

The influence of groundwater table depth was examined for 2020–23 for a 5-m deep shear zone. A benchmark analysis, yielding a constant FS, was performed without considering the effect of temperature (case B in Fig. 7). The analysis assumed a dry slope and used the value of $\varphi'_{res,0}$ evaluated in the laboratory at T=20°C, without any correction for the actual ground temperature (following the typical workflow in conventional analyses). The effect of temperature fluctuations alone (with α = +1.7 %/°C) is represented by case T, where no groundwater was considered but thermal properties remained the same as the back-calculated ones, to allow direct comparison with the coupled case (described below). Notably, while surface temperatures peak in July-August, FS peaks in October-November: a lag of about four months. The minimum FS is recorded in May. All FS values in case T lie below the FS value of the benchmark case. In case W, we show the effect of groundwater table fluctuations on FS in absence of temperature fluctuations. This effect is synchronous: in April, as pore water pressures are at their peak, the lowest FS is attained, while the highest FS is seen in October. Overall, groundwater fluctuations play a lesser role in slope stability compared to the temperature effects for this choice of α. Finally, case T+W captures the combined effect of a temperature-dependent strength and groundwater depth changes. Here, a much lower FS value is computed (FS = 0.806), that is 0.351 less than the benchmark case. This decrease is larger than the sum of the individual effects (W and T cases), i.e., 0.149 and 0.197, respectively. Coupled analyses with α = +0.2 %/°C and α = -0.2 %/°C (not shown) display less pronounced temperature effects; in these cases, groundwater fluctuations play a dominant role.

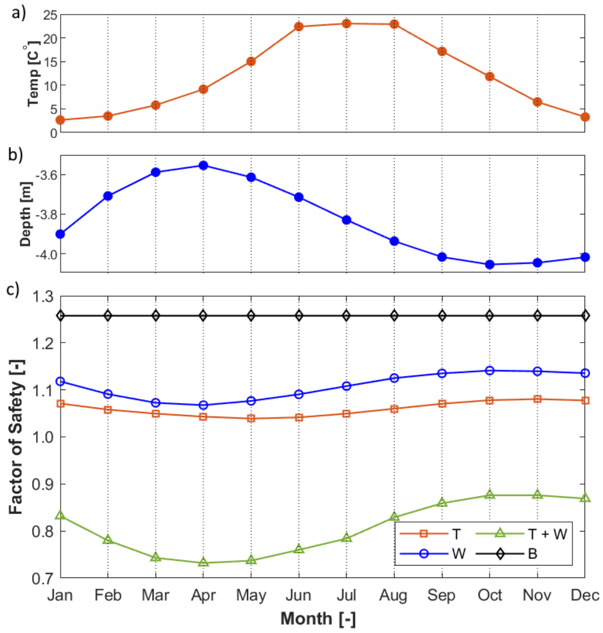


Figure 7. Stability analyses for 2020-23, with a shear zone at a depth of 5 m and α = +1.7 %/°C. (a) Monthly-averaged surface temperature; (b) groundwater table depth; (c) FS. In case B, slope stability is computed in dry condition at T = 20 °C; case T considers the influence of ground temperature on φ'_r*; W accounts for changes in groundwater depth; T+W is the coupled case*

5 CONCLUSIONS

Our study shows that temperature-sensitive soils (α ≠ 0) can exhibit measurable variations in FS due to both seasonal and long-term ground temperature changes. In thermally weakening soils (α < 0), rising temperatures may induce instability through purely thermo-mechanical effects, whereas in thermally strengthening soils (α > 0), warming can enhance stability. When α is small (e.g., α = ±0.2 %/°C), groundwater fluctuations may dominate the response.

In slow-moving landslides, where FS≈1, small increases in available resistance may significantly reduce movement. The nonlinear interaction between temperature and groundwater effects cannot be captured by linear superposition, emphasising the need for coupled modelling. Although most studies predict more frequent landslides under intensified hydro-meteorological forcing, they rarely consider that warming may raise the stability baseline of clay-rich slopes.

Incorporating vegetation will add further complexity to modelling, as vegetation influences heat fluxes, moisture, and strength through coupled physical and biological processes. Moreover, shifts in vegetation dynamics induced by climate change may substantially alter these feedbacks. Capturing such interactions requires coupled soil–vegetation–atmosphere frameworks that integrate biological variability with THM processes—a major challenge that remains largely unresolved in current modelling efforts.

6 ACKNOWLEDGEMENTS

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