

Influence of thermo-mechanical coupling on the stability of shallow landslides

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ABSTRACT: Temperature variations within the typical range experienced in temperate climates are known to influence the shear strength of clay soils, with the effect depending on factors such as soil mineral composition, confining stress, and shear rate. Seasonal temperature fluctuations and long-term climatic trends propagate from the atmosphere into the ground, attenuated and delayed with depth. In the first few metres—more susceptible to landslides than deeper layers—seasonal fluctuations of 2–5 °C are common in temperate regions. This contribution presents a numerical model of slope stability that incorporates temperature-dependent soil strength, calibrated from ring-shear experiments. A simple case study is introduced, which exemplifies the condition of many slow-moving landslides in clayey soil in the Czech Republic. Based on experimental characterisation, this soil demonstrates thermal strengthening when subjected to slow shearing in the residual state. As a result, the stability analysis predicts seasonal variations in the factor of safety, delayed by several months relative to atmospheric temperature fluctuations. It also indicates a gradual increase in stability over the years as the climate warms; consequently, some landslides might shift from seasonal remobilisations to a stable, year-round condition. Accounting for thermal strengthening of clayey soil could improve the accuracy of assessments of shallow slope stability and landslide susceptibility in future climate scenarios.

KEYWORDS: slope stability, residual shear strength, thermo-mechanical coupling, clay, landslide, temperature.

1 INTRODUCTION

Landslides are a major natural hazard whose frequency and severity are affected by climate change. Rainfall, seismic activity, and land-use modifications are recognised factors that contribute to slope instability (Lacroix et al., 2020). However, the processes behind landslide initiation and remobilisation are not always straightforward, as they can involve a combination of various factors, some less well understood than others. The influence of ground temperature, in particular, has often been overlooked in cases that do not involve extreme temperature conditions (Scaringi & Loche, 2022).

Climate change-driven ground warming influences the soil's mechanical response through thermo-mechanical coupling. Specifically, temperature affects the residual shear strength (Shibasaki et al., 2017; Garcia et al., 2023; Kohler et al., 2023; Loche & Scaringi, 2023; Dhakal et al., 2025), a crucial parameter in reactivated landslides. Clay minerals are especially sensitive to temperature variations due to their structure, which is governed by interparticle forces and solid skeleton-pore fluid interactions. Understanding thermo-hydraulic and thermo-mechanical impacts on slope stability can help refine modelling tools, risk assessments, and strategies for risk reduction (Loche et al., 2022b; Loche & Scaringi, 2025).

This note offers insights into how a temperature-dependent shear strength can affect the stability of a landslide mass moving over a slip zone in residual shear condition. The focus is on a model slope representative of the Dubičná landslide in the Czech Republic, which is also considered typical of slow-moving landslides in clay soils within temperate climates. The simulations were also aimed at identifying the combined effect of ground warming and water table fluctuations.

2 MATERIALS

2.1 Dubičná marls

A soil sample was taken from the shear zone of the Dubičná landslide. The material, known as Dubičná marls, belongs to the Březno Formation, a typical lithology where landslides are common in the Czech Republic (Roháč et al., 2020). It exhibits a liquid limit $w_L = 67\%$, plastic limit $w_P = 28\%$, and plasticity index $PI = 39\%$. It consists of 37% clay, 50% silt, and 13% sand particles and contains 30% illite and 5% smectite.

Ring-shear tests were conducted on reconstituted specimens in a modified Bromhead-type apparatus fitted with a temperature control system, consisting of a thermostatic bath that transfers heat to the apparatus's water bath via a closed pipe loop (Loche & Scaringi, 2023). To evaluate the effect of temperature on the residual shear strength ϕ_r , results from independent experiments were compared, carried out either at 20 °C or 70 °C (Figure 1). Shearing was first performed at a rate $v = 0.18$ mm/min until the residual shear condition was attained. Then, slower shearing at $v = 0.018$ mm/min was carried out to ensure a fully drained condition. Higher rates were also explored but are not considered herein. The specimen was then consolidated under another normal stress, and shearing was repeated to build a failure envelope. Assuming a linear dependence between temperature and residual shear strength, a thermal sensitivity coefficient $\alpha = +0.2$ %/°C was evaluated. This coefficient is defined as the percentage variation in residual shear strength per 1 °C change in temperature from the baseline value at 20 °C.

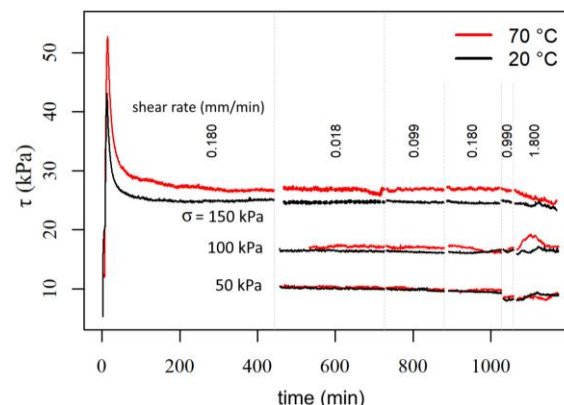


Figure 1. Ring-shear experiments on specimens of Dubičná marls, carried out at 20 °C or 70 °C.

2.2 Other reference materials

Two additional soils with the most pronounced thermal sensitivity were selected (Shibasaki et al., 2017), one expressing strengthening and one weakening (Table 1). For the numerical simulations, the ϕ_r values at $T = 20$ °C for these soils were scaled to match the strength of the Dubičná marls and allow comparisons.

Table 1. Residual friction angle and thermal sensitivity of the studied soils. Sh-TS and Sh-TW exhibit the largest thermal strengthening and weakening, respectively, according to Shibasaki et al. (2017).

Soil	φ_r at $T = 20$ °C (°)	α (%/°C)
Dubičná marls	9.08	+0.2
Sh-TS	3.38	+1.7
Sh-TW	12.24	-0.2

3 NUMERICAL MODELLING

3.1 Landslide characteristics and modelling

A simplified geometry was established in Plaxis 2D (Figure 2). The slope inclination $\beta = 7.6^\circ$, surface geometry, shear zone depth, and landslide length were selected to resemble those of the Dubičná landslide. This slow-moving, reactivated landslide is situated in the Central Bohemian Highlands in the Czech Republic, on a southwest-facing slope at an elevation of approximately 300 m above sea level. It is about 500 m long and develops in high-plasticity Cretaceous marlstones. The landslide thickness of 5 m is controlled by the depth of a layer of altered green marls. The shear zone defining the landslide body runs parallel to the ground surface.

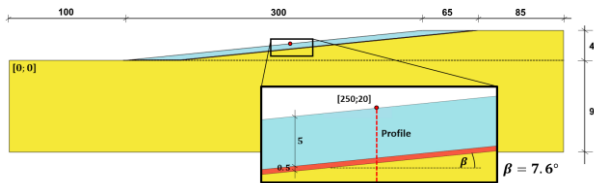


Figure 2. Finite-element model geometry for the model version with a 5 m-deep shear zone. Model dimensions are in metres. A reference vertical profile is indicated.

In the numerical model, the landslide body (in cyan in Figure 2) was given a thickness of 3, 5, or 7 m. Both this layer and the underlying marlstones (in yellow) were simulated with a linear elastic constitutive model. In between them, the 0.5 m-thick shear zone was modelled with a temperature-dependent Mohr-Coulomb model. The friction angle was assumed to change linearly with temperature, as follows:

$$\varphi_r(T) = \varphi_{r,20^\circ\text{C}}[1 + \alpha(T - 20)] \quad (1)$$

In the equation, T is in °C. The other parameters were calibrated using *ExCalibre* (Kadlíček et al., 2022). The stiffness of the marlstone substrate was assumed to be much higher than that of the landslide body (Table 2). To improve numerical stability and avoid local failure mechanisms, an additional material (shear zone toe) characterised by some cohesion was introduced.

Table 2. Material parameters used in the numerical simulations.

Parameter	Landslide body	Shear zone	Shear zone toe	Substrate
γ (kN/m ³)	18	18	18	18
G (kN/m ²)	11,490	5,320	5,320	120,000
ν (-)	0.2	0.2	0.2	0.2
φ_r (°)	-	9.08	9.08	-
c (kPa)	-	0.0	5.0	-

3.2 Thermal parameters and ground temperature

Thermal conductivity λ_s and specific heat capacity c_s were back-calculated to reproduce heat propagation and the spatial and temporal changes of temperature in the ground. Although convection and groundwater flow can influence both the depth

and amplitude of temperature fluctuations, their effect should be small in low-inclination slopes and fine-grained soils. In the simulations, a steady-state hydraulic regime was considered, with the ground remaining fully saturated up to the surface. In a benchmark simulation, a dry soil condition was also considered. The situation in the field can be complicated by a partially saturated topsoil and a water content that varies with depth. However, for the Dubičná marls, these effects should not play a significant role at the shallow depths considered. Constant values of λ_s and c_s were thus assumed, and these allowed for reproducing the observed temperature profiles well (Figure 3). For this calibration, two datasets from the Doksany meteorological station, 22 km southwest of Dubičná, were used. These included daily air temperature data (1960–2023) and ground temperature measurements (0.05–1.0 m), available as seasonal averages for 2000–2020 (Potopová et al., 2021). The same measurements were also used to evaluate the difference between air and ground surface temperatures, which were then used as boundary conditions in the numerical simulations.

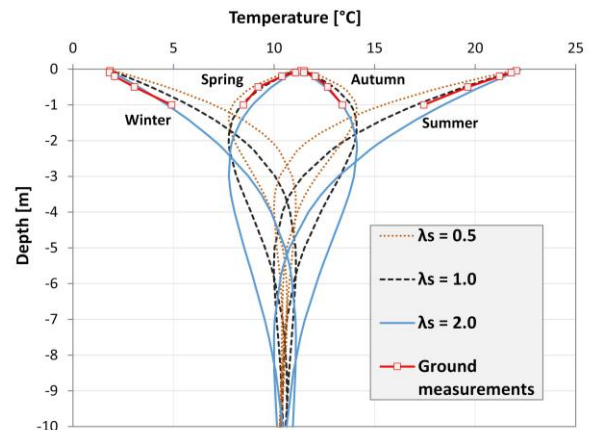


Figure 3. Comparison of model predictions of ground temperature along a reference vertical profile for thermal conductivity $\lambda_s = 0.5, 1.0, 1.5$ W/(m·K) and heat capacity $c_s = 800$ kJ/(m³·K) and ground measurements for the period 2000–2020.

Stability calculations were conducted for three periods: the 1960s, 2020–2023, and 2060s. For the 1960s, the average temperature of the decade 1960–1969 (8.21 °C) was assigned, with a geothermal gradient of 29 °C/km. Thirty years of temperature oscillations were then simulated using 1961–1969 average monthly temperatures to obtain a steady-state temperature profile. After this initialisation, the model was run continuously using historical monthly temperatures until 2023 to simulate long-term thermal evolution. A one-year simulation was performed with the monthly average temperatures over the 2020–2023 period. Finally, monthly average temperatures were simulated until the 2060s, considering the long-term temperature increase evaluated from the historical data (1961–2022).

The influence of progressive warming on ground temperature profiles, according to data from the Doksany station, is shown in Figure 4. At a depth of 10 m, where seasonal temperature fluctuations are almost completely attenuated, the average ground temperature increases from 8.87 °C in 1961–1969 to 10.51 °C in 2000–2020 and 13.04 °C in 2060–2069. At the depth of the landslide shear zone in Dubičná (5 m), the ground temperature rises from 8.76 °C in 1961–1969 to 10.54 °C in 2000–2020 and 13.67 °C in 2060–2069, with a warming of almost 5°C in one century.

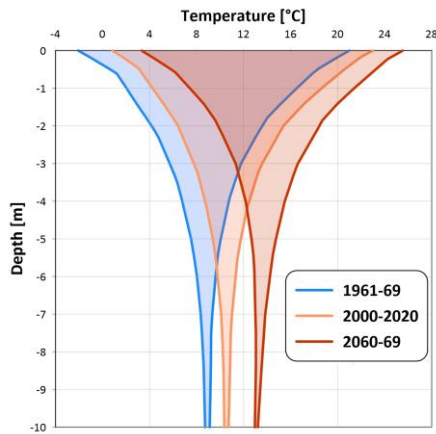


Figure 4. Impact of climate change on ground temperature profiles (first 10 m, envelopes of monthly-averaged values, Doksany station).

3.3 Numerical fluctuations

Because of the small values of α and the small annual temperature fluctuations (less than 1 °C at 7 m depth), the default solver settings in Plaxis 2D had to be adjusted (Table 3) in order to quantify changes in the factor of safety (FS).

Table 3. Settings for the iterative solver in Plaxis 2D.

Solver parameter	Default	New setting
Over-relaxation	1.2	0.8
Error tolerance	0.01	0.001
Maximum number of steps	100	1000

FS can fluctuate in a finite-element stability analysis because of small force imbalances. This fluctuation is more pronounced with the increased non-associated flow rule of the Mohr-Coulomb model. Higher numerical precision can reduce FS fluctuations, and smaller over-relaxation can reduce the chance of overshooting. However, remaining small fluctuations can still affect the model's output (Figure 5). Thus, the average of the minimum and maximum FS values in a numerical cycle was taken as the representative value for the given analysis.

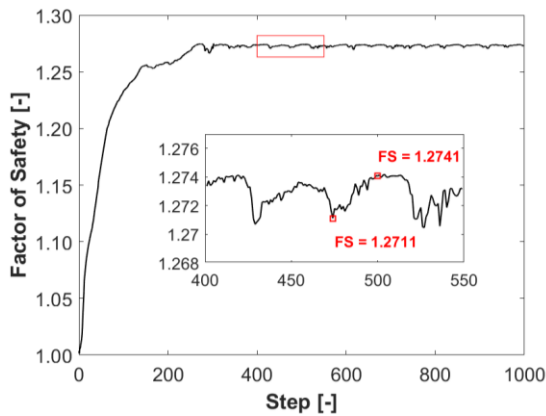


Figure 5. Evolution of the factor of safety in a stability calculation.

4 RESULTS

4.1 Effect of temperature on slope stability

Calculations were done for each month in the three selected periods, using three values of α (Table 1) and three shear-zone depths (3, 5, and 7 m). Figure 6 displays how rising temperatures in the ground affect FS for the case with $\alpha = +1.7$ %/°C. This value is representative of smectite-rich clays subject to slow shearing. The calculations suggest improved stability,

with FS at any depth increasing by over 0.1 and becoming higher than 1 yearlong. This case represents a landslide initially undergoing seasonal reactivation and subsequently becoming stable because of ground warming. Stability envelopes for soil exhibiting mild thermal strengthening (Dubičná marls) or weakening are shown in Figure 7. These analyses do not account for possible changes in the slope's hydraulic regime.

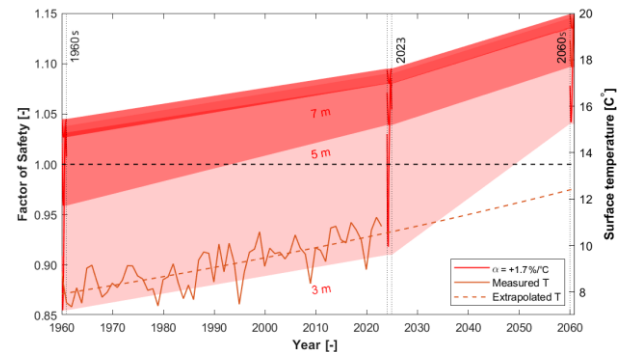


Figure 6. FS envelopes (red solid lines) for the 1960s, 2020–23, and 2060s for $\alpha = +1.7$ %/°C. Monthly-averaged measured air temperature values are also shown (brown solid line).

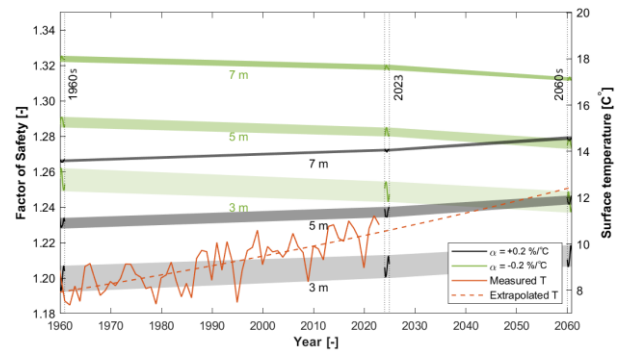


Figure 7. Same as in Figure 6 but for $\alpha = \pm 0.2$ %/°C.

4.2 Combined effect of temperature and water table

The role of groundwater table depth was investigated for 2020–23, for a shear zone depth of 5 m. A benchmark stability analysis without temperature and groundwater effects was first performed (case B in Figure 8), which yielded a constant FS because a constant ϕ_r value at $T = 20$ °C was considered. The effect of temperature alone, with $\alpha = +1.7$ %/°C, is represented by case T. 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. The effect of groundwater table fluctuation on FS is synchronous (case W). In April, as pore water pressures are at their peak, the lowest FS is attained, while the highest FS is reached in October. Overall, groundwater fluctuations play a less dominant role in slope stability compared to the temperature effects for this choice of α .

Case T+W in Figure 8 captures the combined effect of a temperature-dependent strength and groundwater fluctuations. While the individual effects of groundwater and temperature result in average FS values of 1.108 and 1.060, respectively, their combined influence yields a significantly lower average FS of 0.806, representing a decrease by 0.351 compared to the benchmark case. Notably, this decrease is larger than the sum of the individual effects (W and T cases), amounting to 0.149 and 0.197, respectively. Coupled analyses with $\alpha = +0.2$ %/°C and $\alpha = -0.2$ %/°C (not shown) display much less pronounced temperature effects; in these cases, groundwater fluctuations play a dominant role.

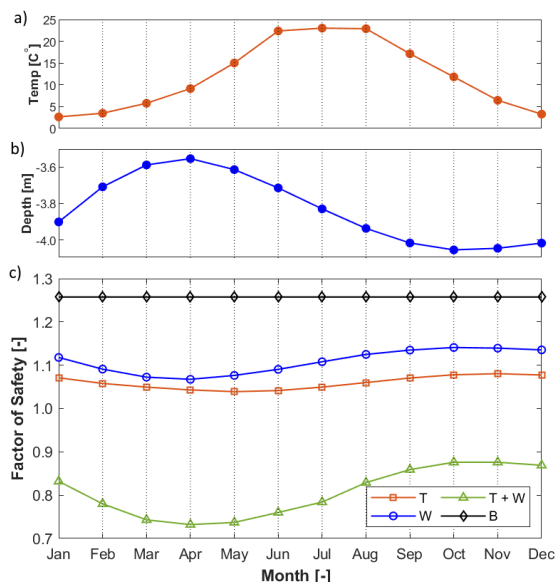


Figure 8. Results of stability analyses for 2020-23, with a shear-zone depth of 5 m and $\alpha = +1.7 \text{ } \%/^{\circ}\text{C}$. (a) Monthly-averaged surface temperature; (b) groundwater table depth; (c) FS. In case B, slope stability is computed in dry condition at $T = 20 \text{ } ^{\circ}\text{C}$; case T accounts for the influence of ground temperature on ϕ_i ; W considers the effect of groundwater depth on the effective stress; T+W is the coupled case.

5 DISCUSSION AND CONCLUSIONS

This study suggests that measurable changes in the slope's factor of safety can be assessed in temperature-sensitive soils ($\alpha \neq 0$) subjected to both seasonal and long-term temperature changes propagating from the surface into the ground. In soils exhibiting thermal weakening ($\alpha < 0$), rising temperatures might induce slope instability via a purely thermo-mechanical mechanism under climate change. Vice versa, in soils displaying thermal strengthening ($\alpha > 0$), such as illite- and smectite-rich clay soils, the ongoing warming might improve stability. However, if thermal sensitivity is small (such as in the studied case of $\alpha = +0.2 \text{ } \%/^{\circ}\text{C}$), groundwater fluctuations might override the effect of an increasing temperature.

The factor of safety of active slow-moving landslides fluctuates around $FS = 1$, and their velocity can vary remarkably with FS varying by just a few percent (Di Maio et al., 2015). In this situation, even a small strengthening (e.g., for $\alpha = +0.2 \text{ } \%/^{\circ}\text{C}$) might suppress landslide movement.

Nonlinear coupling of thermal and hydraulic effects cannot be estimated by linear addition, emphasising the need for thermo-hydro-mechanically coupled modelling. Notably, most studies in the literature predict enhanced landsliding in response to the ongoing changes in hydro-meteorological forcing; however, they do not consider the possibility of a more stable baseline condition in clay-rich soils associated with a warmer ground.

Overlooking the soil's thermal sensitivity can also produce a mismatch between back-calculated and actual slope stability conditions. Further mismatch can arise from the difference in temperature between field conditions and the laboratory. Sampling and testing undisturbed samples from the landslide's shear zone, wherever possible, is greatly beneficial in slope stability evaluations, but only as long as appropriate testing conditions (temperatures, pore water compositions, effective stresses) are ensured.

On a larger scale, where data from soil cores are too coarse, mechanical parameters can be estimated from soil composition data or derived from infrared (Loche et al., 2022a) or hyperspectral remote sensing products by analysing the

minerals' spectral signatures. At this scale, however, implementation of fully-coupled thermo-hydro-mechanical models is unfeasible, owing to the required experimental calibration of many parameters (Jerman & Mašin, 2021) and insufficient information on boundary conditions. Nevertheless, a simplified approach remains possible by generating thermal sensitivity maps via empirical correlations with soil compositional data and computing FS correction maps according to temperatures and shear zone depths. These maps could support decision-makers in landslide hazard reassessments in clay-rich landslide areas.

6 ACKNOWLEDGEMENTS

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