Temperature and rate effects on the residual shear strength of clays: a state of the art

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Abstract The temperature within a landslide's shear zone can undergo changes due to internal processes such as frictional heating and chemical reactions – the magnitude of which can be particularly relevant during fast runout phases in large landslides. Alterations in boundary conditions, including heat transfer from the bedrock or ground surface, but also groundwater flows and changes in vegetation cover can contribute to these temperature variations, over timeframes especially relevant to shallow, slow-moving landslides. The hydro-mechanical properties of soils, particularly those rich in clay minerals, exhibit dependency on temperature. Studies indicate that the residual shear strength, a crucial parameter in reactivated landslides, can vary significantly within typical temperature ranges in landslide shear zones in temperate climates. The literature also highlights the influence of the rate of shearing on the shear strength parameters of soils, including the residual shear strength, with the soil's mineral composition controlling rate strengthening and weakening behaviours in slow to rapid landslides. This contribution summarises the state of knowledge and presents recent findings from ring-shear experiments which indicate the coupled nature of temperature- and rate-dependence of the residual shear strength, which may play a substantial role especially in shallow clay landslides. This influence is particularly noteworthy in the context of climate change, emphasizing the need for explicit consideration in modeling efforts.

Keywords residual shear strength, rate effect, temperature effect, thermo-mechanical coupling, clay, landslide

Introduction

Climate change is a multifaceted and profoundly disruptive phenomenon. It is imperative to comprehend the physical processes driving these disruptions, manifested in various ways such as natural disasters, in order to mitigate the impacts of climatic changes at both local and global levels. Landslides frequently play a crucial role in natural disaster chains and are significantly influenced by the effects of climate change (Gariano and Guzzetti, 2016).

Slope stability is typically explained through mechanical equilibrium and hydraulic flow equations. Models can effectively consider disturbances caused by seismic activity, earthworks, variations in moisture content, and fluid pressure. Soils rich in clay are particularly prone to slope instability due to their low frictional resistance and increased interaction with water. Under compression and shearing, these soils deform easily, resulting in smooth surfaces that facilitate preferential sliding with minimal resistance.

The notion of residual shear strength originated from the experimental studies of Tiedemann, Haefeli, and Hvorslev in the 1930s, and MacNeil Turnbull in the 1950s. However, it was Skempton who synthesized these findings in his Rankine Lecture (Skempton, 1964).

Effect of temperature on the hydro-mechanical behaviour of clays

Clay soils exhibit sensitivity to temperature changes, with their hydro-mechanical properties significantly influenced by temperature (Scaringi and Loche, 2022). Beyond the effects of water phase changes on volume, stiffness, and hydraulic conductivity, this thermal sensitivity is noteworthy even within the temperature range of liquid water under atmospheric pressure. While research on thermo-hydro-mechanical coupling in clays dates back to the 1960s (e.g., Mitchell, 1969), its early findings did not impact norms and engineering practices. Recent developments in energy geotechnics and studies on engineered clay barriers (ECBs) for geological repositories of spent nuclear fuel have brought attention to thermal effects in geomaterials.

It is now recognized that temperature changes can influence internal stresses and water pressures, initiating flows and strains through intricate, coupled mechanisms. The expansion differences between water and clay minerals upon heating result in changes in water pressure. As temperature increases, physico-chemical interaction interparticle forces alter, with water becoming less viscous and more electrically conductive, and clay surfaces losing their capacity to retain water. Heating-cooling cycles in soft soil may lead to stiffening and, unexpectedly, net shrinkage (Tang et al., 2008), while the reverse is true in overconsolidated soil.

The influence of temperature on shear strength is not critical in domains experiencing small strains, such as in the ECB problem, leading to limited research in this area (Scaringi and Loche, 2022; Loche et al., 2021, 2022). Whether shear strength increases or decreases with temperature depends on soil nature and structure, shaped by its stress-strain-thermal history. Residual shear strength (τr), commonly found in landslide shear zones after large strains, remains unaffected by soil history, making the evaluation of its thermal sensitivity more straightforward. However, there is a scarcity of literature on such assessments. In a notable study, the remobilization of clay landslides was attributed to cooling-induced soil weakening (Shibasaki et al., 2017), supported by experiments emphasizing the significance of shearing rate and suggesting distinct effects in slow and fast movements, an area largely unexplored to date.

Temperature – shear-rate coupling

The phenomenon of velocity-weakening has been a focal point in the study of long-runout landslides (especially large rock avalanches), as elucidated by Scaringi et al. (2018). Various mechanisms have been proposed to account for this phenomenon, with most emphasizing the dissipation of frictional heat in the shear zone, where elevated temperatures may be reached. In the realm of slow-moving landslides, the role of frictional heating is minimal, given that heat conduction and convection effectively curtail temperature growth. Consequently, processes dependent on temperature are not typically anticipated in such scenarios.

Nevertheless, factors influencing temperature variation exist, both internal and external. Internally, this can involve endothermic or exothermic chemical and biological processes. Externally, linked to changing boundary conditions, both direct and coupled flows contribute to heat transfer. For example, groundwater flow not only influences pore water pressures but also impacts the thermal energy balance. Despite the plethora of processes potentially altering temperature patterns within the ground and thereby affecting hydraulic and mechanical properties, little attention has been devoted to incorporating these considerations explicitly in landslide studies and most geotechnical problems (Scaringi and Loche, 2022).

Concerning the shearing behavior, the outcomes of shear experiments across a wide spectrum of normal stresses (typical of shallow to deep-seated landslides), shear rates (typical of extremely slow to rapid landslides), experimental setups, and soil compositions are often intricate and occasionally challenging to interpret comprehensively (Scaringi et al., 2018a; Scaringi and Di Maio, 2016). The introduction of temperature adds an additional layer of complexity to the interpretation of these experiments. In a recent review, we underscored the existence of a diverse literature on temperature effects in geomaterials, albeit lacking systematicity and clear field evidence (Scaringi and Loche, 2022).

Modelling thermo-hydro-mechanical behaviour

Traditional slope stability models typically consider only hydro-mechanical coupling, neglecting thermal effects. However, more advanced model formulations, initially developed for other applications like engineered clay barriers modeling, explicitly incorporate thermo-hydro-mechanical processes (Mašín, 2017). Despite their potential, these models have not yet been adapted or further developed for landslide applications. Their usage remains confined to small-scale domains due, in part, to computational complexities.

In the absence of a modeling tool and comprehensive understanding of thermal sensitivity, one might assume that anticipated changes in slope stability in temperate regions under climate change primarily result from altered hydrological inputs. This perception is somewhat justified by the soil's heterogeneity acting as a "dampening role" and temperature fluctuations diminishing at greater depths. However, a thorough examination of the literature (Scaringi and Loche, 2022) reveals that recent studies tend to consider thermal effects as negligible, dismissing the need for investigation. Similar qualitative conclusions can be found in various studies (e.g., Cekerevac and Laloui, 2004). Yet, a quantitative argument either supporting or neglecting the temperature-shear strength dependence systematically, especially in specific conditions like clay-rich formations, pre-existing landslide bodies, or shallow movements, is currently lacking.

Results of recent research and perspectives

In our current research (e.g., Loche and Scaringi, 2023), our goal is to evaluate, quantitatively, the role of changes in temperature in the kinematics of landslides in clay soils. In particular, we are interested in changes in the available (or mobilised) shear resistance in basal shear zones, especially in landslide bodies for which changes in the top boundary condition (ground-atmosphere interaction) produce a measurable effect over a seasonal timescale. In a numerical simulation, we indeed reproduced the seasonal changes in in temperature in shallow landslide bodies (Fig. 1).

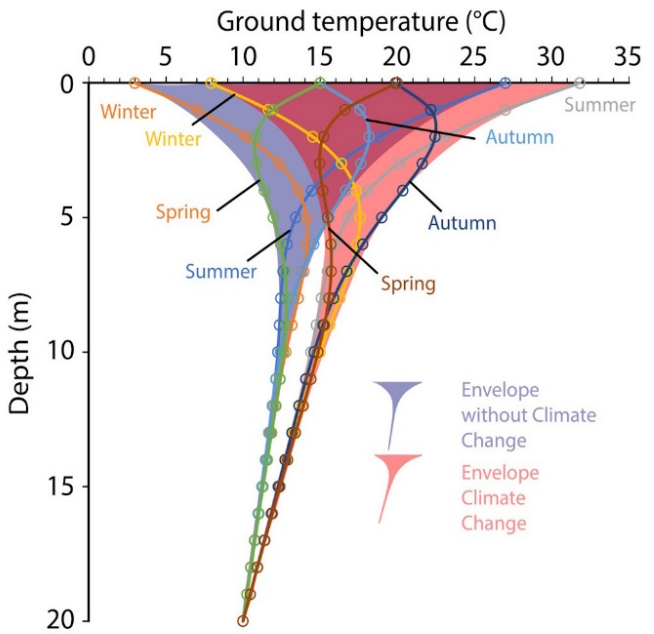

Figure 1 Depth profiles of ground temperature: seasonal variations in a hypothetical baseline case ("no climate change") and after 5°C of warming ("climate change"). Modified from Loche and Scaringi (2023).

Adopting a simplified geometry and considering a homogeneous and saturated soil featuring a groundwater flow parallel to the slope direction, we investigated in a virtual experiment the seasonal and long-term temperature changes in landslide shear zones and how these can affect slope stability via thermo-mechanical coupling with respect to a single soil parameter: the residual shear strength.

In order to quantify this coupling, we performed ring-shear experiments on saturated samples of pure clays (commercial Ca-Mg-bentonite and kaolin) while controlling both the temperature and rate of shearing. During the experiments, after attaining the residual shear condition, we increased the temperature of the water bath (from 20 °C to 50 °C) and kept it elevated for hours to days before restoring room temperature conditions (Fig. 2). During slow shearing (0.018 mm/min), we typically observed a "positive temperature effect" – that is, an increase in shear strength with temperature – when testing bentonite samples under various normal stresses (Fig. 2a). Conversely, kaolin samples did not exhibit any temperature effect or even showed some weakening ("negative temperature effect") under the same test conditions (Fig. 2b).

Interestingly, we observed that the effect of temperature depends in the rate of shearing. In other words, temperature and shear rate effects are somewhat coupled, implying that they should be investigated jointly and that they may be caused by the same or by coupled physico-chemical mechanisms at the micro-scale. As an example, Fig. 3 shows the residual failure envelops for the Ca-Mg-bentonite at 20 °C and 50 °C, sheared at 0.018 mm/min and 0.5 mm/min. Notably, the positive temperature effect is evident at 0.018 mm/min (Fig. 3a) while is absent at 0.5 mm/min (Fig. 3b). This possibly relates to a transition from laminar shearing to transitional or turbulent shearing, which has also been shown to affect the shear rate effect (Tika et al., 1996; Duque et al., 2023).

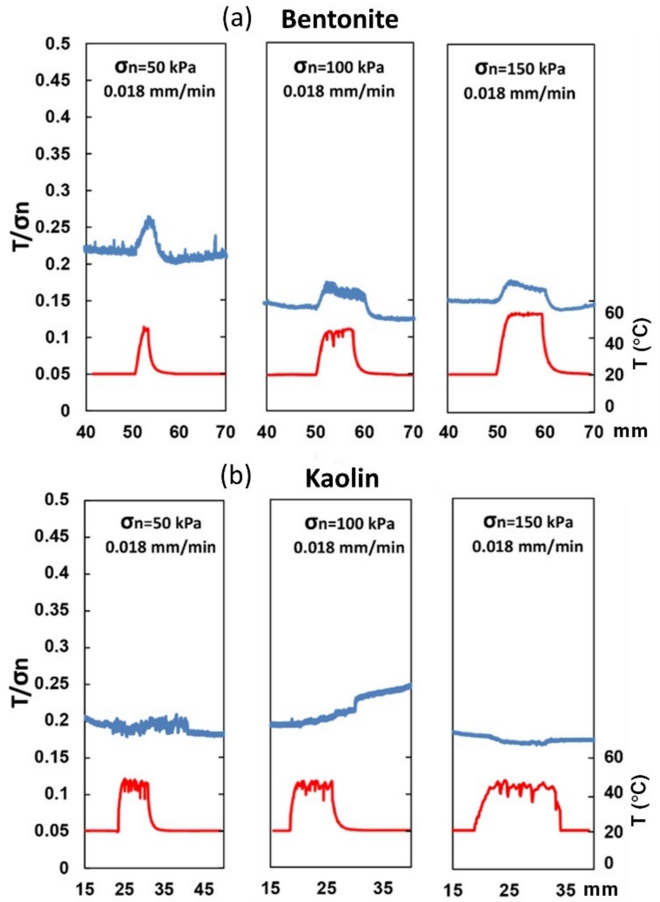

Figure 2 Results of ring-shear tests on (a) bentonite and (b) kaolin: the tests were performed under normal stresses (σ_n) of 50, 100, and 150 kPa and a shear rate of 0.018 mm/min. Modified from Loche and Scaringi (2023).

Overall, our experiments revealed changes in residual shear strength by up to 1.5%/°C, with the sign of the effect depending on both the mineral composition of the clay and the rate of shearing.

By incorporating this temperature effect into a slope stability analysis (Loche and Scaringi, 2023) while also considering seasonal and long-term temperature changes in the underground, we evaluated, for instance, that a smectite-rich landslide body with a curvilinear slip surface down to a depth of ~6 m would experience seasonal changes in the global factor of safety by around 20% solely due to the temperature-dependency of the residual shear strength. Notably, by also accounting for long-term warming (e.g., surface warming by up to +5 °C over decades) we quantified an additional variation by ~7% (Table 1).

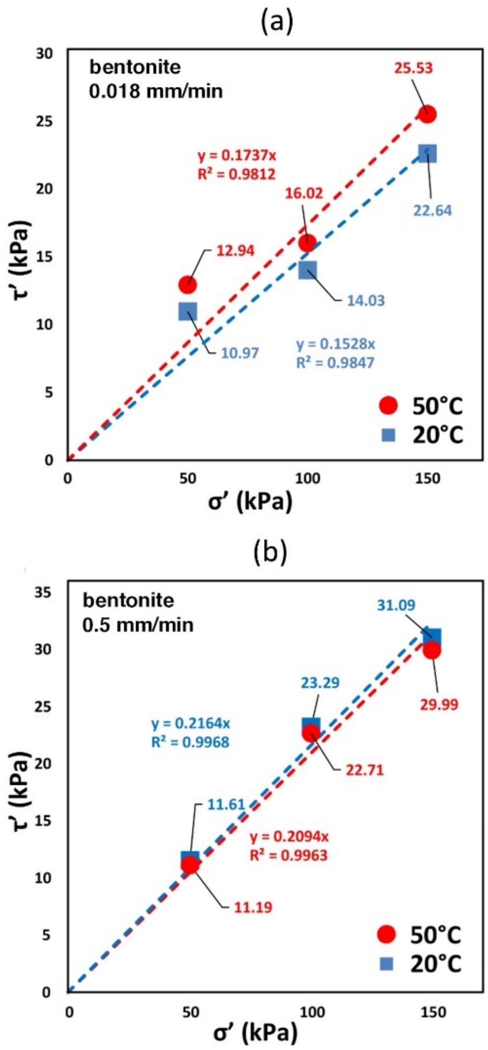

Figure 3 Residual shear strength envelope for bentonite at (a) 0.018 mm/min and (b) 0.5 mm/min: an increase in temperature from 20°C to 50°C caused an increase in friction coefficient from ca. 0.15 to ca. 0.17 (+13%) at 0.018 mm/min but a decrease from ca. 0.22 to ca. 0.21 (-3%) at 0.5 mm/min. Modified from Loche and Scaringi (2023).

Table 1 Example of global factor of safety (FS) for a 6 m deep curvilinear slope failure in smectitic clay (reactivated landslide) according to seasons in the numerical experiments by Loche and Scaringi (2023).

Season	FS in current climate	FS after +5 °C warming
Spring	1.22	1.14
Summer	1.08	1.00
Autumn	1.11	1.02
Winter	1.27	1.18

In our study, we explored a simplified numerical scenario in which no other couplings were introduced – such as dependencies of water retention behaviour and hydraulic conductivity on temperature – and did not consider that, under global warming, atmosphere-ground interaction is affected in a non-straightforward manner by changes in precipitation patterns and (where applicable) vegetation cover. Also, the sensitivity of the residual shear strength on temperature evaluated in our experiments should be considered as an upper limit because natural soils are mineral mixtures in which the components may respond to changes in temperature in opposite ways and specific responses may even emerge from the mineral combinations. In fact, we suggest that experiments on natural soils should be conducted systematically and enhancements in thermo-hydro-mechanically coupled modelling capabilities should be prioritized. Nevertheless, we can still conclude that, by overlooking the dependency of soil properties and behaviours on temperature altogether, errors and misestimations could occur at any scale, from laboratory determinations to slope stability assessments and regional analyses and predictions of landslide patterns and trends, their hazard, and risk.

Acknowledgements

The authors acknowledge financial support from the Czech Science Foundation (GAČR grant No. 24-12316S).

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