Thermo-mechanical modelling of the historical Cimaganda Rockslide

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ABSTRACT

A thermo-mechanical (TM) numerical approach is applied to investigate the stress-strain evolution of an alpine rock-slope along which a massive rockslide event occurred around 900 A.D, recently reactivated. Considering the recent geomorphological history of the Valley (post Last Glacial Maximum), not only the effects of glacial unloading, as usual, but also the surface temperature variations are examined by numerical simulation, in order to evaluate whether and how temperature may serve as a preparatory factor for large slope instabilities and how it can be included in modelling.

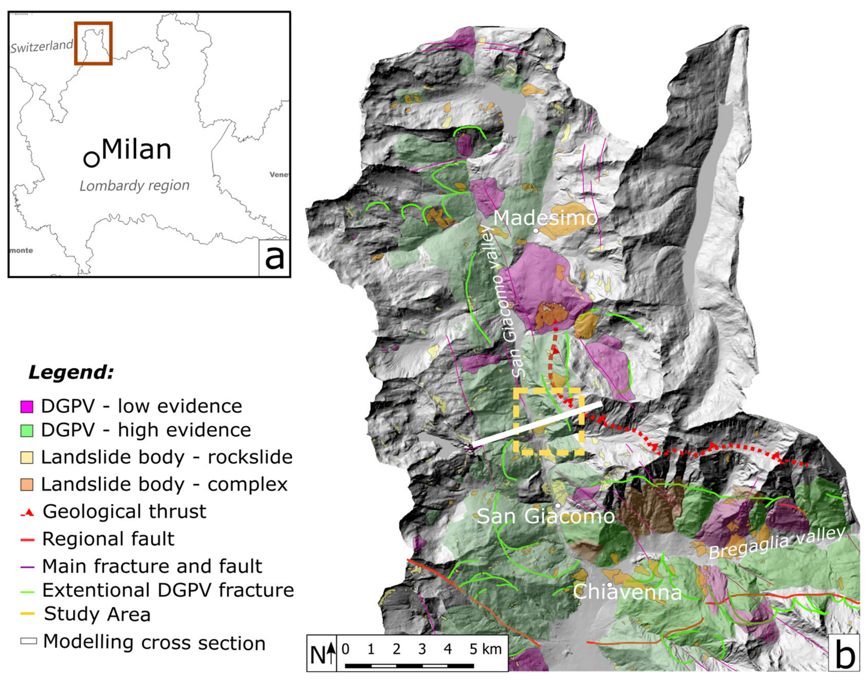


Figure 1 - a) Location of the study area; b) Distribution of the principal DSGSD bodies along San Giacomo and Bregaglia Valley.

1. INTRODUCTION

Cimaganda rockslide

The modelled slope is located on the East flank of the San Giacomo Valley (Central Italian Alps), between the village of Chiavenna and the Splügen Pass (fig. 1). Along the slope, a massive rockslide event (the Cimaganda landslide) occurred mobilizing an estimated volume of rock material of 7.5 Mm³ (fig. 1a-b). The slope is characterized by high sub-vertical rock cliffs related to a complex stress-strain evolution. The presence of highly persistent and opened fracture systems parallel to the Valley axis (fig. 1c-e), result in periodic shallow slope failure phenomena (Morcioni, 2020).

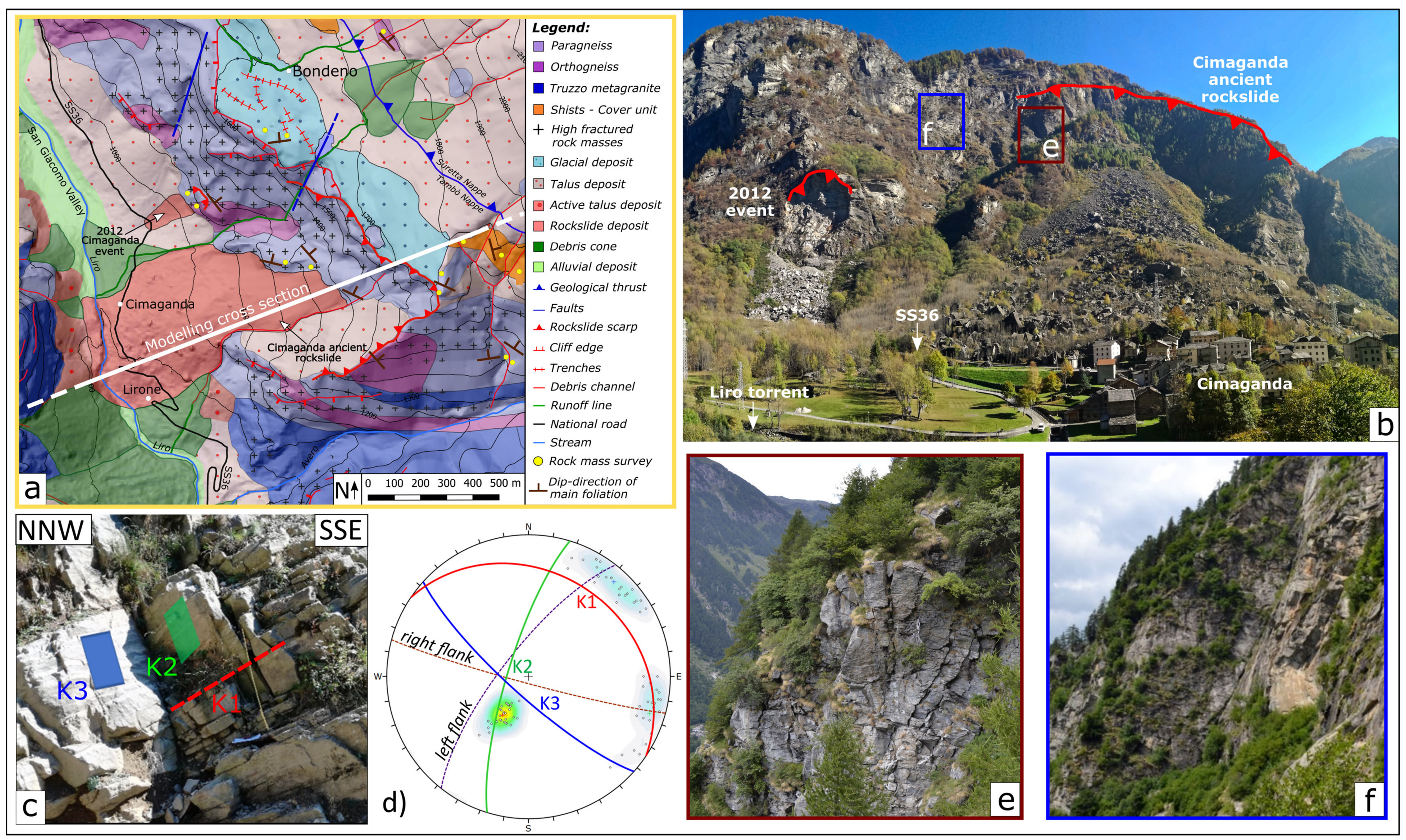


Figure 2 - a) Geomorphological and geological features of the Cimaganda area; b) Failure area and deposit of both 2012 and historical Cimaganda rockslides; c) Detailed geomechanical surveys performed at the scarp of the 2012 event; d) Stereonet representing the orientation of the discontinuity sets and the flanks of the historical rockslide event e-f) Rock masses outcropping along the slope with an high degree of fracturing, persistency and aperture.

2. GEOMECHANICAL MODEL

The stress-strain analysis was performed using the 2D DEM code UDEC (version 7.0 – Itasca Consulting Group). The rock mass was modelled as an assemblage of blocks resulting from the intersection of a multiple joint network, defined by detailed geomechanical surveys and Voronoi polygons representing intact rock and allowing to simulate the process of fracture propagation along the slope (fig. 3). Block were set deformable with thermo-elastic properties, while discontinuous elements were assigned an elasto-plastic behavior based on site-specific laboratory tests.

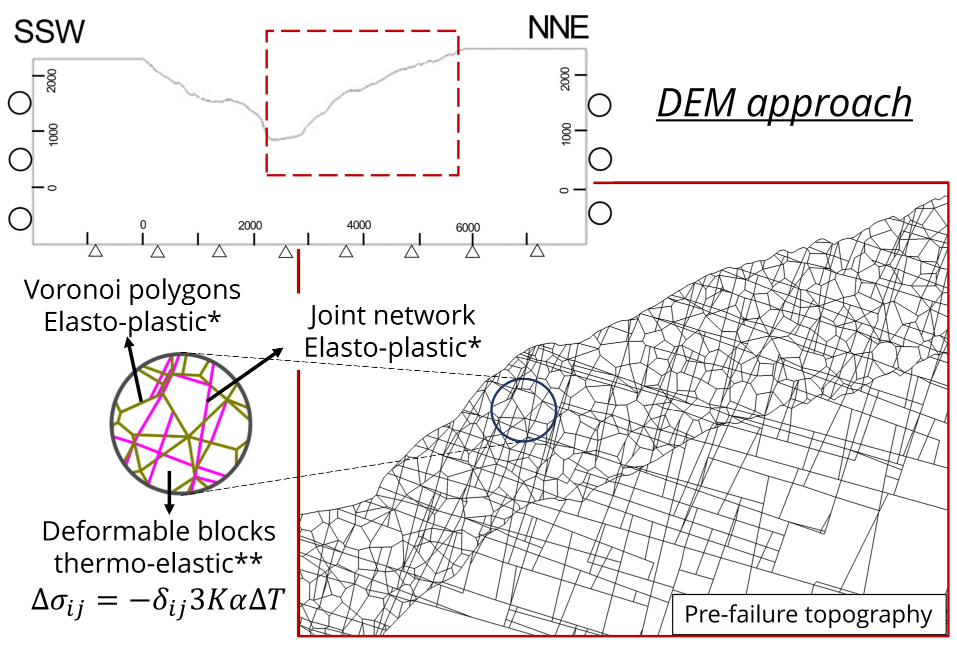
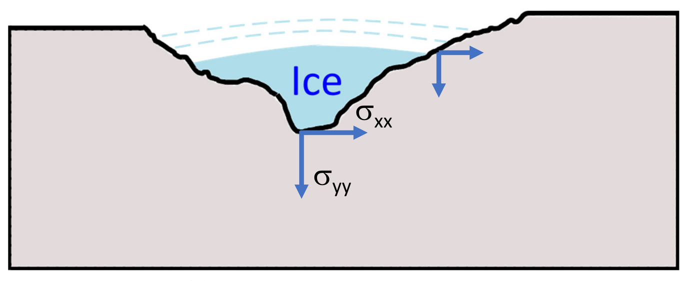


Figure 3 – Model geometry. Mechanical properties from: *site-specific laboratory tests - ** literature.

3. INPUT DATA

Ice unloading

During the LGM condition in correspondence with the Cimaganda slope, the ice level reached altitudes of 2150 m a.s.l. (Tantardini, 2013). The ice load was introduced in the numerical DEM model as a hydrostatic stress applied to the slope surface portion covered by ice. Deglaciation was modelled with thirteen stages corresponding to ice lowering steps of 100 m.

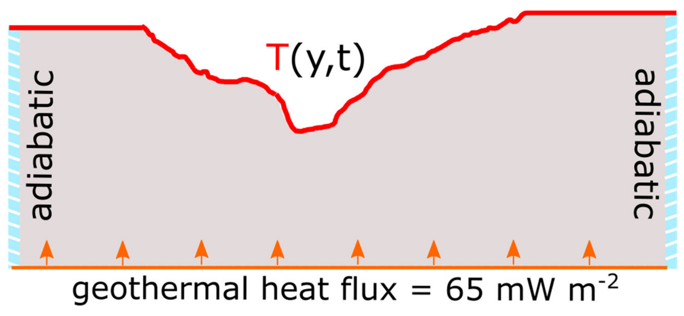


$$\sigma_{XX} = \sigma_{YY} = Z * \rho_{ICE} * g$$

Where Z is the ice thickness, ρ_{ICE} the ice density and g the gravity acceleration.

Long-term temperature

Long-term temperature distribution over the modelled Valley cross section was simulated using the FEM code COMSOL Multiphysics. Considering both the progressive bedrock exposure during LGM deglaciation and the Late Pleistocene - Holocene thermal warming (fig.4), a transient thermal analysis was implemented.



$T(y,t) = 0$ y<ice level (t)

$T(y,t) = 15.3 - 0.005\,(y) + \Delta Tpaleo\,(t)$ y>ice level (t)

(Grämiger et al., 2018)

4. THERMO-MECHANICAL MODELLING

The combined mechanical effects of ice unloading and long-term temperature changes was explored with a semi-coupled thermo-mechanical approach. For each mechanical step of the simulated deglaciation process, temperature distribution was evaluated with the thermal transient analysis and imported in the DEM model, where a temperature value was assigned to each grid point as an input data.

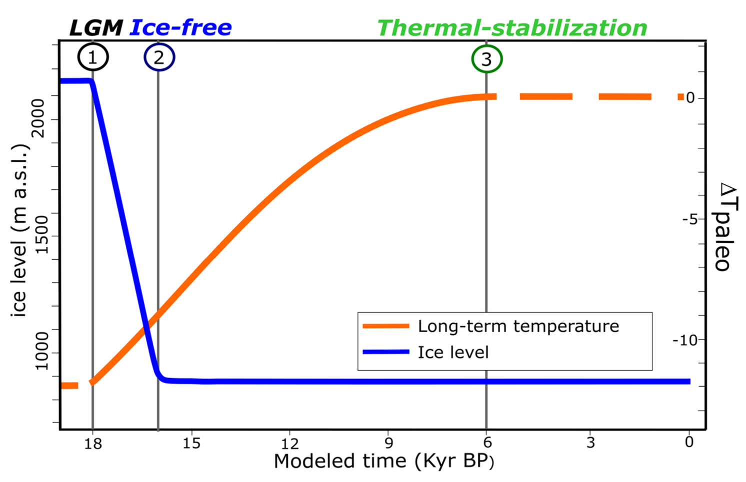


Figure 4 – Modelled glacial and paleo-temperature evolution (Grämiger, 2018; Ivy-Ochs 2008).

Modelling flow-chart

0) Initialization under gravity load
- a) Elastic model, ice-free condition
- b) Elasto-plastic model, ice-free condition

1) Initial conditions (IC), i=1
- a) **UDEC**: Mechanical equilibrium under LGM
- b) **COMSOL**: Thermal equilibrium under LGM

*2) Mechanical glacier retreat (**UDEC**)*
- a) Remove glacier thikness ΔZ_i = 100 m acting on top boundary condition
- b) Run elasto-plastic equilibrium

3) Thermo-mechanical analysis
- a) **COMSOL**: Start from Thermal IC and apply top BC change, assigning to rock surface temperature $\Delta T = T(t_2,y) - T(t_1,y)$ where $t_2 - t_1 = \Delta Z_i * v_{ice}$, and v_{ice}=glacier retreat velocity
- b) **UDEC**: Run thermo-mechanical equilibrium using ΔT

is $\Sigma\Delta Z_i$= total ice thikness? NO → i=i+1; YES ↓

Deglaciation: Now set $t_2 - t_1$ = 1 Kyr

is ΔT_{paleo}=0? NO; YES ↓

Thermal stabilization: END

5. RESULTS

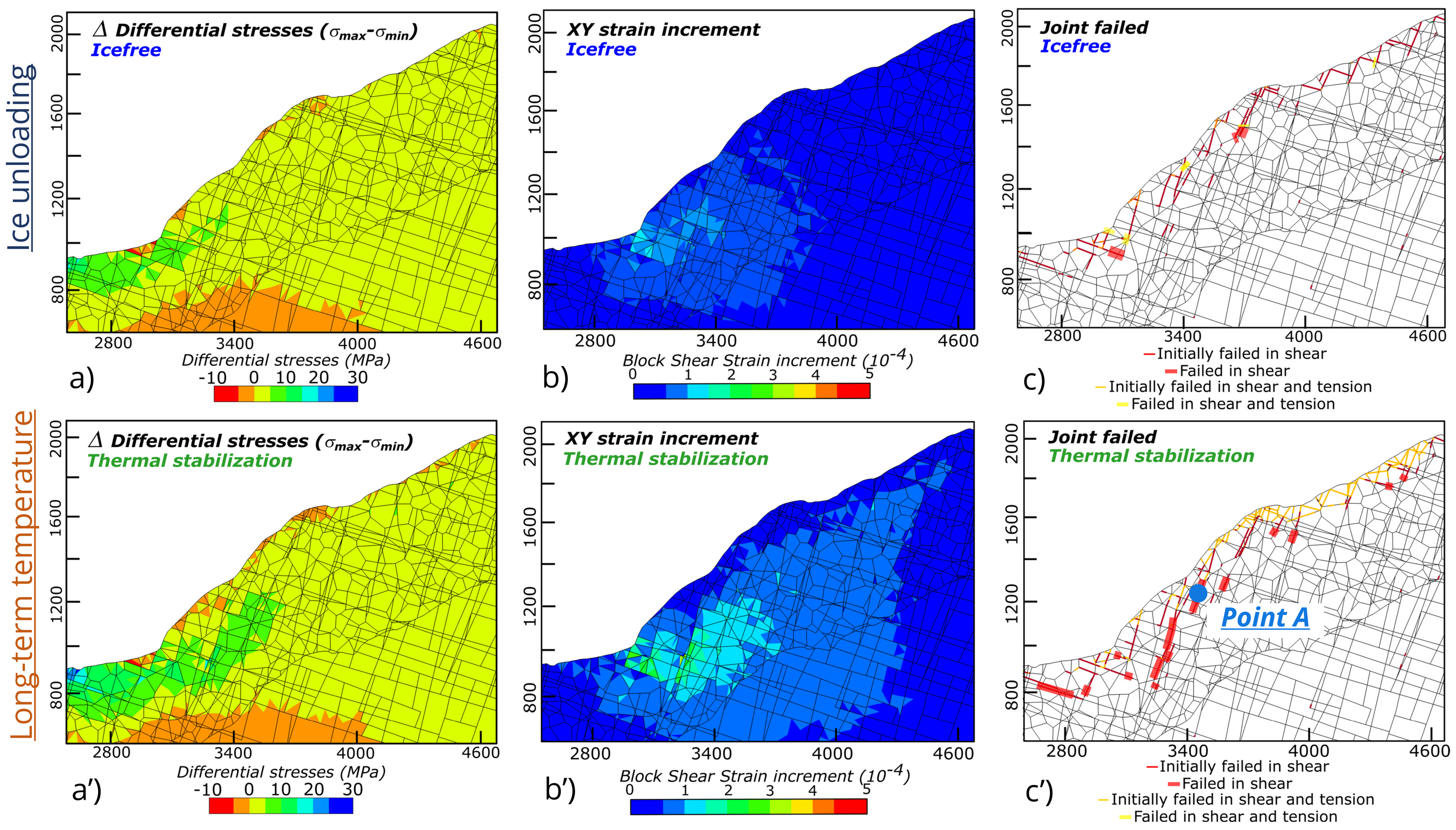


Figure 5 - The effects of ice unloading and long-term temperature change at ‘ice-free’ and ‘thermal stabilization’ conditions, are shown by plotting differential stresses (a-a’), shear strain increment (b-b’) and the spatio-temporal damage distribution (c-c’). In plots (a-a’) extensive stresses are positive, while compressive ones are negative. Increments are referred to the LGM distribution.

Considering a purely mechanical analysis, the effect of ice removal does not create significant rock mass damage, and it mainly results in a post-glacial elastic rebound without critical conditions for slope stability (fi2g. 5a-c). Once long-term temperature factor is introduced the heating process induced a general volumetric expansion of the blocks leading to a significant isotropic increase in the stress state and causing the development of a deep region at which differential stresses and shear strain concentrate (fig. 5a’-b’). Intensive shear straining within the blocks gradually caused plastic yield along subvertical discontinuities particularly in correspondence of the historical sliding surface (fig. 5c’ - 6).

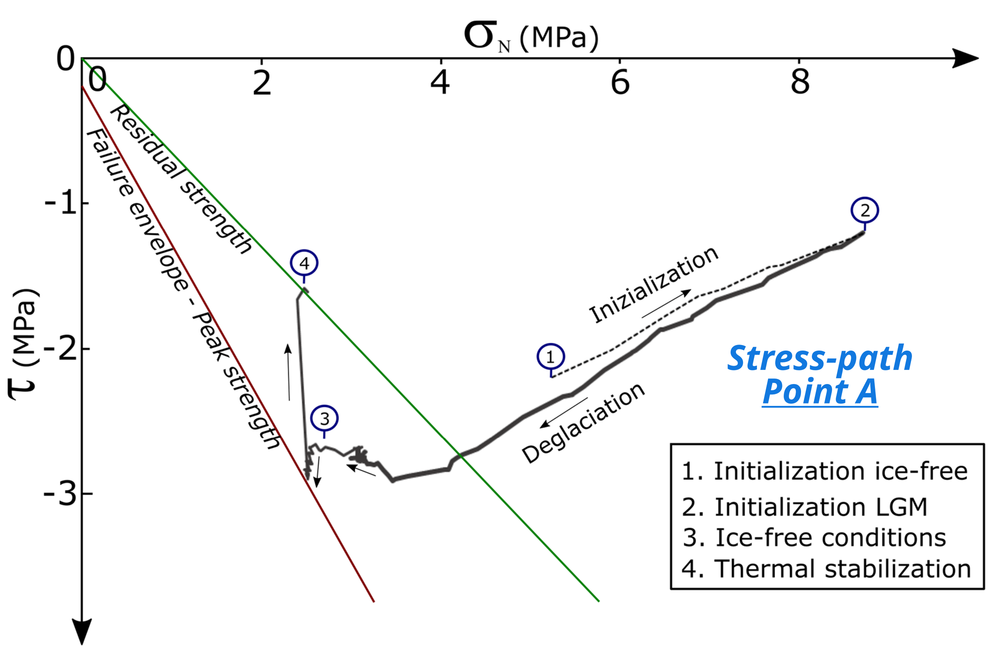


Figure 6 – Stress path recorded at the contact point “A” (figure 5) for the thermo-mechanical analysis.

CONCLUSIONS AND FUTURE PLAN

Results showed a clear relation between TM stresses and the occurrence of damage and failure within the rock mass. The development of a deep shear strain localization zone is in agreement with the evidences of the historical Cimaganda collapse. The implementation of the numerical modeling introducing seasonal temperature fluctuations is undergoing and additional strain and damage increments along the slope are expected. Further afforts will be devoted to include constitutive model able to account for (i) a time-dependent visco-elasto-plastic behavior and (ii) the evolution and degradation of mechanical properties with thermal loads, and additional couplings, such as considering heat advection by groundwater or air circulation and complex constitutive models.

Acknowlegment

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