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# A thermo-mechanical numerical approach for the analysis of a historical rockslide in the Italian Alps

A Morcioni, T Apuani and F Cecinato

Dipartimento di Scienze della Terra “A. Desio”, Università degli Studi di Milano, Via Luigi Mangiagalli, 34, 20133 Milan, Italy.

andrea.morcioni@unimi.it

**Abstract.** In this work, a thermo-mechanical (TM) numerical approach is presented and applied to investigate the stress-strain evolution of an alpine rock-slope located in the Central Italian Alps (Sondrio Province). Along the “Cimaganda” slope a massive rockslide event occurred around 900 A.D. mobilizing an estimated volume of 7.5 Mm<sup>3</sup> of material, and reaching the bottom of the valley. Interest in this historic event was raised again in recent times, as a new rockslide took place in 2012, mobilizing 20.000 m<sup>3</sup> of rock material and blocking the SS36 National Road.

To understand the general evolution of the Cimaganda rock slope, the recent geomorphological history of the Valley (post Last Glacial Maximum) was considered. In particular, to explore how glacial loading and unloading, associated with thermo-mechanical processes can promote rock mass damage, a 2D DEM numerical approach was adopted, calibrated upon the collected experimental and field data, and supported by a 2D FEM analysis to simulate transient heat diffusion over the Valley cross-section due to ice retreat and paleo-temperature evolution. Results show a clear relation between TM stresses and the occurrence of rock-mass damage and slip propagation along discontinuities. Simulated displacement and the development of a deep region of shear strain localization, allow to highlight the significance of temperature influence in preparing the rock slope to instability.

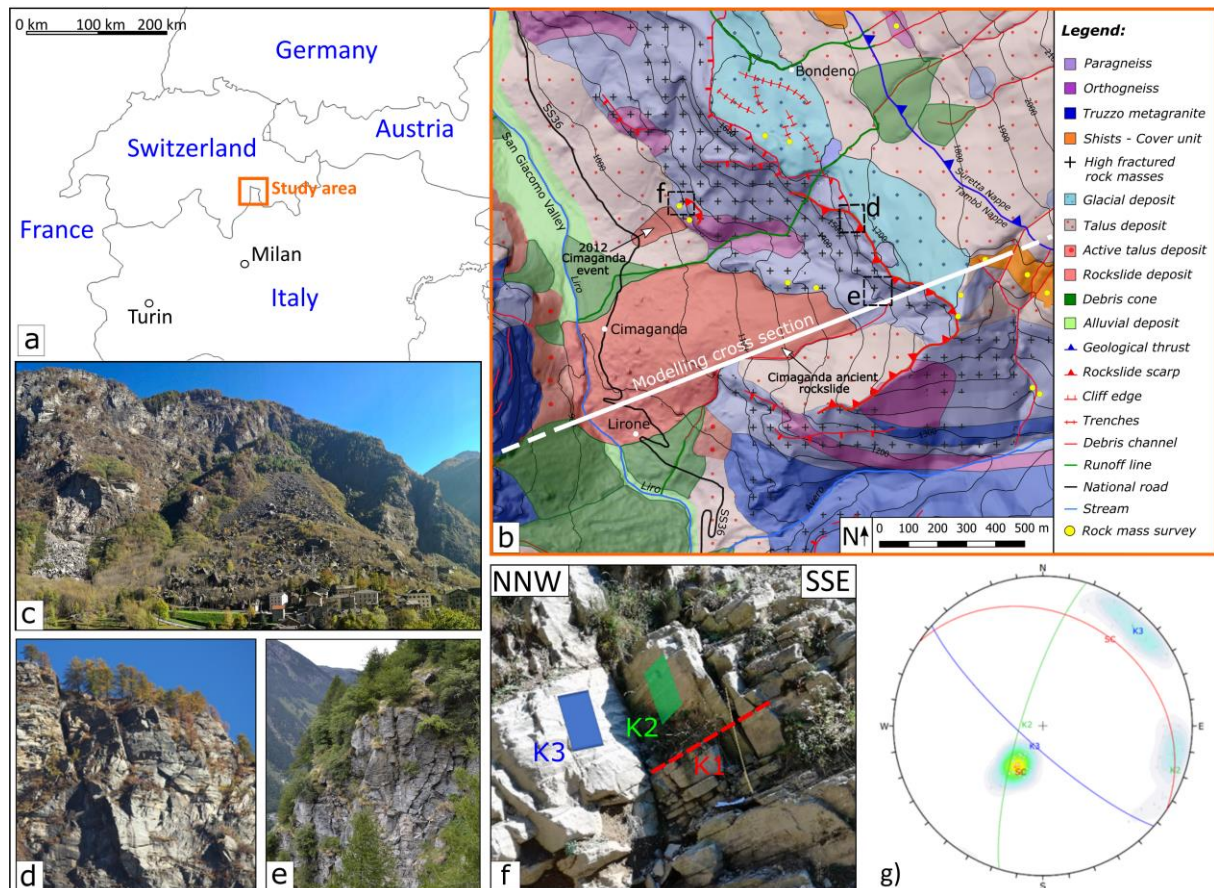
## 1. Introduction

Large rockslide events and deep-seated gravitational slope deformations (DSGSD), result from a complex time-dependent interaction among different geological, geomorphological and climatic factors [1]. Even if the role of temperature in alpine slope instabilities has been widely recognized [2,3], the role of Thermo-Mechanical (TM) and Thermo-Hydro-Mechanical (THM) couplings in driving rock-slope failure is still little explored. In alpine slopes, glacial unloading is often suggested to be the predominant mechanism leading to the development of rock mass tensile damage and large-scale stress release [1,4,5,6]. The deglaciation process, however, is also associated with variations in climatic conditions that promote rock-mass progressive degradation. In this work, a TM semi-coupled approach is applied to investigate the stress-strain evolution of an alpine rock slope, considering both glacial unloading and paleo-temperature evolution resulting from the Last Glacial Maximum (LGM) conditions.

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, connecting Italy to Switzerland (figure 1a). Along the slope, a massive rockslide event (the Cimaganda rockslide) occurred around 900 A.D.



mobilizing an estimated volume of rock material of  $7.5 \text{ Mm}^3$  [7] (figure 1b-c). The Cimaganda rockslide involved gneissic rocks of the Tambo nappe Unit belonging to the Upper-Penninic alpine domain. The slope is characterized by high sub-vertical rock cliffs leading to a complex stress-strain evolution. The presence of highly persistent and opened fracture systems parallel to the Valley axis (figure 1c-e), result in periodic slope failure phenomena which involved limited volumes of material. In September 2012, on the right flank of the historical Cimaganda rockslide, a failure event mobilized  $20.000 \text{ m}^3$  of rock material blocking the SS36 national road (figure 1b) [8].



**Figure 1.** Geomorphological and geomechanical features of the study area; a) Location of the San Giacomo Valley; b) Geomorphological and geological map of the Cimaganda slope; c) Failure area and deposit the Cimaganda rockslide events; d-e) Rock masses outcropping along the slope; f-g) Main set of discontinuity identified from geomechanical surveys.

The work presented in this paper was structured as follows. First, a 2D geomechanical conceptual model of the Cimaganda rock-slope was built using a distinct element approach (DEM). Then, based on local and regional evidences, glacial and paleo temperature evolution along the San Giacomo Valley were evaluated, and a 2D finite element model (FEM) was implemented to simulate heat diffusion over the valley cross section. By importing the temperature fields elaborated with the FEM code into the DEM model, a semi-coupled thermo-mechanical analysis was performed. Starting from the LGM conditions, the effects of both glacial unloading and temperature redistribution related to the gradual exposure of the slope to atmospheric conditions and to the paleo-temperature evolution were analyzed.

The main purpose is to assess the role of thermal loads, associated with glacial unloading, in the stress-strain evolution of the rock-slope. Moreover, focusing on the Cimaganda rockslide, the aim is to explore if TM stresses can represent a significant preparatory factor to the failure event.

## 2. Materials and methods

### 2.1 Geomechanical model

The numerical stress-strain analysis of the Cimaganda rock-slope was performed using the 2D DEM code UDEC (version 7.0 – Itasca Consulting Group), suited to analyze the behavior of discontinuous media. The cross section of modelling extends from the west to the east slope of the San Giacomo Valley, based upon the 2015 Digital Terrain Model of the Lombardy Region, modified reproducing the Cimaganda pre-failure morphological conditions considering the lateral topographical constrains (figure 2).

The rock mass is modelled as an assemblage of blocks resulting from the intersection of discontinuous elements represented by a multiple joint network and Voronoi polygons (figure 2). The joint network is composed by three sets of discontinuity identified from detailed geomechanical surveys conducted along the slope and presented in [8]: K1 ( $34^\circ/27^\circ$  - dip direction/dip), K2 ( $287^\circ/70^\circ$ ), K3 ( $222^\circ/79^\circ$ ) (figure 1f-g). Joints were assigned a Mohr-Coulomb constitutive law including slip-weakening of friction and cohesion. Strength parameters were defined based on direct shear tests conducted according to the ASTM standards on the joint surfaces (table 1).

The Voronoi polygons were introduced to represent the intact rock and allow failure along new potential pathways simulating failure of rock bridges and fracture propagation. They were assigned elasto-plastic properties evaluated from uniaxial compressive tests conducted on intact rock samples collected along the 2012 rock scarp and at the crown of the historical rockslide (table 1). Blocks derived from the intersection of joints and Voronoi elements, were discretized with a triangular mesh. For them, a linear thermo-elastic behavior was assumed considering a homogeneous and isotropic material (table 2).

With respect to the whole modelled area, the interest area was restricted to the east slope of the San Giacomo Valley, where the Cimaganda rockslide developed (figure 2). Roller boundaries were applied to the lateral sides of the model, whereas its bottom boundary was fixed (figure 2).

Once the geomechanical model was defined, the glacial history and the paleo-climatic evolution of the San Giacomo Valley were evaluated and introduced as input data in the model as described below.

**Table 1.** Mechanical properties of joints and Voronoi polygons.

|   | <i>Voronoi</i> | <i>K1</i> | <i>K2</i> | <i>K3</i> |
|---|----------------|-----------|-----------|-----------|
| Peak friction angle [ $^\circ$ ]        | 53             | 32.5      | 28        | 48        |
| Peak Cohesion [MPa]                     | 5              | 0.1       | 0.1       | 0.2       |
| Residual friction angle [ $^\circ$ ]    | 28             | 24.5      | 25        | 33        |
| Residual Cohesion [MPa]                 | 0              | 0         | 0         | 0         |
| Normal Stiffness [GPa m <sup>-1</sup> ] | 20             | 4         | 4         | 1.5       |
| Shear Stiffness [GPa m <sup>-1</sup> ]  | 10             | 1         | 1         | 1         |

**Table 2.** Mechanical properties of blocks.

|  |        |
|--|--------|
| Density [kg m <sup>-3</sup> ]                    | 2700   |
| Bulk Modulus [MPa]                               | 4e4    |
| Shear Modulus [MPa]                              | 1.4e4  |
| Thermal expansion coefficient [K <sup>-1</sup> ] | 9.5e-6 |

### 2.2 Modelling input data

**2.2.1 Glacial history.** During the Pleistocene age, in the last 2.6 million years, European alpine valleys were affected by several glacial and interglacial periods [9]. Considering evidence of glacial

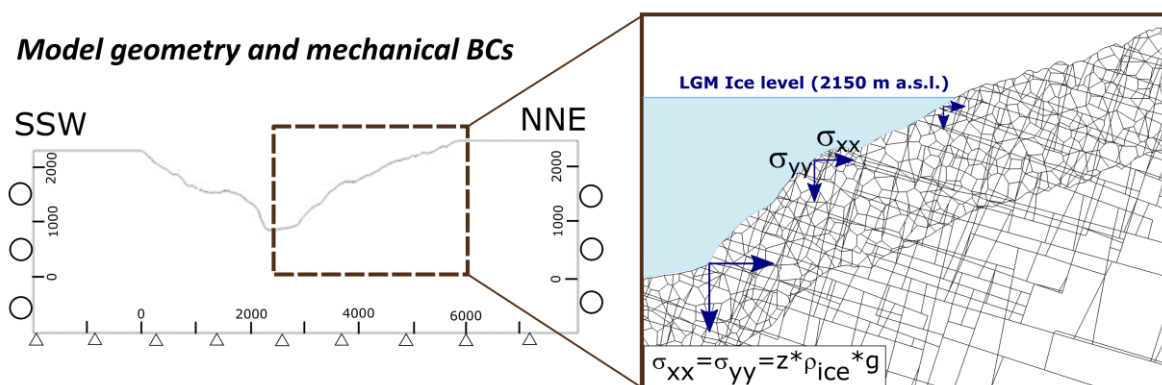
morphologies and deposits [10], the LGM ice extension in the Valchiavenna region was reconstructed. In correspondence with the Cimaganda slope, the ice level reached altitudes of 2150 m a.s.l., resulting in an ice thickness of 1230 m.

The LGM in the Alps is dated at 28 to 18 kyr Before Present (BP) [11]. Despite the maximum expansion of the ice during the LGM has been completely mapped, no exposure ages of surfaces and glacial deposits are available for the study area. It is reasonable to assume glacial maximum conditions until 19-18 kyr BP, followed by a general melting phase [11, 12, 13].

The ice load was introduced in the numerical DEM model as a hydrostatic stress boundary condition applied to the slope surface portion covered by ice (figure 2). Assuming an ice density of  $900 \text{ Kg m}^{-3}$ , ice loads are defined by the following relation:

$$\sigma_{XX} = \sigma_{YY} = Z * \rho_{ICE} * g \quad (1)$$

where  $Z$  is the ice thickness,  $\rho_{ICE}$  the ice density and  $g$  the gravity acceleration. As discussed by [14], for long-term mechanical studies on glacial time scales, modelling ice as a hydrostatic stress boundary condition leads to more realistic results compared to considering the ice body as an elastic material. In fact, the latter assumption would lead to significant overestimation of the damage associated with glacier retreat.



**Figure 2.** Modeled geometry and mechanical boundary conditions.

**2.2.2 Long-term temperature evolution.** The LGM deglaciation in alpine regions was supported by a change in climate conditions [15, 16]. According to [17] the paleo-temperature evolution in the alpine region can be outlined as shown in figure 3a: during the LGM, mean temperatures were about  $12^\circ \text{C}$  colder than today and began to rise following the deglaciation process; at the end of Pleistocene, mean air temperatures had risen to values of  $3.5^\circ \text{C}$  colder than today and stabilized around the current values during Holocene age [2].

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 deglaciation and the Late Pleistocene - Holocene thermal warming. In this context, the rock mass was assumed to be a continuous medium and the process of heat transport was assumed to be governed only by thermal conduction. Adiabatic conditions defined the lateral sides of the model, while a constant vertical geothermal heat flux of  $65 \text{ mW m}^{-2}$  [18] was applied along the lower boundary (figure 3b).

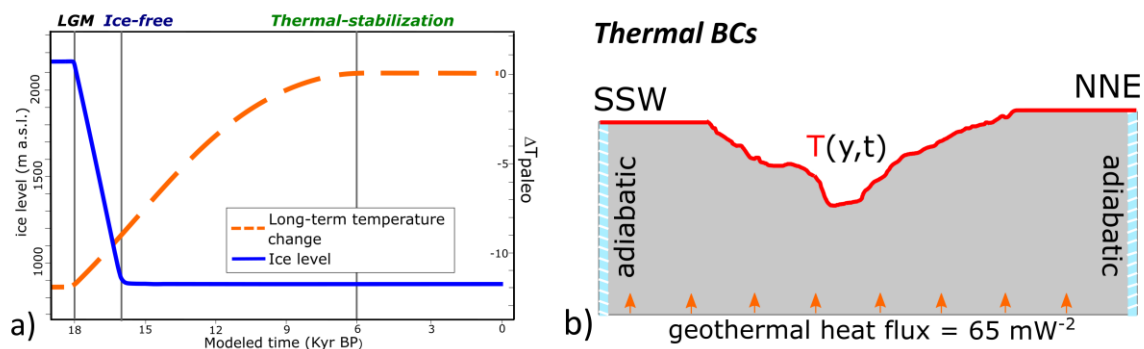
Top boundary conditions are governed by the ice level location. Below the glacier cover, temperatures were held constant at  $0^\circ \text{C}$ , while, above the ice level, mean rock surface temperatures were defined by environmental conditions depending on altitude ( $y$ ) and time ( $t$ ) as described by the following relation [2]:

$$\begin{aligned} T(t, y) &= 0^\circ \text{C} && \text{for } y \leq \text{glacier elevation} \\ T(t, y) &= 15.3^\circ \text{C} - (0.005 * y) + \Delta T_{paleo}(t) && \text{for } y \geq \text{glacier elevation} \end{aligned} \quad (2)$$



where  $15.3^{\circ}\text{C}$  is the mean rock surface temperature at the reference elevation of  $y = 0$  m;  $0.005^{\circ}\text{C m}^{-1}$  represents the effect of rock surface temperature variation with altitude (lapse rate);  $\Delta T_{paleo}(t)$  is the factor that accounts for the paleo-temperature change relative to the present (figure 3a). This function was elaborated by [2] and was assumed valid for the study area considering similar lithologies and comparable climate factors, in the absence of rock surface temperature data.

Initial temperature distribution along the Cimaganda slope was evaluated under the LGM ice occupation with a steady state solution. A transient thermal analysis considering both the ice melting and the paleo-temperature evolution was then implemented following equation 2. Resulting temperature field was finally imported in the DEM model as input data for the TM analysis.



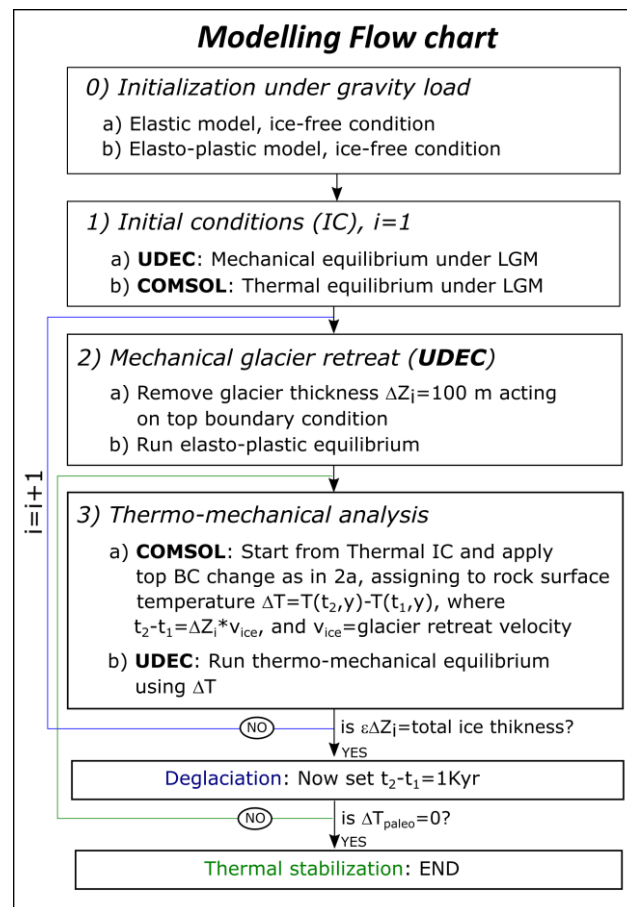
**Figure 3.** a) Modelled glacial and paleo-temperature evolution. The blue line shows the simulated ice level starting from the LGM conditions. The orange dashed line shows the modelled temperature evolution ( $\Delta T_{paleo}$ ) fitting paleo-temperature reconstructions for the alpine region (modified from [2]).  
b) Boundary conditions for the thermal transient analysis.

### 2.3 Thermo-mechanical analysis

Starting from LGM conditions, the combined mechanical effects of ice unloading and long-term temperature changes along the Cimaganda rock slope were explored with a semi-coupled thermo-mechanical approach. The following modelling procedure was applied (figure 4): first the elastic stress field due to the gravity load and model topography under ice-free conditions, was calculated by running the model until force-equilibrium. In this phase the strength of discontinuities was set sufficiently high to prevent failure. In the subsequent calculation step, Mohr-Coulomb elasto-plastic properties of joints and Voronoi polygons were activated allowing failure. Next, the glacial load corresponding to LGM ice level was introduced following equation 1, and the elasto-plastic equilibrium stresses were recalculated. This was set to represent the starting point of the analysis, hence resulting displacements were reset to zero.

After the above described initialization procedure, the glacial unloading phase was modelled by reducing the ice thickness acting on the slope in thirteen stages corresponding to ice lowering steps of 100 m thickness. For each mechanical step of the simulated deglaciation process, temperature distribution was evaluated with the thermal transient analysis presented in the paragraph 2.2.2. The resulting temperature fields were imported in the DEM model, where a temperature value was assigned to each gridpoint as an input data. Simulations were then run to a thermo-mechanical equilibrium considering temperature changes.

Once deglaciation process was completed and ice-free conditions were reached (at  $\sim 16$  kyr BP), temperature distributions were evaluated for every 1 kyr, since paleo air temperature stabilized around the current mean values ( $\Delta T_{paleo}(t) = 0$ ) at 6 kyr BP (figure 3a).

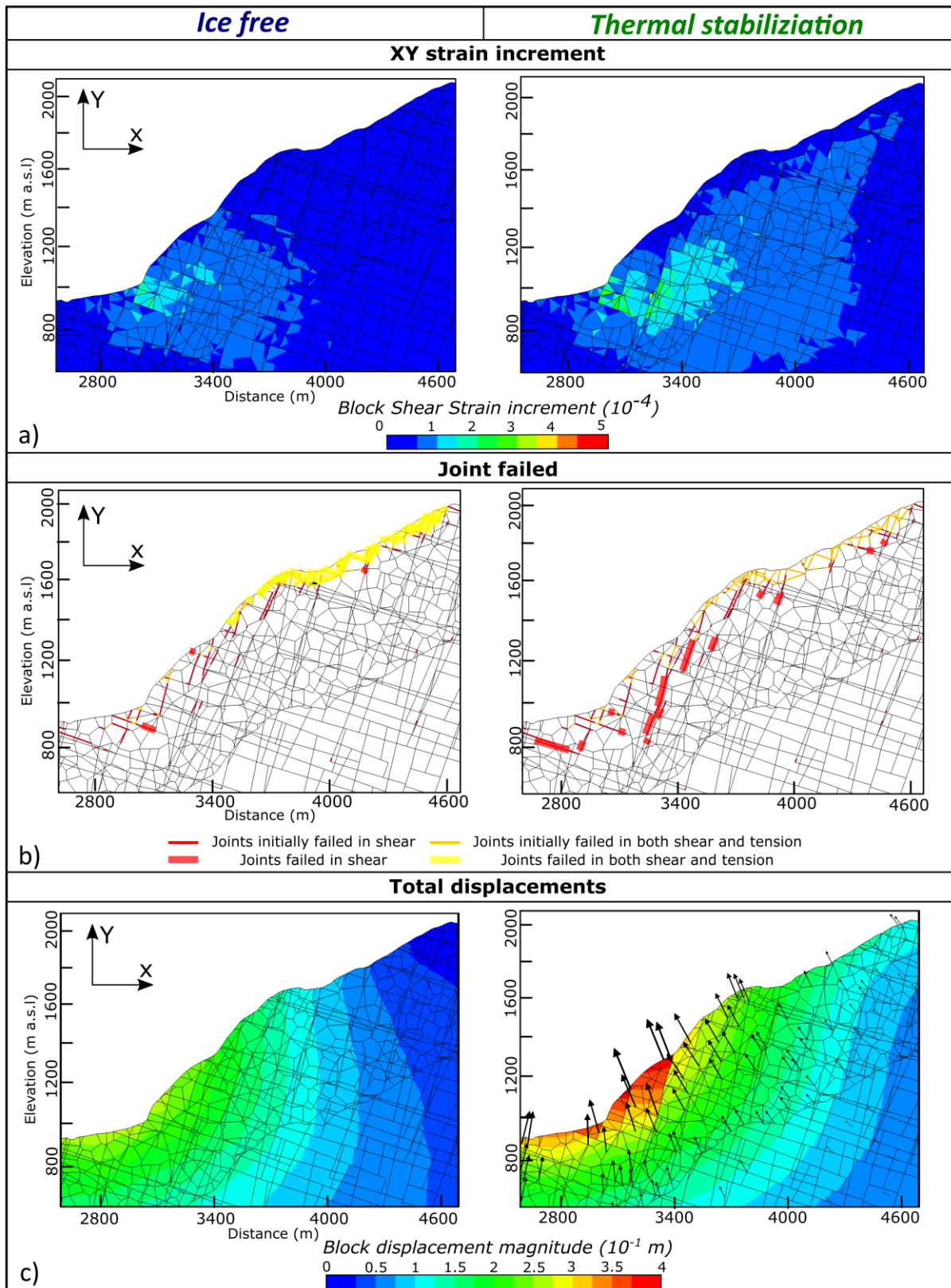


**Figure 4.** Thermo-mechanical modelling flowchart.

### 3. Results

Results showed a clear relation between TM stresses and the occurrence of rock-mass damage and slip propagation along discontinuities (figure 5). During ice melting, the surface rocks were gradually exposed to negative temperatures, as the  $0^{\circ}\text{C}$  isotherm for the mean ground temperature progressively moves at lower altitudes. The process of surface cooling caused rock volumetric contraction along the subsurface, promoting both tensile and shear joint failures (figure 5b). Once deglaciation is completed, and the entire slope is exposed to atmospheric conditions, temperature redistribution depends only on the paleo-temperature evolution resulting in a progressive and homogeneous thermal warming. The heating process induced a general volumetric expansion of the rock blocks leading to a significant isotropic increase in the stress state. Considering that the depth of temperature influence is higher compared to the deglaciation phase, TM induced damage involved deeper and greater volumes of rock-mass. Focusing on the mid-slope area, a shear strain localization region begins to develop at the end of the deglaciation and progressively propagates as a result of the heating process (figure 5a). Intensive shear straining within the elastic rock blocks gradually caused plastic yield along discontinuities and the boundaries of Voronoi polygons. In fact, all discontinuities are assigned an elasto-plastic behavior, hence the stress state there may reach failure and induce irreversible damage. As shown in figure 5b, in this region, a significant increment in failure and slip propagation along sub-vertical discontinuities was observed.

The role of temperature as a preparatory factor to the Cimaganda rockslide event is highlighted by the development of a shear strain localization area at a depth roughly corresponding to the sliding surface position, and by the magnitude of simulated displacements (of the order of  $10^{-1}$  m) that take the maximum values along the actual failed slope (figure 5c).



**Figure 5.** Plots in figure show the distribution of shear strain increment along the slope (a), the spatiotemporal damage distribution of discontinuities (b) and the total displacements (c) at two different steps of the TM analysis: Ice free (left column) and Thermal Stabilization (right column).



#### 4. Conclusions

In this work, a thermo-mechanical semi-coupled approach was presented and applied to investigate the stress-strain evolution of an alpine rock slope where a massive rockslide event occurred. By coupling a thermal FEM with a thermo-mechanical DEM analysis, TM effects associated with ice redistribution and paleo-temperature evolution resulting from LGM conditions up to present, were analyzed. Results showed a clear relation between TM stresses and the occurrence of damage and failure within the rock mass, which may control the stress-strain evolution of the slope. The resulting displacements and the development of a deep shear strain localization zone are in agreement with the evidences of the historical Cimaganda collapse. The simulated strain localization region does not actually result in critical stability conditions, but it defines a preferential zone for the progress of failure, which could extend further if other destabilizing factors were considered in the model. The implementation of the numerical modeling introducing seasonal temperature fluctuations on the slope surface is undergoing and additional strain and damage increments along the slope are expected to promote the general slope instability.

#### Acknowledgments

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