Multi-scale rock slope failure initiation mechanisms: results from multi-parametric field and modeling studies conducted on the Upper Tinée valley (French Alps) over the past 10 years

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ABSTRACT

This paper summarizes part of the results from a multi-parametric study that was conducted for several years on a 70 km long valley located in the Southern French Alps. The valley slopes display several different gravitational features from the valley floor up to the mountain crest. Large landslides (volumes exceeding 5 $10^6 m^3$) with well individualized failure surfaces are located at the slopes foots and pluri-kilometric tensile cracks characterize the slopes tops. A perched saturated-with-water zone located within the cracks is drained towards the slope foot through the landslides. Annual precipitation infiltration induces hydro-mechanical effects up to 400m deep inside the slopes. Those effects mainly participate to the rock strength decrease and the shear plane development with time. Dating of failure surfaces revealed at least 3 main destabilizations of slopes at 11, 7.1 and 2.3 10^3 yr that are not easy to correlate with climatic or tectonic events on the area. This result illustrates the major role played by progressive failure propagation mechanisms during periods between two catastrophic events.

KEYWORDS: Large moving rock mass, hydromechanics, triggering factors, cosmogenic dating, numerical models

INTRODUCTION

Massive natural rock slopes destabilization involves several complex mechanisms relating to geological, mechanical and hydrological processes for which no clear trigger can be asserted [1]. This paper summarizes part of the results from a multi-parametric study that was conducted for several years on a 70 km long valley located in the Southern French Alps. This valley was chosen because it was found representative to study rock slope destabilization under climatic factors and moderate seismic activity.

GEOMORPHOLOGICAL ANALYSES

The Tinée valley is situated at the northwestern edge of the Argentera-Mercantour metamorphic unit (Southern French Alps, Fig. 1A). East side of the valley is made of metamorphic basement with a N150-60°E foliation average trend. Close to the surface of the slope, within a 100 m thick shallow zone, foliation is dipping gently (less than 20°) either to the NE or to the SW [2]. Metamorphic rocks are weathered on a thickness ranging from 50 m to 200 m depending on the zones of the valley. Three sets of faults can be distinguished, trending N010°E-N030°E, N080°E-N090°E and N110°E-N140°E with a dip angles close to 90° (Fig. 1A and B). The valley slopes display several different gravitational features that can roughly be grouped in two main zone types, a tilted zone which is located at the foot of the slope between the elevation of the valley floor and the mid-slope elevation and a sagging zone that is located between the mid-slope elevation and the mountain crest (Fig. 1A). In the tilted zone, metamorphic rocks are strongly toppled and affected by landslides with volumes ranging between 5 and 50 10^6 m^3 (about 29 landslides are documented in the valley). This zone contains some currently active large landslides like the "La Clapière" landslide which is located less than 1km downstream from the Saint-Etienne de Tinée village and whose behavior is typical of rock masses movements in the zone (Fig. 1B). The top of the La Clapière landslide is a 120 m high scarp that extends over a width of 800 m at elevation 1600 m. The depth of the failure surface may not exceed 100 m to 200 m (Fig. 1). The landslide itself is divided into three main compartments limited by pre-existing faults. The main central volume is bounded by the main failure surface. It moves downward with 45 to 90 mm.yr-1 velocity and N010°E and N115°E motions. The upper northeastern compartment (5 million m^3 volumes) behaves like a block landslide sliding along its own failure surface and overlapping the main landslide with downward 100 and 380 $mm.yr^{-1}$ motions. The upper northwestern compartment is bounded to the south by the 150 m high scarp of the main landslide failure surface and to the north by a 50 m high scarp. This compartment behaves like a fractured rock mass with active tension cracks and motions ranging between 20 and 70 $mm.yr^{-1}$. It is not certain that this compartment should be included in a failure surface at the present time. The tilted zone is nested in the larger sagging zone which has been active (Fig. 1A and B). This zone is characterized by extensional deformation structures like large tension cracks with a pluri-kilometric length and several meters high downhill scarps. These landforms involve displacements along penetrative preexisting tectonic joints consistent with gravitational movements. Tension cracks correspond to a meter-scale horizontal opening of the superficial part of the faults that induce a 10 to 50 m deep trench. Scarps correspond to shear displacements with a vertical throw ranging from 1 and 50 m. Gravitational features of this zone extend deep inside the slope if we consider their pluri-kilometric extension and they follow major tectonic faults trends rather than the valley slope main direction (Fig. 1B).

HYDRO-MECANICAL PROCESSES WITHIN SLOPES

- Geometrical coupling between hydrogeology and gravitational structures

Slope hydrogeology can be regarded like 3 nested discontinuous fractured reservoirs [3]. Water flows into fractures whose openings depend on the depth and mainly on the gravitational structures of the slope. Rock matrix (gneisses) can be considered as impervious. First zone is the lower tilted zone which is drained through the landslides that can be taken as highly permeable fractured reservoirs where displacements induce the formation of large pores inside opened fractures, breccias and blocks. The landslides are drained at there foot by perennial springs (springs S18, S7, S1 on Fig. 1A) with discharges comprised between 0.95 and 2.35 $l.s^{-1}$. Second zone is the upper sagging zone which is a highly fractured area where tension cracks create highly permeable linear drains. Many of the cracks are filled with colluvial deposits which constitute small reservoirs with an interstitial porosity. These tiny reservoirs are interconnected via the tension crack network. Typically, the filling has a 4 to 20 m wide triangular geometry and, depending on the places, it can be completely dry or it can be drained by perennial springs (springs S3-6, S9-14, S16, S19-20, Fig. 1A). In the first case, water infiltrating in the colluvial deposits is drained deeper in the slope through the underlying tectonic fault. In the second case, water is partially or totally trapped in the filling. The interconnection of the fillings creates a perched perennial saturated zone that could explain the presence of springs rising in the upper part of the slope in the Tinée valley slope and in the adjacent valleys (Fig. 1A and B).

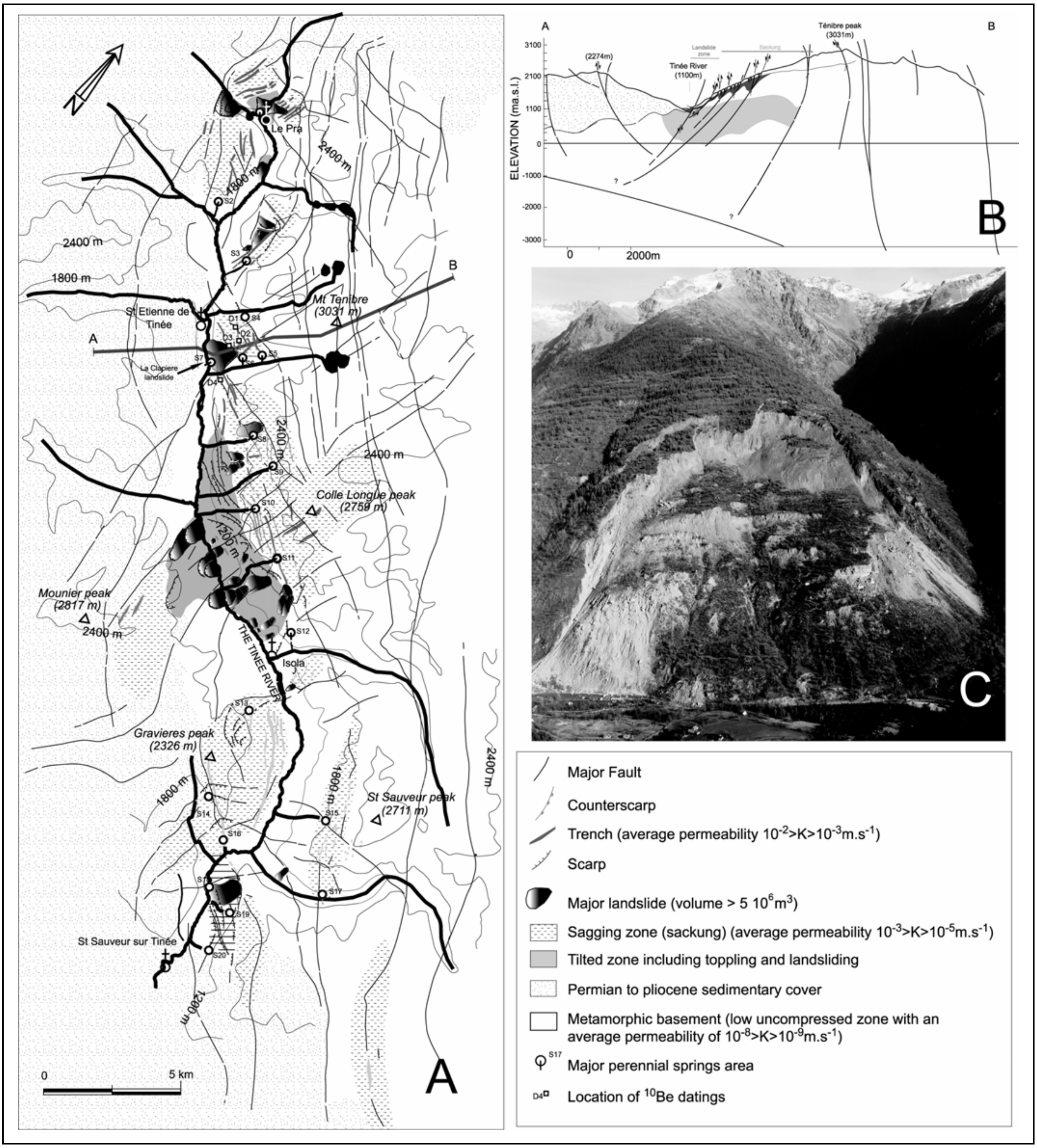

Figure 1. Hydro-geomorphological map (A) and cross section (B) of the Tinée valley; Photo of the La Clapière active landslide (C)

All these springs discharge display large variation depending on their location in the valley but their flow-rates are more important that the tilted zone springs ones ranging between 5 and 10 $l.s^{-1}$. Third zone is the low uncompressed deep part of the slope that was only explored through galleries and deep wells within the area. This zone is fractured by major tectonic joints and can be considered as a relatively low-permeability fissured reservoir (Fig.1B). There is a continuity between the joints and the tensile cracks mapped in the uncompressed toppled zone. Small discharges were measured within fractures located in that zone with flow-rate values less than 0.1 $l.s^{-1}$.

- Temporal coupling between infiltration yields and slope deformations taking the example of the la Clapière slope

In order to characterize long term coupling, we compared historic Tinée river flood (RTM database) to landslide annual velocities (CETE database) since 1920 (Fig. 2A). It appears that the activation of the La Clapière, currently active movement, begins around the years 1950-1955. From 1951 to 1987 there is a constant non linear velocity increase up to a 6 $m.y^{-1}$ peak. After 1987, there is a small decrease of velocities that show annual variations ranging between 4 and 2 $m.y^{-1}$ values. During the 1920-1999 period, there are 7 Tinée major flood events that correspond to major precipitation events that caused numerous damages to the valley landscape.

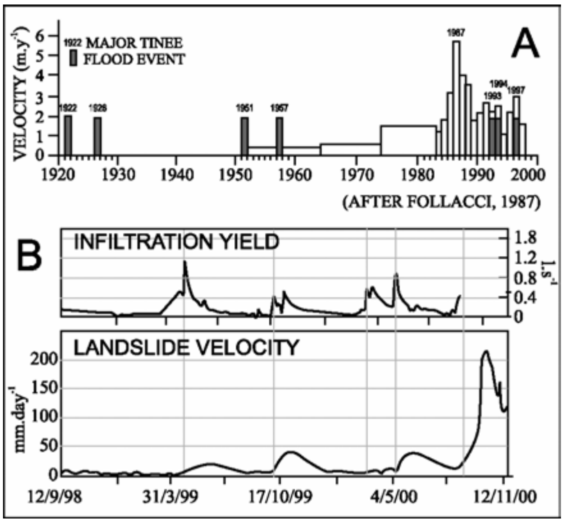

Figure 2. (A) Long-term comparison between La Clapière landslide velocity and Tinée river major flood events (after [4] modified) - (B) Correlation between infiltration and velocity variations at the year scale.

It clearly appears that La Clapière movement activation fits with 1951 and 1957 major floods. It also appears that 1922 and 1926 flood events did not cause any slope destabilization and that 1987 maximum velocity does not correspond with any major flood event. For the 1987 to actual period, speeds fluctuations roughly fit with annual precipitation fluctuations [5]. At the year scale and for recent years (since 1998), a reconstitution of infiltration yields were performed using hydrogeochemistry of springs waters [3]. There are two main infiltration peaks that correlate with long duration moderate precipitation amounts (for ex. 426 mm/30 days during 3/99 period) or with short duration high precipitation amounts (for ex. 122 mm/2 days during 18-22/10/99 period). For a 0.6 km^2 infiltration area, such amounts correspond to precipitation yields respectively ranging between 0.7 and 2.8 $l.s^{-1}$. Landslide velocities curves show accelerations that range between 0.02 and 0.25 $m.day^{-1}$ (Fig. 2B) synchronous to the infiltration peaks periods. Acceleration periods begin when there are spring S5 chemical peaks events and roughly reach a maximum value when there are spring 1 chemical peaks events (Fig. 2B). Accelerations curves have an asymmetric shape with a rapid rise synchronous with the increasing part of the infiltration yield curve (main groundwater flood infiltration) and a slow decrease synchronous to the decreasing and the drying up part of the infiltration yield curve (slope drying up). Duration of acceleration periods is about the same as infiltration periods.

DATING THE EVENTS FROM 10^3 YEARS TO PRESENT USING ^{10}Be AND ^{14}C

A reconstitution attempt of the Tinée valley history from 20 kyr to present was performed by combining various dating methods [6]: ^{10}Be, ^{14}C and geomorphologic approach. A local deglaciation rate of about 0.2 to 0.25 $m.yr^{-1}$ can be estimated. Since the glacier front was at Saint-Sauveur (elevation: 500 m) 20 10^3years ago, this implies that it reached Saint-Etienne de Tinée (elevation: 1100 m) roughly 17 10^3 yr ago. This is consistent with ^{10}Be age of 18970 ± 4543 ^{10}Be-yr obtained at an elevation of 1600m just above Saint-Etienne de Tinée and with a ^{14}C age of 13300 ± 139 yr obtained on a travertine at 1100m in the valley. The main glacier from the Tinée valley disappeared a long time before the lateral ones where deglaciation took place less than 13 10^3 yr ago.
The first destabilization is dated at about 11 10^3 yr. It was sampled at point D4 located at the bottom of a major scarp that bounds a large sagging zone immediately downward the La Clapière landslide (Fig. 1A). This destabilization could be linked to decompression of the slope following this late deglaciation. Since the main scarp dated extends up to the Tinée valley eastern crest, this decompression could be the first destabilization of the whole slope. A second main destabilization phase is dated at about 7.1 kyr. It was sampled at points D1 (6.747 10^3 yr, fig.1A) and D2 (7.257 10^3 yr) located within the middle part of La Clapière slope. This second gravitational event is roughly synchronous to the so called “climatic optimum”, a period of forest cover development on the valley slopes. It could be interpreted as a period of high precipitation rate propitious to landslide triggering as it was recognized in other European areas [7]. Last evidenced destabilization before the historic one occurred 2.3 ± 0.5 ^{10}Be 10^3 yr ago. It was sampled on a scarp that is the lateral continuation of the currently active La Clapière landslide upper scarp. No characterized climatic event is related to this destabilization phase. It could be the consequence of a catastrophic event on a Tinée valley scale or the effect of rock slope strength decreasing as a consequence of a long multi-phase destabilization history.

TOWARDS A HYDRO-GEOMECHANICAL MODEL OF SLOPE FAILURE INITIATION

Numerical methods were used to provide approximate solutions to such complex rock slope stability problems. A huge literature grew, dealing with modeling the effects of all kind of landslide triggering factors. In this study, we focused on two mains processes, slope strength decreasing and fluid hydro-mechanical effects. We considered a vertical cross-section oriented NE-SW perpendicular to the topographic surface and extending from the slope crest (2600 m a.s.l) to the Tinée valley (1100 m a.s.l).

- Modeling of strength decreasing

We have used a two-dimensional finite-element code (ADELI, [8]) using a Lagrangian description of the geological medium [9]. The model use quadrilateral elements of constant strain, while using an adaptative remeshing method [10] to accurately follow strain localization phenomena. Material behaves as strain-softening or strain-hardening elastic plastic materials according to the Drucker Prager law. The strain-softening/hardening parameter depends both on the internal friction angle and on the dilatancy angle. The reference parameters values were taken from field measurements [11] and from laboratory tests: Young’s Modulus, E = 6.4 MPa, cohesion, c = 210 kPa, angle of internal friction, ϕ = 29°, Poisson’s ratio, v = 0.3 and density, ρ =2400 kg/m^3. From the five parameters given previously, two have been tested systematically: the cohesion (c) and the friction angle (ϕ) in order to model the strength degradation of the slope.

All the converged static solutions display three plastic deformation zones. The first zone which is 200m thick extends from the slope foot up to 1400 meters elevations. The second zone extends from 1400 m to 1800 m elevations and it is about 100 m thick. The third zone is at the top of the slope (Fig. 3A). When the couple (c, ϕ) is lowered, the divergence of the numerical experiment result in a strong plastic deformation initiated at the foot of the slope. Then, this plastic deformation leads to the destabilisation of the massif by a regressive evolution of the plastic zone towards the top of the slope. This deformation propagates up to 1800 m, which is currently the top of the currently active “La Clapière” landslide. This deformation concerns only a depth of around 100 – 200 m.

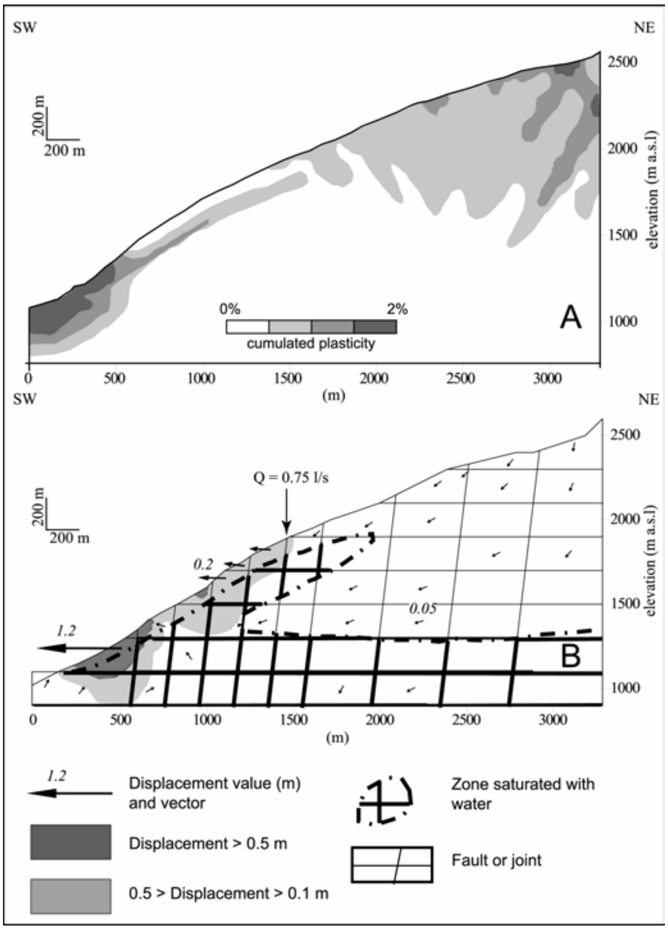

Figure 3. (A) Strength decrease model with ADELI - (B) Coupled hydro-mechanical modelling with UDEC

- Modeling hydro-mechanical processes

We performed parametric simulations with UDEC code in order to estimate water infiltration influence during the initial 1951-1987 behavior of the slope and during the actual post 1987 seasonal behavior of the slope. In the test shown in Fig. 3B, only preexisting fractures were taken into account. UDEC code allows large finite displacements/deformations of a fractured rock mass under pressure loading [9]. We considered the same vertical cross-section as the one modeled previously with ADELI code where 9 discrete penetrative vertical fractures represent the major faults mapped on the site were added. So as to hydraulically connect faults between them and to approximate foliation planes geometry, horizontal joints were included in the model. We used the same mechanical boundary conditions and matrix mechanical parameters that for the ADELI model. Impervious hydraulic boundary conditions were set. Rock matrix mechanical behavior is taken as linearly elastic and isotropic. Faults are assumed to behave according to an elasto-plastic law with the Mohr-Coulomb failure criterion. Fault hydraulical parameters were deduced from field measurements [11].

A perched saturated zone is simulated affecting a local zero permeability at faults segments corresponding to the basal boundary of this zone (dashed line between 1500 m and 2000 m elevation - Fig. 3B). Flow in the faults was set to be compressible. Gravity acceleration was applied. We performed a static hydromechanical calculation with steady-state flow. The cross-section is first consolidated to gravity until stress and displacements are numerically stabilized. Then, initial groundwater conditions were simulated in the basal saturated zone. No interstitial pressure was set in the perched saturated zone. A 0.75 l.s-1 effective infiltration is simulated in the slope at 1900 m elevation (Fig. 3B). On the cross-section, we plot maximum displacements induced by the hydraulic loading.

Pressures increase from 0 to 1 MPa in the perched aquifer. In the basal aquifer, a 0.5 MPa piezometric bump extends from 300 to 1500 m along the x-axis. The maximum calculated values of displacement vector are located between the foot of the slope at 1100 m and the middle part of the slope at 1900 m. This strain zone extends from 50 m to 400 m inside the slope. Displacements values vary between 0.1 m and 1.3 m in that zone. Water pressures are situated in two distinct zones which hydraulically communicate with each other: a basal 500 m thick saturated zone with interstitial pressures ranging between 0 MPa and 5 MPa, and a perched 200 m thick saturated zone with interstitial pressure ranging between 0 MPa and 2 MPa. In the middle part of the slope there is swelling with vectors' dip towards the top linked with mechanical opening of fractures under pressure elevation in the perched saturated zone. In the upper part of the slope there is a lowering (sackung) with vertical vectors'dip.

CONCLUSION

The Tinée valley current landslides are "only" one more reactivation of larger and older slope movements. The oldest known movements correspond to large scale sagging of the upper part of the slope up to the mountain crest. Such movements could be linked to the last deglaciation event where the controlling mechanism involves the release of strain energy leading to the generation and reactivation of tensile extensional features [1]. Nevertheless, such rebound effect can induce deep seated gravitational deformations in the case of a high magnitude glacial retreat like it was measured in the northern French Alps [12] or in Canada for example (Kinakin et al., 2004). This was not the case of the Tinée valley which was located at the southern boundary of the ice front. Thus, some tectonic effects like the high-deformation rate at the Mediterranean margin located 50 km southwards of the valley [13] can also be taken into consideration.

Following destabilizations are obviously influenced by this first event which strongly modified rock slope strength and hydrogeology. Destabilized volumes are smaller and are located towards the foot of the slope. They can be linked to strength decrease of the rock slope and one predominant mechanism is then hydro-mechanical effects of water flow within fractures. We show in this study that tensile features are filled with local material of the slope and that they constitute perched reservoirs at the boundaries of the toppled rock columns. Hydrostatic pressures are concentrated in the middle and upper parts of the slope where a relatively low infiltration yield (mean inter-annual value for example) can cause sufficient hydrostatic pressures elevation in the cracks to increase rock columns destabilization. Tilting at the column surface and failure propagation deep in the slope can be generated roughly from the theoretical bottom of the perched aquifer down to the slope foot. At La Clapière such a failure through tilt could have worked until 1987 when it is taken [5, 14] that a general failure surface was created. When a major failure surface is generated, a large mass slides downslope. The slope drainage becomes more active through this failure surface and there is a general lowering of the hydrostatic pressures in the slope. The perched aquifers is partly drained by the landslide and, at the reverse, waters coming from this aquifer impose pressures elevations in the landslide failure surface upper segments which are closer to failure than lower parts (where stress state is high and segment dip is low or 0). In regions with moderate seismicity, such typical rock slope gravitational structures [15, 16] can then be activated in a few tens of years under precipitations induced periodic hydromechanical effects.

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