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Prediction of landslide movements caused by climate change: Modelling the behaviour of a mean elevation large slide in the Alps and assessing its uncertainties

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ABSTRACT: The consideration of predicted climate change conditions in the hydrogeological and geomechanical modelling of a large landslide allows the assessment of its future behaviour in case of crisis. This application shows that the predictions are not necessarily pessimistic, despite of the uncertainties of the needed assumptions.

1 INTRODUCTION AND OBJECTIVES

For many decades there has been a clear consensus within the scientific community to express various quantitative or semi-quantitative relations between climatic conditions and general landslide movements of different kinds, as well as to use these experimental or empirical relations to try to predict future movements (Terzaghi 1950, Wieczorek 1996). However such relations have often proved to be deceiving as many short-term or long-term complex factors influence the crises of landslides.

One of the possible predictive approaches with neural networks has tried to combine observed past movement data and climatic information to predict future movements (Vulliet et al. 2000) Such a prediction is nevertheless reliable only in a short-term perspective and when no critical situation is likely to occur (Bonnard 2006), which is indeed the case when a reliable forecast is wished!

On the other hand, because of the numerous impacts that a changing climate can have on many elements of the planetary environment, it is of essence to predict the future course of climate forced by enhanced concentrations of greenhouse gases in the atmosphere. Predicting the speed and amplitude of climatic change can thus provide a measure of guidance to decision makers and climate-impact specialists.

In terms of land-surface processes, and particularly slope instability events, climatic factors are often assessed as a key factor in the triggering and/or the amplification of various forms of landslides, rockfalls, debris flows, etc. Precipitation is certainly today the dominant driving mechanism for many forms of slope instabilities, through water loading in soils beyond a critical threshold, or through excessive runoff that will lead to rapid surface erosion and debris flows. Both heavy but short-lived precipitation or moderate but continuous rainfall can thus provoke various forms of slope response, either in a natural or a man-made surrounding. Extremes of temperature can also contribute to slope instability, notably through repetitive freeze-thaw mechanisms at high elevations that tend to weaken rocks by progressively enlarging fractures. In addition, permafrost degradation in high mountains resulting from milder atmospheric temperatures can also contribute to slope instabilities by reducing the cohesion of slope material currently embedded within subsurface ice.

In a changing global climate, it is thus of interest to know how temperature and precipitation patterns may change, both in space and time, and also in terms of mean and extreme conditions. Such changing conditions may result in increased or even new forms of slope hazards compared to those encountered under current climate.

It is also essential to model the complex infiltration process of rainfall and snowmelt in large slides, in order to be able to establish a transient distribution of groundwater pressure at any point of the landslide mass and within the slip surface, so as to model the movements induced by these pressure changes in a FEM.

The objective of this paper is thus to present the global trend of climate change and then to illustrate its possible long-term effect in the case of a large slide. The obtained results will show that in some cases, the so-called evidences are not granted for sure. It is also important to trace and quantify all kinds of possible uncertainties in this multiple process in order to assess the reliability of long-term predictions.

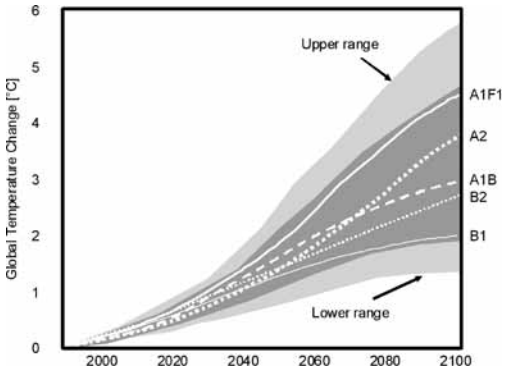


Figure 1. Range of climate futures according to greenhouse-gas emission scenarios; the dark gray zone represents the more likely range of global temperature change (IPCC 2007). For the emission scenarios, see Nakicenovic et al. (2000).

2 TREND OF GLOBAL CLIMATE CHANGE

Perhaps the most exhaustive source of information concerning future climatic change is provided by the Intergovernmental Panel on Climate Change (IPCC). In the succession of reports published in 1996, 2001 and 2007 (IPCC 2007), a number of global climate simulation models have been applied to assess the response of the climate system to anthropogenic forcing in the 21st century, based on a number of greenhouse-gas emission scenarios developed by Nakicenovic et al. (2000). According to the scenario, itself a function of assumptions on population growth, economic growth, technological choice, and policy decisions, the global mean temperature change over present ranges from 1.5–5.8°C, as illustrated in Figure 1. This represents an amplitude of change that is probably one order of magnitude larger than changes reconstructed for the past 20, 000 years (i.e., since the last glacial maximum), and a speed of change that is up to two orders of magnitude greater than typical natural fluctuations of climate.

Climate model solutions suggest that the change in temperature will be stronger in the high latitudes compared to the equatorial region. This is because of the strong positive feedback that can be expected as a result of smaller areas covered by snow in the northern continents, a shorter winter period, and reduced sea-ice cover in the Arctic Ocean. Reduced snow and ice cover will substantially modify the surface energy balance, particularly through increased absorption of solar energy. Temperature change will also be greater over the continents than over the oceans, because of the larger heat capacity of the oceans.

While a warmer climate will enhance the hydrologic cycle, precipitation will not necessarily increase everywhere. The latest climate models published by the IPCC (2007) suggest that the northern latitudes may experience greater precipitation than currently, but that rainfall in Mediterranean and arid climates may decrease (i.e., many semi-arid and arid regions could become even drier in the future). Precipitation totals will probably increase by 2100 in the Monsoon climates of India and China, and in the inter-tropical convergence zone around the equatorial belt.

Temperature in Europe will increase on average by 4–6°C, with strong regional and seasonal differences; for example, summertime warming in southern Europe is expected to be greater than during the winter, because of the positive feedback effect of dry soils during this season (Seneviratne et al. 2006). In the Alps, wintertime temperatures will rise by 3–4°C by 2100 compared to current climate, according to the level of greenhouse gases. Summer temperatures may rise by more than 6°C during the same period, as a result of positive feedback effects from dry soils and reduced snow and ice cover in the Alps (Beniston et al. 2007). Figure 2 shows the difference between summer temperatures for current (1961–1990) and future climates in Basel, Switzerland, not only for mean conditions, but also in terms of the upper quantiles that essentially represent heat-wave conditions.

Simulated results for the low emissions B2 scenario and the high emissions A2 scenario are shown; interestingly, the difference in temperature between the high and low emissions scenarios is less than between the B2 scenario and current climate. This implies that even with rather stringent policies to abate greenhouse gas emissions, the increase in temperatures as seen for the B2 scenario will result in summer heat waves that are as intense, or even stronger, than the 2003 heat wave, with an even greater potential for strong heat waves in the A2 scenario. Indeed, statistically-speaking, the 2003 heat wave could occur one summer out of two in a future climate (Schär et al., 2004).

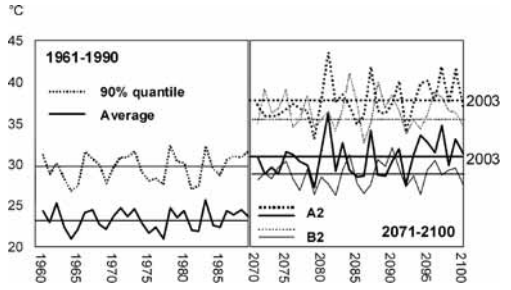


Figure 2. Observed summer temperatures for 1961–1990 (means and 90% quantile values), and simulations for 2071–2100 for the low emissions B2 and the high A2 emissions scenarios established by the IPCC (2007). See text for further details.

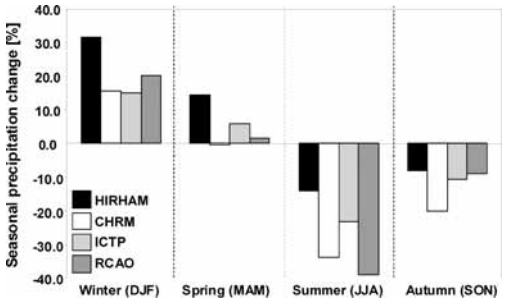


Figure 3. Percentage change in average seasonal precipitation for the control and scenario climates as simulated by 4 different regional climate models; see text for further details.

In a future climate, whatever the emissions scenario considered, the freezing level will thus rise by about 500–600 m in winter and close to 1, 000 m in summer, thereby accelerating glacier retreat and exacerbating the natural hazards associated with deglacierized landscapes. Positive temperatures at increasingly high elevations will penetrate into permafrost layers, leading to its progressive melting and thus reducing the cohesion of soils.

Christensen & Christensen (2003) have shown that northern Europe will experience more precipitation on average, while in a large band stretching from France to the Black Sea and beyond, summer precipitation is projected to diminish by as much as 40%. Simultaneously, many regional climate models point to a strong increase of short-lived but very intense precipitation events in certain regions that are already prone to such hazards, such as parts of central Europe, the Alps, southern France, and northern Spain.

In Switzerland, simulations of climate forced by high greenhouse-gas emissions for the period 2071–2100 compared to the reference 1961–1990 period shows a marked shift of the seasonality of mean precipitation (e.g., Beniston 2006), with strong increases in winter and spring, and substantial reductions in summer and fall, as seen in Figure 3 for four different regional climate model simulations (the Danish HIRHAM; the Swiss CHRM; the Italian ICTP; and the Swedish RCAO models); while the absolute value of change differs from one model to another, all models agree on the seasonal sign of change. The principal cause of these changing patterns is related to the strong summer warming and drying in the Mediterranean zone that would also affect the Alps and regions to the north, and the enhanced winter precipitation that a milder climate may bring to the region, rather under the form of rain than of snow. As a result of the change in mean precipitation, the frequency of extreme rainfall events also changes in seasonality compared to current climate. Model simulations suggest that springtime extremes will increase the most, while summer events may decline by as much as 50%. However, when heavy precipitation occurs in a warmer climate, it may be even more intense because of the additional energy provided by a warmer atmosphere than today.

In terms of the potential for floods, natural hazards and damage that the changes in means and extremes of precipitation may trigger in the Alps, it should be emphasized that heavy precipitation is a necessary but not sufficient condition for strong impacts. For example, Stoffel and Beniston (2007) have shown that while debris-flows of the past have occurred mostly during wet summers, it is conceivable that in a greenhouse climate the frequency of such events could decrease because of the shifts in the occurrence of extreme precipitation from summer to spring or fall by 2100. The response of slopes and watersheds to high precipitation levels varies from one event to another for a number of reasons, in particular the prior history of precipitation, evaporation, permeability of soils and the buffering effect of snow during an event. That may lead to decrease at mean altitude. The more elevated the freezing level, the greater the potential for strong runoff and high intensity of erosion since there is a larger surface area upon which water can flow off the slopes. Under current climate, the most intense events are observed to occur during the summer months, where the freezing level is higher than 3,500 m above sea level. In a future climate, on the other hand, the freezing level associated with heavy rainfall will be on average 500 m lower because many events will take place either in spring or in autumn, at a time of the year where conditions will be cooler than for current summers. However, even if their frequency is likely to decrease, the magnitude and impacts of future summertime debris flows, mudslides or rock-falls could be greater than currently because of warmer temperatures and higher precipitation intensities.

3 TYPES OF LANDSLIDES AND SLOPES LIKELY TO BE AFFECTED BY CLIMATE CHANGE

It is evident that all kinds of shallow slides and improperly drained engineered slopes, as well as potential debris flow creeks are likely to present a higher hazard level in the future, as one of the major characteristics of climatic conditions in the 21st century is to display more intense storms occurring probably with an increased frequency. Another reason for this increased hazard is the always extending area of impervious zones in the concerned watersheds, due to the development of urbanization and roadways. This situation causes higher peak floods in streams or excessive discharges in inappropriate sewage or drainage ducts that are likely to divert sudden flows at the surface of slopes through manholes or pipe failure and thus generate destructive mud flows, if specific retention works are not foreseen.

In the case of high mountain slopes, the increasing melting of the permafrost zone due to higher summer temperatures can also be a cause of unexpected debris flows, even outside of a rainfall event. The loosened fan material at the toe of mountain cliffs provides more sediments for the debris flows that can generate more extensive impacts in the valley floor; this critical situation is especially due to the intense tourist development of chalets in zones providing space with a view and easy access.

In all these cases there is a nearly simultaneous occurrence between the storm triggering the landslide and the development of the landslide process leading to severe visible impacts on buildings or agricultural land, so that there is no doubt about the relation between the climatic conditions and the consecutive damage. However in the cases of larger slides such a correlation is not evident to demonstrate and a nearly similar rainfall pattern can cause a slight increase of the movements of a slide during one winter and a severe crisis during the next winter, as it was observed and monitored at La Chenaula landslide in Switzerland in 1982 and 1983 (Noverraz & Bonnard 1992).

In the case of large to very large slides, extending on an area of one to several km^2, with differences of elevations between scarp and toe that can reach several hundreds of meters, the situation is even more complex, as several factors may influence the reaction of the landslide mass, namely:

- variation of rainfall amount with elevation
- offset of snowmelt episodes along the slope
- capacity of snow cover to absorb a large amount of rainfall before infiltration occurs
- variation in vegetation implying different interception and evapotranspiration patterns

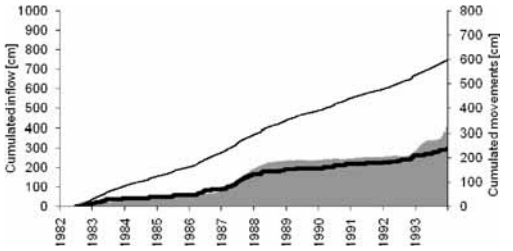


Figure 4. Relationships between horizontal displacements and computed flux entering the La Frasse landslide in a cumulated representation. Thin line: infiltration issued from COUP model (considering temperature, snowmelt, vegetation, soil, sun exposure...). Thick line: weighted and truncated infiltration over several years in the past. The best fit of the thick curve with the displacements (grey area) is concluded from the shape of the curves rather than from the value of the corresponding points.

- distribution of permeability fields at the surface of the slide and in the landslide mass
- possibilities of differentiated infiltration along streams flowing on the slide as well as in cracks
- occurrence of floods in the stream flowing at the toe of the slide and likely to cause erosion
- development of urbanization and collecting water pipes and ducts
- differences of reaction of the landslide mass along the slope (swelling and depletion zones).

In such cases it is also necessary to consider the effect of climatic impact not only for one specific event, but for a crisis period that can be caused by antecedent conditions extending to several years before the observed crisis. In the case of La Frasse Landslide, in Switzerland, it has thus been shown (Tacher et al. 2005) that several factors like interception of modest rainfall and evapotranspiration had to be considered in order to express a good correlation between infiltration flow and movements (Fig. 4).

It is then necessary to analyse the changing climatic situation through the formulation of scenarios implying different episodes along the yearly cycle. It is of course essential to gather enough long-term data on the movement of the slide as well as continuous displacement information on so as to understand its global behaviour and to confront the observed and modelled displacement vectors.

4 LONG-TERM MONITORING OF THE IMPACT OF CLIMATE CHANGE ON LANDSLIDE BEHAVIOUR

In order to determine the possible effect of climate change conditions on the behaviour of large slides,

it is first necessary to gather available data providing information on their long-term movements. Such an investigation has been carried out in Switzerland within a national research project (PNR31), considering a dozen of very large slides, extending over areas from one to some 40 km^2, and for which ancient geodetic survey data had been collected (Noverraz et al. 1998).

In the specific case of Lumnez Landslide, in the Canton of Graubünden in Eastern Switzerland, the position of the spires of 7 village churches has been regularly monitored for more than a century (up to 17 monitoring campaigns beginning in 1887). The results showed in general a very constant average velocity, varying from 3 to 20 cm/year (Fig. 5).

Only one point located near the toe of the slide (village of Peiden) displayed a clear reduction of velocity after the years 1940, which can be partially explained by a series of dry years and then by the construction of a dam on the river Glenner flowing at its toe, upstream of the slide. As far as the annual rainfall is concerned, the long-term trend is not so marked in this region (average value of 950 mm/year—Figure 5) as in western Switzerland, in which a clear increase of annual rainfall by some 10% has been observed since the years 1980 (this fact has induced the Swiss hydrological service to change the long-term reference rainfall value from the period 1901–1960 to that extending from 1961–1990 for all rain gauge stations).

It can thus be observed that most of the very large slides monitored display a fairly constant velocity even if the are affected by long periods of higher precipitation. This fact can of course be due to their size and depth, inducing a certain mechanical inertia, as well as to the large storativity of their hydrogeological conditions. But this observation is not necessarily valid for all slides.

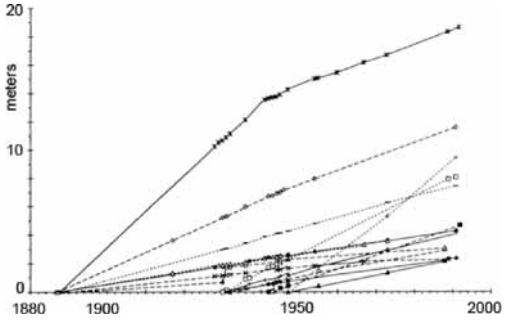


Figure 5. Cumulated displacements of several topographic points at Lumnez landslide over a period of more than one hundred years.

In a few cases, indeed, some monitored points of these large slides have displayed an acceleration phase that may last from several months to a year, like in the case of La Frasse landslide, for which crisis periods of a few months duration have been recorded in 1966, 1982–83 and 1993–94 (Tacher et al. 2005). In most of the duly monitored slides, this major acceleration phase does not imply the whole landslide mass, but a part of it, generally located at its toe or eventually in an area in which the depth of the slide is reduced. Such a situation was clearly put forward in the case of Chlöwena Landslide in Switzerland, in 1994: the crisis lasted for 4 to 5 months, with a peak velocity of 6 m/day at the end of July that was reduced to a few cm/year at the end of September (Vulliet & Bonnard 1996).

A comprehensive approach of such complex phenomena therefore requires first a long-term monitoring and then a detailed modelling in order to understand the hydrogeological and geomechanical conditions that explain the crisis episodes. In a second step it is possible to determine the probable effects of climate change in a quantitative way, considering several crisis scenarios. Such an approach has been applied to various slides and in particular to the Triesenberg landslide.

5 MODELLING THE CLIMATE CHANGE CONDITIONS : THE TRIESENBERG LANDSLIDE

The Triesenberg landslide extends over a significant part (i.e. 5 km^2) of the Principality of Liechtenstein (160 km^2), located to the East of Switzerland (Figure 6). It also includes two villages, Triesen at its toe and Triesenberg at mid-slope, the infrastructures of which incur occasional damage, in particular during crisis episodes.

The movements of this landslide are quite ancient and date back to the end of the Wurmian period; presently they are generally slow (i.e. some mm/year to cm/year) in normal conditions and locally may reach velocities of a few dozens of cm/year during severe crisis periods. As the slide displays a relatively slow movement, many buildings have spread on the slope in particular during these last decades, due to the real estate development.

The objectives of the research were the following:

– to determine the critical hydrogeological conditions that cause an acceleration of the slide and that may justify the triggering of an alarm system;
– to foresee the behaviour of the slide under the possible effect of climate change, so as to establish bases for the sustainable development of the slope.

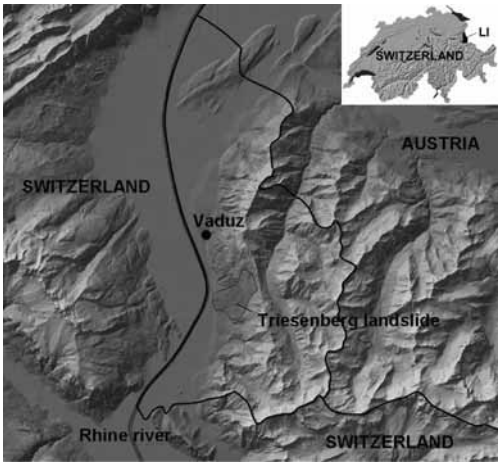


Figure 6. Location of the Principality of Liechtenstein and of the Triesenberg landslide.

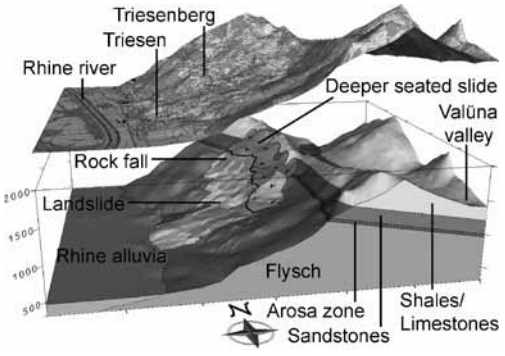


Figure 7. Geological model of the Triesenberg landslide. The draped topographic map is lifted to display the geological units.

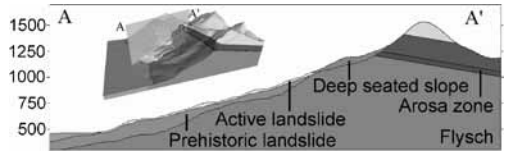


Figure 8. Geological vertical cross-section.

The first aim of the models developed does not consist in determining the possibilities of stabilizing the overall slope, as it can be expected that such works would by far pass the planned investments by the authorities of the Principality. What is aimed at is to live with the slide, and not to slow it down.

The specific difficulties presented by the Triesenberg landslide mainly refer to its large area, to its essentially unsaturated hydrogeological conditions and to the slow movement velocities.

After calibrating the model parameters with respect to the crisis of 2000, the impact of climate change has been analysed by modifying the boundary conditions of the hydrogeological model, on the basis of the relevant climatic scenarios, as set up by the Swiss Commission for the assessment of climate change (OcCC, 2004). Then the respective computed groundwater pressures have been introduced in the geomechanical model, as it was done for the year 2000.

5.1 *Main features of the landslide*

5.1.1 *Morphology and geology*

The slope is oriented from North-East (up) to South-West (down). It presents some small undulations but is generally fairly regular. Based on a digital terrain model, the mean slope is 24° (Figures 7 and 8). Three parts are distinguished:

– In the upper part, deep-seated slope movements occurred, probably at the end of the Wurmian glacial retreat (14,000 years); they are now underlined by a terrace in the topography at the top of the slope (Figure 8) and were triggered by a deep landslide, the so-called Prehistoric landslide. This upper zone, largely inactive, is not considered to cause a driving force on the slope. Approximately, it covers 1.7 km^2 with a volume of 74 million m^3.
– The prehistoric landslide is known by some boreholes. It is more than 80 m deep and is made of flysch (clayey shales). This zone is today stabilised; moreover, no movement has been observed at the toe of the landslide, where it lies under the Rhine river alluvia (gravels).
– The active landslide (Table 1) covers the prehistoric one. It is also composed of flysch and takes place on a slip surface located at an average depth of 10–20 m. According to the inclinometer data, available from 1995 to 2002, the slip surface is approximately one meter thick.

The analysis of the observed intensities and directions of the movements (Figure 9) showed that the area is indeed composed of three instability zones that can be considered as independent.

This is confirmed by the reduced depth of the slip surface close to the assessed boundaries of the three areas and by the spatial distribution of damage to infrastructures (Frommelt AG 1997).

The practical consequence of the decomposition of the landslide into three distinct systems is to allow defining three different modelling areas for the 3D

Table 1. Main features of the Triesenberg active landslide.

Aspect	Characteristics
Area	3.1 km^2
Altitudes	min. 460 m, max. 1500 m a.s.l.
Length	2300 m
Width	1500–3200 m
Mean depth	10–20 m
Volume	37 millions m^3
Mean slope	24°
Mean velocity	0 to 3 cm/year
Soil	Flysch (clayey shales) including elements of limestone and sandstone
Vegetation	Pasture land and some wooded zones
Investigations	Hydrogeology, boreholes with inclinometers, GPS, RMT geophysical methods, laboratory tests, modelling
Possible damage	Infrastructures of two villages

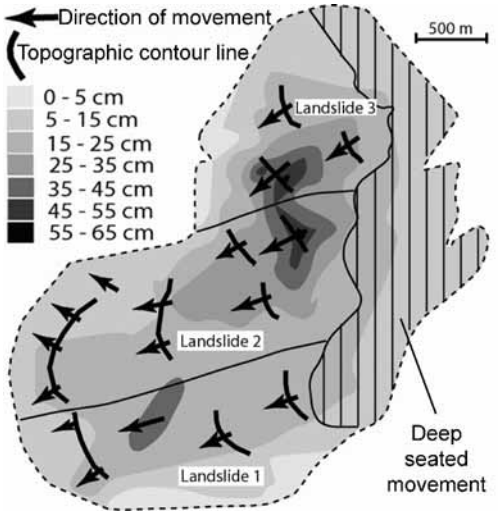


Figure 9. Total displacements between 1976/1981 and 1996/1997 (i.e. during some 20 years) in the whole instability area, and boundaries of the three so called independent landslides.

mechanical modelling, supposing negligible kinematic interactions between them (the hydrogeological model involves a single regional area).

5.1.2 *Hydrogeology*

Besides supplying the geomechanical models with hydraulic pressures, the hydrogeological analysis and modelling aims at a better understanding of the particular hydrogeological behaviour of the slope.

The yearly observation of displacements shows a close dependence of the movements on the seasons. A reactivation is generally perceived in the spring, which corresponds to the snowmelt period. This indicates that the main driving force of the movements is the variation of pore water pressure in the slope. However, a reactivation may also occur following a storm event.

The tectonic Arosa zone (Fig. 8) is a very important feature of the hydrogeological system due to its low permeability: a part of the Valüna Valley groundwater (Fig. 7) flows on the Arosa zone and feeds the basal surface of the landslide, causing the Triesenberg groundwater basin to be much larger than its topographic watershed. This mechanism is proven by several observations (Tacher & Bonnard 2007).

Such a double feeding is also effective outside intensive infiltration periods. Both a hydraulic balance of the Triesenberg slope (Bernasconi 2002) and a numerical model calibration suggest that about one half of the inflow in the landslide is supplied by a base flow from the Valüna Valley through the sandstones covering the Arosa zone (ca. 9 mio m^3/year). Groundwater discharge occurs through some one hundred springs distributed over the landslide, as well as at its toe, in the River Rhine alluvia. The water table is located about 20 to 30 m below the soil surface at the top of the landslide, whereas at the bottom, it almost reaches the ground surface.

5.2 *Hydrogeological modelling of the year 2000*

The year 2000 was chosen to perform the modelling; during this year, a critical phase with a reactivation of the movements was observed, showing a good correlation with the snowmelt phase in April. A violent thunderstorm also occurred on August 6th. This year has a return period of the annual rainfall of 42 years, according to the Gumbel law. Another reason of this choice is the availability of calibration data for both hydrogeological and geomechanical models. As the slide is very thin, the unsaturated zone is of relatively high importance, which justifies computing groundwater flows in unsaturated regime, i.e. the flows are governed by Richards' equation (Hillel 1980).

From the model results, in terms of volumes, the direct infiltration reached 7.52 mio m^3 in 2000, while the inflow through the Arosa zone was about 9.86 mio m^3 (Figure 10). The cumulated rate of the springs reached 1.06 mio m^3, which represents only a few percent of the total outflow; the balance flow seeps in the Rhine river alluvia.

The outflow curve is smoother than the inflow events, due to the capacitive function of the landslide. Typically, the August 6th storm response was absorbed and delayed. In May, the snowmelt episode did not lead to spectacular changes in the hydraulic

balance because, due to the slope topography, the melting occurred progressively from the bottom to the top. For example, when the snowmelt occurred in the Valüna Valley, it had already finished on the landslide several days to weeks earlier.

More relevant from the geomechanical point of view is the piezometric behaviour. It is illustrated by piezometer B8 (Fig.11). The respective calibration was carried out by comparing the water table data with the hydraulic head computed at the bottom node at this site, i.e. at the slip surface. Both main events of the year 2000 led to a peak more than 2 m high. Just after these peaks, the head decrease was slower in the model than in the reality. This can be explained by the relative smoothing of the parameter field, mainly over depth.

Heterogeneities are also responsible for another observation: during the snowmelt event, the model reacted with a delay of some days with respect to the monitoring data. Local pervious heterogeneities that were not considered in the model accelerated the piezometer response to inflows in the Valüna Valley. Such a delay did not occur at the beginning of August since inflows concern both the Triesenberg and Valüna basins.

The numerical results suggest that the model globally fits with reality, despite a simplification of the parameter fields, a rough estimation of the unsaturated parameters and a minimal knowledge of the real hydraulic balance. Computed hydraulic pressures are thus suitable as an input in the hydro-mechanical models in order to describe the direct causes of the movements during crises.

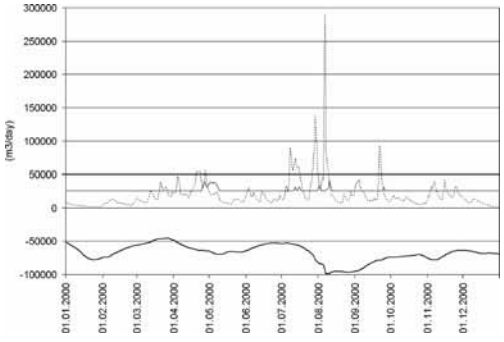


Figure 10. Hydraulic balance of the model for the year 2000. Thin line: Feeding by the Arosa zone. Dot line: Direct infiltration on the slope. Thick line: Outflow rates through springs and the River Rhine valley.

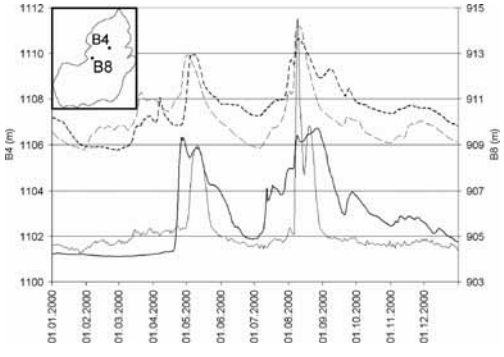


Figure 11. Measured and computed hydraulic heads in piezometers B4 and B8. Thin line: B4 measured. Thick line: B4 computed. Thin dotted line: B8 measured. Thick dotted line: B8 computed.

5.3 *Geomechanical modelling of the year 2000*

The effect of the hydraulic head variation with time, as determined by the hydrogeological modelling, on the mechanical behaviour of the whole slide, has been modelled by a FE code, Z-SOIL (2-D and 3-D), using a Biot-type formulation, implying the conservation of mass and momentum of both fluid and solid phases (François et al. 2007).

In the 3-D model, the maximum displacement values are in general slightly lower, but they appear within zones where damage has been reported (Fig. 12).

Parametric studies have also been carried out to evaluate the effect of the selected friction angles (between 30 and 21°) and of the range of water pressure variation (the computed data through the hydrogeological model were multiplied by 1.25 and 1.5 respectively).

Both simulations display nearly linear variations and prove that, even in extreme conditions, it is not expected that the movements will lead to a catastrophic behaviour of the whole slope.

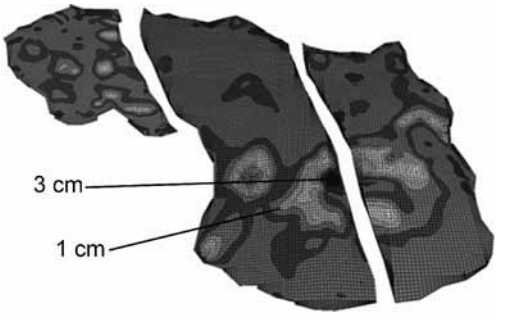


Figure 12. Distribution of the obtained displacements after 291 days of simulation, from January 1 to October 18, 2000 (water pressure data multiplied by 1.25) and location of the more active zone in the central slide (3 cm).

5.4 *Modelling of Climate change impact and related uncertainties*

According to (IPCC 2007), the air temperature should increase in the medium term, especially in summer, and the rainfall should increase in winter, but decrease in summer. The climatic scenario for 2050 used in this study is issued from the Swiss "Organe consultatif sur les Changements Climatiques" (OcCC 2004), more specific to the North of the Swiss Alp context (Fig. 13).

According to this scenario, it can thus be expected that:

- In winter, the total infiltration would increase and rain would partly replace snow accumulation. On the other hand, snowmelt at the beginning of the spring would be less important.
- In summer, the storm events would remain similar, if not slightly worse, but the total infiltration would be smaller than today because of higher evapotranspiration.

In this study, the rainfall in 2050 is considered to increase by 2 mm/day in winter and to decrease by 2 mm/day in summer. Those values are added as a one year sinusoidal transformation to the records for the year 2000. Similarly, the temperature curve for 2050 is obtained by adding a one year sinusoidal function to the records of the year 2000, considering a warming of 1.5°C in winter and 3.5°C in summer (Figure 14).

Considering the impact on landslides, such a scenario is not obviously more severe, mainly for the landslide zones in altitude. Indeed, besides the total infiltration, the groundwater pressure fluctuations have a major effect on the movements. By diminishing the rather massive infiltration period of snowmelt, the 2050 scenario smoothes out the groundwater head curve at spring time. In particular in the Valüna valley, the fast snowmelt at the beginning of May 2000 might be replaced by a succession of less important episodes of rain, falling on a thin accumulation of snow.

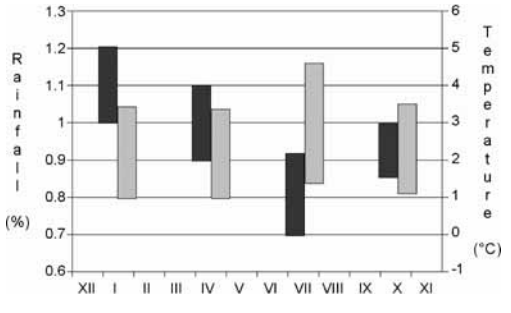


Figure 13. Climatic scenario for 2050 for the North of the Alps, after OcCC. Horizontal axis: months of the year. Black bars: Rainfall change in % with respect to present average seasonal values. Grey bars: Temperature change in °C.

The target of the models is here to consider the most unfavourable scenario as far as the landslide movements are concerned. Thus these worst case infiltration conditions for 2050 are as follows, even if they are not the most plausible:

- No consideration of the decreasing of gross rainfall in summer. The infiltration curve is left intact from May 1st,
- Keeping the snowmelt event of the end of April,
- In winter, adding infiltration periods without decreasing the accumulated snow height.

In practice, the 2050 infiltration scenario implies to add infiltration days between January 1 and April 20 to the year 2000 conditions. For all altitude classes of infiltration, a 5 mm/day event is introduced each ten days (Fig. 15). This represents an additional infiltration of 55 mm/year.

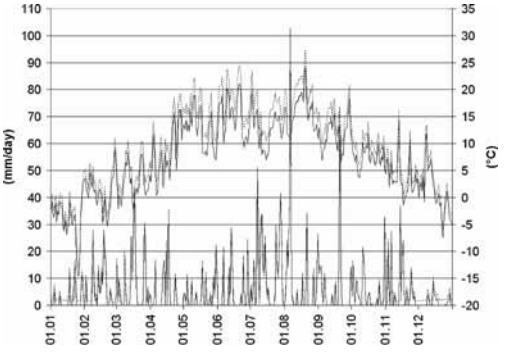


Figure 14. Climatic scenario for 2050 in the Valüna valley. Upper curves: Temperatures in 2000 (solid line) and in 2050 (dotted line). Lower curves: Gross rainfall in 2000 (solid line) and in 2050 (dotted line).

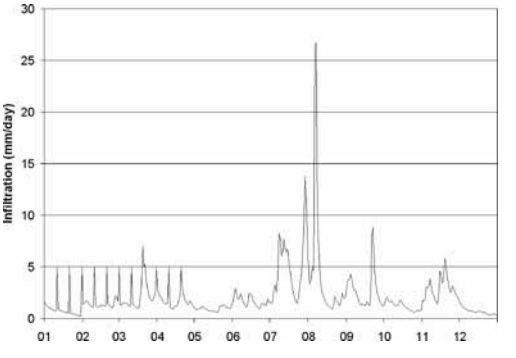


Figure 15. Scenario 2050. Infiltration conditions for altitudes below 625 m.

The results of both hydrogeological and geomechanical models with such modified boundary conditions are very similar to those obtained for the year 2000. Typically, the hydraulic heads in piezometer B8 (Fig. 11) are changed by some centimetres only.

Considering uncertainties on climatic changes, the modelled scenario appears to be probably the worst case. In such conditions, the computed velocity field for 2050, if the parameter calibration on year 2000 is considered as reliable, is a rather pessimistic global assessment of the slope. However, the transition to a stormier climatic regime may have local consequences (hectometric slides, mudflows) not considered in this regional modelling.

6 CONCLUSIONS

A detailed hydrogeological and geomechanical modelling as it was recently applied at the Triesenberg and La Frasse landslides allows a significant modelling of large landslide movements during crises, provided sufficient information is available. The application of predicted climatological conditions in the future then supplies quantitative values of possible movements, considering appropriate scenarios. However, extremely rare conditions with a very remote probability cannot be modelled reliably, as the boundary conditions may significantly differ from the ones considered in the original model.

The analysis of several large landslides in other contexts (Bonnard et al. 2004) also shows that the effect of climate change on landslides within the next 50 years or so must not be overemphasized. Indeed, as shown here, the progressive snowmelt that will begin earlier than before tends to reduce the occurrence of critical situations in the spring or summer. On the contrary, it is clear that the expected increase of storm intensity, as foreseen by some climatologists, may produce more violent and frequent small slides and debris flows; but this specific prediction is not relevant for large landslides and cannot justify a development of more severe disasters related to this type of phenomena. Indeed, due to the heterogeneity of the material at a large scale, to the increased range of altitude where infiltration occurs, to the capacitive function of the landslide mass and to the more complex hydraulic relationships with the bedrock, the response to climatic events may be significantly smoothed and delayed, which explains this relatively optimistic vision.

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