THE SECOND
WORLD
LANDSLIDE FORUM

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# The Cassas Landslide and its impacts on an international & Olympic transportation corridor: studies, monitoring, solution and crisis plans

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**Abstract** The Cassas landslide is located in NW Italian Alps and impinges on a corridor encompassing main transportation lines between Italy and France, hydro facilities and a village. The largest potential reactivation phenomenon is considered to be of approximately 10 $Mm^3$, with a maximum depth of the main body of approximately 80 m and an average slope of 20-25 degrees. The slide was the object of monitoring for more than a decade and special attention was devoted to it in view of the 2006 Torino Winter Olympics (the highway at its toe was the main Olympic lifeline). A formal quantitative risk assessment (QRA) and related monitoring program were performed. The integrated approach yielded interesting predictive/observational results, which drove stabilization actions including a drainage tunnel and the compilation of a highly sophisticated alert/crisis plan in case of future accelerations.

**Keywords** landslide, risk assessment, monitoring, tunnel, drainage, QRA, transportation, hydro, monitoring.

## 1 . Introduction

The Cassas Landslide is located in the NW Italy Piedmont region and impinges on a corridor encompassing main international transportation lines (highway and railway) between Italy and France, hydro-electrical facilities and a village.

The slide, or more precisely, the slides system, covers a very wide and inaccessible area in a National Park. Analyses showed that the largest potential reactivation phenomenon, which underwent a paroxysm in 1957, would have a volume of approximately 10 $Mm^3$, with a maximum depth of the main body of reaching 80 m and an average slope of approximately 20-25 degrees. If this reactivation would occur, both the highway and the railways at the toe would be severed for many months, the community would be damaged and flooded.

The sliding mass is very elongated and presents, in its zone of depletion, secondary scarps and intermediary tension cracks areas, recognizable by geomorphological approaches.

The slide was the object of monitoring for more than a decade by various agencies. Special attention was devoted to it in view of the 2006 Winter Olympics (the highway at its toe was the main Olympic lifeline), especially since the slide underwent a significant acceleration in the aftermath of the 2004 Piemonte Flood.

A formal quantitative risk assessment (QRA) (Einstein, 1988, IUGS, 1997, Oboni, 2003) and related monitoring program were carried out based on geological studies, borings, monitoring data, etc.. Within the QRA the slope was modeled by using the Oboni-Bourdeau (1983) probabilistic slope stability analysis method. Data for this approach were also derived from pre-existing studies.

A specific monitoring program led to complement pre-existing data with new evidence and allowed regular updates of the probabilistic model until it was suspended for administrative reasons. The integrated approach yielded interesting predictive/observational results, which drove stabilization actions in the form of a drainage tunnel and the compilation of a highly sophisticated alert/crisis plan in case of future accelerations.

## 2. A critical phenomenon

Quantitative Risk Assessments (QRA) studies should be developed when dealing with complex phenomena and potentially catastrophic consequences (Roberds, 2001, Cheung et al., 2001, IUGS, 1997, Fell, 1994). The massive Cassas potential slide reactivation has many critical potential targets (multi-modal transportation corridor, electrical facilities, damming of the river and resulting flood). Public authorities governing the territory requested such a study in 2004 also considering the importance of the highway for the winter Olympic games to be held in Torino in 2006.

At the time of the request, the slide had already been monitored – geotechnical studies, deformations, water table - since many years. The approaching international event required however to step up the analyses and to deliver concrete solutions to the problem.

After a preliminary geology, geotechnique data interpretation, the first step was to perform a probabilistic modeling of the stability of the slope by using the Oboni-Bourdeau probabilistic slope stability analysis method (Oboni & Bourdeau, 1983, Engel et al., 1983, Bonnard & Oboni, 1985) as a main tool to quantify the probabilities of initiation of the reactivation and the potential extent of the reactivation mechanisms. The prototype model was developed after careful evaluation of all the available data. The main results of the analyses can be summarized as follows:

- The slope would behave as a series of "independent" bodies where the uphill one would reactivate, slide down to take support on the prior, downhill one, cause its sliding, slow down and repeat the cycle unless a major heave of the water table would create the conditions for a massive reactivation.
- The slope was not prone to sudden reactivations, but could feature paroxysms (accelerations) lasting various weeks in case of particularly unfavorable meteorological conditions.
- It was predicted that the heave of 6-8 m of the water table in certain areas, monitored by piezometers, would most likely cause a significant acceleration of the sliding velocity in that area. This was confirmed by the data available for the slope after the major 1994 and 2000 floods, related to high rains and water table heaves.

## 3. Monitoring Programs

With the need of updated data to support the QRA a massive existing instruments repair and restoration campaign was implemented as shown in Figure 1. The repeated shearing of inclinometric tubes every 2 – 3 years did not offer a favorable outlook.

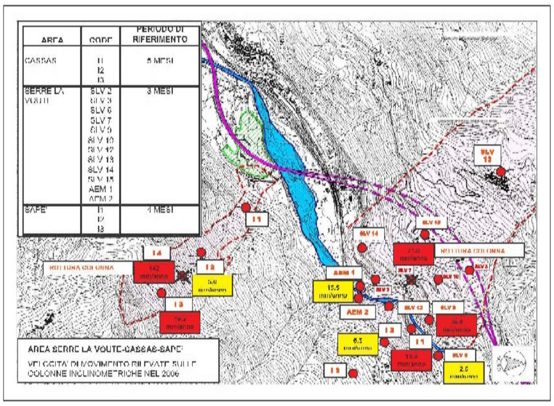


Figure 1 – The complex monitoring program on the slides system

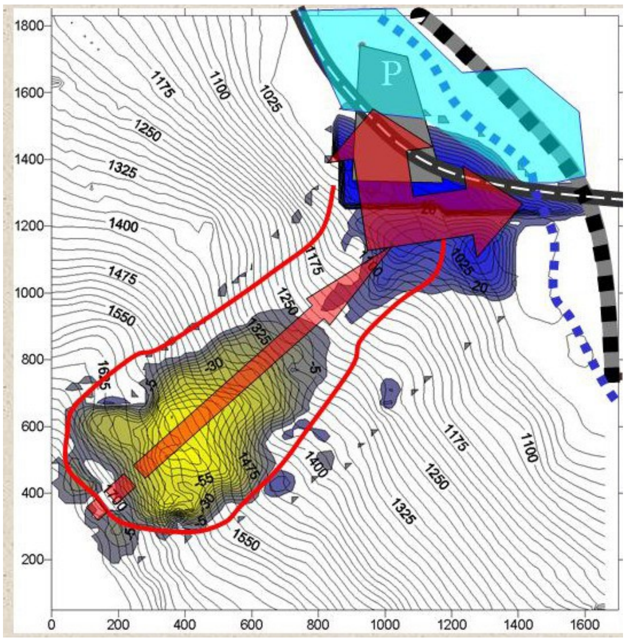
Thus motorized optical instruments were added on the slope, reporting via GSM to a central monitoring center (CTM, 2002, Piemionte, 2004). The center was responsible for triggering emergency plans specifically designed for various types of potential reactivation, i.e. volumes going from a few hundreds of thousands cubic meters to the largest considered potential reactivation phenomenon.

Models were developed to predict how a future catastrophic paroxysm would interact with the valley floor, the river and various structures/potential targets (Fig. 2), leading to the formulation of appropriate emergency plans.

Figure 2 - Study of the areas potentially invaded by a 10 $Mm^3$ potential paroxysm of the Cassass Landslide.

## 4. Alert levels

A five level velocity- alert criteria was established for the Cassas landslide (Polithema & Oboni, 2003). This criteria drives the alert status, changes in the frequency of monitoring, and, of course, can trigger the emergency plan, which encompasses several reactivation scenario.



The landslide went in a pre-alert level in the period following the year 2000 flooding which was captured by the monitoring program implemented within the risk assessment study.

## 4. Modelling Results

The main objective of this paper is to show how the results of the long term monitoring program have been used, i.e. how these results complement the initial predictive analyses and the risk management decisions.

Two separate series of data were used, namely:

- from June 1999 to November 2001, where only data from one inclinometer (I2) were missing
- from October 2001 to September 2002, where piezometric data were missing

The two periods allowed studying possible similarities between a period culminating with the year 2000 flood and a relatively calm period following this extreme event.

Data were:

- rain (mm)
- sliding velocity (cm/yr), as measured at inclinometers I2, I3, I4 and

- piezometric readings at point Pz3, Pz4.

Raw rain data were used to compile mobile rain averages (MRA) for periods going from 3 months to 12 months (90 days to 360 days, i.e. $MRA_{90}$ to $MRA_{360}$), with the aim of studying correlations between antecedent rains and sliding velocity. $MRA_t$ of day d is the average rain calculated on t days before and including day d.

## 5. Data Analysis

### 5.1 Determining the most significant rain as slide activity parameter

The sliding mass is rather porous at large scale and most rain ends up infiltrating the sliding body before it reaches the toe. Very little water runs in surface channels along the slope. This lead to think that it would be erroneous to subtract runoff from the total rain; evapotranspiration, on the contrary, is quite strong, especially during summers, and should be subtracted from the total rain. It was assumed, as a first level of analysis, that evapotranspiration can be evaluated using empirical factors developed for the European region for latitudes between 45° e 50°, during vegetation (30th March- 30th October), i.e. a value of 1 to 2,5 mm/day. With this assumption a hydrological deficit can be evaluated towards the end of summer (September-October) for the $MRA_{90}$-$MRA_{180}$, meaning that evaporations and transpiration overcome precipitations during the 3-4 summer months preceding September-October.

### 5.2 Correlation Analysis

The available raw data and $MRA_t$-evapotranspiration data were analyzed by means of a multivariate correlation approach yielding a correlation matrix for various $MRA_t$, the velocity in I3 and I4, and the water levels in the piezometers Pz3 and Pz4. The matrix is depicted in Table 1 truncated of rows and columns that did not display significant correlations. The correlation matrix allows understanding of which variables are more (absolute value of correlation higher than 0.5) or less (absolute value of correlation lower than 0.5) linked to the others. Correlation of one means "perfect" link, minus one "perfect" antithetic link, and nihl means no link at all between two variables.

In Table 1, the strongest correlations are shaded. For example $MRA_{240}$ (4th row in the original table) has a correlation of 0.80 with the velocity of inclinometer I3 ($VI_3$, 7th column in the original table) respectively 0.82 with I4 ($V_{I4}$, 8th column in the original table). Correlation matrices are symmetrical with respect to the diagonal, which always displays values of 1 (the correlation of a parameter with itself is, of course, "perfect"). The symmetry comes from the fact that the correlation of parameter A with parameter B is the same as B with A.

| | **$MRA_{240}$** | **$MRA_{300}$** | **$MRA_{360}$** | **$V_{I3}$** | **$V_{I4}$** |
|---|---|---|---|---|---|
| **$MRA_{240}$** | 1 | 0.86 | 0.79 | 0.80 | 0.82 |
| **$MRA_{300}$** | 0.86 | 1 | 0.86 | 0.88 | 0.90 |
| **$MRA_{360}$** | 0.79 | 0.86 | 1 | 0.81 | 0.85 |
| **$V_{I3}$** | 0.80 | 0.88 | 0.81 | 1 | 0.99 |
| **$V_{I4}$** | 0.82 | 0.90 | 0.85 | 0.99 | 1 |

Table 1 Truncated Correlation Matrix between 30-6-1999 and 20-11-2001. Only the strongest correlations are shown.

### 5.3 Comments and Results

The correlation between $MRA_t$-evapotranspiration and inclinometer velocity increases at the Cassas landslide for increasing antecedent rain periods up to t=300 days, then decreases. This means that the landslide mostly responds to rain occurred in a period of ten months prior to the date considered (Figure 3).

Thus the 300 days antecedent average rain (net of evapotranspiration) is the best indicator (to date) to predict movements of this landslide.

Long term monitoring confirmed a tendency predicted by interpreting (Oboni et al., 1984) the Oboni-Bourdeau probabilistic slope stability analysis results of inclinometers I3, I4 to behave antithetically (when I4 accelerates, I3 slows down and vice versa). Indeed, for the years 2000-2001 $V_{I4}$=appx.15 cm/yr (I4 being down-slope of I3) is higher than $V_{I3}$= approx. 11.8 cm/yr, whereas in other periods the contrary happens (Figure 3).

After a long rainy period the sliding is more active in I4 than I3, global permeability increases due to the movements and piezometric levels drop. Also piezometer Pz4 behaves antithetically with respect to Pz3 (when water table raises in Pz3, it drops in Pz4), (Figure 3). This phenomenon indicates that a "compressive, breaking/stabilizing" area exists between I3/Pz3 and I4/Pz4. Correlation between piezometers and rain is not very high, mostly because of all these mechanical simultaneous effects result in changes of porosity on a large scale.

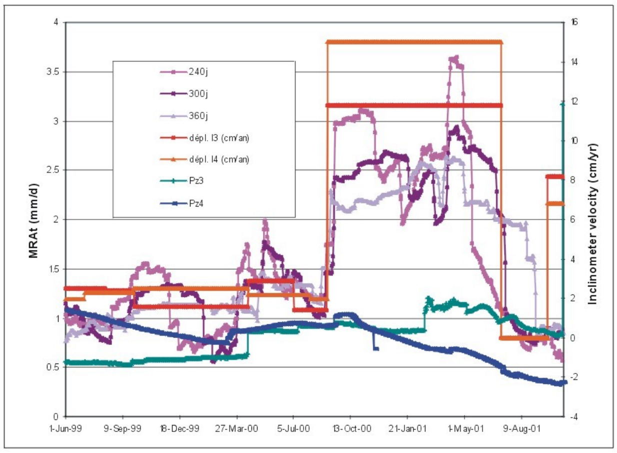


Figure 3 - MRA t=180, 240 and 300 days, inclinometric sliding velocities and water table levels as measured in the piezometers.

Finally the analyses demonstrated that at the Cassas Landslide there is a pluviometric threshold, located around 800 mm of rain in the antecedent 300 days, critical for triggering sudden acceleration of the mass. This threshold value was attained only once during the observation period corresponded to a heave of the water table of approx. 8 m and, as predicted by the Oboni-Bourdeau probabilistic stability analysis results triggered a violent acceleration (velocity three fold of the precedent average velocity).

That acceleration was in its turn the trigger for the decision to implement stabilization work under the form of drainage, as developed in the next sections.

## 6. Modelling with AI, artificial intelligence

During the years an attempt has also been done to model the slide with Artificial Intelligence, A.I. AI systems are capable of predicting performances in many fields and have been used in missiles guidance systems, environmental engineering, commerce and stock exchanges, mechanical and maintenance engineering. The application to natural hazards, namely landslides is an important evolution in the civil protection/geohazard field. Thus Artificial Intelligence (AI) was used to analyze monitoring data response with respect to antecedent rain.

The AILandslide system “learns” from the past and based on its cumulated “experience”, makes predictions that become more and more precise as the experience on a specific landslide widens. Before the learning cycles begin, the model has to be custom tailored for any given monitoring point. AI allows reliable predictions based on past performances, significantly reducing false alerts, thus avoiding many costly errors.

Results, as shown in one of the paper of the references (Oboni, Angelino, Moreno, 2007), look very promising even if more data and prolonged period of monitoring are envisaged to obtain better and more reliable results.

## 7. Risk Management Decisions

Several alternative stabilization techniques were studied, taking into account their life expectation, maintenance criteria, environmental impact, costs, and, of course residual risks.

The last three design alternatives were the ones listed below with some of their main pros/cons:

- ➢ A deep drainage by vertical shafts equipped with submerged pumps.
    - Low cost.
    - Need for regular construction.
    - Low environmental impact.

- ➢ A 600 m long tunnel in "stable" ground, reaching underneath the slide from a side, equipped with ascending drainage boreholes at its ends.
    - High costs.
    - Long to build.
    - High environmental impact due to the need of a road in a stable forested area.
    - Low maintenance.

- ➢ A 150 m long tunnel within the sliding mass, parallel to the movement vectors, equipped at its end with sub-horizontal drains reaching the sliding surface.
    - Intermediate cost.
    - Short building time.
    - Low impact because access runs through devastated areas.
    - May require heavy maintenance in the future.

Finally, the 150 m long tunnel alternative was chosen and was completed in 2008. The excavation of the tunnel, roughly 3 m x 3 m, was performed with light point attack engines and no explosives, under an umbrella of sub-horizontal micro-piles to stabilize the ceiling. At each stage an exploration drill was performed at the point of excavation to gain information on the next 30 m of terrain.

## 7. The drainage tunnel

The tunnel (Figure 4) was completed after 3 years of works, restricted to a short summer period between July and mid October given the location of the site, high in the Alps, on a North facing slope with heavy snowfalls.

The first season was completely supported by helicopter lifts, given the fact that the site was not yet reachable by road, and that the permission to build it within an highly environmental susceptible area included in a Regional Park was very time consuming.

In the second season the road was built and then used to the end of works, thus speeding up the entire procedure, particularly by allowing a more comfortable (and economic) material supply via small trucks.

A topographic monitoring system designed to monitor the slope and the tunnel movement was deployed during construction.

Figure 4 – The tunnel entrance during construction

## 8. Conclusions

Probabilistic geotechnical analyses of the slope stability of the Cassas landslide have been successfully coupled with the data of an appropriate monitoring system and following a period of calibration and observation good results have been achieved in terms of understanding the parameters that are actually influencing and dictating the behavior of the slope.

The study also aimed at finding a correlation between antecedent rain, net of evapo-transpiration, and the slope response, in terms of movements. Rains over a period of 300 days were found to display the strongest correlation with inclinometers data. The strong correlation made it possible to propose a relationship between net antecedent rain and the velocity in a given point.

As a result of the quantitative risk assessment (QRA), a drainage tunnel was designed and constructed to mitigate potential reactivations due to water table heave in case of long rainy seasons. The tunnel proved to be a difficult engineering task due to the harsh mountain environment and the difficult geotechnical challenges involved in the construction. The finished tunnel has performed satisfactorily for 3 years now, helping the drainage of more than 1300 $m^3$ per month of water from the slide body with highly positive effects in terms of overall stability.

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