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LANDSLIDE DAMS: ANALYSIS OF CASE HISTORIES AND NEW PERSPECTIVES FROM THE APPLICATION OF REMOTE SENSING MONITORING TECHNIQUES TO HAZARD AND RISK ASSESSMENT

L. Ermini, N. Casagli & P. Farina

Earth Sciences Department of the University of Florence - Via G. La Pira, 4 - 50121 Firenze, Italy

INTRODUCTION

Landslide dams may form suddenly and unexpectedly, thereby posing hazards that must be rapidly assessed. In areas placed upstream, respect to the river dammed section, waters blocked by the dam may provoke floods spreading for kilometers, causing damages to human activities and interrupting communication lines. This can happen downstream as well, because of the risk of a sudden outburst of the landslide dam, especially when it is not possible to set up a control system for water drainage. As a result the dam may breach and an anomalous flood wave propagate downstream. The higher the peak discharge originated by the dam failure, the more devastating are its effects. Most important issues connected to a landslide that threat to block a river valley are:

- Is the landslide capable of blocking the river provoking a dam formation?
- Which will be the post formation behavior of the landslide dam?

In 1995 the Earth Sciences Department of the University of Firenze within the research activities carried out by the National Group for Hydro-geological Disaster Prevention (CNR-GNDCI), has started a project aimed at the study of landslide dams in order to estimate the hazards deriving from their formation, and consequently to reduce the risks to which inhabited areas, human activities and infrastructures are subjected. In this framework of activities two different datasets have been produced:

- Inventory of case histories from Italy (Alps, Apennines, Sicily). It contains more than 100 episodes, mostly quite well known in details, following the original data-form for landslide inventory, set up by Casagli & Ermini (1999).
- Inventory of damming episodes worldwide collected, updating the original work of Costa & Schuster (1991). It contains mainly cases inventoried by review work.

Results of presented investigations can be resumed in the setting up of geomorphological tools that could be useful in the decision making processes associated to the management of emergencies deriving from a landslide dam formation. In this paper the theoretical contents of those analyses will be presented, coupled with an examination of the possible contributions that can derive from the application of new monitoring techniques with particular reference to radar interferometry. The application of satellite and ground based radar systems to the study of surface deformation due to landslides, can really represent a successful tool for the management of emergencies deriving from damming events.

PROCESSES

Costa & Schuster (1988; 1991), starting from a database of cases worldwide collected, gave a very detailed outline of the processes that can lead to the blockage of a river channel. Presented researches mainly try to highlight which are the most representative characters of landslide dams from Italy. In this country important works concerning the setting up landslide dam databases are those of Eisbacher & Clague (1994) and Pirocchi (1992) for Alps, Casagli & Ermini (1999) for the Northern Apennines, while Nicoletti *et alii* (2000) and Pacino (2003) presented analyses carried out in Sicily. As a general consideration, data from Italy are in agreement with what proposed by Costa & Schuster (1988): most part of landslide dams usually fail by overtopping or piping shortly after their formation. Figure 1 shows the dam longevity curve. It was constructed updating with Italian case histories the original database carried out by Costa & Schuster (1991). It takes into account 206 events worldwide collected that went through a collapse during their lifetime. The 40 % of these collapses were recorded one day after dam formation, while the 80 % one year since their formation.

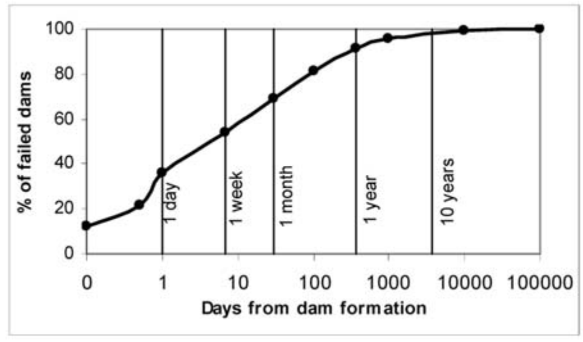

Figure 1 - Length of time before failure of failed landslide dams, based on 206 case histories (after Casagli & Ermini, 2003)

In other episodes the dam failure occurred long after its formation. When this happens the frequency of loss of life is in the same way high as testified by several literature examples, because all the emergency measures and preparedness had been already removed. For instance Biasca (Switzerland) landslide dam formed on September 30th 1513, thus provoking the impoundment of a lake with a volume of more than 100x10^6 m^3 of water (PIROCCHI, 1992). The landslide dam catastrophically collapsed on May 20th 1515 (after 20 months since its formation) and more than 600 people died in the consequent downstream flood.

CASE HISTORIES FROM ITALY

Most important conceptual difference between database of cases collected worldwide and the one from Italy is that this second contains also incomplete damming episodes. It was decided to take into account those episodes in order to get a better understanding of natural dam formation and consequently to improve the management of civil protection emergencies, where a landslide threat to block a river channel. Figure 2 (a, b) shows the utilized data form for landslide inventory (CASAGLI & ERMINI, 1999). The philosophy at the base of the data-form was easiness of compilation and maximum clearness in the distinction of different options, in order to obtain a wide and univocal characterization of the phenomenon in all its aspects.

For this reason the sheet is organized in separate sections and the number of descriptive fields has been reduced to a minimum, giving preference to fixed-option fields. The latter are of two main types: multiple-choice fields (represented as a *check-box button* ☐) and single-choice fields (represented as a *radio-button* ○). To simplify data acquisition for the relational data-base, the number of multiple-choice fields has been reduced to a minimum.

When a landslide reaches the valley bottom, the possibility of formation of a complete blockage depends on several factors, such as valley width, grain size and texture of failed material, landslide velocity, volume of displaced material, shear stress and transport capacity of the stream. Several cases of incomplete blockage have been inventoried in the Tosco-Emilian Apennine. A example occurred in locality Marano near Gaggio Montano (Bologna) where, on February 1st 1996, an earth slide of 0.7x10^6 m^3 reached the channel of the Reno river. The relatively small amount of material which actually invaded the channel, its erodibility and the high discharge of the Reno river in that section, permitted a successful excavation of the landslide toe, avoiding a complete blockage. This eventuality was expected since historic documents describe an occlusion of the Reno which occurred in the early Middle Ages, probably provoked by a reactivation of the same landslide.

When complete dam forms, unless the permeability of the dam is high enough to permit seepage of the river water, a channel blockage normally causes the formation of an impoundment upstream. The rapid rise of the water level upstream is the most frequent cause of hazard to human lives and property. In some of the case histories, chronicles report casualties due to upstream flooding as in the cases of Pieve Santo Stefano (Arezzo), Quarto di Savio (Forlì), Gamberara (Firenze).

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DATA-FORM FOR INVENTORY OF LANDSLIDE DAMS

GENERAL INFORMATION ON THE LANDSLIDE EVENT

Compilation	*Localisation*	*Hydrographic basin*
Inventory No.:	Region:	1° order:
Date:	Province:	2° order:
Reporter:	Municipality:	3° order:
Affiliation:	Locality:	Date of landslide:

Cartography		*UTM Co-ordinates of landslide top*	
Map edition:		East:	Fuse:
Scale:	Reference No.:	North:	

LANDSLIDE MORPHOMETRY

General data		*Displaced mass*	*Surface of rupture*
Crown elevation Q_c (m)	Horizontal length L_h (m)	Length L_d (m):	Length L_r (m):
Head elevation Q_h (m)	Height difference H (m)	Width W_d (m):	Width W_r (m):
Toe elevation Q_t (m)	Travel angle β (°)	Depth D_d (m):	Depth D_r (m):
Total length L (m)	Travel azimuth α (°)	Area A_d (m^2):	Area A_r (m^2):
Center-line length L_{cl} (m)	Total area A (m^2)	Final volume V_f (m^3):	Initial volume V_i (m^3):

GEOLOGY

Formation 1

Formation 2

Description

1 2 **Slope-strata relationship**
- ○○ horizontal strata
- ○○ Anaclinal slope
- ○○ Orthoclinal slope
- ○○ Plagioclinal slope
- ○○ Cataclinal (generic) slope
- ○○ Cataclinal under-dip slope
- ○○ Cataclinal over-dip slope
- ○○ Cataclinal omo-dip slope

LAND USE
- ○ urban areas
- ○ quarry area
- ○ abandoned area
- ○ bushes
- ○ riparian vegetation
- ○ rangelands
- ○ croplands
- ○ arborated croplands
- ○ specialised coltures
- ○ reforestation
- ○ coppice
- ○ wood

LANDSLIDE CLASSIFICATION

Description of the first and second movement

1 2 **Moviment**
- ○○ fall
- ○○ topple
- ○○ rotational slide
- ○○ translational slide
- ○○ spread
- ○○ flow

NOTE: 1. *First movement*
2. *Second movement*

1 2 **Material**
- ○○ rock
- ○○ debris
- ○○ earth

1 2 **Water content**
- ○○ dry
- ○○ moist
- ○○ wet
- ○○ very wet

1 2 **Velocity**
- ○○ extremely slow (< 16 mm/year)
- ○○ very slow (< 1.6 m/year)
- ○○ slow (< 13 m/month)
- ○○ moderate (< 1.8 m/h)
- ○○ rapid (< 3 m/min)
- ○○ very rapid (< 5 m/s)
- ○○ extremely rapid (> 5 m/s)

Activity

State
- ○ active
- ○ reactivated
- ○ suspended
- ○ dormant
- ○ abandoned
- ○ stabilised
- ○ relict

Distribution
- ○ moving
- ○ advancing
- ○ retrogressive
- ○ widening
- ○ enlarging
- ○ diminishing
- ○ confined

Style
- ○ single
- ○ complex
- ○ composite
- ○ multiple
- ○ successive

LANDSLIDE CAUSES

Geological
- ☐ weak materials
- ☐ sensitive materials
- ☐ weathered materials
- ☐ sheared materials
- ☐ adversely oriented mass discontinuity
- ☐ adversely oriented structural discontin.
- ☐ contrast in permeability
- ☐ contrast in competence
- ☐ jointed or fissured materials

Geomorphological
- ☐ tectonic or volcanic uplift
- ☐ glacial rebound
- ☐ fluvial erosion of slope toe
- ☐ marine erosion of slope toe
- ☐ glacial erosion of slope toe
- ☐ erosion of lateral margins
- ☐ deposition loading slope or its crest
- ☐ subterranean erosion (piping,solution)
- ☐ natural vegetation removal

Physical
- ☐ intense rainfall
- ☐ prolonged exceptional precipitation
- ☐ rapid snow melt
- ☐ thawing
- ☐ freeze & thaw weathering
- ☐ shrink & swell weathering
- ☐ rapid drawdown (floods and tides)
- ☐ earthquake
- ☐ volcanic eruption

Anthropic
- ☐ excavation of slope or its toe
- ☐ loading of slope or its crest
- ☐ rapid drawdown (reservoir)
- ☐ critical pool level
- ☐ water leakage
- ☐ irrigation
- ☐ deforestation
- ☐ artificial vibrations
- ☐ mining or quarrying
- ☐ accumulation of tailings

NOTE: (X) *preparatory* (■) *triggering*

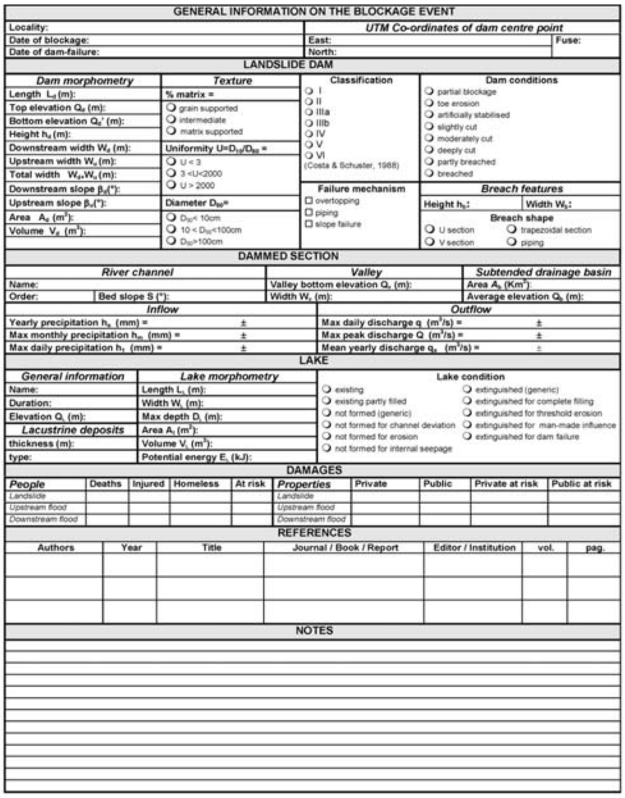
Figure 2a - First sheet of the data-form for landslide inventory (after CASAGLI & ERMINI, 1999)

The Pieve Santo Stefano landslide dam formed on February 14th 1855. A rapid rock-slide caused the complete obstruction of the Tevere River, the major river of the Apennine, causing the rapid rise of a lake which submerged the urban center of Pieve Santo Stefano, causing seven deaths and the destruction of several artworks, such as paintings of Piero della Francesca and Ghirlandaio.

On March 21st 1812 a landslide occurred at Quarto sul Savio (Forlì, Italy); it completely blocked the Savio river, causing the formation of a huge landslide dam (BERTONI, 1843; CASAGLI & ERMINI, 2000). On this occasion 18 people died, most of them drowned in the lake that inundated the areas located upstream from landslide dam. In this case no casualties were recorded in the downstream area, because of the stability of this huge natural blockage that in 1923 was selected as the site for the construction of an artificial concrete dam, still working as a power plant.

On the 14th of April 1899, near Marradi (Firenze), a very rapid rock-slide caused the blockage of the Campigno creek and the complete submersion of the Gamberara village causing 3 victims.

Taking into account cases of dam collapse, one of the most catastrophic events from Italy is represented by the Kummersee lake that was located in the upper reach of the Passirio River basin (Alto



GENERAL INFORMATION ON THE BLOCKAGE EVENT

Locality:
Date of blockage:
Date of dam-failure:

UTM Co-ordinates of dam centre point
East:
North:
Fuse:

LANDSLIDE DAM

Dam morphometry
Length L_d (m):
Top elevation Q_d (m):
Bottom elevation Q_d' (m):
Height h_d (m):
Downstream width W_d (m):
Upstream width W_u (m):
Total width W_d,W_u (m):
Downstream slope β_d(°):
Upstream slope β_u(°):
Area A_d (m^2):
Volume V_d (m^3):

Texture
% matrix =
○ grain supported
○ intermediate
○ matrix supported
Uniformity $U=D_{10}/D_{90}$ =
○ U < 3
○ 3 <U<2000
○ U > 2000
Diameter D_{50}=
○ D_{50}< 10cm
○ 10 < D_{50}<100cm
○ D_{50}>100cm

Classification
○ I
○ II
○ IIIa
○ IIIb
○ IV
○ V
○ VI
(Costa & Schuster, 1988)

Failure mechanism
☐ overtopping
☐ piping
☐ slope failure

Dam conditions
○ partial blockage
○ toe erosion
○ artificially stabilised
○ slightly cut
○ moderately cut
○ deeply cut
○ partly breached
○ breached

Breach features
Height h_b:
Width W_b:
Breach shape
○ U section ○ trapezoidal section
○ V section ○ piping

DAMMED SECTION

River channel
Name:
Order:
Bed slope S (°):

Valley
Valley bottom elevation Q_v (m):
Width W_v (m):

Subtended drainage basin
Area A_b (Km^2):
Average elevation Q_b (m):

Inflow
Yearly precipitation h_a (mm) = ±
Max monthly precipitation h_m (mm) = ±
Max daily precipitation h_t (mm) = ±

Outflow
Max daily discharge q (m^3/s) = ±
Max peak discharge Q (m^3/s) = ±
Mean yearly discharge q_a (m^3/s) = ±

LAKE

General information
Name:
Duration:
Elevation Q_l (m):

Lacustrine deposits
thickness (m):
type:

Lake morphometry
Length L_l (m):
Width W_l (m):
Max depth D_l (m):
Area A_l (m^2):
Volume V_l (m^3):
Potential energy E_l (kJ):

Lake condition
○ existing
○ existing partly filled
○ not formed (generic)
○ not formed for channel deviation
○ not formed for erosion
○ not formed for internal seepage
○ extinguished (generic)
○ extinguished for complete filling
○ extinguished for threshold erosion
○ extinguished for man-made influence
○ extinguished for dam failure

DAMAGES

People	Deaths	Injured	Homeless	At risk	*Properties*	Private	Public	Private at risk	Public at risk
Landslide					*Landslide*				
Upstream flood					*Upstream flood*				
Downstream flood					*Downstream flood*				

REFERENCES

Authors	Year	Title	Journal / Book / Report	Editor / Institution	vol.	pag.

NOTES

Figure 2b – Second sheet of the data-form for landslide inventory (after CASAGLI & ERMINI*, 1999)*

Adige, Italy). The dam had formed as a consequence of a landslide that in 1404, completely blocked the Passirio River. In the period between 1419 and 1774 the landslide dam went for six times through partial failures that originated the landslide toe reactivation, blocking again the river channel. The complete and catastrophic outburst of the landslide dam took place 370 years after its first formation and triggered a flood wave that provoked much damages to the downstream reach of the valley where the village of Merano is located (EISBACHER & CLAGUE, 1984; PIROCCHI, 1992).

ANALYSES

Studies on landslide dams are typically multidisciplinary, taking into account topics concerning slope deformation and river dynamics. Most original contributions carried out by the Earth Sciences Department of the University of Firenze are referred to a) geotechnical tests on debris materials and to b) the setting up of geomorphological criteria for forecasting landslide dam evolution that can be utilized in the management of emergencies deriving from damming events. On this topic, analyses mainly based on geomorphological field survey, were coupled by investigations deriving from the application of radar interferometry that can play a crucial role in the emergency management for civil protection purposes.

GEOTECHNICAL TESTS ON DEBRIS MATERIALS

Of course material forming a landslide dam exerts a great control on landslide dam evolution, but it is really difficult to asses the geotechnical properties of debris materials. On this topic investigations are mainly referred to analyse the role played by grain size distribution of debris forming landslide dam (CASAGLI *et alii*, 2003). Despite its importance, there are few quantitative studies directed at determining grain size distribution of debris dams, mainly because customary bulk sieve analyses are impractical when dealing with materials often ranging in size from blocks tens of cubic metres in size, to microscopic particles. CASAGLI *et alii* (2003) present results of field investigations carried out in the Northern Apennines applying to landslide dams the same kind of approach developed by KELLERAHLS & BRAY (1971) in the grain size analysis of materials forming gravel bed rivers. They selected two great group of debris sampling methods: (a) volumetric methods, and (b) grid by number methods. Figure 3 shows cumulate distributions of debris forming 42 case histories of landslide dams from the Northern Apennines.

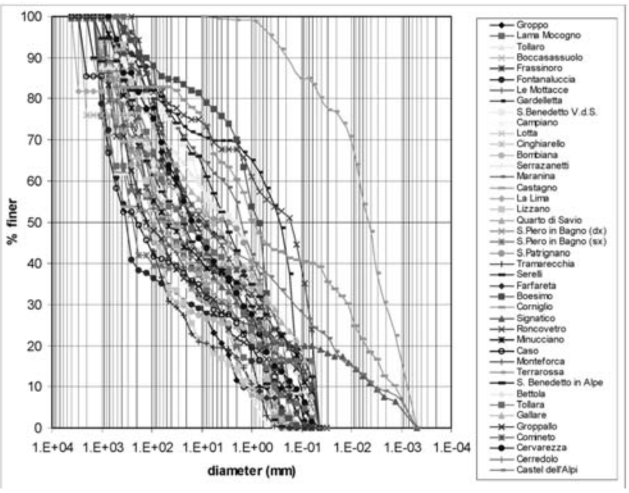


Figure 3 - Cumulative grain size distribution of 42 landslide dams in the Northern Apennines (after CASAGLI *et alii, 2003)*

As a general comment it should be underlined that previous mentioned techniques permit to obtain very similar grain size distributions for the coarser part of the debris material, while some differences persist for the finer fraction. For this reason results of their extensive application have to be critically analysed. A support may derive by the knowledge of the composition and degree of alteration of the parent rocks where landslides leading to damming episodes, originated. This type of data, as demonstrated by CASAGLI & ERMINI (1999), can allow a preliminary qualitative grain size classification of debris forming dams and if integrated in a more general process, where they are compared with quantities (on site measurements), they can be useful also in the interpretation of the role played by grain size in the determination of the stability of landslide dams.

GEOMORPHIC INDEXES

Swanson *et alii* (1986), Pirocchi (1992), Canuti *et alii* (1998), Casagli & Ermini (1999) Korup (2004) showed how several geomorphic variables exert a control on landslide dam behaviour. All their efforts were aimed to highlight relationships that control the interaction between river and landslide systems.

Concerning the forecasting of post dam formation behaviour, all previously mentioned authors affirm that dam volume is the variable that better identifies the landslide dam itself, while the watershed area, computed upstream from the fluvial blocked section, is the most important factor in the characterization of a dammed river channel. Canuti *et alii* (1998) and Casagli & Ermini (1999), starting from the database of cases collected in the Northern Apennines, defined the Blockage Index as the best parameter for forecasting blockage evolution:

$$I_b = \quad Log\left(\frac{V_d}{A}\right) \qquad (1)$$

as being V_d the landslide dam volume (m^3) and A the basin drainage area (km^2) computed upstream from the dammed section.

The results seemed very encouraging leading to the setting up of a graphical method that allowed a broad assessment of landslide dam evolution to be performed. The setting up of a database containing case histories collected worldwide however allowed Ermini & Casagli (2003) to demonstrate that this method owned regional constrains, as being valid only for cases inventoried in the Northern Apennines. In an attempt to improve this approach the same authors carried out an analysis based on a larger number of landslide dams defining the *dimensionless blockage index* I_b*'*, as:

$$I_b' = \quad Log\left(\frac{V_d}{A \times H_d}\right) \qquad (2)$$

where H_d represents dam height. From a physical point of view, dam height is a quite important variable in assessing the stability of a landslide dam compared to both overtopping and piping failure mechanisms Costa & Schuster (1988). The results of this further investigations have been represented in the diagram of Figure 4, that can be utilized for forecasting purposes, taking into account very simple and easy to be acquired geomorphological variables.

A complete blockage cannot be formed if the valley is wide enough to lead to the deviation of the river channel or if the stream energy is high enough to permit continuous erosion of the landslide toe. In both cases the landslide produces only a partial occlusion and the impoundment may not form. Concerning the issue of forecasting the possibilities of a landslide to block a river channel Swanson *et alii* (1998) proposed an interesting comparison between valley geomorphological settings and landslide velocity and dimensions. Casagli & Ermini (1999) followed the original approach of Swanson *et alii*, (1998) and proposed some analyses, updated by the work of Ermini (2003) who formulated the *Dimensionless Constriction Index - DCI,* as the result of the following expression:

$$DCI = \left(\frac{v_l \times W_l \times D_l \times D_{30}}{Q_p \times W_v}\right) \qquad (3)$$

where Q_p is the water discharge with a return period of 5 years, v_l the landslide velocity, D_l the landslide depth, W_l the landslide width, W_v the valley width and D_{30} the 30° percentile of the cumulate grain size distribution. The Index was carried out taking into account case histories from Italy where it was found that a moving landslide is not able to block the river channel in all those situation where the DCI < 0.002 (Ermini, 2003).

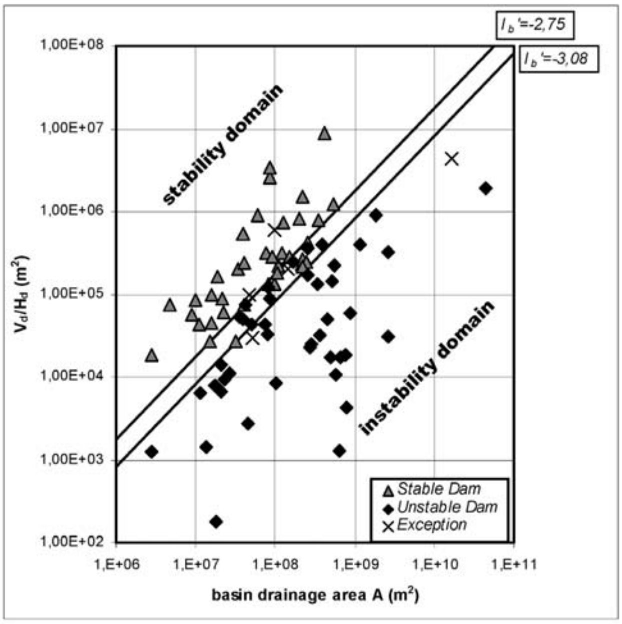


Figure 4 - Ratio between dam volume and dam height plotted versus basin drainage area for 83 cases collected worldwide (after Ermini & Casagli, 2003)

LANDSLIDE MONITORING SAR SYSTEMS

As previously mentioned, an important feature in the forecasting of the possibilities of a landslide to block a river channel is represented by the knowledge of dimensions of the moving mass and of the landslide velocity. Application of landslide monitoring techniques based on radar interferometry, can really give significant results, as they may provide very detailed velocity measurements in a wide range of slope movements.

Synthetic Aperture Radar (SAR) interferometry from satellite platform has been strongly applied in the last years for studies regarding terrain deformations induced by natural and anthropogenic phenomena, such as earthquakes, volcanic activity, subsidence, etc. (Massonet & Feigl, 1998). Even if few promising results have been reached also for retrieving ground deformations related to mass movements (Kimura & Yamaguchi, 2000; Fruneau *et alii*, 1996), the application of Differential SAR Interferometry (DInSAR) as a tool for landslide monitoring, by using the current satellites equipped with SAR sensors, is not realistic. Indeed, several drawbacks, mainly related to the low spatial resolution of the radar images, the exposure of landslide respect to the satellite line of sight and the signal de-correlation induced by the vegetation coverage, affect the quality of DInSAR results in landslide monitoring.

The development of the Permanent Scatterers (PS) interferometric technique (FERRETTI *et alii*, 2001), a particular processing, patented by the Politecnico of Milano, based on the use of large dataset of SAR images (at least 20-25) and which takes into account only pixels characterized by high levels of reflectance (PS), has allowed the overcoming of some of these problems, providing an useful tool for the remote assessment of ground movements related to landslides (COLOMBO *et alii*, 2003; FARINA *et alii*, in review). The technique permits to measure the displacement along the satellite line of sight and with a millimetre accuracy on a network of radar benchmarks. Due to the large spatial coverage of a single SAR image (about 100 x 100 km for an ERS image) the technique represents an effective and fast tool for the monitoring of mass movements over wide areas, such as river valleys. In this paper the results from the application of Permanent Scatterers for the monitoring of the Carbonile landslide will be shown. This phenomenon represents an earth-slide occurred in the prehistoric age which caused the deviation of the Arno River, threatening to block the river valley. Several re-activations within the landslide body occurred in the last 20 years, provoking damage to civil buildings and to the road network. The monitoring of the landslide body through the use of PS technique has allowed the evaluation of activity distribution of the unstable area, highlighting the effectiveness of the performed remedial works.

SAR interferometry can be also implemented by means of ground-based systems (GBInSAR). Such configuration has proved its capabilities in landslide monitoring, both as a permanent monitoring system and during emergencies. Different typologies of phenomena, in terms of material involved and kinematics, have been monitored obtaining excellent results (TARCHI *et alii*, 2003a; 2003b). Table 1 reports schematically the conceptual range of applicability of radar sensors to the management of emergencies deriving from dam formation. As a general consideration space-borne InSAR is best suited for monitoring slow moving landslides on large valley sectors. For instance through the Permanent Scatterers technique it is possible to detect also sliding precursory movements (characterized by very modest displacements ~ 1 mm) that can lead to the collapse of a slope and the subsequent damming of a river valley. Regarding the question of landslide dam stability assessment, satellite sensors can be helpful in reconstructing long term deformation of whole dam surface. The reference goes to all those damming sites not easy to be accessed and equipped by ground based monitoring instruments.

Ground based radar sensors find a wide range of applicability during decision making processes associated to the management of damming events. Differently from space-borne sensors, their configuration can vary depending on the local landslide geometries. In the monitoring of landslides that threat to block river valleys they are usually posed in front of the landslide toe, allowing the measurements of the displacement vector in the direction of the river channel.

As an example of application of radar technique to the monitoring of landslide dams, it was decided to show results of two radar campaigns performed in the Italian territory, one from satellite transported sensor and the other referred to a ground based sensor.

	Formation	Stability
Ground based sensors	Detailed measurements of landslide velocity	Reconstructing surface deformation of landslide dams abutments
Space-borne sensors	Detection of precursory signals of landslide activation	Detection of precursory signals of landslide activation

Table 1 – The possible application of radar monitoring techniques to the management of landslide dams

THE CORTENOVA ROCKSLIDE (LECCO, ITALY)

The Cortenova rock slide is located in the Lombardia Prealps, to the east of the Lecco lake (northern Italy) along the Valsassina valley. After two weeks of prolonged and intense rainfall, with values up to 128.4 mm/day, as recorded at the Introbio pluviometric station (Figure 5), during the night of December 1st 2002, between 3.00 and 5.00 a.m., a large rock slide, which involved about $8x10^5$ m^3 of rock, came down on the Bindo village, wiping out 15 houses and 3 factories, and causing severe damage to infrastructures and services. Further, the mass movement created a temporary landslide dam along the Pioverna stream flowing close to the village. The potential landslide evolution required the evacuation of about 900 people living close to the run-out area (Figure 6). The landslide represent the reactivation of a portion of a dormant mass that occupies the right slope of the valley, here highly tectonized and composed by metamorphic crystalline lithologies mainly belonging to Lombardy Verrucano of Permian age.

At the beginning of January 2003 the area hit by the landslide went through a radar campaign aimed at the monitoring of the slope, in order to manage and to prevent the possible emergency deriving

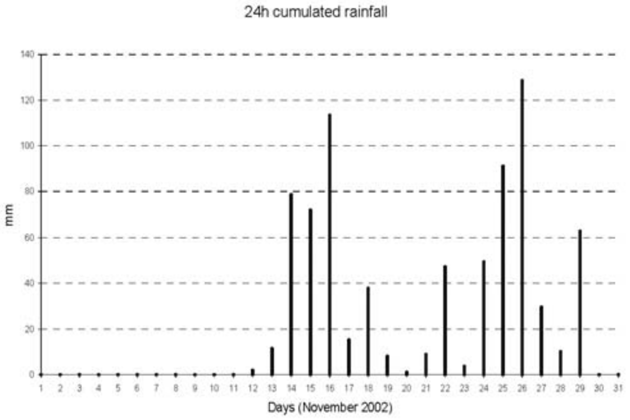


Figure 5 –Rainfall registered in the landslide area during November 2002

from a blockage of the T. Pioverna (Figure 7). All the efforts were posed to find the best installation for the ground-based equipment.

CARBONILE

The Carbonile sliding area is located in the territory of Pelago municipality (Firenze, Italy). Four distinct landslides can be recognized that in different times provoked damage to edifices and cultivations. Movements affected the right slope of the Arno River valley probably causing in prehistoric age its damming as can be assumed from the sharp deviation of the river course.

Figure 6 –Views of the Cortenova landslide

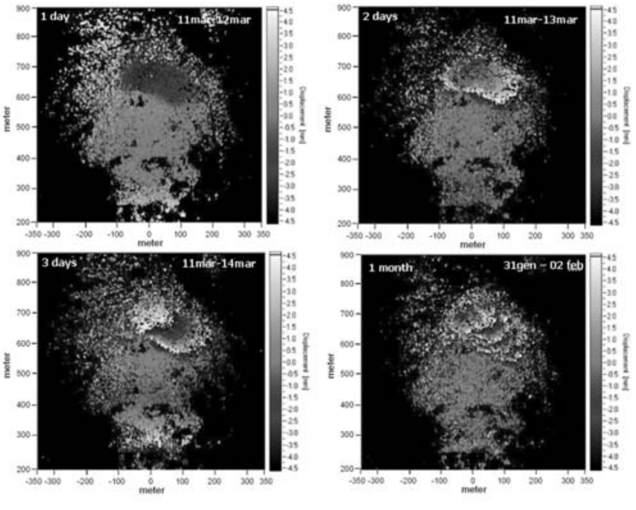


Figure 7 - The results of a radar campaign at the Cortenova landslide. Interferograms show displacements cumulated on four different time periods (1 day, 2 days, 3 days, 1 month). In all the cases interferometric fringes show a marked sliding activity in the upper part of the landslide, near the landslide crown, while the toe of the landslide does not show important rate of displacement

Outcropping lithologies belong to the Basal complexes of Supergruppo della Calvana Unit, consisting of an association of clays, sandstones and limestones. All the slope is highly tectonized and this is, coupled with the weakness of the involved materials, the most important cause for the sliding movement. Landslides basing on the work by CRUDEN & VARNES (1996) can be classified as active rotational slides, characterized by moderate to slow velocities, with retrogressive distribution and moving as reactivation of ancient movements. Most important activations occurred in recent times dated to 1984 and 1985 when they induced the evacuation of 8 houses and severe damages to industrial manufacture buildings. All the area in the following years was interested by important remedial works for slope stabilization. In particular it was realized a system for draining water from the landslide area, consisting in the installation of surface and underground drains.

In 2004 a radar campaign by the tool of the Permanent Scatterers technique was conducted within the SLAM project funded by the European Space Agency for the monitoring of landslides inside of the Arno river basin. The analysis of the results obtained for the Carbonile landslides are shown in Figure 8. From these preliminary data it can be assumed that present time movement are located in the proximity of landslide crown and landslide flanks, while the landslide toe is substantially stable. Interpretation of these results lead us to the setting up of a project for an on site monitoring equipment and allow to understand that movements do not represent a menace for the correct discharge of the Arno river waters.

CONCLUSIONS

Experiences developed in the study of landslide dams lead us to assume that as a general rule formation of a landslide dam and its post formation behaviour can be represented as the extreme synthesis of slope and river processes. For this reason whatever kind of

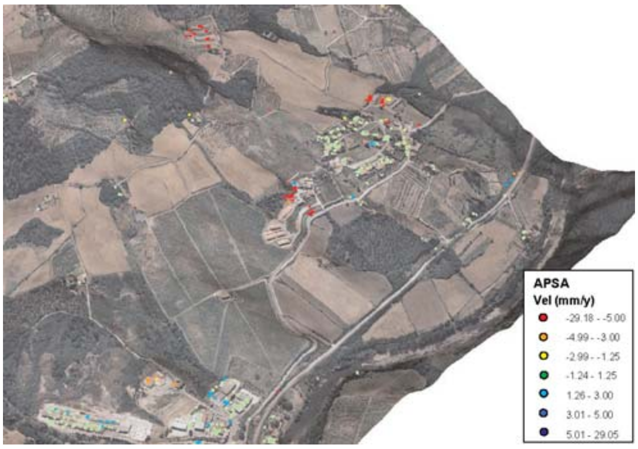


Figure 8 –The Carbonile sliding area (Firenze, Italy). On the right displacements measured by the Permanent Scatterers technique

analysis has been taken into account it should try to represent this process by its most important controlling factors. Results obtained by field survey, geomorphological analysis and application of remote sensing techniques have been shown in the course of the paper. In conclusion three most important topics can be remarked:

- grain size analyses and geotechnical tests on debris materials forming landslide dams should be more extensively carried out, in order to understand their physical behaviour and forecast both the evolution of processes that lead to dam formation and the stability degree of debris abutments toward overtopping and piping phenomena;
- geomorphological Indexes for forecasting the evolution of damming events can be of help in the emergency management, giving "easy to be applied general criteria" that should be implemented by on site investigations at local scale;
- new monitoring techniques, in their satellite platform configuration, can give, on wide sectors of a valley, very detailed measures of surface deformation associated to landslides that threat to dam rivers, with particular reference to not accessible sites; on the other hand ground based systems can be more properly installed for the emergency management, allowing the local monitoring of slopes and of their toe interactions with river channels.

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