Landslide activity as a geoindicator in Italy: significance and new perspectives from remote sensing

P. Canuti · N. Casagli · L. Ermini · R. Fanti · P. Farina

Abstract Landslide activity responds to rapid environmental changes and represents a relevant geoindicator in mountainous or hilly areas. This paper discusses the socio-economic relevance of landslide hazard in Italy and the problems encountered in establishing relationships between landslide frequency, climate and vegetation changes at different time scales. Landslides blocking a river channel have been carefully taken into account because they are usually characterized by high intensities (with regard to the involved masses and movement velocities) and their occurrences are often datable via radiocarbon dating. This is due to the recovery of organic matter in the landslide dammed lakes. For these reasons they can be considered important geoindicators in the wider category of slope failures. The marked effects of the anthropogenic activity on slope instability processes in the last 50 years are discussed with reference to two case histories: the Chianti hills in Tuscany and the Cinque Terre National Park in Liguria. Finally, two novel techniques of remote sensing are proposed as tools for a systematic monitoring of slope instability at different time and spatial scales. Both techniques are based on the interferometric synthetic aperture radar (SAR) technology and differ on the type of platform (satellite and ground-based) used to acquire data.

Keywords Geoindicator · Landslide · Landslide dam · SAR

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Introduction

Landslide activity is strongly related to environmental changes, such as climate conditions and land cover. Moreover landslides are, among natural hazards, one of the main sources of loss for life and property. These are the reasons why slope instability has been included amongst the 27 Geoindicators in the report by the Cogeoenvironment Working Group on Geoindicators [COGEOENVIRONMENT (IUGS) Working Group on Geoindicators 1995].

However several scientific problems must be solved for a practical use of slope instability as an indicator of rapid environmental changes:

1. Landslide activity undoubtedly reflects environmental variations even on a short time scale, but the relationships between landslide events and climate or vegetational changes are not well defined;
2. To be relevant as a geoindicator, landslide activity should be monitored at different spatial and temporal scales;
3. The use of new remote sensing technologies for measuring landslide parameters and for landslide monitoring is markedly unexploited, whereas these techniques allow a rapid acquisition of data over wide areas and represent a fundamental tool for a practical use of landslides as geoindicators.

In this paper note the authors explain these problems with reference to their experience in Italy. This paper is organized into three main sections: the first deals with the socio-economic significance of slope instability in Italy and it presents those statistics to be used as resuming indexes; the second describes the relationship between landslide frequency and climatic and anthropogenic factors; the last proposes the practical use of remote sensing techniques for assessing landslide activity in space and time.

Significance

About 75% of the Italian territory is composed of mountainous and hilly terrain. Two main orogenic chains are present: the Alps (maximum elevation of 4,810 m a.s.l.) stretching from W to E in the northern part of Italy, and the Apennines (maximum elevation of 2,913 m a.s.l.) elongated from NW toward SE along the Italian peninsula. Extensive areas of the mountainous and hilly ranges are affected by landslides, which strongly influence the socio-economic conditions of the country, threatening urban areas, anthropogenic activities and cultural and environmental heritage (Fig. 1).

Synthetic indexes on the socio-economic significance of landslides in Italy, can be based on statistics recently completed by the National Research Council Group for Hydro-Geological Disaster Prevention (CNR-GNDCI):

- The average toll rate is 59 victims/year in the last century and 54 victims/year in the last 50 years, corresponding to an average mortality rate of about 10^{-6} victims/(year × person) considering the present population of Italy (Guzzetti 2000);
- Estimates of the total cost of direct damage range between 1 and 2 billion Euro per year, corresponding to an average of 0.15% of the Gross Domestic Product (GDP); these data are probably underestimated because a relevant part of landslide damage is attributed to other natural disasters, such as floods, earthquakes and volcanic eruptions, which are commonly associated with landslides (i.e. seismically induced failures, rainfall induced debris floods, lahars and rock avalanches associated with volcanism).
- Considering also the indirect losses, related to the loss of productivity, the reduction of real estate value, the loss of tax revenues and other induced economic effects (Schuster 1996), a better estimate of the landslide economic impact in Italy probably ranges between 0.3 and the 0.4% of the GDP.

Fig. 1
Distribution of sliding areas in Italy (Data source: GNDCI AVI Project, http://www.gndci.pg.cnr.it)

Separate considerations apply to cultural and natural heritage in Italy, for which the damage caused by landslides is immeasurable. A significant percentage of more than 10,000 cultural heritage sites classified by the Governmental Authorities are exposed to landslide risk. Considering only the 36 Italian sites included in the UNESCO World Heritage List, 13 cases are affected by slope instability problems (namely Portovenere and Cinque Terre, Costiera Amalfitana, San Gimignano, Firenze historical centre, Sassi di Matera, Pienza, Piazza Armerina Villa Romana del Casale, Agrigento, Cilento and Valle di Diano National Park, Urbino, Assisi, Eolie archipelago, Val di Noto).

According to the GNDCI databases, more than 18,000 landslides have produced losses in the last century (Guzzetti et al. 1994) and about 9,600 areas within Italy have been recently classified as “at extremely high landslide risk” according to the Law n.267/1998 promulgated by the Government after the Sarno disaster. The history of landslide hazard in Italy is summarized in Table 1, which lists the major disasters that have occurred in historical times from the losses to Hannibal’s Army crossing the Alps in the 218 BC UP TO THE RECENT SARNO DISASTER IN 1998.

These data show that in Italy the “landslide problem” is particularly relevant and has unique characteristics within Europe and the Mediterranean basin. On a worldwide scale it is second only to Japan among technologically advanced countries.

Some Regional Administrations have recently completed the mapping of landslides over their territory and, in these cases, it is possible to draw some statistical indexes based on the spatial distribution of landslides. In the case of the Emilia-Romagna region, which is composed of 12,685 km^2 of mountainous or hilly terrain, where 32,337 landslides have been systematically mapped at a scale of 1:10,000. The percentage of the area covered by landslides is 20%, 235 major urban areas and 1,911 villages are affected. Regarding transportation facilities, landslides affect 12 km of railways, 15 km of motorways, 1,032 km of regional and provincial roads and 2,234 km of municipal roads (Regione Emilia-Romagna, 1999).

Landslides as indicators of environmental changes

Most of the current landslides in the Apennines are the reactivation by pre-existing ones, which have occurred in periods of climatic and geomorphological conditions different from those of the present. Most of these landslides are dormant and covered by vegetation that, in some cases, makes the recognition of the phenomena difficult. These dormant slides, in which the strength parameters are reduced to values, close to the residual ones, can be reactivated by natural causes, such as rainfall or snowmelt, as well as man-made disturbance.

Table 1
Most important landslide disasters in Italy during historical times (modified after Guzzetti 2000)

Date	Place	Country	Description	Damage
218 BC	Moncenisio Pass, Alps	Piemonte	Landslides and avalanches	While crossing Alps to conquer Rome, Hannibal's army lost 18,000 men, 2,000 horses and several elephants
91 BC	Modena mountains	Emilia-Romagna	Large landslide	Many houses destroyed, many deaths
68 AD	Chieti mountains	Abruzzo	Large landslide	Many houses destroyed, many deaths
79 AD	Ercolano	Campania	Lahars[1]	2,000 deaths, due also to a volcanic eruption
883 AD	Lavini di Marco, Rovereto	Trento	Landslide dam	The Adige River was dammed
May 15, 1335	Castagno d'Andrea	Toscana	Rock avalanche	Hundreds of deaths, Castagno village buried
Sept. 22, 1419	Valle Passer	Trentino Alto Adige	Failure of rock-slide dam	400 deaths
1580	Giffoni Valle Piana	Campania	Landslides	Few hundreds deaths
Sept. 4, 1618	Piuro (Val Bregaglia)	Lombardia	Rock-debris avalanche	1,200 deaths
Dec. 6, 1631	Vesuvio	Campania	Lahars[1]	4,000 deaths, due also to a volcanic eruption
July 27, 1642	Antronoapiana, Monte Pozzoli	Piemonte	Rock avalanche	150 deaths
Oct. 15, 1691	Castiglione dei Genovesi	Campania	Large landslide	70 deaths
Aug. 15, 1692	Borta Monte Auda	Friuli Venezia Giulia	Rock avalanche	>53 deaths
Feb. 1698	Pisticci	Basilicata	Large slide	Several hundred deaths
Aug. 14, 1748	Valle di Vanoi, Canale di Sotto	Trentino Alto Adige	Debris flow	72 deaths
Gen. 1, 1762	Cetara	Campania	Large landslide	50 deaths
Nov. 15, 1762	Primaluna, Gero and Barcone	Lombardia	Rock fall (?)	100 deaths
June 24, 1765	Roccamontepiano	Abruzzo	Vary large slide	600 deaths
June 2, 1789	Groscavallo	Piemonte	Landslides and debris flows	275 deaths
Apr. 21, 1814	Mt. Antelao (Cancia)	Veneto	Rock avalanche	314 deaths
May 1, 1826	Valle di Vanoi, Remesori	Trentino Alto Adige	Failure of a debris-cone dam and debris flow	52 deaths
1840	Verres	Val d'Aosta	Failure of a natural dam and debris flow	80 deaths
Jan. 22, 1841	Gragnano, Rione Trivioncello	Campania	Landslide	116 deaths
Oct. 24, 1910	Costiera Amalfitana	Campania	Landslides and debris flows	247 deaths
Apr. 17, 1916	Col di Lana	Veneto	Rockslide set off purposely by the Italian Army	110 deaths in the Austrian Army (1st World War)
Jan. 11, 1922	San Fratello	Sicily	Landslide	Hundreds deaths in the town of San Fratello
March 26, 1924	Costiera Amalfitana	Campania	Landslides and debris flows	237 deaths
Feb. 17, 1925	Mt. Antelao (Cancia)	Veneto	Rock avalanche	341 deaths
Nov. 9, 1932	Ionian Coast	Calabria	Landslides and debris flows	56 deaths
Oct. 16, 1951	Ionian Coast	Calabria	Landslides and debris flows	Flood taking 105 deaths (70 due to landslides), 2,330 damaged buildings and 6,500 people left homeless
Oct. 25, 1954	Costiera Amalfitana	Campania	Debris flows	319 deaths, 113 injured
Oct. 9, 1963	M. Toc (Vaiont)	Veneto	Rockslide into a reservoir and outburst flood	1917 deaths
Dec., 1982	Ancona	Marche	Landslide	Damage to two hospitals, an university building, two highways, the national railway, 280 private buildings; more than 3,000 people homeless
July 19, 1985	Stava	Veneto	Mudflow – tailings dam failure	269 deaths

Table 1
(Contd.)

Date	Place	Country	Description	Damage
July 28, 1987	Mt.Zandila (Val di Pola)	Lombardia	Rock avalanche	27 deaths or missing, 25,000 evacuated
May 5, 1998	Sarno	Campania	Debris flows	153 deaths, hundreds homeless

[1] According to some interpretations, during the Vesuvio eruptions of 79 and 1631 AD, much of the damage was produced by lahars

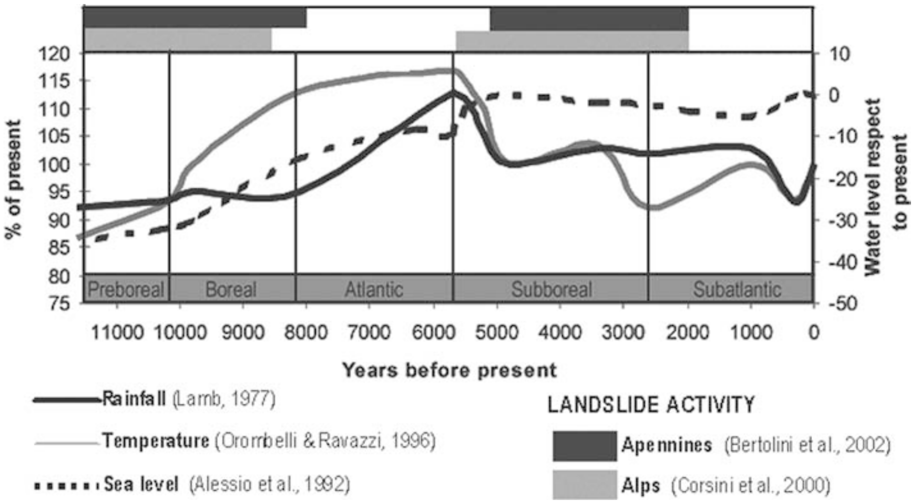

Fig. 2
Relation between the time of the temporal occurrence of selected landslides and Holocene climate. Temperature values are modified from Orombelli and Ravazzi (1996), an overview of the evolution of the paleoclimate, essentially on the basis of the Greenland ice-core records

The reconstruction of the landslide distribution through time can help to establish activity patterns as a response to past climatic oscillations and to forecast possible scenarios related to future climate changes (Dikau and Schrott 1999). Canuti et al. (1998) assumed that the first activation of the major landslides in the Apennines, at the end of the Pleistocene and in the early Holocene, correlated to the fluvial deepening and to the rainfall and snowmelt increase that occurred during the improvement of climatic conditions following the last glaciation.

A correlation between landslide activity and colder/wetter climatic periods during the Holocene has been observed in the Alps by Corsini et al. (1999, 2000), and by Bertolini et al. (2003) in the Apennines, on the basis of radiocarbon dating of organic matter entrapped into landslide bodies or within deposits of landslide-dammed lakes. The data acquired by these authors show two main clusters (Fig. 2): one at early-Post glacial (Preboreal and Boreal: 10,000–8,000 yr BP) and one at the Sub-Boreal (5,000–2,500 yr BP), whereas the Atlantic period (8,000–5,000 yr BP) and the Sub-Atlantic (2,500–0 yr BP) seem to be characterized by a lower landslide activity associated, in both cases, to the global amelioration of the climatic conditions. Bertolini et al. (2003) observed also that there was a tendency of the large landslides (area >400,000 m^2) to being concentrated around the main mountains in the Northern Apennines. They were probably triggered as a consequence of the sharp climatic variation that characterized the beginning of the Holocene and took place with a maximum intensity in areas located around the upper snow limit. During the Holocene these large landslides went through partial reactivations, probably related to the colder and wetter conditions.

As far as historic times are concerned, data on landslide frequency can been drawn from historical chronicles and recent inventories. One of the world largest historical landslide catalogues is available for the Italian territory: the AVI Project database (Guzzetti et al. 1994) which reports at present 22,074 events since the year 1,000 AD up to present. The distribution of events in the last eight centuries and the limits of the main climatic periods are shown in Fig. 3. The importance of this dataset is influenced by an exponential growth of information however it is possible to note a sudden increase of landslide records from the second half of the 16th century, just at the beginning of the global climatic deterioration period known as Little Ice Age, which in Southern Europe caused an increase in the average amount of precipitation (Marabini and Veggiani 1993). In this perspective the relative maximum between 1675 and 1750 is particularly significant.

Data represented in Fig. 3 include all the landslides recorded in Italy; in order to establish a relationship between slope processes and climate change it is probably necessary to select the most significant events. Several criteria can be adopted; for instance, it was decided to take into account only those cases that formed major landslide-dammed lakes over the Alps and Northern Apennines in historic times (Casagli and Ermini 1999). Landslide dams are important geoindicators since the blockage of rivers often determines major environmental disturbances to fluvial ecosystems and human activity. Costa and Schuster

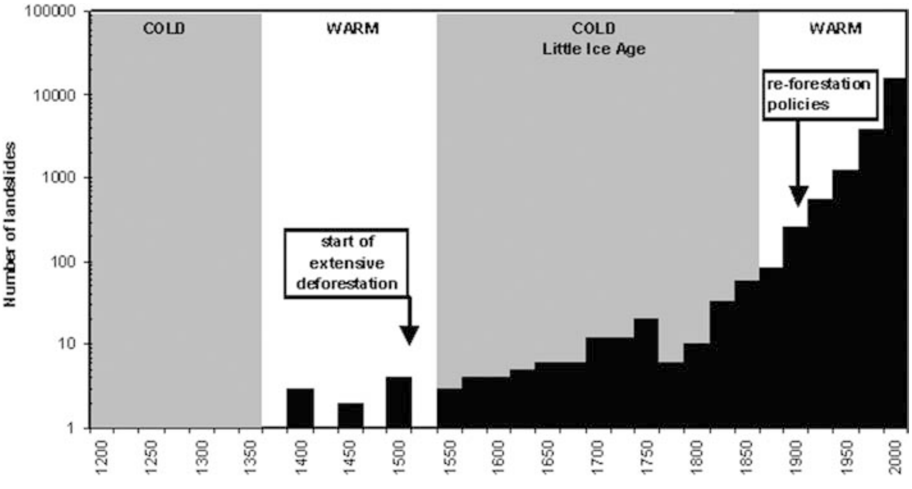

Fig. 3
Temporal distribution of landslide events in Italy compared with the main climatic periods in the last eight centuries (Data source: GNDCI AVI Project, http://www.gndci.pg.cnr.it)

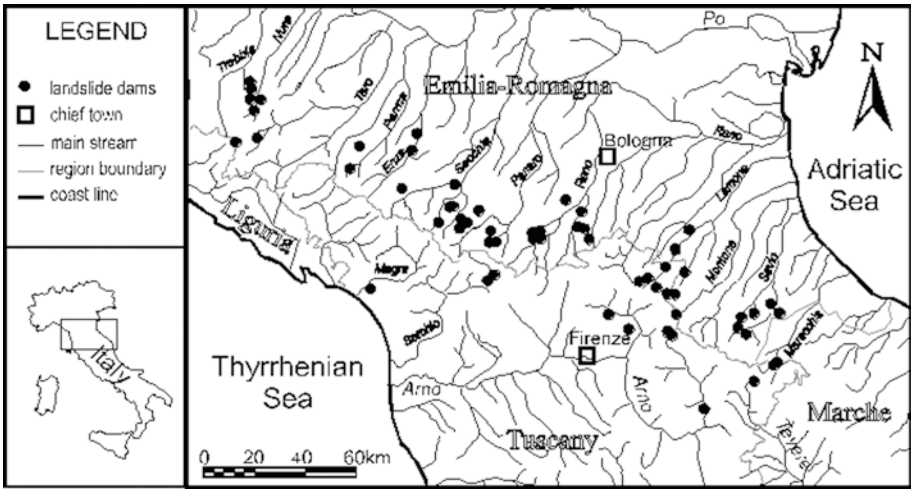

Fig. 4
Location map of landslide dams from the Northern Apennines (after Casagli and Ermini 1999)

(1991) and Ermini and Casagli (2003) gave an outline of the deep social impact derived from a landslide dam formation in an inhabited area, because of the inundations that can affect the territories located both upstream and downstream of the dammed river section. In these cases most catastrophic effects are related to the rapid lake drawdown, as a consequence of a dam collapse with an abrupt discharge of the impounded waters. A landslide hitting a valley, although representing a natural process, can exert a strong control also on the fluvial ecosystem (Naiman et al. 1992), changing the river channel morphological configurations and provoking for instance damaging effects to the reproduction of migrating salmons.

Landslide dams are also useful as geoindicators because their formation can be easily recorded. In fact landslide-dammed lakes are ideal conditions for the recovery of organic matter that, once dated by the radiocarbon techniques, gives the age of the landslide (minimum age), providing information on sliding activity for a period not normally covered by historic data or improving the available documents. An example of sliding information obtained by radiocarbon dating is the Marano (Bologna, Italy) landslide, that took place during February 1996, and provoked the partial blockage of the Reno River. It represents an example of the more that 60 landslide dams inventoried in the Northern Apennines (Fig. 4) by Casagli and Ermini (1999). From geomorphological surveys it was established that this event was a reactivation of an ancient landslide. The only available historical reference is that of Calindri (1781) who affirms that in an unknown time (maybe the Middle ages) a landslide intersected the confluence between Marano Creek and the Reno River. In a test borehole drilled through the toe of the landslide an organic level, located under the debris and maybe displaced by the last movement, was recovered. It seemed reasonable to correlate this level to the presence of a peat bog that probably developed in that site as a consequence of a past blockage of the Reno River. The radiocarbon dating of a charcoal fragment from the organic level gives the age of 850 cal yrs BP, in agreement with Calindri's information (Bertolini et al. 2003).

This kind of data, if extensively gathered, can increase the length of time covered by landslide inventories carried out on the basis of historical information, improving the knowledge of the relationships between climate changes and sliding activity. Figure 5 refers to only historic information. Once again, we can observe the sudden increase in

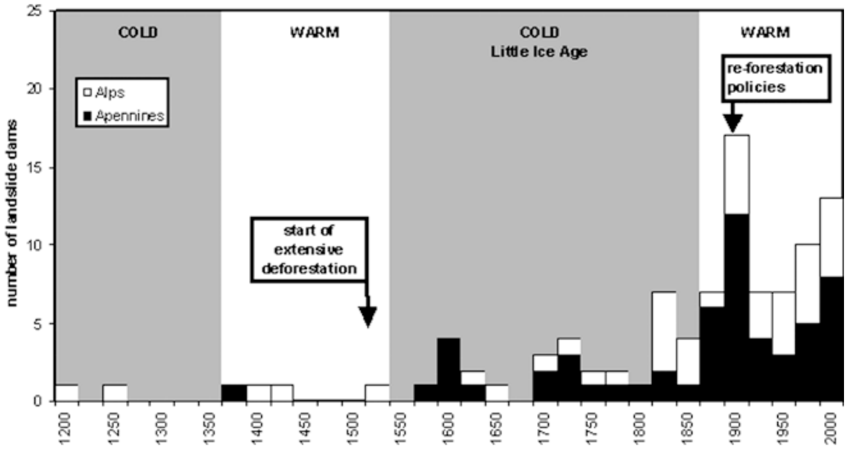

Fig. 5
Temporal distribution of landslide dams in the Alps and in the Apennines compared with the main climatic periods in the last eight centuries (Data source: University of Firenze, Earth Sciences Department, data-base of landslide dams)

frequency in the second half of the 16th century. The peak of case records at the beginning of the 20th century is apparent, since it is due to the large amount of information collected in the first national report on landslides published by Almagià (1907).

However, climate changes are not the only causal processes behind responsible for the variation of landslide frequency in historic times. The influence of human activity must also be considered especially in a country such as Italy, where, since the Iron Age, man has been a principal factor of geomorphological evolution. In fact, the increase in landslide activity at the beginning of the "Little Ice Age", is probably also due to the extensive deforestation that took place in Italy from the 15th century.

Policies for re-forestation and erosion prevention started in Italy only at the beginning of the 20th century. Their effectiveness is proved by a substantial reduction of flood hazard (Canuti et al. 2001) but as far as landslide activity is concerned, the available data do not show any tendency towards a reduction. On the contrary, the rapid increase in landslide frequency during the 20th century is related to the increase in the amount of available information and to the demographic growth (the Italian population rose in this period from 33 to 57 million), which led to the rapid urbanization of unstable land.

Modification in sliding activity induced by human actions

Human actions are capable of accelerating or diverting natural changes and geoindicators can help in the recognition of the effects of the anthropogenic activity within a natural changing environment (Berger and Iams 1996). A useful index for monitoring changes in slope stability is represented by the landslide density index (LDI) expressed as the percentage of the area occupied by landslides, within a given zone, at a specific time.

A good example of the acceleration of natural slope processes caused by anthropogenic activity is represented by the Chianti hills around the city of Firenze. These hills are one of the main areas of wine production in the world, with an annual income of about 500 million Euro. This environment is particularly vulnerable to the concurrence of geological and climatological attributes with economic factors associated with specialized vineyards and olive groves. The farming changes that have taken place since the 1960's through the introduction of agricultural mechanization, extensive slope leveling for new vineyards and the abandonment of past drainage systems, have altered the fragile slope stability, generating accelerated erosion and landslides, in particular superficial earth flows and complex landslides have occurred. These conditions caused, in a short period, a substantial reduction of soil productivity and difficulties in the management of the agricultural areas with huge economic losses. In particular Canuti et al. (1979, 1986, 1988), through the multi-temporal comparison of aerial photographs, reported an increase in the LDI of 122% from 1965 to 1977, following an increase, for the same period, in the extension of vineyards of about 450%.

LDI spatial representations are known in literature as *isopleth* maps. First introduced by Campbell (1973) for landslide hazard mapping, isopleths are contour lines enveloping map points with the same LDI of a pre-determined value. This kind of analysis was also proposed by De Graff and Canuti (1988) in a study aimed at evaluating landslide activity in relation to land use changes due to agricultural practices. The same authors underlined that changes in landslide occurrence over time can be readily represented by comparing isopleth maps of the same area, prepared from inventories compiled at different times. The same kind of approach can represent a profitable method of measurement of landslide activity as a geoindicator.

As in many other technologically developed countries, Italy was subjected since the 1960's to an extensive abandonment of the countryside. This abandonment has been reflected in changes of vegetation cover and landslide activity. One of the best examples of this situation is represented by the area known as of the Cinque Terre. The Cinque Terre (The Five Lands) is the name given to the Ligurian coastal region encompassing five small towns along the sea, connected with a coastal pathway that represents an important national tourist attraction. Since 1997,

Fig. 6
Landscape transformation in the Cinque Terre National Park: comparison between photographs taken in 1958 (*left*) and 2000 (*right*) (photo courtesy of Cinque Terre National Park, 2000)

this rocky coast with terraced vineyards, antique towers and picturesque villages, has been included in the "World Heritage List" of UNESCO, for its high scenic and cultural value. More recently, in 1999, it has also become a National Park for its environmental and naturalistic relevance. The form and disposition of the small towns and the landscape testify that there has been a continuous history of human settlement in this region over the past millennia. The landscape appears as an "agricultural monument" characterized by terraces, supported by dry-stone walls, for the cultivation of vineyards. These terraces are not only an important cultural heritage, but also a complex system of "landscape engineering" which, for centuries, ensured effective soil conservation by reducing surface erosion and controlling surface drainage and runoff.

The recent abandonment of farming has resulted in the lack of maintenance of the terrace system, which consequently has led to a rapid increase in the land degradation. The instability of the dry-stone walls and the clogging of drainage channels are now the main causes behind landslide propagation. The growing pressure of tourism on the seaside and the coastal paths has also created serious civil protection problems. The most frequent landslide mechanisms within the Cinque Terre are rock falls and topples along the sea cliffs and earth slides and debris flows on the terraced area.

A comparison between two photographs of the same area, taken in 1958 and in the year 2000, (Fig. 6) highlights the dramatic change in slope stability which has occurred after the abandonment of the agricultural activity. The pictures show how the typical terraced landscape was subjected to extensive land degradation over the last 40 years: the dry-stone walls are abandoned or no longer maintained and most of them have collapsed due to earth pressure or shallow landslides.

Landscape changes due to landslides can be highlighted also on a shorter time period: in Fig. 7 two aerial photographs are shown both covering the Monasteroli area between 1973 and 1993. The significant changes in agricultural practices resulted in the reactivation and enlargement of the highlighted landslides, bordering Monasteroli, while river catchments seem to have generally deepened their beds.

The general abandonment caused a change in vegetation cover, favoring the decrease of woodland and the reappearance of the Mediterranean shrubs. The LDI increased from 0.6% up to 70% in the investigated period with a net increment of 115%. The recent instigation of the National Park has made it possible to set up landscape-restoration policies, based on the inventory of allotments of uncultivated land and their allocation to the Park for a productive recovery based on the consolidation and maintenance of the terrace system.

Remote sensing as a tool for measuring landslide activity

Remote sensing techniques are a powerful tool to assess modifications on the Earth surface, over wide areas, at a relatively low cost. In particular SAR (Synthetic Aperture Radar) interferometry (Gabriel et al. 1989; Massonnet and Feigl 1998) has proved an effective instrument to monitor slow ground deformations. SAR interferometry (InSAR) in its different configurations, implemented by using spaceborne, airborne or ground-based sensors, has demonstrated its potentiality in landslide monitoring and detection. In this section two different applications of InSAR are discussed, applicable for the quantitative assessment of landslide displacements at diverse temporal and spatial scales by using respectively satellite SAR imagery and ground-based instrumentation.

In general, InSAR is based on the quantitative comparison between paired and complex radar images of the same area, taken at different times, to produce interferograms representing, pixel by pixel, the phase difference between the two images. This phase difference depends on four main components:

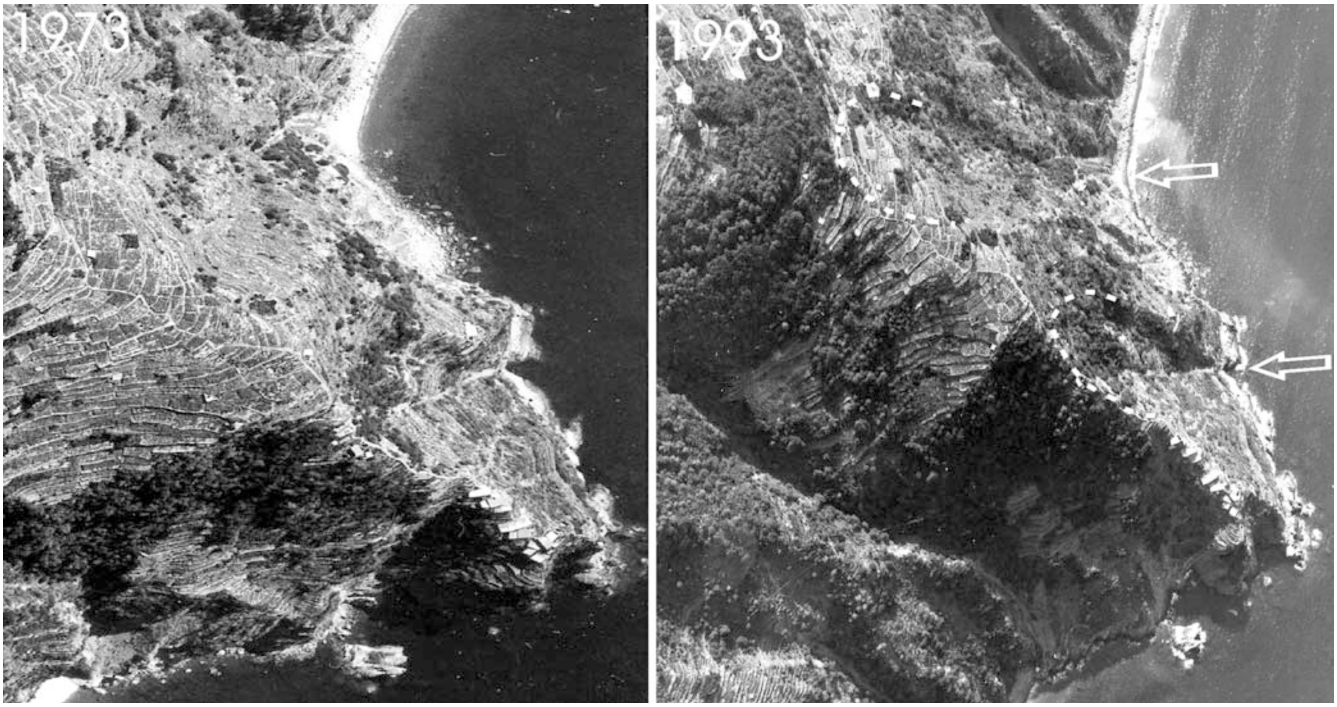

Fig. 7
Two aerial photographs showing the Monasteroli area (Cinque Terre). Comparison between the two photographs taken in 1973 and 1993 show the significant changes in sliding activity mainly due to abandonment of agricultural practices. In particular on the 1993 photograph two landslide crowns not so clearly detectable on the 1973 picture can be observed. Those features can be considered as evidences of reactivation of those landslides

- topography, connected to the acquisition geometry, (generally the images are taken from a slightly different position);
- atmospheric effects;
- noise caused by the temporal decorrelation of the microwave signals connected to changes in the dielectric properties of the target area during the time interval between the acquisition of parameters, induced, for instance, by changes in soil moisture or surface roughness and vegetation growth;
- ground-displacements which have occurred in the time span between the two acquisitions, being the objective of landslide monitoring.

The data processing technique known as differential SAR interferometry (DInSAR), applied to satellite images, permits the removal of the topographic component. In those cases where the atmospheric and noise effects are negligible, the residual phase difference can therefore directly be related to the superficial displacements in the observed area along the line-of-sight of the satellite. DInSAR from satellite platforms allows the monitoring of slow ground movements which involve large portions of the land surface, such as subsidence phenomena, fault movements and along volcano displacements (Strozzi et al. 2001; Massonnet et al. 1993; Massonnet et al. 1995). The accuracy is a small fraction of the employed wavelength and it is usually centimetric or millimetric; the pixel resolution is usually within the order of tens of meters. In the case of landslides, the characteristics of the currently operational satellites (Table 2) put strong constraints on the use of DInSAR as a monitoring instrument. In particular the spatial resolution of the SAR images, the time-interval between the successive passages of satellites and the wavelength of the radiation are unsuitable for a systematic monitoring of relatively rapid movements, concentrated in small areas and on steep slopes or narrow valleys (Rott et al. 2000; Refice et al. 2001). Quantitative information on landslide activity can be obtained in the case of extremely slow movements (velocity less than a few centimeters per month), affecting large areas with sparse vegetation (Fruneau et al. 1996; Rott and Siegel 1999; Kimura and Yamaguchi 2000; Rizzo and Tesauro 2000). Moreover, DInSAR results are affected by an intrinsic ambiguity of phase, since phase differences between two acquisitions can be correctly interpreted only if they are less than half a wavelength. Only if the displacement pattern is "smooth" enough and extended over a wide area, the phase wrapping produces typical fringes that, in many cases, can be interpreted in order to assess the displacements of several wavelengths, without phase ambiguity. The final product of the DInSAR technique application consists of a series of interferograms showing fringes related to phase differences and, hence, to ground displacements. These fringes can be interpreted to detect anomalies, displacement patterns and, eventually, to derive local contours of landslide velocity over the investigated time span (Fig. 8).

The technique of Permanent Scatters (PS), recently developed by Ferretti et al. (2000, 2001), allows a significant reduction of the atmospheric and noise effects as well as the acquisition of information (sub-millimetric) at the

Table 2
Operational parameters of radar satellite already launched or foreseen for the next years

Satellite	ERS 1	ERS 2	Radarsat 1	JERS	Envisat	Radarsat 2	Alos	Terrasar	Cosmo Skymed*
Space agency	ESA	ESA	CSA/USA	NASDA	ESA	CSA/USA	NASDA	DLR/ BNSC	ASI
Launch date	16/7/91	20/7/95	4/11/95	11/2/92	March 2002	Oct. 2002	2004	July 2003	2004
Lifetime	9 years	Active	Active	Active	Active	7 years	5 years	3 years	5 years
Band	C	C	C	L	C	C	X-L	L	X
Wavelength (cm)	5.7	5.7	5.7	23.5	5.7	5.7	3.0–23.5	23.5	3.0
Polarization	VV	VV	HH	HH	HH/VV	All	All	HH/VV	HH/VV
Incidence angle (°)	23	23	20–50	39	15–45	10–50	15–60	8–60	Variable
Resolution range (m)	26	26	10–100	18	30	3–100	1–15	10–44	1–3
Resolution azimuth (m)	28	28	9–100	18	30	3–100	1–15	10–44	1–3
Scene width (km)	100	100	10–500	75	10	10–500	10–60	40–70	Variable
Passage rate (days)	3, 35, 176	35	24	44	35	24	≤ 2	44	0.25–0.67
Orbital elevation (km)	780	780	800	568	800	800	660	691	600

*COSMO/SKYMED is a constellation of four satellites

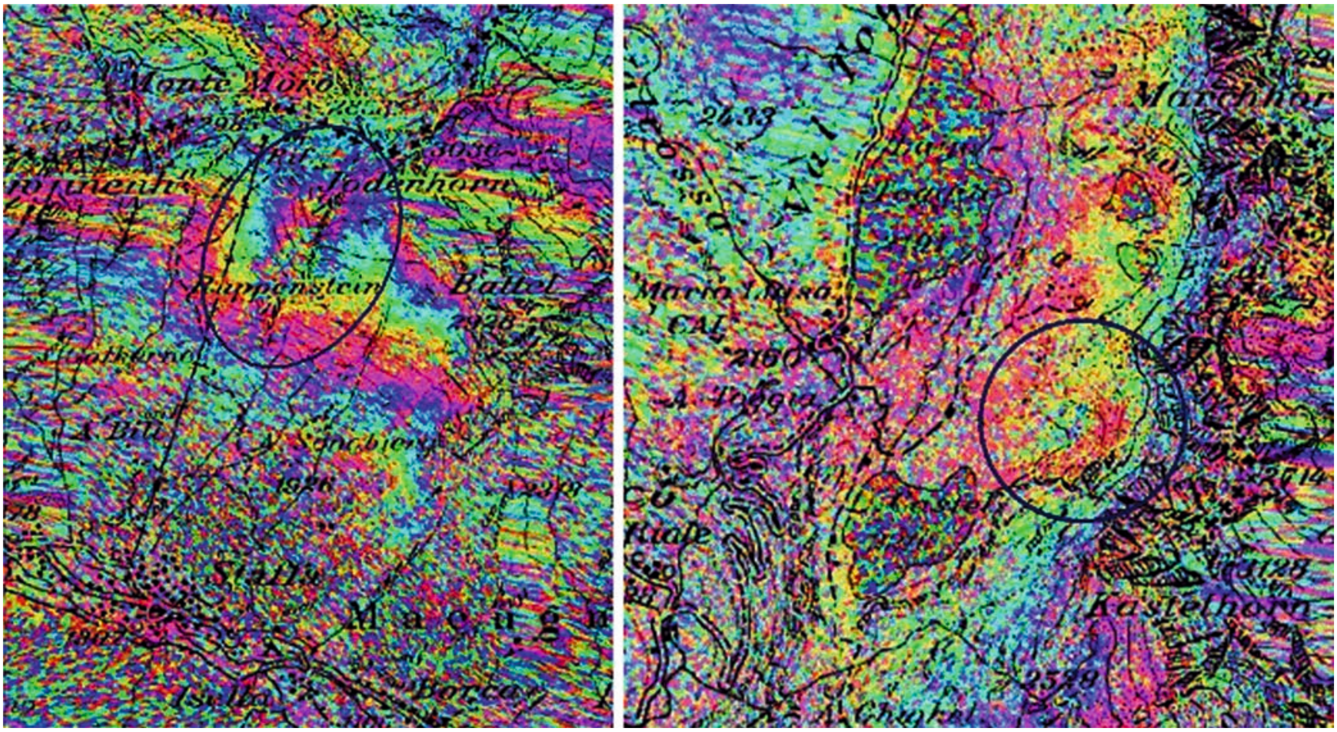

Fig. 8
SAR differential interferograms in the Alps (Piemonte region): *Left*: Macugnaga (time interval: 736 days, baseline = 18.6 m); *Right*: San Giacomo Pass (time interval: 1120 days, baseline = 18.5 m). The interferometric phase has been displayed on a topographic map. Anomalies in the phase values (as the ones within the *circles*) can be related by RS specialist to ground deformations induced by mass movements. In the first case the *circled fringes* correspond to a landslide in the second to a rock glacier (Picture courtesy of Gamma Remote Sensing Ltd)

displacements on selected points, corresponding to the natural stable ground reflectors (e.g. rock outcrops, single houses or buildings). The technique is based on the interferometric processing of long temporal series of SAR images and it has been successfully applied for monitoring both single slope movements (Ancona landslide: Ferretti et al. 2001) and slope instability at a regional scale (Northern Lombardia: Allievi et al. 2003). In addition, the acquisition parameters of the SAR missions scheduled for the near future, such as the Japanese ALOS or the Italian COSMO/SKYMED program, seem to meet the operational requirements for an effective and systematic monitoring of slope movements. Many of the limitations associated with spaceborne SAR interferometry can be currently overcome by applying the same technique but with ground-based instrumentation (ground-based differential SAR interferometry: GBInSAR).

In recent years, the Joint Research Center of the European Commission developed a portable interferometric radar device known as LISA (Linear SAR: Rudolf et al. 1999) for monitoring engineering structures (Tarchi et al. 1997). The

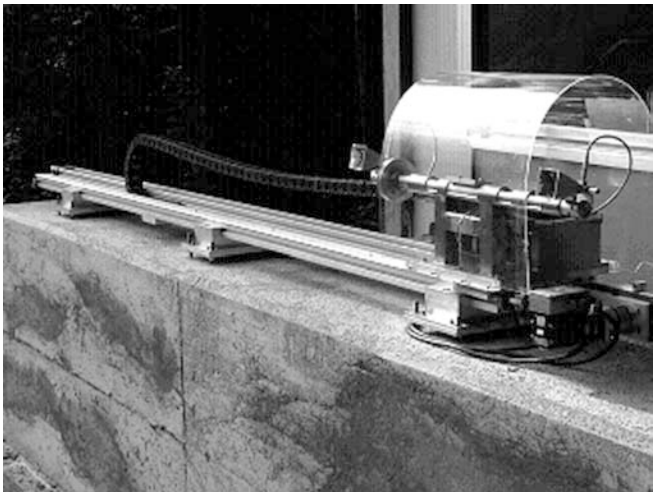

Fig. 9
The LISA ground-based system for landslide monitoring

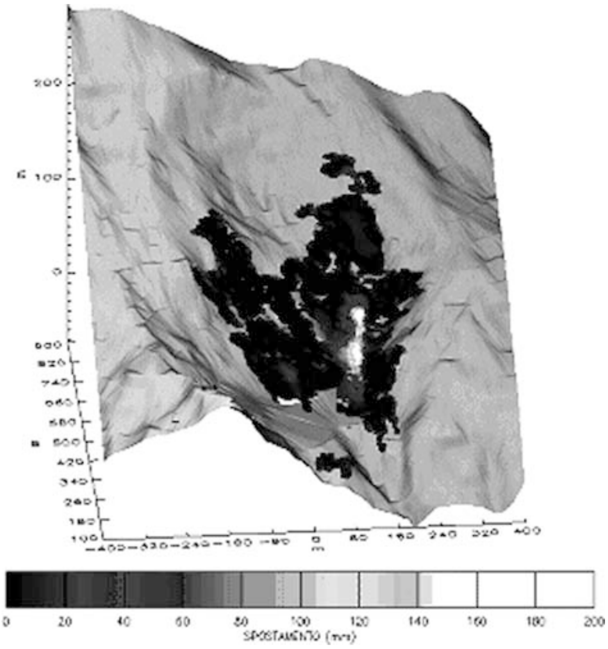

Fig. 10
Deformation map of the Tessina landslide in the Eastern Alps derived from ground-based SAR interferometry. The *scale* shows cumulated displacement over a time span of 34 hrs and 58 min starting from 27/6/2001 14:34 (after Tarchi et al. 2003b)

system is composed of a couple of radar antennae (transmitting and receiving), fixed on a motorized sledge which moves, at regular spaced intervals, along a straight rail of about 3 m in length (Fig. 9). The synthetic aperture radar (SAR) takes repeated measurements, while the sensors move along the rail. In the last two years, the LISA system has been successfully applied to the monitoring of landslides in the Italian Alps and Apennines (Atzeni et al. 2002; Canuti et al. 2002; Casagli et al. 2002; Tarchi et al. 2003a, 2003b).

By using ground-based sensors it is possible to markedly increase the potentiality of the interferometric technique. First of all it is possible to acquire images from exactly the same position, in a condition known as “zero baseline”; in this way the recorded phase differences directly correspond to ground movement, since the topographic contribution of phase is null. By operating with microwaves in the Ku band (frequency between 12.5 and 18 GHz) and at a distance of 1–2 km, it is possible to obtain spatial resolutions of the order of a few meters with an accuracy of displacement detection equal to fractions of a millimeter. It is also possible to reduce to a few minutes the temporal interval between successive acquisitions, which allows the reduction of many of the temporal decorrelation problems, noise and phase ambiguities associated with satellite observations.

These characteristics are optimal for a continuous monitoring of slope movements, even in cases of relatively rapid evolution (up to 1 m/day). The system can be installed in a few hours in front of the unstable area. The entire data processing chain, which includes the acquisition of SAR raw data, their calibration, their focalization on the digital elevation model of the slope and their geocoding in a standard co-ordinate system, can be implemented directly in the field, using portable instrumentation and a laptop computer.

The final result of GBInSAR, after the interferometric analysis, consists of a series of multitemporal deformation maps of the target area showing, pixel by pixel, the field of displacements, along the system line-of-sight, over the observed area (Fig. 10). By operating in the Ku band, as mentioned above, it is possible to obtain a resolution and an accuracy comparable, or even better than traditional geotechnical and topographic instrumentation, currently employed in the monitoring of landslides. In this band, however, the phase is strongly disturbed by the presence of vegetation and, for this reason, the acquired data are significant only for bare or sparsely vegetated areas. This is not normally a problem in active landslide areas where large portions of the slope are actually poorly vegetated.

The technique’s capacity of delivering spatially distributed information and its remote sensing nature (without the necessity of installing benchmarks or reflectors within the unstable area) are elements of absolute innovation in the realm of landslide monitoring. The practical use of slope instability as a geoindicator needs an adequate system for measuring landslide activity, at different spatial and temporal scales. The described remote sensing techniques provide important tools of investigation and combined use can solve many of the problems encountered in landslide monitoring.

Satellite and ground-based SAR interferometry apply at different spatial scales; satellite SAR frames cover areas up to 100×100 km wide, with resolutions of a few tens of meters, therefore they can be used for monitoring slope instability from a patch to a regional scale. The area covered by the LISA ground system depends on the distance from the point of observation, but it is usually limited to a few hundreds of meters up to a few kilometers, corresponding to a patch-landscape scale (Table 3).

Regarding the temporal scale, this is controlled by the time interval between the successive acquisitions (Table 4). The passage rates of the present satellites over the same area range between 24 and 44 days (Table 2), thus allowing a monitoring periodicity of approximately one month.

The LISA ground system can presently acquire an image every 3 minutes and it is consequently more suitable for faster slope movements which require a close series of successive measurements. These considerations reflect on the type of slope movements that can be kept under observation through the two systems. The standard landslide velocity scale proposed by the IUGS Working Group on Landslides (IUGS/WGL 1995) is shown in Table 5. The problems of phase ambiguity and temporal decorrelation, both linked to the interval between successive acquisitions, are the two constraints on the capability of the technique: satellite data allow the monitoring of extremely or very slow movements only, whereas the LISA device allows the assessment of moderate velocity landslides. This is usually enough to detect precursory trends of more catastrophic failures.

Table 3
Present capability of the spaceborne and ground-based SAR interferometry for monitoring slope movements over the standard spatial scale used in ecology

Spatial scale	Dimension (km)	SAT DInSAR	GB DInSAR
Patch	0–1	Yes	Yes
Landscape	1–10	Yes	Yes
Mesoscale	10–100	Yes	No
Regional	100–1,000	Yes	No
Continental	1,000–10,000	No	No

SAT, satellite; GB, ground-based; DInSAR, Differential Interferometric Synthetic Aperture Radar

Table 4
Present capability of the spaceborne and ground-based SAR interferometry for monitoring slope movements at different temporal intervals

Temporal scale	SAT DInSAR	GB DInSAR
Second	No	No
Minute	No	Partly
Hour	No	Yes
Day	No	Yes
Week	No	Yes
Month	Yes	Yes
Year	Yes	Yes
Decade	Yes	No

Discussion and conclusions

The stability of slopes is undoubtedly an important geoindicator, very sensitive to rapid environmental changes. Landslide inventory data are the key for a practical use of landslide frequency as a geoindicator. Using inventory data some indexes have been presented, describing the socio-economic significance of the "landslide problem" in Italy. These indexes represent overall parameters to be used by policy makers or economists to assess the dimension of the problem and to evaluate the feasibility or the effectiveness of landslide hazard reduction policies.

The present scientific knowledge is not enough for establishing the precise cause-effect relationships between landslide activity and changes in the driving environmental factors, such as climate changes or vegetational variations. This picture is complicated in countries like Italy where the human activity has exerted a fundamental control on the geomorphological evolution and on the land cover. Radiocarbon dating of landslides both in the Alps and the Apennines seems to put in evidence peaks of landslide activity in periods of climatic deterioration during the Holocene. Historical data needs a more complex interpretation, even in a country like Italy where one of the most complete databases of historical events is available. An influence of the last period of climatic deterioration, the so called Little Ice Age, seems to be ascertained but in the same period wood cutting reached a peak capable of accelerating the processes of slope instability all over the national territory. In the last 50 years the evolution of the slopes appears to be mainly controlled, directly or indirectly, by the anthropogenic activity. The Chianti hills and the Cinque Terre National Park are examples of this but, whereas the former shows the marked increase in landslide activity following the introduction of mechanization in vineyards, the latter shows how the same effect is reached in a case of uncontrolled re-naturalization of slopes, following the farming abandonment. This second example needs further investigation because it is closely linked to the intrinsic meaning of geoindicators and it can provide indications on the natural trends no more affected by human activity.

Finally, the potentiality of two remote sensing techniques have been discussed, based on radar interferometry,

Table 5
Velocity scale proposed by the IUGS/WGL (1995) and present capability of the spaceborne and ground-based SAR interferometry to assess the indicated displacement rates

Class	Description	Speed	Speed (m/s)	SAT DInSAR	GB DIn SAR
1	Extremely slow	16 mm/year	$5\ 10^{-10}$ m/s	Yes	Partly
2	Very slow	1.6 m/year	$5\ 10^{-8}$ m/s	Partly	Yes
3	Slow	13 m/month	$5\ 10^{-6}$ m/s	No	Yes
4	Moderate	1.8 m/h	$5\ 10^{-4}$ m/s	No	Partly
5	Rapid	3 m/min	$5\ 10^{-2}$ m/s	No	No
6	Very rapid	5 m/s	5 m/s	No	No
7	Extremely rapid			No	No

implemented by using satellite imagery and ground-based instruments. These techniques have revealed very promising tools for landslide monitoring at different spatial and temporal scales. Present-day satellites are already capable of providing a quantitative assessment of ground displacements at a regional scale in sparsely vegetated areas (e.g. at altitudes above the vegetation limit). The next generation of SAR satellites will probably become the routine tool for monitoring slope evolution at a regional scale. Recent experiments have shown that the application of the SAR interferometric technique, using ground-based sensors, is already a very powerful instrument for monitoring single landslides or unstable slopes. The combined use of satellite and ground-based systems, considering also their future improvements, can significantly help in overcoming many of the limitations of data and monitoring associated with the "landslide geoindicator".

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