Engineering Geology 147–148 (2012) 124–136

Contents lists available at SciVerse ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Design and implementation of a landslide early warning system

Emanuele Intrieri *, Giovanni Gigli, Francesco Mugnai, Riccardo Fanti, Nicola Casagli

University of Firenze, Firenze, Italy

ARTICLE INFO

Article history:
Received 7 April 2011
Received in revised form 28 May 2012
Accepted 24 July 2012
Available online 3 August 2012

Keywords:
Landslide
Early warning system
Risk management
Wireless sensor network
Ground-based interferometric radar
Monitoring

ABSTRACT

In this paper all the phases for the realization of the early warning system for the rockslide of Torgiovannetto in Central Italy are described. The landslide consists in a 182,000 m^3 rock wedge threatening two roads which are important for local transportation. The present work encompasses all the components of an early warning system, including the geological knowledge, the risk scenarios, the kinematic characterization of the landslide, the choice and installation of the monitoring system, the setting of appropriate alarm levels and the definition of plans of civil protection. The focus is on practical and logistical issues met in all these phases and the counter-measures adopted.

At present the system consists in 13 wire extensometers, 1 thermometer, 1 rain gauge and 3 cameras. Should a velocity threshold be exceeded by two or more sensors, the attention level would be entered, causing improved monitoring and surveillance. In case the behavior of the landslide changes and, by using expert judgment and forecasting methods, an imminent failure is hinted, then an alarm is issued and the upper road is closed.

This paper can provide ideas and solutions for a landslide early warning system that aims to be simple, flexible, versatile and with a low probability of giving false alarms.

1. Introduction

In landslide prone areas, risk mitigation must often face problems related to economical resources, environmental impact and logistic issues. This is particularly true for structural counter-measures, which aim at mitigating the risk by reducing the probability of failure (bolts, anchors, piles etc.), by preventing the landslide from reaching the elements at risk (barriers, ditches, retaining walls etc.) or by reinforcing existing buildings. On the other hand, early warning systems (EWSs) are an alternative cost-effective means to reduce the risk with a low environmental and economical impact. In some cases, for instance when a landslide is so large that it cannot possibly be stabilized, they can even be the only solution.

Several definitions of EWS can be found in the literature. Medina-Cetina and Nadim (2008) define them as “monitoring devices designed to avoid, or at least to minimize the impact imposed by a threat on humans, damage to property, the environment, or/and to more basic elements like livelihoods.” According to United Nations International Strategy for Disaster Reduction (UNISDR, 2009) they are “the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss.”

Whatever the definition, EWSs always work as risk mitigation tools by acting on the exposure of the elements at risk, especially people, by keeping them away from the dangerous area in case of expectation of an imminent collapse.

However it must be clear that an EWS is not just a cluster of monitoring systems or the forecast of failure, but it also involves other aspects such as the identification of risk scenarios, emergency plans, societal considerations, public awareness, etc. Each one of these components is necessary; if any element fails, the whole chain would collapse and would render the system useless. For example, a lack in the monitoring or forecasting can cause a missing event or conversely a false alarm and the consequent loss of confidence in the system. On the other hand, a bad planned evacuation can produce damages and economic losses; this explains why redundancy is so important, so that a single rupture of a chain's ring should not compromise the whole chain.

Indeed an efficient EWS should comprise the following activities (DiBiagio and Kjekstad, 2007):

- monitoring, including data acquisition, transmission and maintenance of the instruments;
- analysis and forecasting, which can be done by using thresholds, expert judgment, forecasting methods and so on;
- warning, i.e. the dissemination of understandable messages alerting for the impending threat;
- response, concerning if people are able to understand and how they react to the warning.

* Corresponding author.
E-mail address: emanuele.intrieri@gmail.com (E. Intrieri).

0013-7952
http://dx.doi.org/10.1016/j.enggeo.2012.07.017

Beside these activities, the International Early Warning Programme (IEWP, 2008) also includes the risk knowledge. This probably represents the first fundamental step for the design of every EWS, since a thorough geological and geomechanical knowledge is necessary in order to identify the most critical parameters to be monitored. In addition, an EWS must take into account factors such as the elements at risk, the hazards, the vulnerabilities, the lead time, the residual risk and many other precious information that can only come from in depth studies and risk assessments.

By joining the two previous definitions, the scheme of activities presented in Fig. 1 can be obtained.

Of all these components the one representing the major constraint for the effectiveness of an EWS is probably the response of people, i.e. how they will react to the alarm. In order to answer this question, preparedness training of the public must be considered within an EWS, otherwise even the most sophisticated monitoring system can fail, as happened for instance for the EWS at San Francisco Bay (Keefer et al., 1987; Wilson, 2004).

An excellent example of how to face this social issue is reported in Mak et al. (2007) where a detailed description of the awareness campaigns adopted for the EWS in use in Hong Kong (Pang et al., 2000; Yu et al., 2004) is given. Moreover a correct education of the population is by far the most cost-effective means of reducing the risk.

Finally it is worth remembering that at present there is no EWS valid for all cases; in fact every EWS must be designed purposely for a specific site. For instance the precursors and monitored parameters may largely vary depending on the type of landslide (Lacasse and Nadim, 2009).

Beside the cases presented above, many other examples of this huge variability can be found in the literature from all over the world (Froese et al., 2006; Stucky, 2007; Blikra, 2008; Badoux et al., 2009).

In this paper the detailed design and implementation of an EWS installed at the Torgiovannetto landslide is described. Considering that the early warning approach is more and more used and often references and detailed methodologies are lacking, this work can give useful suggestions for other similar cases.

2. The Torgiovannetto landslide

The landslide is located in a former quarry on the southward facing slope of Mount Subasio, 2 km NE from the city of Assisi (Perugia, Umbria Region, Central Italy, Figure 2). It was first observed on May 2003 and it is assured that the main predisposing factor of the instability was the quarrying activity.

Mount Subasio is part of the Umbria-Marche Apennines, whose geological formations represent the progressive sinking of a marine environment. It consists in a SSE-NNW trending anticline (Lavecchia et al., 1988; Tavarnelli, 1997; Mirabella and Pucci, 2002) with layers dipping almost vertically in the NE side of the mountain and with several NW-SE striking normal faults on the eastern and western flanks.

In the quarry area only the micritic limestone belonging to the Maiolica formation (Upper Jurassic–Lower Cretaceous) outcrops. The average thickness of the layers ranges between 10 cm and 1 m and, sporadically, thin clay interlayers may occur. The dip direction and the dip may vary respectively from 350° to 5° and from 25° to 35°, which means that, in general, the layers dip in the same direction of the slope but with a gentler angle (Figure 3).

The landslide, classified as a rockslide (Cruden and Varnes, 1996), has a rough trapezoidal shape. The sub-vertical back fracture is a tension crack with an E-W strike, which in some places displays a width up to 2 m (Figure 4). The downhill boundary, associated to a major clay interbed, is represented by a stratigraphic layer (355°/24°) that acts as sliding surface and cuts obliquely the quarry front. which is associated to a major clay interbed. The western side of the landslide is un-continuously delimited by persistent fractures belonging to a sub-vertical set having an N–S strike (Figure 5A).

The whole moving mass has an estimated volume of 182,000 m^3 (Canuti et al., 2006), and is represented in 3D in Fig. 6, where the orientations of the main delimiting planes are also reported in stereographic projection.

Two main elements at risk are individuated: the Provincial Road 249/1 and the Regional Road 444 (Figure 2). These roads are very important, since they are the only connection between the city of Assisi and the surrounding towns.

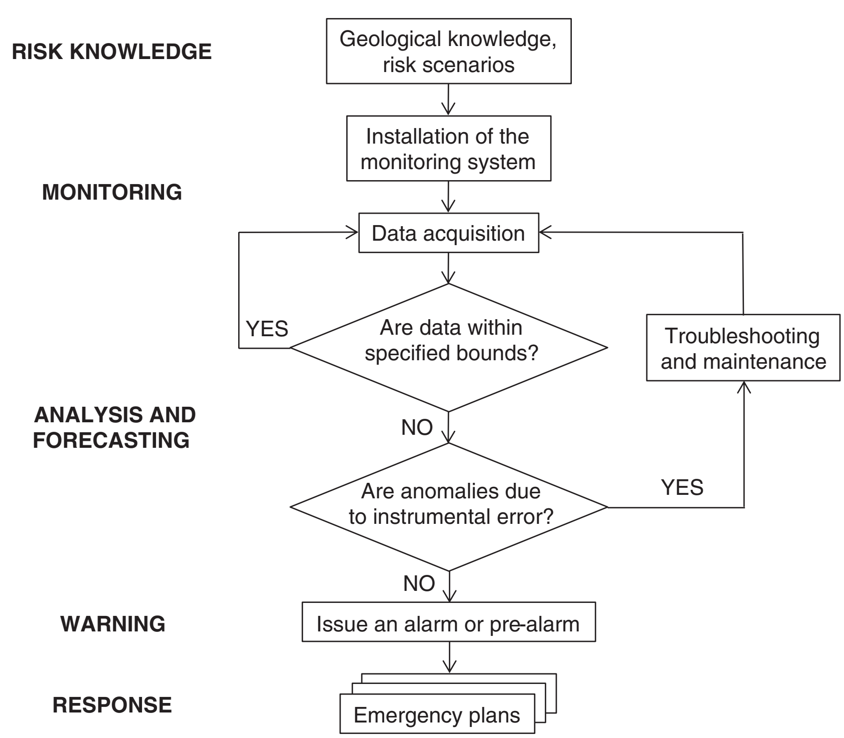

Fig. 1. Flow chart of the activities of a generic early warning system. Modified from DiBiagio and Kjekstad (2007).

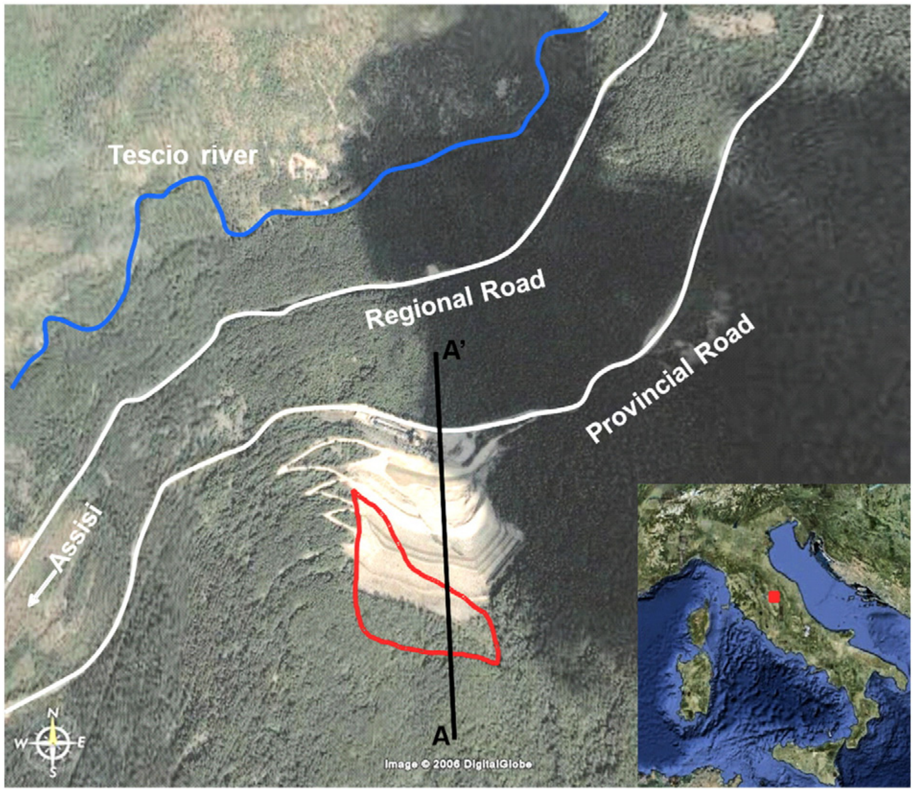

Fig. 2. Localization of the Torgiovannetto landslide above the streets that represent the main elements at risk; the black line (AA') indicates the trace of the geological cross section in Fig. 3. Quickbird image of 24/05/2003 from Google Earth.

Models and simulations of the maximum credible scenario (Balducci et al., 2011) showed that either in the case of a total collapse or in the case of rock falls, only the Provincial Road could have been directly endangered; therefore the street was closed for several months for safety reasons, causing economic losses and troubles to the population. In order to reduce the risk represented by the landslide and to open the street again, in 2008 a retaining wall has been built right above the road (Balducci et al., 2011).

Two minor landslides detached during spring 2004 and December 2005 (Graziani et al., 2009b) with a volume of respectively few tens and 2500 m^3. A back analysis carried out on these events provided some hints for the mechanical behavior of the whole slope movement.

3. Monitoring and movement pattern

3.1. Traditional monitoring systems

A first monitoring campaign had been carried out since 2003. A topographic monitoring was performed through 27 control points

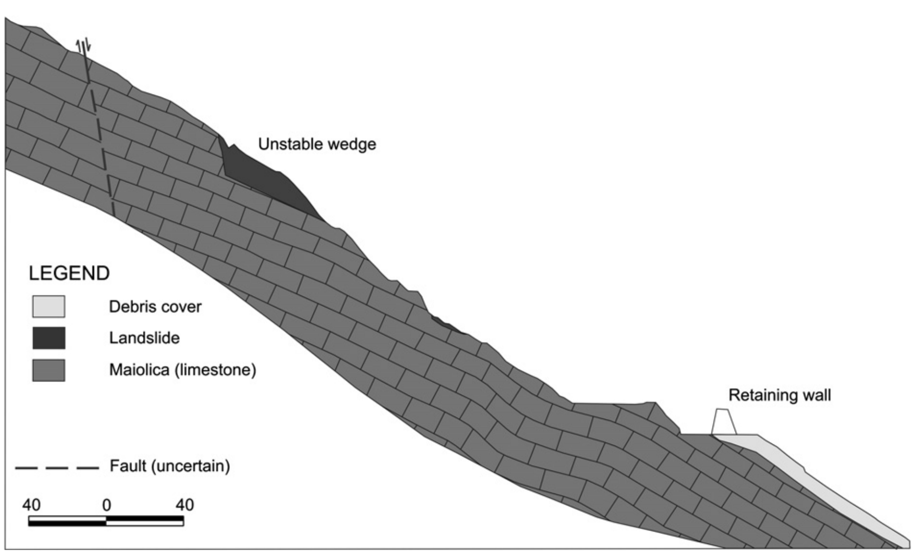

Fig. 3. Geological cross-section of the northern slope of Mount Subasio. Modified from Balducci et al. (2011).

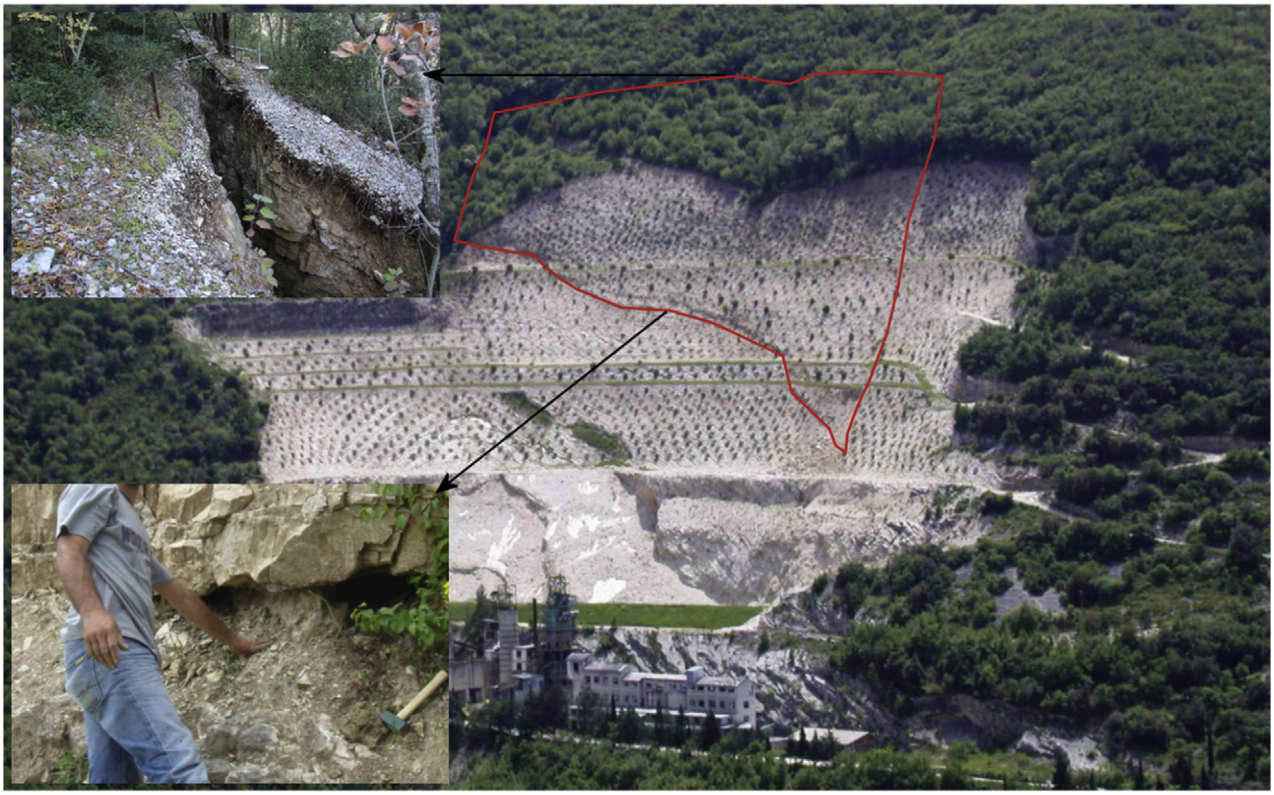

Fig. 4. Photograph of the Torgiovannetto landslide and details of the sliding surface and of the tension crack on the rear side.

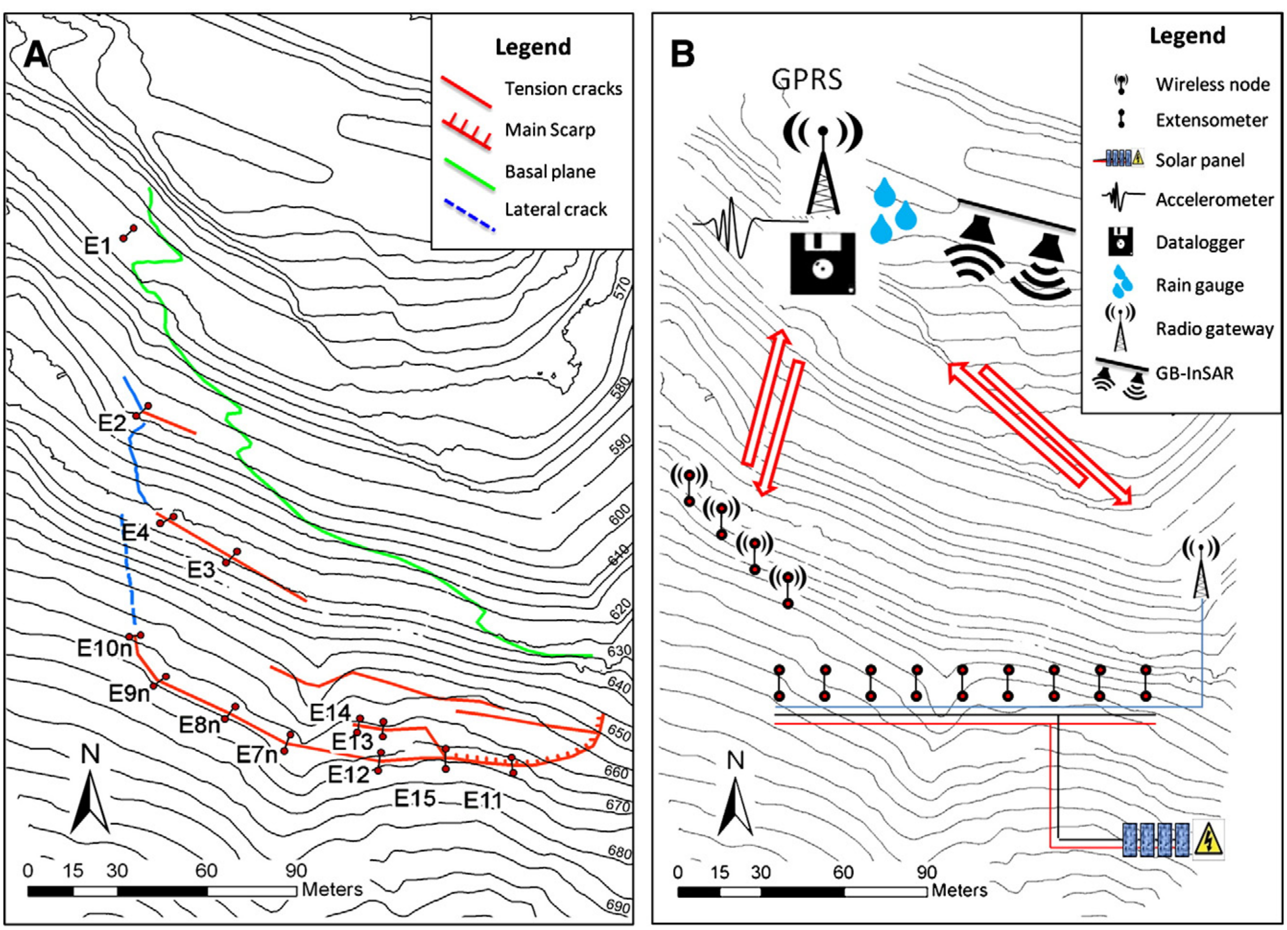

Fig. 5. A: Location of the extensometers installed at the Torgiovannetto landslide. The main fractures are also shown. B: Schematic view of the monitoring system.

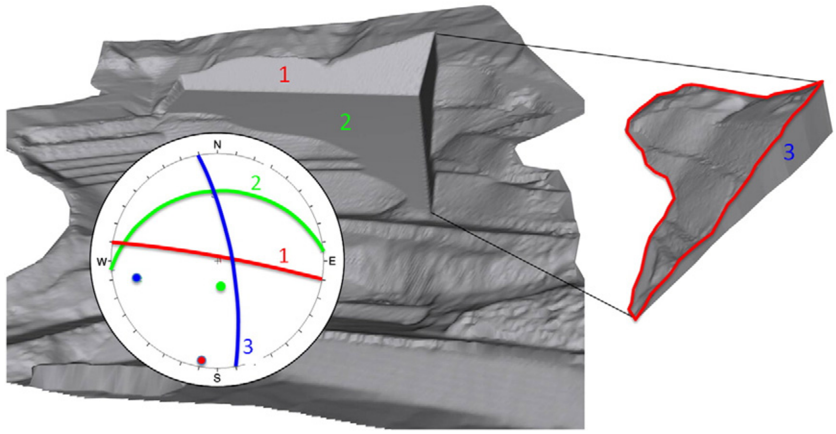

Fig. 6. 3D representation of the sliding block and stereographic projection of the main planes delimiting it.

localized within the landslide area; moreover 10 wire extensometers were installed across the main fractures (Graziani et al., 2009a).

Measurements obtained from the topographic benchmarks from spring 2004 to spring 2007 showed that the fastest moving part was the eastern one, close to the back fracture, and as moving westward the displacements decreased (Graziani et al., 2009b). Moreover, the benchmarks located on the eastern side revealed that the vertical displacements prevailed upon the horizontal ones, while the contrary occurred on the western side.

The extensometers gave similar results and during the period March 2005 to May 2007 recorded the highest velocity of 1.2 mm/day nearby the eastern limit of the back fracture. Here, the opening measured by the extensometers represented the 50–65% of the displacements recorded by the topographic measurements (Graziani et al., 2009b).

During summer 2007, the monitoring system has been re-configured, with the aim of making it as suitable as possible for early warning purposes (Balducci et al., 2011).

As the most indicative parameter of instability was believed to be the opening of fractures bounding and within the unstable mass, a wire extensometric monitoring was preferred. Furthermore extensometers are characterized by a quite easy installation and employment within an early warning procedure, low vulnerability and high reliability.

The technology available for EWS is so accessible and advanced that the main limitation is often represented by logistic issues (Nadim and Intrieri, 2011). While setting up the system for managing data, a few of these issues have been dealt with, as described in the following part.

The system was initially designed to be fully wireless; nevertheless, the high incidence of multi-path phenomena made it necessary to avoid radio transmissions in areas with strong obstacles.

At present 13 extensometers and a thermometer–rain gauge station are installed on the landslide. The location of each extensometer is shown in Fig. 5A, together with the main fractures. A video surveillance system is also active in real-time with remote connection.

Extensometers E10n, E9n, E8n, E7n, E12, E15 and E11 (from W to E) are located in correspondence of the back fracture. E14 and E13 measure the aperture of a secondary fracture just below the main one. A crack within the landslide body is monitored by extensometers E4 and E3, while another one in the lowest part by E2. The extensometer E1 is positioned at the NW corner of the landslide and the meteorological station outside the unstable mass.

The sensor network is based on five sets of macro-components: radio processors, transducers, analog-digital converter, data-logger and gateway (Figure 5B).

The radio processors adopted are MICA2 MPR400CB (produced by Crossbow). These were installed after an accurate field transmission test, and were integrated with cable connections in those areas where permanent obstacles did not guarantee an efficient wireless communication.

The current transducers are Celesco PT8101-0020, capable of a measuring range of 500 mm. The choice of such a long range was influenced by the will to avoid any intervention of repositioning.

Adopting a 16 bit A/D converter allowed us to provide a resolution of 0.007 mm even using transducers with this range. Thanks to the high resolution and the good repeatability, these linear position transducers may be used in this type of applications, even if the EWS needs small velocity threshold values.

The extensometers positioned on the upper part of the slope (E11, E12, E13, E14, E15, E7n, E8n, E9n and E10n) are connected through cables to a data-logger installed on the top of the landslide and are powered by a set of solar panels. The other instruments (E1, E2, E3, E4, thermometer and rain gauge) are radio connected to another data-logger installed in a rest area close to the road at the base of the slope and each of them is provided with its own solar panel (Figure 5B).

Data collected by the data-loggers are transmitted by a gateway (RS232 MIB 510 by Crossbow) via GPRS to an ftp server. Redundancy is therefore implemented at this point, as data are stored in more delocalized storage systems.

Since the nodes are installed within the landslide body, they are subject to the impact of rolling stones and to the multi-path effect due to the high roughness of the soil and to the presence of vegetation. Tough steel shelters were used to limit instrument damages and increase robustness.

The sensors of the WSN make an acquisition every 60 s, but only a 5 min mean datum is sent to the data-logger in order to save energy. In fact, a WSN implies an energy consumption proportional to the measurement frequency, as each operation activates the radio processor, the A/D converter and the transducer. The power supply is another important aspect of an EWS that must be taken care of, since interruptions of the monitoring due to a lack of energy can be very critical during the periods when the landslide is most active.

The whole data set covers the time span from 2007 to present, with some missing data due to alimentation issues, works for the realization of the retaining wall or lacks in coordination between stakeholders (Figure 7A); in more recent times, having learnt the lesson, communication has been improved and the monitoring did not experience other stops. From the second half of 2007 to October 2011, the periods showing the highest movements were April 2008 (when E11 measured a daily velocity up to 2.77 mm/day), December 2008 to February 2009 (with a maximum daily velocity of 1.39 mm/day recorded by E11) and February 2010 (during which the highest velocity was 1.02 mm/day, measured by E11).

Fig. 7B shows the displacement seasonal fluctuation recorded at E11. In particular the landslide is quite active from November to

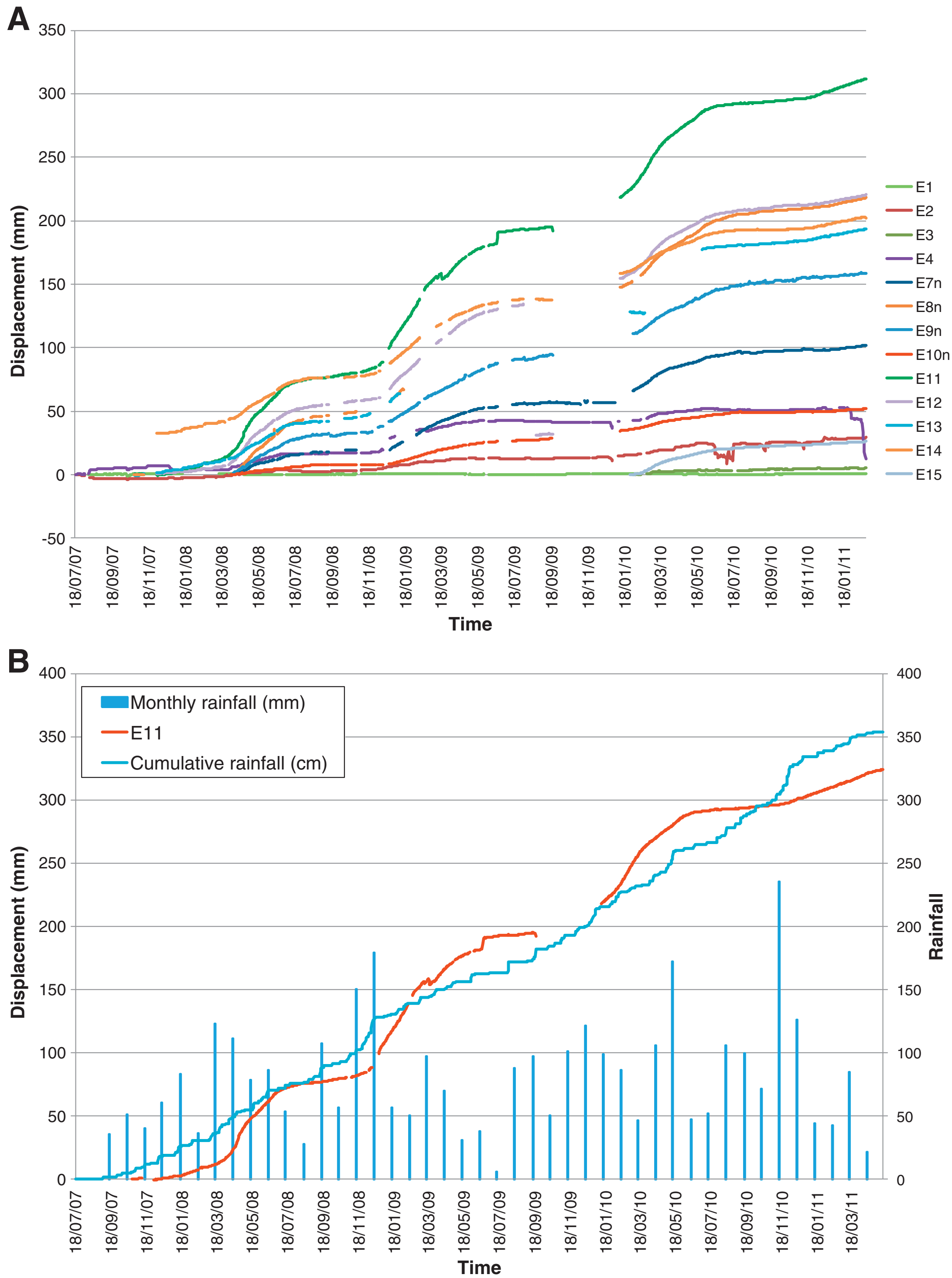

Fig. 7. A: Displacement data from the extensometers installed at Torgiovannetto. B: Displacement data of extensometer E11 overlapped with monthly and cumulated rainfall. The cumulative precipitation is expressed in cm, while monthly value is in mm.

May and remains almost stable during the dry period. This behavior seems to be related to the rainfall distribution and is in accordance with the previously discussed results (Graziani et al., 2009a, 2009b).

The highest velocities are observed in the eastern sector of the back fracture (E11) and regularly decrease toward E10n at the western end; the only exception to this pattern is represented by E7n which, even if it is in the middle of the fracture, is characterized by low movement rates. E13 and E14 show smaller displacements, similar to those of E8n. The fracture monitored by E3 and E4, and the one by E2, measures even smaller movements, although a daily velocity of 1.63 mm/day was reached by E2 in April 2010 and 1.65 mm/day by E4 in April 2008. Finally, no movement has been recorded by E1.

3.2. Interferometric campaigns

In addition to the traditional measurements, two short-term ground-based interferometric synthetic aperture radar (GB-InSAR) monitoring campaigns were carried out; the first one was performed in collaboration with LiSALab-Ellegi from March 29th to April 14th 2006. In 2008 Ingegneria Dei Sistemi (IDS) society wanted to test some features of their new-born system (called IBIS-L) on a landslide and asked the authors for a suitable test-site. In authors' opinion this represented a good chance to verify the conditions of the landslide after the last campaign; moreover the use of these two different systems (which are the first and probably the most used GB-InSAR apparatuses in the world) is by itself an added value since this is the only documented case study (to the best of author's knowledge) where both radar have been employed. Therefore a second interferometric campaign was carried out from April 11th to April 18th 2008.

It should be noted that the aim of these campaigns was to define the deformation field of the landslide and to assess its precise boundaries, in order to calculate its volume, fundamental for building a reliable kinematic model and risk scenarios (Balducci et al., 2011). Hence the role of the GB-InSAR within the EWS was restricted to gaining a deeper insight of the landslide behavior and of the associated risk.

The radar systems adopted are different but share the same basic principles (Rudolf et al., 1999; Luzi et al., 2004): two microwave signals are emitted in two different times; the waves reach the target (e.g. the landslide) and are backscattered to the radar, where their amplitude and phase are measured. Should any movement occur between the two acquisitions, a phase difference is measured. Then from the phase difference it is possible to calculate the actual superficial displacement along the line of sight with millimeter accuracy. If the radar acquires data while moving along a rail (Synthetic Aperture Radar) displacement maps can be computed. Many applications of this technique to monitoring of unstable slopes can be found in the literature (Atzeni et al., 2001; Barla et al., 2010; Casagli et al., 2010).

The only true difference between the two apparatuses adopted at Torgiovannetto lies in the microwave signal generation (IBIS-L uses an industrialized method derived from a prototype developed in collaboration with the Department of Electronics of the University of Firenze, while the LiSA device is based on a Network Analyzer), in the length of the rail (which resulted in a slightly higher azimuth resolution for the first campaign), in the gain of the antennas (resulting in a slightly different field of view) and in the software adopted for data elaboration. However, in the end, both systems operate in Ku band, with the same bandwidth and polarization. Moreover they were installed exactly in the same position, above a concrete block that was purposely built, in order to share the same scenery and line of sight. All of this means that the two datasets are perfectly comparable.

The traditional monitoring showed that April generally was the month during which the highest velocities were reached. For this reason both interferometric campaigns were carried out in this period, in order to assess the landslide behavior during the most active month. This was also done in an EWS perspective to evaluate the maximum risk scenario and to define reliable velocity thresholds.

A comparison with an optical image (Figure 4) is useful to correctly interpret the velocity maps presented in Figs. 8 and 9.

The whole moving area is clearly detectable, with the exception of the vegetated sector above the anthropic cut; in fact, the surrounding zones (in blue) are completely stable. The fastest moving portion is the one at the left (eastern) side, corresponding to the red region, where the average velocity, calculated by analyzing radar data from March 29th to April 14th 2006, is around 1.5 mm/day (Figure 8). This value is underestimated by 5% in consideration of the drift between radar line of sight and the maximum movement vector detected by ground instruments. The velocity decreases while moving toward the up-right corner (SE) and reaches the minimum nearby the green-blue area (0.4 mm/day). Downhill, all along the basal discontinuity, the velocity ranges from almost 1.3 mm/day in the orange zone to almost 0.8 mm/day in the middle, while in the right-down corner it reaches 0.9 mm/day. Along the downhill boundary, a thin green line (0.4 mm/day) bordering the landslide can also be noted (Figure 8). It corresponds to a sector which marks a transition between the stable area (below the sliding surface) and the moving wedge and is mainly composed of the clay interbed (Figure 4) along which the movement occurs.

The velocity of each sector remained almost the same along the whole duration of the campaign, witnessing a linear deformation with time.

A comparison with the 2008 campaign (Figure 9) shows that the geometry and kinematics of the landslide remained almost the same during 2 years, with some minor differences. The trapezoidal shape is unchanged, meaning that the mass movement did not extend to concern other areas of the rock mass. It is still evident that the fastest moving part is the eastern corner, with decreasing velocities as moving toward W.

With respect to 2006, the values have slightly changed but do not modify the general movement pattern: the slowest sector is still the SW corner which, during the campaign, displayed on average 0.3 mm/day; as in the previous campaign, the E corner recorded the highest displacement and reached an average velocity of 1.4 mm/day, while the downhill part of the landslide, close to the lower boundary, was still characterized by intermediate values.

The occurrence of rain events during this campaign did not seemingly affect the landslide behavior, at least in a short term.

The results from the interferometric campaigns confirm and complete the general picture and pattern deformation furnished by the traditional instrumentation. Even the average velocity values of each zone are confirmed, and minor differences are due to the absence of interferometric data exactly on the points where extensometers are installed and to the fact that the radar measures absolute displacements of each pixel area (comprehending the contribution of many fractures) while the extensometers determine the relative aperture of a single fracture. Finally it is also caused by the different directions of measure (along the line of sight and along the wire direction for the GB-InSAR and the extensometers, respectively).

3.3. Rockslide kinematics

All the monitoring systems employed and the field surveys suggest a rock slide mechanism with a planar surface along a bedding plane associated to a major clay interbed that cuts the quarry face (Figure 3).

However, the inhomogeneous deformational field suggests a counter-clockwise rotation of the wedge (in plan), with the highest displacements recorded along the eastern side of the moving mass. The displacement variation along a longitudinal profile for both campaigns shows a generally linear behavior (Figures 8 and 9), suggesting that a single movement affects the individuated block as a whole; the differential behavior can be explained by the shear strength caused by the western lateral crack, not fully developed yet (Figure 5A), as confirmed by the stability analysis (Graziani et al., 2009a; Balducci et al., 2011).

These evidences are supported by the asymmetric development of secondary fractures within the unstable wedge (Figure 5A), where the presence, in the eastern portion, of major internal cracks parallel to the rear one can explain the different behavior between the eastern and western sectors.

Fig. 9 also compares the velocity map obtained from the 2008 GB-InSAR campaign with the results from the extensometric measurements acquired during the same period. The circles indicate the extensometers, represented on the basis of the recorded opening, using the same color bar as the velocity map. Furthermore, their values have been projected along the radar line of sight, by considering the local wire direction of each instrument.

It can be assessed that, in general, there is a good correlation between the readings, although the extensometers appear to give smaller values than the radar. This is due to several factors; the main one is that

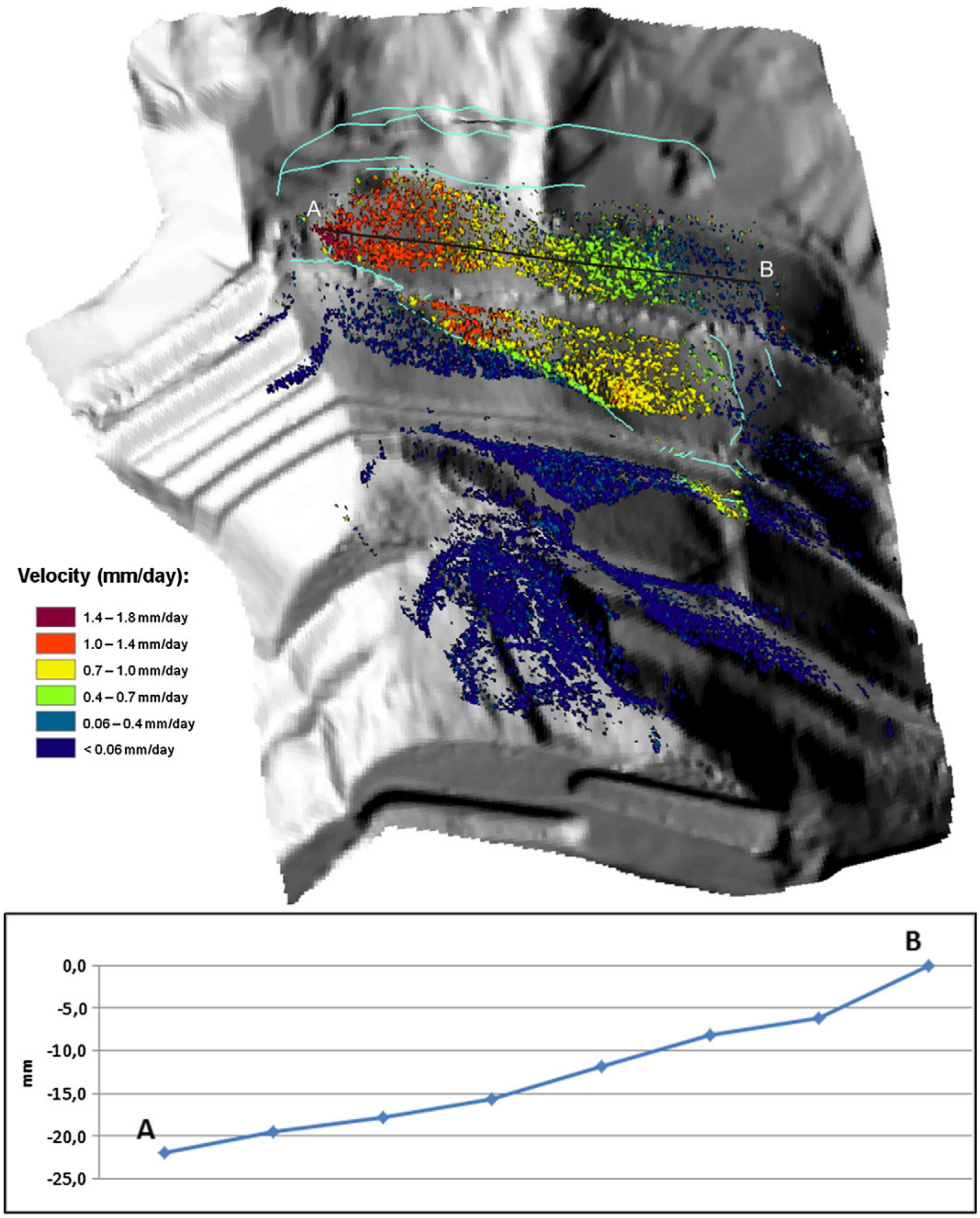

Fig. 8. LiSA GB-InSAR velocity map referred to the time interval from March 29th to April 14th 2006 and longitudinal displacement profile along the AB scan-line. The values are referred to the displacements along the line of sight.

the extensometers only measure the aperture of a single fracture, whereas the GB-InSAR registers the global movement of a continuous surface which can be affected by more than a single fracture located uphill. In fact, by summing the displacements of both E12 and E13, placed one above the other, a total value of 5.54 mm, comparable with that of the velocity map, is obtained.

Furthermore it must be noted that there are no interferometric data exactly in correspondence of the points and so a perfect comparison is not possible. Finally, the GB-InSAR apparatus measures the effect of movements on the surface, while the extensometers' recordings are referred to the aperture of deep fractures.

The precise knowledge of which are the slowest and fastest zones greatly helped when deciding where it was necessary to install new extensometers for the EWS. Moreover it implied the use of different threshold levels for different areas of the landslide, depending on the velocity characterizing each sector.

From the analysis of monitoring data, the rockslide seems to be more influenced by long rainy periods such as winter and spring seasons, during which the probability of exceeding thresholds and hence of failure is higher, rather than by short events (Figure 7B). For example in August 2008 a rainfall event of 88 mm was followed by negligible displacements in the next weeks, while the 87 mm precipitation recorded during 3 weeks in November 2009 was associated with a displacement of 24 mm (extensometer E11). Such seasonal behavior is more common for larger rockslides. For this case it can be explained with the presence of the clay interlayers, which are more sensitive to the influence of rainfall. However the landslide is experiencing a progressive deceleration through the years regardless of the precipitations, as proved by the most recent data in Fig. 7B which shows slow movements (87 mm from November 2010 to May 2011) during a rainy winter season (555 mm of rainfall in the same period).

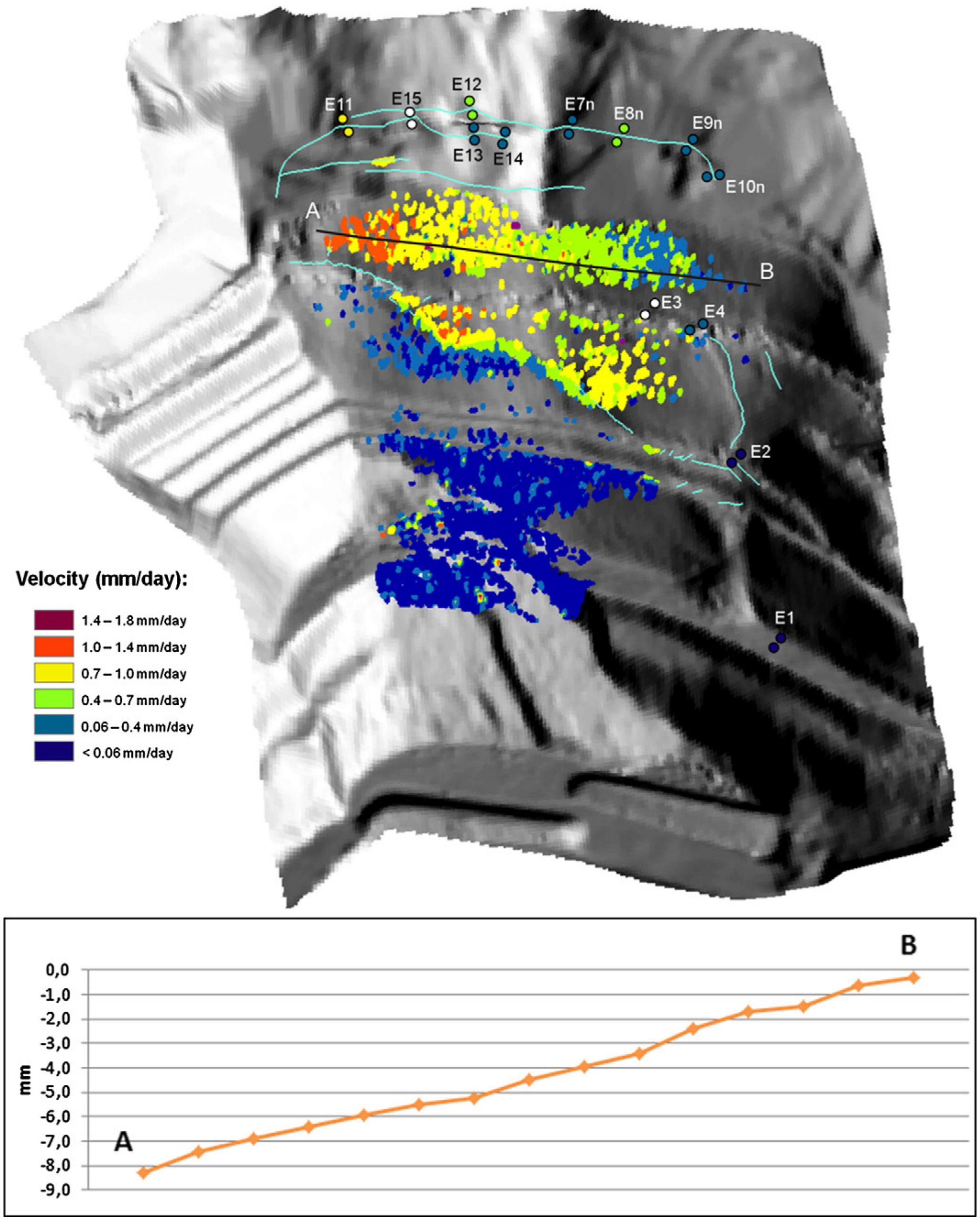

Fig. 9. IBIS-L GB-InSAR velocity map referred to the time interval spanning from 11th to 17th April 2008 and longitudinal displacements along the AB scan-line. The circles represent the extensometers whose velocities are shown using the same color bar as the map (E15 and E3 are colored in white because they were not installed at the time).

This general slowdown can be assessed also by comparing data since 2007 with the ones obtained from previous works (Graziani et al., 2009a, 2009b). For example E11 measured around 300 mm from December 2007 to February 2011, while the corresponding instrument during the previous campaign (E5) recorded up to 250 mm from March 2005 to April 2006; this can be only in a minimal part explained by comparing data from the rain gauge, which recorded a total of 1125 mm from April 2005 to March 2006, and a mean yearly value of 1017 mm from April 2008 to March 2011. The main exception to this behavior is represented by E10n, which maintained a similar velocity throughout the years.

4. The early warning system

In order to guarantee safety conditions to the personnel involved in the retaining wall construction and to keep a low residual risk after its completion, an EWS has been specifically designed for the Torgiovannetto rockslide.

Before starting with the actual design of the EWS, a few design criteria will be pointed out.

Simplicity was adopted as a criterion here. In fact, in emergency conditions everything must be simple and straight-forward; the action to be taken must be clear and fast, and misunderstandings or human errors are not tolerable. Furthermore, trying to forecast the imminent failure of a landslide and to alert people is a very complicated task; for this reason some simplifications must be done. Creating an EWS that reflects all the possible features of a landslide can bring very little improvements and even compromise the whole system. Simplicity can be implemented in many different ways within an EWS, as in the choice of few warning levels or of schematic thresholds.

Table 1
Sketch of warning levels and activities adopted for the early warning system of Torgiovannetto.

Warning level	Trigger	Definition	Response
Ordinary level	Default level	Normal activity encompassing, to some degree, seasonal variations	Data are checked daily. Monthly monitoring bulletin
Attention level	When 2 or more extensometers exceed their own velocity thresholds	Increased activity possibility due to prolonged rainfalls. Potentially dangerous	Data are checked more frequently. Daily monitoring bulletin. H24 personnel from each stakeholder are alerted. Preparing for alarm
Alarm level	Based on expert judgement and on the use of forecasting methods	Accelerating trend far beyond any seasonal fluctuation. Collapse is expected	Data are checked even more frequently Two monitoring bulletins per day. The Provincial Street is closed

Another criterion, more site-specific, was the avoidance of false alarms. Adopting counter-measures against false alarms can make the EWS less conservative. However, in this case the presence of the retaining wall and the absence of houses among the elements at risk made this solution possible. Moreover, as stated by Lacasse and Nadim (2009), an automatic EWS generating a false alarm may cause more severe consequences than the landslide itself, inducing additionally a loss of credibility in the population.

A key issue considered during the design phase was that the landslide is expected to show an accelerating trend a few days before the failure, allowing some time for the emergency procedures. The EWS has been designed accordingly; in fact some adopted solutions, like expert judgment and the manual closure of the street, would not be suitable for landslides that leave a short forewarning. This piece of information demonstrates once more the importance of the geological knowledge of the slope movement.

Since there were not any houses among the elements at risk, but only a road, drills and training were not necessary; furthermore the people driving the street often do not live in the area. Nevertheless public events (such as for the construction of the wall) have been organized to increase the public awareness.

The system has three warning levels (Table 1):

- Ordinary level: no emergency. Data collected by extensometers are checked daily and a monthly monitoring bulletin is released. Other activities imply the collaboration of every institution involved and include: constant communication between stakeholders, maintenance and daily weather forecasting.
- Attention level: when entering the attention level after the exceeding of velocity thresholds by at least two extensometers, all the stakeholders are immediately notified as well as their h24 personnel on duty. Data are checked more frequently and a daily bulletin is released. In this level each stakeholder prepares for a possible alarm and personnel are activated. No public communication is made yet.
- Alarm level: through expert judgment it is decided whether to enter or not the alarm level. In case of alarm all the other stakeholders are immediately notified. Data checking frequency is further increased and two monitoring bulletins are emitted every day. The Provincial Street 249/1 is manually closed through the prompt lowering of two gate bars. Municipal emergency plan is activated.

For each extensometer a velocity (mm/day) threshold has been assigned; for the lower extensometers (E1, E2, E3, E4) and E10n a value of 0.50 mm/day has been assigned and 1.00 mm/day for the remnants. The velocity is obtained by averaging the values of the previous 24 h, in order to reduce the noise of measurements and so to improve the reliability of the system. These thresholds have been defined by analyzing the most critical periods of the whole monitoring dataset.

The chart in Fig. 10 shows the velocity trend of extensometers E11 and E10n from October 2007 to May 2011. The two different threshold values were chosen by taking into account the respective displacements recorded by those instruments. Data from only two wire extensometers were reported for reasons of clarity, but they are representative of the values recorded by the other instruments.

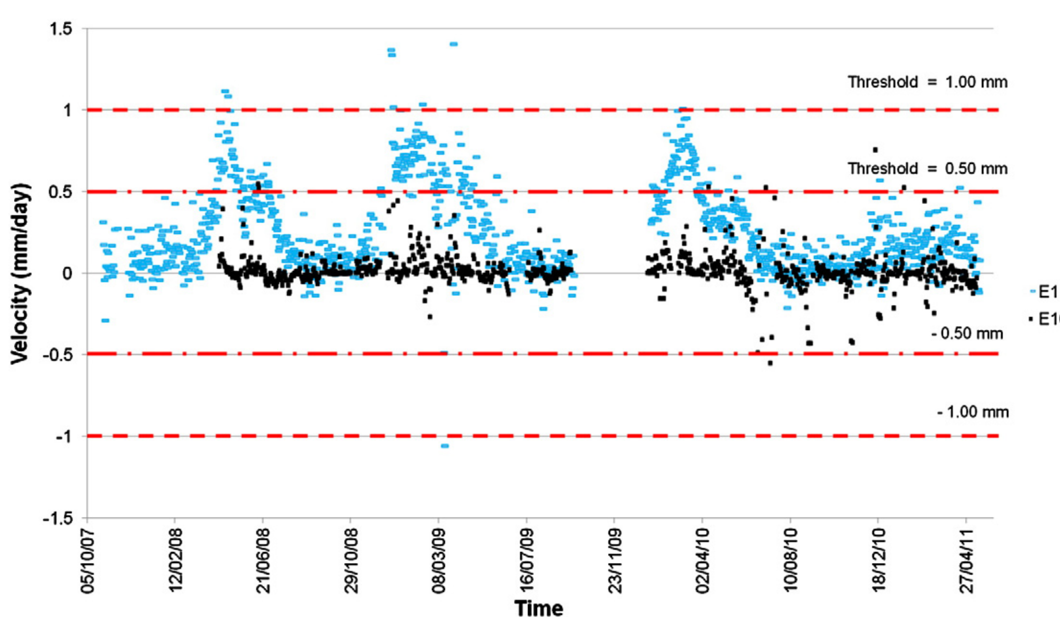

Fig. 10. Velocity vs. time for extensometers E11 and E10n. The dashed lines indicate the adopted threshold values.

E11 exceeded 9 times its threshold value of 1.00 mm/day during the whole period, whereas E10 exceeded 7 times its threshold value of 0.50 mm/day.

Fig. 11 shows the uncertainty chart of measurements at extensometer E15. As the EWS adopts quite small threshold values, the uncertainty of the system is an important factor. The reported measurements were obtained by using the infield instrumentation, and the total uncertainty value is caused by the interaction between the transducer, the digital converter and the mechanical anchorage. The resulting uncertainty value is about 0.02 mm and is more than one order magnitude smaller than the threshold level considered.

The velocity is manually checked every day; in addition, an automatic check is executed every 8 h. Whenever two or more sensors exceed their respective threshold an automatic notification is sent to the personnel in charge of monitoring, who verify the reliability of the information. If it is confirmed, they will communicate to the other stakeholders that the attention level has been reached. The level will return to ordinary when, after a comparison with the velocity thresholds, the conditions for the triggering of the attention level no longer exist.

The reliability of the thresholds has been verified by performing a back analysis which showed that during the previous 2 years and half of monitoring, the attention level would have been entered only 7 times, due to heavy rains or, in few occurrences, to instrumental errors. This has been considered a good result also because the cases due to instrumental errors can be filtered out by a manual check. After the implementation of the system, the attention level occurred only once, after a rainy period, and it lasted only 1 day. During the rest of the time the landslide showed no worrying behavior.

The triggering of alarm level is not connected with any threshold. Instead it makes use of expert judgment and interpretation mainly based on the application of the empirical forecasting methods by Saito (1969) and Fukuzono (1985). Successful applications of these methods can be found in Rose and Hungr (2007), Casagli et al. (2009) and Gigli et al. (2011).

For each sensor the forecasting methods mentioned above are applied. If an upcoming failure is hinted, either by using this approach or by a remarkable acceleration suggesting that the landslide entered the tertiary creep (Dusseault and Fordham, 1993), the alarm level will be declared and all the actions previously described will be taken. Also the revocation of the alarm level is subject to expert judgment.

Since communication is of great importance, bulletins mark every phase of activity; they indicate the present warning level, the current status of the monitoring system and any notes and comments. Extraordinary bulletins are emitted whenever the current warning level changes or in case of significant malfunctioning of the instruments.

Finally, to visually assess the conditions of the landslide, of the retaining wall and of the street, three cameras have been installed on the site.

5. Discussion

One of the main features that usually characterize an EWS is the choice of the warning levels. Here only three levels are considered the best solution for several reasons. First of all because in this case the needed activities are only an increase of monitoring and the closure of the street, so there is no reason for more than three levels. Secondly because further levels would have probably required the definition of more thresholds; when they cannot be calibrated on past events, as in this case, they are basically arbitrary and, as such, the definition of too many thresholds can bring little improvements; on the contrary it can just result in a pointless loss of simplicity. Finally, other experiences (Medina-Cetina and Nadim, 2008) demonstrated that the reduction of warning levels can be more cost-effective.

The next step consists in the selection of appropriate thresholds. The choice of reliable values depends on both scientific and social considerations. In fact lower and more conservative thresholds are more likely to produce false alarms that may have strong impacts on the society. Conversely, higher values result in a shorter time left for taking action or, in the worst case, in missing events. In other words the thresholds can only vary within a range between two boundaries defined by tolerability of false alarms and acceptable risk criteria (Nadim and Intrieri, 2011).

Although the extensometers installed are 13, only two different values have been chosen as thresholds. In the early stages of the design process different thresholds for each instrument had been considered. This solution was discarded for the reasons explained above. Also note that the values themselves, other than being representative of the behavior of the landslide, are also very simple; in fact, a high precision in the definition of thresholds can be rarely exploited. Anyway, the system is designed to be flexible so that, if necessary, thresholds can be changed as soon as new data are available.

Moreover these thresholds are above the background noise level so that their exceeding can be assessed with a high level of reliability.

Extensometer E10n has been considered together with the lower sensors because of its slow rate of movement. Also, it has always showed a constant behavior and, due to its position close to the fracture that works as a lateral constraint, it plays a key role in detecting the instability of the rockslide. This is the reason why this sensor has been assigned a more sensitive threshold.

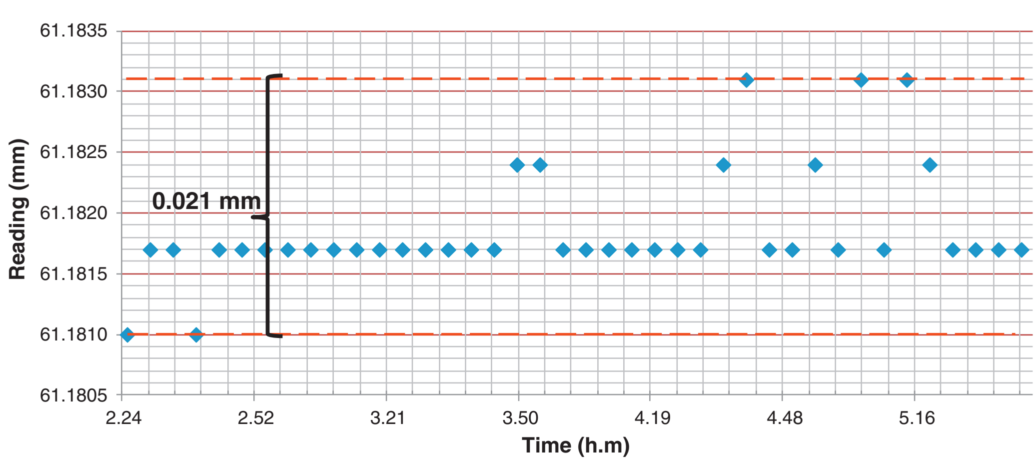

Fig. 11. Uncertainty plot for the extensometer E15.

As stated before, in more than 1 year of activity, the attention level was reached only once, after a period of prolonged rainfall, whereas no alarms occurred. This is the result of the simple procedures that were applied, such as data averaging to prevent spikes and the introduction of redundancy (two or more extensometers must exceed their threshold in order to enter the attention level, since we are only interested in the detection of the collapse of the wedge as a whole). For the same reason expert judgment has been chosen as a means to assess the alarm level. In fact even if a particular behavior of the landslide is expected in the last phases before failure, it would be difficult if not impossible to establish precise thresholds able to represent that behavior, due to some degree of uncertainty. Furthermore expert judgment is a flexible tool capable of handling unforeseen situations such as a malfunctioning of the instruments during a crisis or in case the proposed forecasting methods fail to converge toward a coherent result.

Bulletins are another very simple and versatile tool to avoid false alarms (since any anomalous data will be interpreted and commented inside the bulletin) and also to keep a constant communication between stakeholders, which is a critical need for a good EWS (Lacasse and Nadim, 2009). During particular events (severe malfunctioning, passage from a level to another, crises, unexpected events etc.) communication is real-time and interaction between all stakeholders is always granted by the Umbria Region.

A manual road block with gate bars and traffic lights was preferred to an automatic one in order to guarantee a last visual check of traffic conditions by the operator. This is possible in this site, since the geomechanical context of the landslide suggests that the failure will be foreseeable a few days in advance, making an automatic closure not necessary.

Since the early stages, an operator has been appointed to reboot the monitoring system in case of black out. The assignment of simple tasks like this, which may be beyond the duties of ordinary instrumental maintenance, is very important to keep the EWS functioning and should be considered since the beginning.

At present rainfall data are not being used as thresholds because a clear correlation between precipitations and displacements has not been found yet. Moreover displacement (and its derivatives) gives a much more direct indication of potential instability rather than rainfall (Lacasse and Nadim, 2009). However, ground water content simulations and weather forecasts, provided by Umbria Region, are considered during expert judgment before entering the alarm level.

6. Conclusions

In order to reduce the residual risk imposed to the Provincial Road 249/1 by the Torgiovannetto landslide, an EWS has been implemented. The Torgiovannetto landslide is a 182,000 m^3 rockslide which has been studied since 2004. During these years many data have been collected and there is now a good knowledge of the threat and associated risks, which are necessary in order to design the most suitable EWS.

The EWS currently in use adopts 13 wire extensometers, 1 thermometer, 1 rain gauge, and 3 cameras. The system automatically acquires data every minute and uploads them on an ftp.

Aiming at simplicity, only 3 warning levels have been defined (ordinary level, attention level and alarm level). Velocity thresholds have been defined just for the attention level, while the alarm level can be reached only following expert judgment mainly based on empirical forecasting methods (Saito, 1969; Fukuzono, 1985). Beside expert judgment, redundancy and data averaging have been added in order to reduce the possibility of false alarms. For the same reason rainfall data are not included as thresholds, due to a loose correlation between them and potential failure. However ground water content simulations and weather forecasts are considered before entering the alarm level.

Although site-specific, the detailed description of this EWS can be useful for facing similar situations. Furthermore some solutions can be widely applicable, even in completely different contexts.

Acknowledgements

The authors wish to thank the National Civil Protection, Umbria Region, Perugia Province and Assisi Municipality for their collaboration in the realization of the early warning system described in this paper. Special thanks to Mauro Reguzzoni from Hortus s.r.l. for his precious work with the monitoring system. The authors are grateful to Paolo Farina and Lorenzo Mayer from IDS for the 2008 GB-InSAR campaign. The results from the 2006 interferometric campaign have been collected through a GB-InSAR apparatus designed and produced by the Ellegi s.r.l. and based on the proprietary technology GB-InSAR LiSALAB derived from the evolution and improvement of LiSA technology licensed by the Ispra Joint Research Centre of the European Commission.

References

Atzeni, C., Basso, M., Canuti, P., Casagli, N., Leva, D., Luzi, G., Moretti, S., Pieraccini, M., Sieber, A.J., Tarchi, D., 2001. Ground-based SAR interferometry for landslide monitoring and control. ISSMGE Field Workshop on Landslides and Natural/Cultural Heritage, Trabzon (Turkey), 23–24 August 2001, pp. 195–209 (CNR GNDCI Pub. No.2375).

Badoux, A., Graf, C., Rhyner, J., Kuntner, R., McArdell, B.W., 2009. A debris-flow alarm system for the Alpine Illgraben catchment: design and performance. Natural Hazards 49, 517–539.

Balducci, M., Regni, R., Buttiglia, S., Piccioni, R., Venanti, L.D., Casagli, N., Gigli, G., 2011. Design and built of a ground reinforced embankment for the protection of a provincial road (Assisi, Italy) against rockslide. Proc. XXIV Conv. Naz. Geotecnica, AGI, Napoli, 22th-24th June 2011.

Barla, G.B., Antolini, F., Barla, M., Mensi, E., Piovano, G., 2010. Monitoring of the Beauregard landslide (Aosta Valley, Italy) using advanced and conventional techniques. Engineering Geology 116, 218–235.

Blikra, L.H., 2008. The Åknes rockslide: monitoring, threshold values and early-warning. 10th International Symposium on Landslides and Engineered Slopes, 30th Jun - 4th Jul, Xian, China, pp. 1089–1094.

Canuti, P., Casagli, N., Gigli, G., 2006. Il modello geologico nelle interazioni fra movimenti di massa, infrastrutture e centri abitati. In: Barla, G., Barla, M. (Eds.), Instabilità di versante, interazioni con le infrastrutture i centri abitati e l'ambiente, XI ciclo di conferenze di meccanica e ingegneria delle rocce, Torino, 28th-29th November 2006, pp. 41–61. In Italian.

Casagli, N., Tibaldi, A., Merri, A., Del Ventisette, C., Apuani, T., Guerri, L., Fortuny-Guasch, J., Tarchi, D., 2009. Deformation of Stromboli Volcano (Italy) during the 2007 eruption revealed by radar interferometry, numerical modeling and structural geological field data. Journal of Volcanology and Geothermal Research 182, 182–200.

Casagli, N., Catani, F., Del Ventisette, C., Luzi, G., 2010. Monitoring, prediction, and early warning using ground-based radar interferometry. Landslides 7, 291–301 http://dx.doi.org/10.1007/s10346-010-0215-y.

Cruden, D.M., Varnes, D.J., 1996. Landslides Types and Processes. In: Turner, A.K., Schuster, R.L. (Eds.), Landslides: Investigation and Mitigation. Transportation Research Board Special Report 247. National Academy Press, WA, pp. 36–75.

DiBiagio, E., Kjekstad, O., 2007. Early Warning, Instrumentation and Monitoring Landslides. 2nd Regional Training Course, RECLAIM II, 29th January - 3rd February 2007.

Dusseault, M.B., Fordham, C.J., 1993. Time-dependant behavior of rocks. In: Hudson, J.A. (Ed.), Comprehensive rock engineering, 3. Pergamon Press, Oxford, pp. 119–149.

Froese, C.R., Carter, G., Langenberg, W., Moreno, F., 2006. Emergency response planning for a second catastrophic rock slide at Turtle Mountain, Alberta. First Specialty Conference on Disaster Mitigation, Calgary, Alberta, Canada, 23th-26th May 2006.

Fukuzono, T., 1985. A new method for predicting the failure time of a slope. Proceedings of 4th International Conference and Field Workshop on Landslide, Tokyo, pp. 145–150.

Gigli, G., Fanti, R., Canuti, P., Casagli, N., 2011. Integration of advanced monitoring and numerical modeling techniques for the complete risk scenario analysis of rockslides: the case of Mt. Beni (Florence Italy). Engineering Geology 120, 48–59.

Graziani, A., Rotonda, T., Tommasi, P., 2009a. Stability and deformation mode of a rock slide along interbeds reactivated by rainfall. Proc. of the 1st Italian Workshop on Landslides, Napoli, 8th-10th June 2009, 1, pp. 62–71.

Graziani, A., Marsella, M., Rotonda, T., Tommasi, P., Soccodato, C., 2009b. Study of a rock slide in a limestone formation with clay interbeds. Proc. Int. Conf. on Rock Joints and Jointed Rock Masses, Tucson, Arizona, USA 7th-8th January 2009.

IEWP, International Early Warning Programme, 2008. The four elements of effective early warning systems UN/ISDR [Accessed: 19th November 2009]. Available at: http://www.unisdr.org/ppew/iewp/IEWP-brochure.pdf.

Keefer, D., Wilson, R., Mark, R., Brabb, E., Brown III, W., Ellen, S., Harp, E., Wieczorek, G., Alger, C., Zatkin, R., 1987. Real-time landslide warning during heavy rainfall. Science 238, 921–925.

Lacasse, S., Nadim, F., 2009. Landslide risk assessment and mitigation strategy. In: Sassa, K., Canuti, P. (Eds.), Landslides—Disaster Risk Reduction. Springer -Verlag, Berlin Heidelberg, pp. 31–61.
Lavecchia, G., Minelli, G., Pialli, G., 1988. The Umbria-Marche arcuate fold belt (Italy). Tectonophysics 18, 108–118.
Luzi, G., Pieraccini, M., Mecatti, D., Noferini, L., Guidi, G., Moia, F., Atzeni, C., 2004. Ground-based radar interferometry for landslides monitoring: atmospheric and instrumental decorrelation sources on experimental data. IEEE Transactions on Geoscience and Remote Sensing 42, 2454–2466.
Mak, S.H., Yeung, Y.S.A., Chung, P.W.K., 2007. Public education and warnings in Landslide Risks Reduction. Proc. 40th Anniversary Vol. SEAGS, pp. 367–375.
Medina-Cetina, Z., Nadim, F., 2008. Stochastic design of an early warning system. Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards 2, 223–236.
Mirabella, F., Pucci, S., 2002. Integration of geological and geophysical data along a section crossing the region of the 1997–98 Umbria-Marche earthquakes (Italy). Bollettino della Societa Geologica Italiana 1, 891–900 (Special).
Nadim, F., Intrieri, E., 2011. Early warning systems for landslides: challenges and new monitoring technologies. 5th Canadian Conference on Geotechnique and Natural Hazards. Kelowna, BC, Canada. 15th - 17th May, 2011.
Pang, P.L.R., Pun, W.K., Yu, Y.F., 2000. Estimation of failure frequency of soil cut slopes using rainfall and slope information. Proc. of GeoEng2000 – International Conference on Geotechnical and Geological Engineering, Melbourne, Australia, 19th-24th Nov. 2000.
Rose, N.D., Hungr, O., 2007. Forecasting potential rock slope failure in open pit mines using the inverse-velocity method. International Journal of Rock Mechanics and Mining Science 44, 308–320.
Rudolf, H., Leva, D., Tarchi, D., Sieber, A.J., 1999. A mobile and versatile SAR system. Proceedings of Geoscience and Remote Sensing Symposium, IGARSS 1999, Hamburg, pp. 592–594.
Saito, M., 1969. Forecasting time of slope failure by tertiary creep. Proc. of 7th Int. Conf. on Soil Mechanics and Foundation Engineering, Mexico City, 2, pp. 677–683.
Stucky, 2007. Lake Sarez Mitigation Project -Component A. Final Report to Ministry of Emergencies and Civil Defence of the Republic of Tajikistan. Renens, Switzerland. 109 pp.
Tavarnelli, E., 1997. Structural evolution of a foreland fold-and-thrust belt: the Umbria-Marche Apennines, Italy. Journal of Structural Geology 7, 751–754.
UNISDR (United Nations International Strategy for Disaster Reduction), 2009. Terminology on Disaster Risk Reduction. Available at http://www.unisdr.org.
Wilson, R., 2004. The rise and fall of a debris-flow warning system in the San Francisco bay region, California. In: Glade, T., Anderson, M., Crozier, M. (Eds.), Landslide hazard and risk. John Wiley and Sons, pp. 493–516.
Yu, Y.F., Lam, J.S., Siu, C.K., Pun, W.K., 2004. Recent advance in landslip warning system. Proceedings of the 1 day Seminar on Recent Advances in Geotechnical Engineering, organized by the Hong Kong Institution of Engineers Geotechnical Division, pp. 139–147.