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GB-InSAR monitoring and observational method for landslide emergency management: the Montaguto earthflow (AV, Italy)

F. Ferrigno, G. Gigli, R. Fanti, and N. Casagli

Department of Earth Sciences, University of Florence, Via La Pira 4, Florence, Italy

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Correspondence to: F. Ferrigno (federica.ferrigno@unifi.it)

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Abstract

On 10 March 2010, due to the heavy rainfall that occurred on the previous days, the Montaguto earthflow reactivated, involving the road SS 90 “Delle Puglie”, as had happened previously in May 2005 and in September 2009, and reaching the Roma–Bari railway.

~~This determined a special attention of~~ the National Civil Protection Department and a widespread monitoring and analysis program was initiated. A monitoring activity using GB-InSAR (Ground Based Interferometric Synthetic Aperture Radar) system began, in order to investigate the landslide kinematics, to plan urgent safety measures for risk mitigation and to design long term stabilization work. In this paper the GB-InSAR monitoring system results and its applications in the Observational Method (OM) approach are presented. The paper also highlights how the OM based on the GB-InSAR technique can produce savings in cost and time on engineering projects, without compromising safety, and how it can also benefit the geotechnical community by increasing scientific knowledge. This study focuses on the very much active role played by the monitoring activities, in both the design and plan modifications; with a special consideration for the emergency phase.

1 Introduction

Landslides ~~can be very dangerous~~, often causing casualties, ~~huge~~ damage and significant economic loss.

In order to mitigate the landslide hazard, ~~when the processes are well known~~, and to support the management of landslide risks, ~~during the~~ recent ~~years the~~ studies ~~of~~ new monitoring technologies ~~were performed~~. Unfortunately the preventive measures are often lacking or not adequate to guarantee the total protection of the people and infrastructures involved in complex landslide systems, in mountainous and hilly areas.

~~In this case, monitoring with advanced technology, even used to support the work planning and realization, represents an efficient method for approaching landslide risk management. Thanks to its characteristics the Montaguto landslide was chosen to analyse the interaction between monitoring systems and OM.~~

~~As the landslide toe sector represents the most critical area,~~ a real-time ~~monitoring through a~~ GB-InSAR system was installed. The GB-InSAR technique applied to landslide monitoring, ~~guarantees~~ a low cost, multi-temporal deformation maps (almost) in real time, constitutes a valuable and versatile tool for rapid mapping, functional both in case of rapid alert (early warning) in emergency conditions and as a scientific-technological support during the phases of emergency management.

The use of GB-InSAR as a landslide monitoring technique is well documented in the last decade, with applications in different risk scenarios (Tarchi et al., 2003; Canuti et al., 2004; Casagli et al., 2010). In some cases, the system was used for controlling slope movements, threatening one or more lifelines (Casagli et al., 2008; Gigli et al., 2011, 2014; Intrieri et al., 2015), as in the Montaguto site. However, the velocity of this landslide at the beginning of the reactivation was high in comparison to the usual resolution power of the GB-InSAR systems: in this sense, the Montaguto case history represents a very interesting benchmark for the application of this technique. The main aim of this paper is also to highlight the efficiency and the important role of a continuous, panoramic and high resolution monitoring system as a support in work design.

The integration between the monitoring system and the application of the OM, in the Montaguto earthflow stabilization was therefore characterized by three principal phases, during:

- the emergency phase, when the main aim was the removal of the landslide from the road SS90 and the railway, supporting the work management;
- the long term stabilization works (lasted three years), suggesting and driving the project design;

- the post-operam period (onwards), checking the landslide response in terms of deformation.

2 The Montaguto earthflow

~~Due to~~ the kinematic, morphological, and lithological characteristics the Montaguto landslide, it can be classified as an earthflow~~;~~ slow, intermittent flow-like movement of plastic, clayey soil, facilitated by a combination of sliding along multiple discrete shear surfaces, ~~and~~ internal shear strains~~.~~ Long periods of relative dormancy alternate with more rapid “surges”~~,~~ (Hungr et al., 2013).

The earthflow has a source sliding area and an eroding depositional toe. The source has a series of rotational crown scarps due to the presence of weak rock, while the body of the earthflow, ~~eventually~~ evolves into a depositional lobate toe that extends to the valley floor. A ~~creek~~ system runs through the body of the slide along its entire length. The main acceleration of the landslide occurs when the source ~~slide~~ becomes unstable: due to saturation, which causes increased driving forces caused by temporary increases in pore pressure and weight of the slide mass. A kinematic wave propagates through the soil mass to advance the toe into a stream.

The Montaguto landslide is located in the Daunian Apennine, Avellino province in Southern Italy. It is one of the largest active earthflows in Europe. The earthflow has carved its own valley and created distinct morphology on the north-side slope of the Cervaro Valley. It spans a nearly 3 km; the upper sector (832 m a.s.l.) is bounded by the ridge “La Montagna” on the north and by the valley bottom (410 m a.s.l.) on the southern side, with an elevation drop of about 420 m, Fig. 1. The lithotypes of clay, silty clay, sandy marl, marly-calcareous and clayey flysch influence the morphology and the ~~hydrography~~ causing significant articulation from strong structural controls. In fact, while the high sector of the slope presents a general W-SW exposure, with ~~hydrographic~~ and secondary ridges oriented in the general direction SW-NE, the lower middle of the slope is exposed to the south with the hydrographic network and secondary ridges oriented in the general direction SSE-NNW. As a result, the earthflow moves slowly and intermittently. There are four main stratigraphic outcrop units: the Faeto Flysch, the Marne and the clay of the Toppo Capuana, the Altavilla Unit, and the Cervaro River alluvial deposits. (Guadagno et al., 2005).

The first historical information related to instability phenomena along the road up to Montaguto dates back to 1763, when Borboni first started stabilization works. There are reports about the royal road and the Cervaro River being influenced by the occurrence of a lobate landslide deposit.

Other well-documented reactivations occurred during the two-year period from 1957–1958. ~~Through~~ 1958 ~~to~~1980, activity was very low. In 1990 a landslide external to the system interrupted the hydraulic connection between the Fosso Montagna and the Tre Confini River, causing a ~~major water supply~~ in the Fosso Nocelle, Fig. 2.

In 2003 and 2004 minor landslide reactivations occurred, the active part (between elevation 830 and 460 m a.s.l.) of the landslide covered the deposits of the inactive ~~pre-existing~~ landslide.

Other periods of mobilization occurred ~~during the first months of 2006 through 12 May 2006~~, when the landslide continued to advance towards the bottom of the valley, ~~reaching and interrupting the~~ highway (Lollino et al., 2014). The same dynamic also occurred in 2009. On 10 March 2010 the greater surge of landslide movement event occurred. Although there were no causalities, there were serious damages to highway and railroad infrastructure, completely disrupting the two main transportation connections between the Campania and Puglia regions (Guerriero et al., 2013).

3 The GB-InSAR monitoring system

~~The~~ monitoring project integrated different techniques. ~~Particularly~~, a ground-based real-time monitoring system (based on SAR interferometry technique GB-InSAR) was installed, at the same time design and plan of the emergency and stabilization works begun, with the precious support of the data coming from the monitoring system.

The adopted technique provides measurement of ground displacement through remote sensing. It is able to detect a continuous 2-D deformation field of the observed ground portion, without the necessity of positioning targets on the ground and without any physical contact with the slope (Tarchi et al., 1997). This technique is based on SAR (Curlander and McDonough, 1991) and on interferometric techniques (InSAR), originally developed for earth observation from satellites (Zebker and Goldstein, 1986). InSAR is based on the quantitative comparison of the phase information between two radar acquisitions of the same scenario. ~~Using a pair of complex SAR images, where the former and the latter are referred to as master (*m*) and slave (*s*) images, respectively, an interferogram (*I*) is formed according to the following relationship:~~

~~$I(k,l) = m(k,l)s(k,l)^*$~~

~~where * indicates the conjugate.~~

Depending on the installation method and on the distance between the sensor and the observed scene, different properties of SAR images are acquired with the GB-InSAR technique, and in particular, ~~the value of~~ spatial resolution ~~exists~~. The synthetic aperture is realized by moving, t~~hrough~~ a linear positioner, a motorized sled hosting the radar head along a straight rail 2.7 m long. The main operational parameters adopted during the monitoring surveys are summarized in Table 1.

The GB-InSAR provides displacement measurements of up to a few square kilometres with sub-millimetre precision and high temporal frequency of acquisition (more then ten scans per hour).

On 29 April 2010, the apparatus was installed on the opposite stable slope located at approximately 4 km from the earthflow, in order to measure the component of the movement along the line-of-sight of the radar (Fig. 3).

The system was adapted to the landslide features, the revisiting time lapse was set to 3.5 min to assure sufficient real time movement detection.

The displacement rate reached about $1.0\,\mathrm{m\,day^{-1}}$, although there were significant intraday fluctuations. Maximum-recorded velocity was measured at $2.9\,\mathrm{m\,day^{-1}}$ on 1 June 2010.

During the GB-InSAR monitoring, data were transferred via ftp to the processing and post-processing unit for the generation and production of multi-temporal deformation maps (Fig. 4), and ~~cumulated~~ displacement maps (Fig. 5). ~~Through this data the time series of displacements are exemplified (Fig. 6).~~

Based upon the results of the landslide velocity pattern, the Civil Protection Department, with the operational support of the Army, started stabilization efforts with large earth-moving machinery along the toe of the earthflow. As a result of the monitoring and subsequent stabilization efforts the railway was re-opened on 7 June 2010 ~~while~~ the road SS 90 on 10 July 2010.

The GB-InSAR system was the key element in the work planning~~, and in reporting interferometric data on a daily basis that could drive the interventions~~. Worker safety was increased because alerts could be provided about sudden accelerations that would require work stoppage or immediate clearance of the area.

From the project start, the GB-InSAR instrument was partnered with a webcam (for a visual calibration of SAR images) (Fig. 3), and with a thermal infrared camera during the first weeks. The latter allowed a very accurate control of water flow paths and drainage directions (Fig. 7)~~, providing useful data for the earth-moving works~~.

This first emergency phase ended in July, when the displacement rate decreased, ~~thanks~~ to the works and to the dry season.

Other 3-D displacements products for the Montaguto landslide were obtained with other ~~high-technology applications~~, such as multi-temporal airborne LiDAR data (Ventura et al., 2011): even if the detail the latter technique is higher (particularly in terms of georeferencing), the GB-InSAR data have great benefit from frequent data collection, which is often unaffordable for airborne LiDAR. In addition, GB-InSAR allows also the detection of movements in zero-balance mass areas, due to its precision and monitoring frequency.

4 GB-InSAR data

From the installation site, the toe of the landslide, which had the highest detected displacement velocity ~~reached~~ during the emergency phase, is highly visible ~~and therefore, a very clear image can be obtained~~ (Fig. 3). To understand the kinematics of the entire landslide, the first interferograms and the optical images were used to identify different behavioral landslide zones (Fig. 3). Six sectors were identified (A, B, C, D, E and F) to represent the main reference points for assessing landslide activity, especially for the daily report emission activities, where the displacement velocities for each sectors are given. From the beginning, the methodology used in the monitoring activities for the production and interpretation phases, and use of the interferograms, has been subjected to many variations induced by the landslide's evolution.

During the early stages, due to the high $1\,\mathrm{m\,day^{-1}}$ displacement rate, the monitoring was based solely on the observation and interpretation of 4 min interferograms. In these cases the very short 4 min time interval allowed, in a ~~very~~ clear ~~and unambiguous way~~, discrimination of the variations in rate of displacement (Fig. 4).

Following July 2010, the deformation rate began to decrease; hence it was necessary to include interferograms processed on a wider interval time, switching from 4 min to 4 h. Similarly, over the next few months, for the same reason, interferograms processed with time interval of 24 h were introduced. During March 2011, with the aim of making the monitoring activities even more suitable for landslide evolution analysis, monthly-cumulated maps were processed for the entire acquisition period (Fig. 5).

Some monitored sectors, have slowly continued to deform. For example, the D sector and a strip upstream in sector A continued slow movement from December 2010, while the E and F sectors started their slow and intermittent movement later, in November 2011 and December 2013. Movement in the E sector, located in the middle-upper part of the landslide that corresponds to the so called "elbow" zone, had movement detected in November 2010; while the F sector, in the upper main scarp of the landslide began its deformation in December 2013.

From the data analysis and interpretation, it was possible to recognize and define the evolution of the observed phenomenon, both in terms of deformation rate decrease and increase.

Since the stabilization projects are continuously recorded and highlighted by the GB-InSAR monitoring system and because the hydraulic works are efficiently portrayed, it was possible to determinate that the deformation processes and movement speeds were globally, yet gradually decreasing.

The displacement trend demonstrates that mitigation efforts have been effective to date (Fig. 6), yet it is clear that this monitoring system should continue to play a role in future management and monitoring projects over time.

5 The observational method

The development and the use of the OM started in the 1940's. Its historical evolution can be summarized by the two most important theories, stated by Terzaghi and Peck:

> Every job is a large scale experiment. The information obtained from such experiments cannot be secured by any other means. It is of inestimable value in connection with future construction work of similar nature, provided the observations were reliable and complete enough to permit fairly definite interpretation (Karl Terzaghi).
>
> Peck's observational method involves developing an initial design based on most probable conditions, together with predictions of behavior. Calculations are made and these are used to identify contingency plans and trigger values for the monitoring system. Peck proposed that construction work should be started using the most probable design. If the monitoring records exceeded the predicted behavior, then the predefined contingency plans would be triggered. The response time for monitoring and implementation of the contingency plan must be appropriate to control the work.

The Montaguto earthflow case study demonstrates the key reliance on the OM application for both monitoring activities and stabilization design.

Usually monitoring has the aim of verifying the conformity between the design plan and the observed behaviors, and checking the works full functionality over time. When it is coupled with the OM, its goal is also to validate the adopted design solution or to identify the most appropriate design solution among the planned ones.

The OM facilitates design changes during stabilization works and establishes a framework for risk management.

Peck set out the OM in his 1969 Rankine lecture and defined two OM approaches:

(a) "*Ab Initio*" approach, adopted from inception of the project;

(b) "*Best Way Out*" approach, adopted after the project has commenced and some unexpected event has occurred that is different to the predefined design or failure occurs, and where OM is required to establish a way of getting out of a difficulty.

The GB-InSAR system became a key element in the work planning, and reporting on a daily basis interferometric data that drove the interventions. It allowed people to suggesting when to stop work in the event of abrupt accelerations.

As described before, this first emergency phase ended in July 2010, when the displacement rate decreased.

After the analysis of all available data from previous studies, results of recent surveys and direct observation of the area, a design was established, to be updated and adaptable to the landslide response to the stabilization efforts.

In September 2010 the main work phases were outlined (Fig. 8). In May 2012, most of the stabilization works were complete, thereby improving the general earthflow stability. In addition, GB-InSAR approach proved to be very useful during the emergency phase, for support in quickly defining the stabilization work plan, and to provide significantly increased safety for people that were either working on or near the slide area. The efficiency of the undertaken activities can be evaluated by observing the time history of the velocity recorded at critical points during the period (Fig. 6).

This methodology has been placed at the base of all the activities carried out on the landslide up to now and led to indisputable results, although it cannot certify, at least at present, the definitive stabilization of the landslide. The analysis started from the preliminary definition of the work criteria and proceeded to the subsequent phases of design and construction.

The area affected by the landslide is very large, therefore it has been divided into 3 zones, to better plan and carry out the required interventions.

The landslide consists in three main areas, involved in stabilization works as follow:

- Upper sector (depletion zone): lake drainage, upstream surface drainage (diversion ditches), re-profiling of the main scarp, modification of the slope profile, stream channels restoration to natural conditions.
- Middle sector (main track): modification of the slope profile, surface drains coupled with deep trench drains, left-bank stream channelization, right-bank stream channelization.
- Lower sector (deposition zone): landslide deviation on the left side, surface drains coupled with deep trench drains, gabion toe drain and buttressing, re-profiling of landslide deposits on the right side, left-bank stream channelization.

As water was the main engine of the landslide, the primary objective of the undertaken actions was to remove it, both from the surface and from the deep layers. The restoration of an effective surface circulation has thus been planned, coupled with drainage trenches that are able to collect deep ground water.

The upper part of the landslide was characterized by the presence of a system of lakes, whose water was directed by drainage trenches and shallow channels into a well and is then channelled into a watershed located outside the landslide.

Shallow channels with hydraulic jumps were constructed in the middle part of the landslide. Deep drainage trenches that allowed deep ground water to spring outward at the sites of hydraulic jumps were an integral part of the design.

The construction of shallow channels coupled with deeper ground water drainage trenches was repeated at the lower part of the landslide. The water from the lower part and from lateral channel system is conveyed towards a natural watercourse that flows beyond the toe of the slide.

In this way, the abundant standing water within the surface depressions that had been created by the landslide was eliminated, thus reducing water infiltration and the rate of movement.

The stabilization works were first started at the toe of the slide, where the interventions for water drainage were completed with the aim of protecting the main elements at risk. At first, steel reinforced gabions were installed to build a drainage systems of considerable size. Next, the landslide was reshaped in accordance with the constructed drainage works.

A very interesting example of the coupled action (GB-InSAR and work design), is the analysis of the landslide behavior in the mid-sector, the so-called “elbow” (E sector): the movement became significant during November 2011–May 2012. Its evolution was highlighted by GB-InSAR data. To verify this information, some observational reconnaissance were performed and the evidence of the landslide activity was renewed deformation and damage to three weirs and the geotextile filter, Fig. 8.

The E Sector presently has the most active deformation, this is why a design variation involving additional drainage elements in the two main channels was incorporated into the design. By interferometric analysis it was possible to detect the deformation phenomena affecting the E Sector and subsequently a design variant was outlined (Fig. 10). The monthly displacement cumulated maps refer to the two highest deformation rate times (March–April 2012), when the velocity reached about 1 cm day^{-1}.

To highlight the project’s efficiency in relation to the to the slowing rate of displacement, a velocity graph was made to compared the beginning and end of the different stabilization works, Fig. 10.

The first but considerable stabilization work phase, concerning the shallow and subsurface water removal was accomplished. The Montaguto landslide represents a very interesting example of naturalistic engineering techniques in stabilization work with a low environmental impact (Fig. 11).

6 Conclusions

The application of the GB-InSAR technique for monitoring the Montaguto earthflow has demonstrated its capability to continuously acquire accurate displacement measurements over large areas. Its high image acquisition rate and the capacity to provide displacement maps with sub millimetre accuracy are specifically suited for assessing emerging slope instability problems, especially during emergency conditions.

The GB-InSAR approach has proved to be very useful for the application of the OM during the emergency phase. It supports quick delineation of the slide, and provides the basis for stabilization and excavation planning and design. Moreover, it allows planning of work phases that will greatly increase the safety of workers and the community. The aerial mapping of displacements over the entire slope is very useful in identifying areas of complex deformation patterns with different rates of movement.

The results during this study period show a general decrease in rates of displacement, referable to the whole temporal landslide system. Nevertheless sectors and unstable zones are characterized by deformations having both characteristics of temporal persistence (the landslide is inactive but not stable) and heterogeneity (some areas reach displacement speed more often than others sectors and/or at different times).

Use of real time monitoring with new technologies allowed us to accomplish documenting 4 years of daily activity.

Through the daily monitoring activities, it was also possible to enrich the study by using the OM approach. This allowed us to establish the efficiency of the works and to direct the possible project variations.

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References

Canuti, P., Casagli, N., Farina, P., Leva, D., Tarchi, D., and Nico, G.: Some examples of slope movements monitored by ground-based SAR interferometry, in: Proceedings IC-FSM2003 International Conference on Fast Slope Movements: Prediction and Prevention for Risk Mitigation, Sorrento (Italy), 11–13 May 2003, edited by: Picarelli, L., 71–77, 2003.

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

Curlander, J. C. and Mcdonough, R. N.: Synthetic Aperture Radar: Systems and Signal Processing, Wiley, UK, ISBN: 978-0-471-85770-9, 672 pp., 1992.

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

Gigli, G., Intrieri, E., Lombardi, L., Nocentini, M., Frodella, W., Balducci, M., Venant, L. D., and Casagli, N.: Event scenario analysis for the design of rockslide countermeasures, J. Mt. Sci., 6, 1521–1530, 2014.

Guadagno, F. M., Forte, R., Revellino, P., Fiorillo, F., and Focareta, M.: Some aspects of the initiation of debris avalanches in the Campania Region: the role of morphological slope discontinuities and the development of failure, Geomorphology, 66, 237–254, 2005.

Guerriero, L., Revellino, P., Coe, J. A., Focareta, M., Grelle, G., Albanese, V., Corazza, A., and Guadagno, F. M.: Multi-temporal maps of the Montaguto Earth Flow in Southern Italy from 1954 to 2010, J. Maps, 9, 135–145, 2013.

Hungr, O., Leroueil, S., and Picarelli, L.: The Varnes classification of landslide types, an update, Landslides, 11, 167–194, doi:10.1007/s10346-013-0436-y, 2013.

Intrieri, E., Gigli, G., Nocentini, M., Lombardi, L., Mugnai, F., and Casagli, N.: Sinkhole monitoring early warning an experimental and successful GB-InSAR application, Geomorphology, 241, 304–314, 2015.

Lollino, P., Giordan, D., and Allasia, P.: The Montaguto earthflow: a back-analysis of the process of landslide propagation, Eng. Geol., 170, 66–79, 2014.

Peck, R. B.: Advantages and limitations of the observational method in applied soil mechanics, Géotechnique, 19, 171 –187, 1969.

Tarchi, D., Ohlmer, E., and Sieber, A. J.: Monitoring of structural changes by radar interferometry, Research in Nondestructive Evaluation, 9, 213–225, 1997.

Tarchi, D., Rudolf, H., Luzi, G., Chiarantini, L., Coppo, P., and Sieber, A. J.: SAR interferometry for structural changes detection: a demonstration test on a dam, in: Proceedings IGARSS, 28 June–2 July 1999, Hamburg, 1522–1524, 1999.

Tarchi, D., Casagli, N., Fanti, R., Leva, D., Luzi, G., Pasuto, A., Pieraccini, M., and Silvano, S.: Landside monitoring by using ground-based SAR interferometry: an example of application to the Tessina landslide in Italy, Eng. Geol., 68, 15–30, 2003a.

Tarchi, D., Casagli, N., Moretti, S., Leva, D., and Sieber, A. J.: Monitoring landslide displacements by using ground-based radar interferometry: application to the Ruinon landslide in the Italian Alps, J. Geophys. Res., 108, 10.1–10.14, 2003b.

Ventura, G., Vilardo, G., Terranova, C., Bellucci and Sessa, E.: Tracking and evolution of complex active landslides by multi-temporal airborne LiDAR data: the Montaguto landslide (Southern Italy), Remote Sens. Environ., 115, 3237–3248, doi:10.1016/j.rse.2011.07.007, 2011.

Zebker, H. A. and Goldstein, R. M.: Topographic mapping from interferometric synthetic aperture radar observations, J. Geophys. Res., 91, 4993–4999, 1986.

Table 1. Operational parameters list, set up for the Montaguto landslide monitoring.

Rail length	2.7 m
Minimum observed area distance	800 m
Maximum observed area distance	4000 m
Displacement estimate accuracy	0.5–0.7 mm
Theoretical resolution in range (constant)	~ 3.5 m
Theoretical resolution in azimuth a 800 m	~ 3 m
Theoretical resolution in azimuth a 2000 m	~ 7 m
Theoretical resolution in azimuth a 4000 m	~ 14 m
Scan time interval	3.5 min

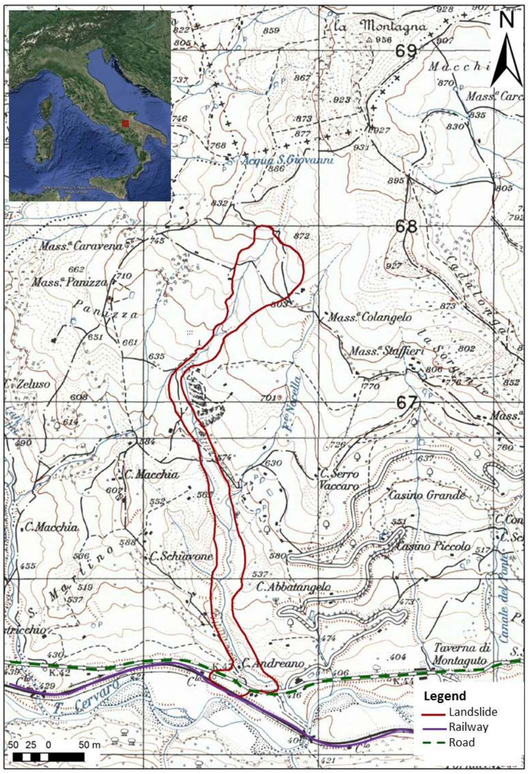

Figure 1. Topographic map of the Montaguto area is shown with the active earthflow limits, affecting elements at risk as the railway and the road.

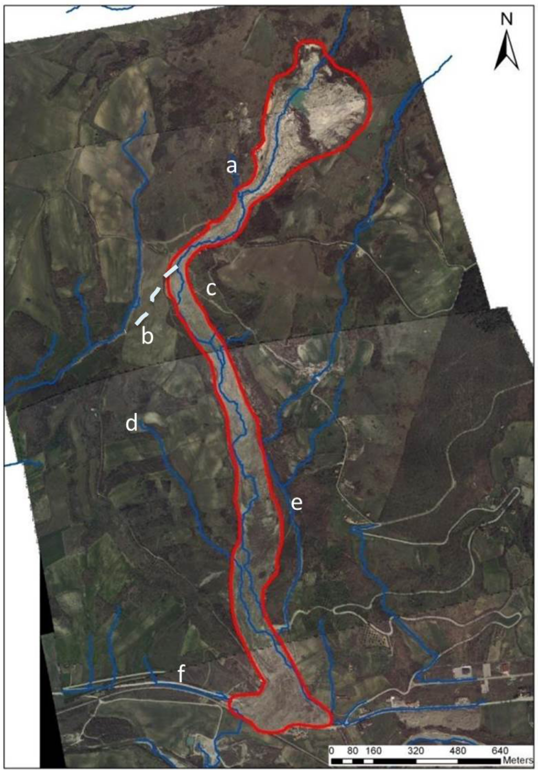

Figure 2. Montagna Creeck deviation into the landslide zone occurred in 1990. **(a)** Montagna Creek; **(b)** previous natural channel; **(c)** Channel deviation; **(d)** Tre Confini stream; **(e)** Rio Nocelle stream and **(f)** Cervaro creek.

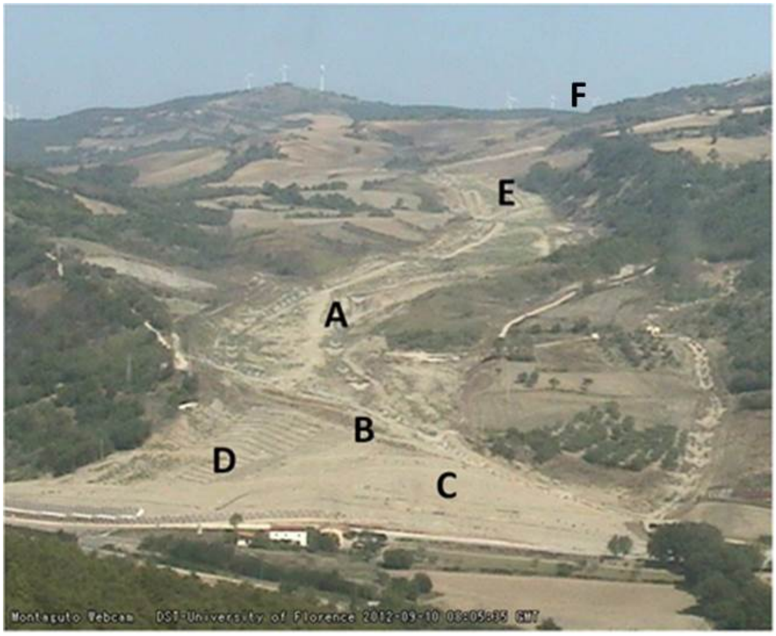

Figure 3. Optical image of the Montaguto earthflow from the GB-InSAR installation point (acquisition time: 1 June 2010 – 8:02 a.m.). Capital letters indicate sectors selected for velocity estimation.

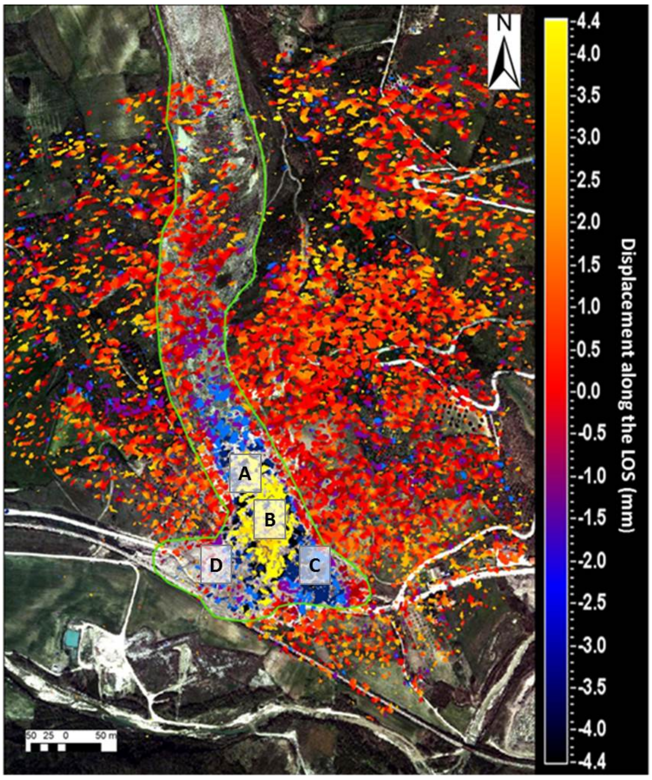

Figure 4. Interferogram with the monitored sectors covering a period spanning 4 min from 9:04 to 09:08 p.m., 1 May 2010. Negative values indicate movement towards the instrument.

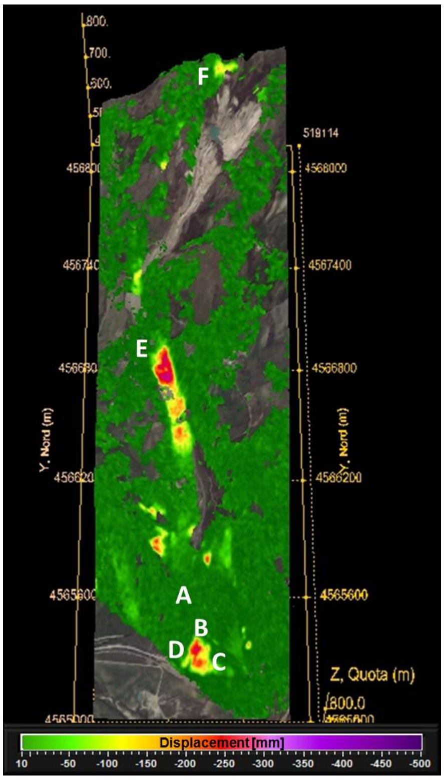

Figure 5. Monthly cumulated displacements (mm) map recorded between 1 and 31 March 2011. Negative values indicate movement towards the instrument.

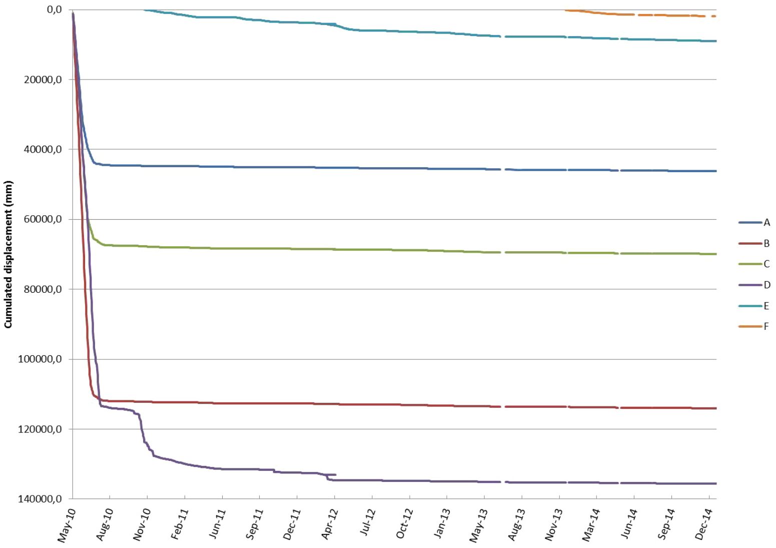

Figure 6. Time history of recorded displacements at selected points (monitored sectors).

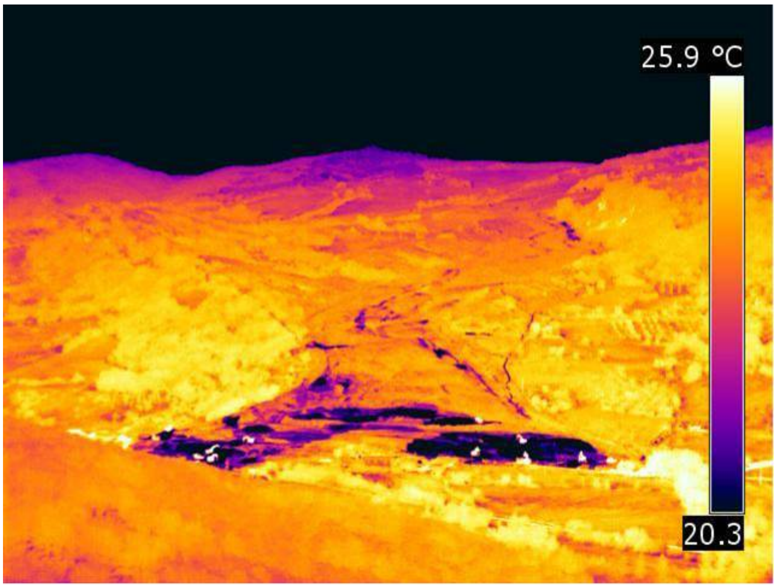

Figure 7. Thermal image of the Montaguto earthflow from the GB-InSAR installation point (acquisition time: 11 May 2010 – 11 a.m.); dark pixels correspond to wet areas.

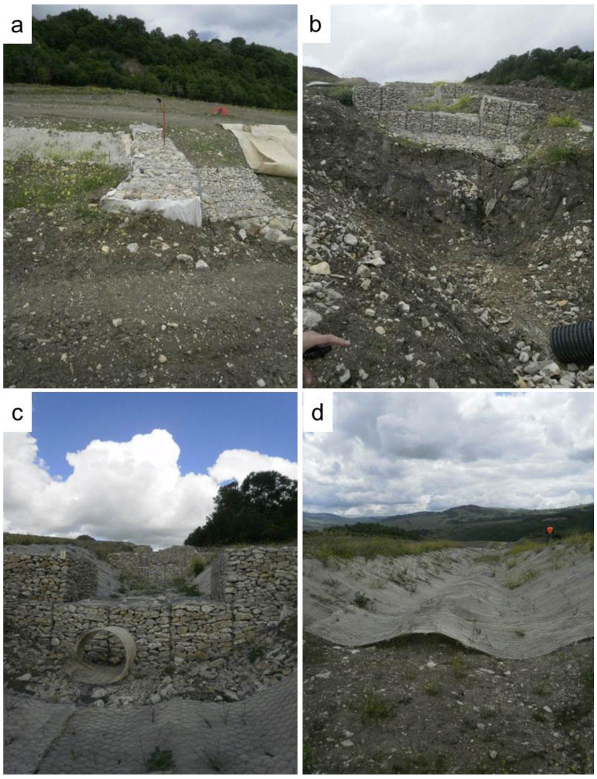

Figure 8. Damage to the weirs (**a**, **b** and **c**) and to the channel geotextile filter **(d)** is shown in these photos. It was caused by the slow and constant displacement located in the E sector and documented by interferometric data (May 2012).

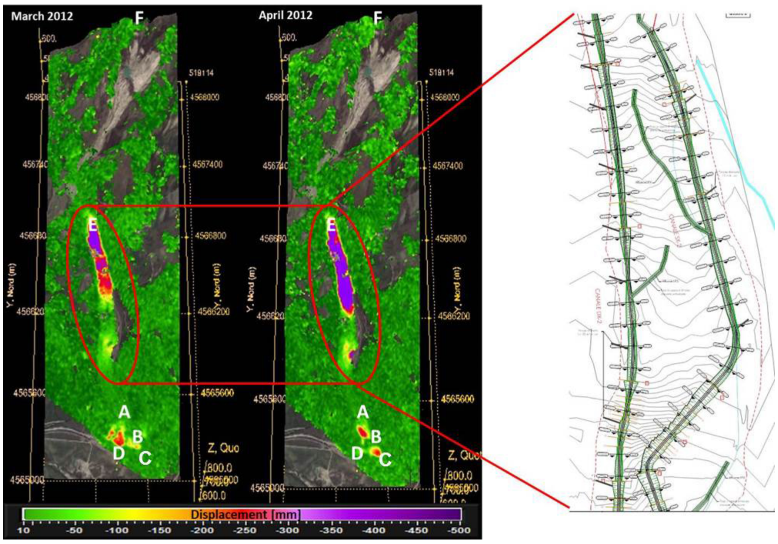

Figure 9. Monthly cumulated maps refer March and April 2011 show the interferometric evidence of the deformation phenomena affecting the E Sector and the subsequent design variant.

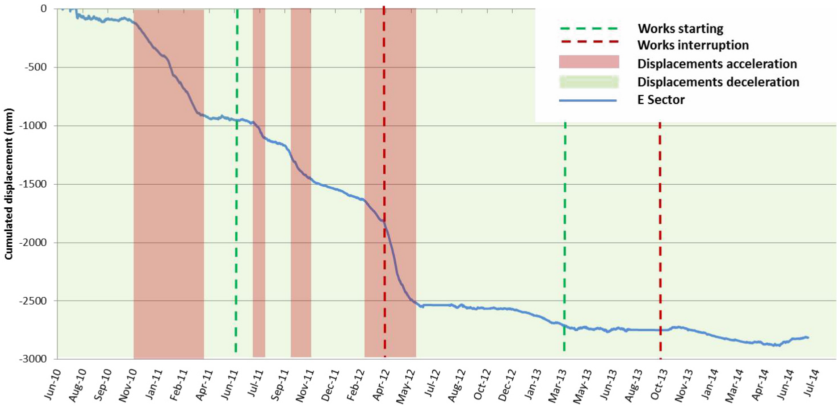

Figure 10. Cumulated displacement recorded at the E sector and works phases distribution among the time.

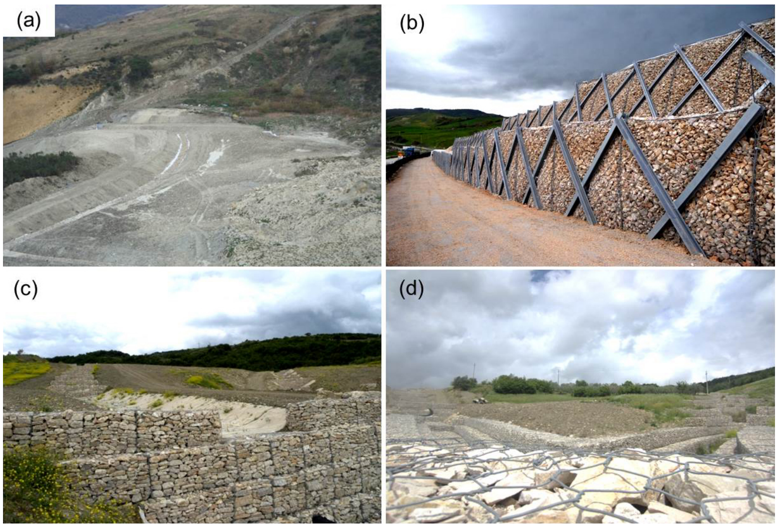

Figure 11. Images showing the main important completed works. **(a)** Drainage systems at the bottom of the main scarp; **(b)** gabions rock toe buttress and drain; **(c)** surface drains coupled with deep trench drains; **(d)** Rio Nocelle water channelling.