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Ground-Based Remote Sensing Techniques for Landslides Mapping, Monitoring and Early Warning

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Abstract

The current availability of advanced remote sensing technologies in the field of landslide analysis allows rapid and easily updatable data acquisitions, improving the traditional capabilities of detection, mapping and monitoring, optimizing field work, and allowing to investigate hazardous and inaccessible areas while granting at the same time the safety of the operators. In the recent years in particular, ground-based remote sensing techniques have undergone a significant increase of usage, thanks to their technological development and quality data improvement, offering advantages with respect to air- or spaceborne remote sensing techniques, in terms of data spatial resolution and accuracy, fast measurement and processing times, and portability and cost-effectiveness of the acquiring instruments. These advantages can be highlighted in the framework of landslide emergency management, when it is often urgently necessary to minimize survey time when operating in dangerous environments and gather all the required information as fast as possible. In this paper, the potential of some ground-based remote sensing techniques and the effectiveness of their synergic use is explored in several case studies, analyzing different slope instability processes at different scales of

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emergency or post-emergency management. Thanks to them and to the support of existing bibliography, the most common fields of application are suggested for all the considered ground-based sensor technologies and their level of effectiveness is evaluated in relation to the dynamics of landslide types.

Keywords

Landslide mapping and monitoring · Early warning
Terrestrial laser scanning · Infrared thermography · GB-InSAR

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1 Introduction

Landslides play an important role in the evolution and shaping of subaerial landscapes (Brunetti et al. 2015) and are a major cause of loss of life, injuries, property damage, socio-economic disruption and environmental degradation in many areas of the emerged continents (Alexander 1993), especially if they are associated with other natural hazards (like earthquakes, volcanic eruptions, meteorological events and wildfires). Because of such habitual combinations, reliable numbers for the social impact only due to landslides are difficult to obtain on a global scale and the economic losses are certainly underestimated (or not quoted at all). This general condition often contributes to reducing the concern of

individuals and authorities have about landslide risk (Kjekstad and Highland 2009). However, some remarkable statistics are nowadays available for the worldwide exposure to landslide hazard issues. For example, a recent World Bank report (Dilley et al. 2005) presents the following profile:

- Land area of the globe exposed to landslides: 3.7 million km²
- Population exposed: 300 million, or 5% of the world population
- Land area identified as high risk zones: 820,000 km²
- Population living in high risk areas: 66 million people

Although in most of the disaster-prone areas the consideration of the social-cultural and socio-economic conditions in relation to their physical safety is still very confused, the application of appropriate technologies for landslide detection, monitoring and early warning systems are increasingly considered crucial by local authorities in reducing the risk of landslide disasters.

In the field of slope instability detection, mapping and monitoring, during a short/long term landslide management (real time and near real time and deferred time), advanced ground-based remote sensing technologies are nowadays available (Lillesand et al. 2014). They

are characterized by operational efficiency and accuracy of data not reached by traditional methods: high-resolution acquisition, multifunction versatility, device portability, low cost sensors, easy and fast data processing. Such equipment allows for systematic and easily updatable acquisitions of data that may also enhance the implementation of effective early warning systems at slope scale. In this paper, the potential of the most used terrestrial remote sensing techniques is introduced through a description of their main technical features and applicability in different observed scenarios (typology of landslide and geomorphological setting). Some case studies affected by criticalities in the framework of Civil Protection, are also shown and discussed in order to exhibit good practices in landslide characterization and prediction by means of different techniques and sensors in synergic action.

2 Theoretical Principles of Techniques

2.1 Terrestrial Laser Scanner (TLS)

A Terrestrial Laser Scanner (TLS) device consists of a directional, coherent and in-phase electromagnetic radiation beam (or discrete pulses) transmitter, a back-scattered signals receiver and a scanning mechanism (e.g. a rotating mirror) (Fig. 1a). The TLS device, by measuring with high accuracy (millimeter or centimeter) the laser time-of-flight between the sensor and the reflecting targets, is capable of obtaining the exact position of a mesh of points (point cloud), characterized by (x, y, z) Cartesian coordinates and reflectance value $R(x, y, z)$, providing in a short time a high resolution 3D surface digital model of the scanned object (Slob et al. 2007; Frohlich and Mettenleiter 2004) (Fig. 1b). The high acquisition rate (up to hundreds of thousands points per second) makes the detailed 3-D shape of the object immediately available. TLS is more and more used for the analysis of slopes characterized by instability processes, as it safely allows in a short time a high detailed and

accurate 3D representation of the investigated rock mass plano-altimetric morphological and geostructural setting, and is therefore particularly suitable for geostructural characterization and unstable rock cliffs monitoring applications (Abellán et al. 2006, 2011; Ferrero et al. 2009; Gigli et al. 2014a, b; Oppikofer et al. 2009). Thanks to the high resolution of the laser scanning survey it is also possible to extract even the smallest features, such as the structural crack pattern, the crack opening direction (Gigli et al. 2009), and the orientation of critical discontinuities within the rock mass (Gigli and Casagli 2011; Gigli et al. 2014b). Furthermore this technique is capable of measuring ground 3D temporal displacements by comparing sequential datasets of the same scenario (Rosser et al. 2005; Kasperski et al. 2010; Abellán et al. 2011). Furthermore, for each point the intensity of the reflected signal is acquired. The intensity data can provide some information about the type of material and the soil moisture content of the targets (Pesci and Teza 2008; Voegtle et al. 2008; Franceschi et al. 2009). The point cloud high resolution and the variable laser return intensity values can also add information regarding the landslide main geomorphologic features. Finally, by placing several laser reflectors within the surveyed area, and defining their coordinates by means of a differential RTK-GPS survey (Tapete et al. 2015; Morelli et al. 2012), it is possible to link the different acquired point clouds to a global reference system.

2.2 Ground-Based Interferometric Synthetic Aperture Radar (GB-InSAR)

Ground-Based Interferometric Synthetic Aperture Radar (GB-InSAR) is an apparatus adopting a technique derived from satellite interferometry, with which shares the same base working principles but on a ground-based platform (Fig. 1c). Basically, the system emits two microwave signals 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

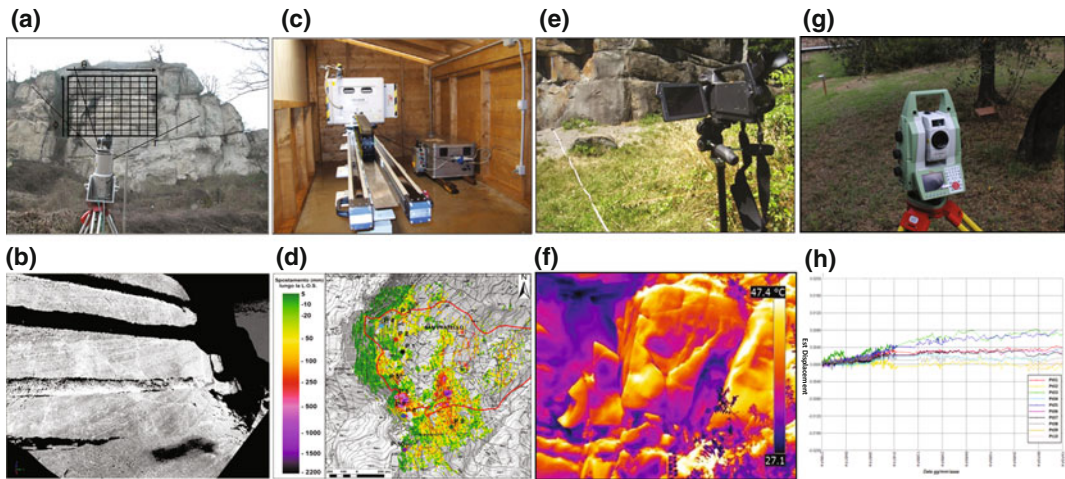


Fig. 1 The employed ground-based landslide surveying devices and related product: **a, b** terrestrial laser scanner; **c, d** GB-InSAR system and displacement map; **e, f** infrared

thermal camera and surface temperature map; **g, h** robo-tized total station and target time series

measured. Should any movement occur between the two acquisitions, a phase difference (called interferometric phase) is measured (Fig. 2). Then from the phase difference it is possible to calculate the actual surface displacement along the radar line of sight (LOS) of the with millimeter accuracy (Figs. 1d and 2b). This means that interferometry provides only the displacement component along the radar LOS. From the amplitude, power images relative to the radar reflectivity of the scenario can be obtained; this is useful to understand the main morphological features on the radar image. On the other hand, from the phase it is possible to compute interferograms, i.e. images in which every pixel corresponds to a phase difference, from which it is possible to obtain 2D displacement maps (Figs. 1d and 2b).

In an interferogram the chromatic scale that indicates the displacement (directly related to the phase difference) covers a total value corresponding to half of the wavelength used. However, since the phase is periodic, it cyclically assumes the same values. This may cause problems in interpreting the image as the same colour can indicate any displacement equal to the value represented on the scale plus a multiple of $\lambda/2$ (Fig. 2b). This issue, known as phase ambiguity, is the same phenomenon that makes it possible to

confuse 12 P.M. with 12 A.M. on an analogical watch. It can be solved through interpretation based on geological knowledge and through adopting apposite phase unwrapping algorithms that count the number of cycles performed by the wave (Ghiglia and Romero 1994). Unwrapping algorithms permit to represent the displacement as a linear colour bar in which the correspondence between colour and displacement is one-to-one. The resulting images are usually called cumulated displacement maps. In order to calculate the displacement from the phase difference, it must be assumed that a series of other contributions influencing the phase (such as air humidity and temperature, the dielectric constant of the target, relative position of the main reflectors within a pixel cell) keep constant and therefore are elided during the computation of the interferometric phase. A measure of how much the scenario is “stable” is given by the coherence parameter, ranging from 0 (total change) to 1 (maximum stability). The pixel of a radar image are not square and are instead characterized by two different resolutions: range resolution (along the LOS direction) and azimuth resolution (perpendicular to the LOS direction). These vary with certain parameters as indicated in Fig. 2. The main research applications of GB-InSAR

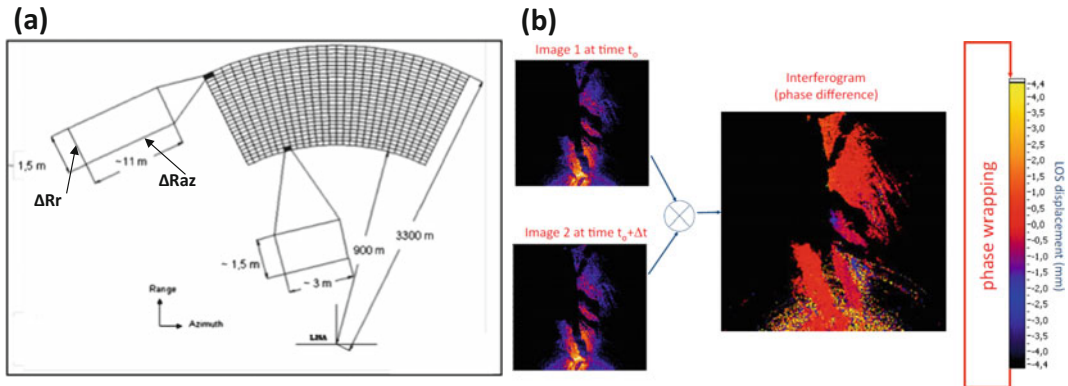


Fig. 2 a Resolution grid size and parameters; b simplified interferometric principles

soon became focused on slope monitoring (Tarchi et al. 2003; Pieraccini et al. 2003), for civil protection purposes (Del Ventisette et al. 2011; Intrieri et al. 2012; Bardi et al. 2014) and, more recently, for mining safety (Farina et al. 2011; Severin et al. 2014). Other successful or promising fields include monitoring volcanoes (Casagli et al. 2003; Di Traglia et al. 2013, 2014a, b; Intrieri et al. 2013; Calvari et al. 2016), cultural heritage (Tapete et al. 2013; Pratesi et al. 2015), glaciers and snowpack (Caduff et al. 2015a), sinkholes (Intrieri et al. 2015).

2.3 InfraRed Thermography (IRT)

InfraRed Thermography (IRT), or thermal imaging, is a remote sensing technique capable of mapping the surface temperature pattern evolution, leading to the detection of thermal anomalies within the investigated scenario (Spampinato et al. 2011). In recent years, IRT has undergone a significant increase of applications in the geosciences, thanks to the technological development of portable and cost-effective thermal imaging cameras, as well as the fast measurement and processing times of thermographic data. Nevertheless in the study of slope instability processes IRT is still not widely applied, apart from a few interesting experimental studies (e.g., Wu et al. 2005; Squarzone et al. 2008; Baroň et al. 2012; Teza et al. 2012; Gigli et al. 2014a; Frodella et al. 2014a, b, 2015).

The product of an infrared thermographic survey is a pixel matrix (thermogram), collected through the thermal camera array detector (Fig. 1e, f). After the correction of the sensitive parameters (object emissivity, path length, air temperature and humidity), the thermogram represents a radiant temperature map of the investigated object, which is a function of heat flow crossing the analyzed surface and of local boundary conditions (Maldague 2001). The presence of any inhomogeneity within the surface (i.e. cracks and fractures, moisture and seepage zones, sub-surface voids), will influence the material thermal parameters (density, thermal capacity and conductivity), modifying its heat transfer (Teza et al. 2012). Therefore, the inhomogeneity will be displayed in the radiant temperature map of the analyzed scenario as a “thermal anomaly” (an irregular thermal pattern with respect to the surroundings). As regards the analysis of instability phenomena, thermal anomalies can reveal the presence of potential criticalities such as open fractures, scarps, moisture and seepage zones.

2.4 Robotic Total Station (RTS)

A RTS is an advanced electronic instrument used in modern field surveying for topographic measurements (macro- and micro-scale application), as it allows the operator to control the instrument from a distance via remote control (Kvamme et al. 2006). Its main operational advantage is the

ability to collect, store and process data at very high accuracy (10^{-3} to 10^{-2} m), for multiple benchmarks on the landslide surface with a high measurement frequency (Giordan et al. 2013). This device is based on an electronic theodolite, which exactly measures angles, and it is integrated with an electronic distance meter capable of reading distances from the instrument to points on the landslide surface (Fig. 1g). After a first processing within its own polar coordinate system x, y, z , having a common origin point coincident with the optical center of the instrument, it provides three-dimensional topographic measurements in reference to a standard grid system (e.g. UTM-WGS84) (Fig. 1h). RTSs require the installation of optical benchmarks on the point to be monitored. However, installation of benchmarks for TSs is less onerous (in terms of cost, time and technical skills deployment) than the installation of GPS antennas in the same observed points. Similarly to GPS technique, TSs can be used to perform repeated surveys at defined time intervals on medium-long periods, or high frequency measurements (<20 min, depending on the network characteristics). Another advantage of RTSs consists in the ability to measure a large spectrum of topographic change rates, from mm day^{-1} to m day^{-1} , without changing the instrumentation setting. All these properties are significant for a landslide early warning system which exploits topographical measurements, especially when monitoring landslide types characterised by large areas and variable temporal modification rates. On the other hand, the effectiveness of RTSs may be reduced by: (i) adverse weather conditions (e.g. mist and intense rainfall) influencing the accuracy measurement; (ii) high distance (measurements are performed along the free optical LOS between the instrument and the individual optical benchmarks) and (iii) great plano-altimetric changes (the operational lifetime of individual benchmarks is limited where the rates of plano-altimetric change are $>2 \text{ m day}^{-1}$). State-of-the-art image processing technology delivers live video streaming with images of very high quality. By means of the installed remote control system, it is possible to steer the RTS,

transfer and process all the collected data according to a planned schedule that may vary according to the landslide speed and the total amount of monitored points.

2.5 Digital Photogrammetry Workstation (DPW)

Terrestrial digital photogrammetry is a well-established technique for acquiring dense 3D geometric information in slopes from stereoscopic overlaps of photo sequences captured by a calibrated digital camera set in a fixed position on the ground in front of scenario and without any physical contact (Zhang et al. 2004). During past few years, with the rapid development of digital photogrammetry techniques and the availability of ease-using, focusable and relatively cheap digital cameras, the method and device used in terrestrial photogrammetry changed greatly. Therefore, thanks to its increasing efficiency through time it gained wide applications in many fields such as 3D building reconstruction, heritage protection and landslides studies (Fan et al. 2016; Grussenmeyer et al. 2008; Scaioni et al. 2015). However, in spite of great development of traditional terrestrial photogrammetry over years, it is still necessary to set some control points on the slopes to be measured (Stavroulaki et al. 2016) if not supported by other technologies (Forlani et al. 2014). For the complex nature of the observed scenarios the setting control points around the objects is sometimes a very time-consuming and labour-intensive job. Principally, photogrammetry can be divided into two fields of activity depending on the lens-setting: Far range (with camera distance setting to indefinite) and Close range (with camera settings to finite values; i.e. up to about 300 m) (Gopi 2007). In the field of landslides studies and disaster management the first type is usually more exploited for landslide characterization and general mapping (Wolter et al. 2014) while the second type finds a wide applicability in high precision metrological and deformation monitoring applications (Cardenal et al. 2008; Scaioni et al. 2015). The processed outputs that

address the needs of these objectives can be summarized as follows: (i) coordinate of required object points; (ii) topographic and thematic maps; (iii) rectified photographs or orthophotos (Gopi 2007).

3 Applications in Case Studies

In this section, we present three exemplifying case studies, in which some of the above-mentioned ground-based techniques were profitably exploited for the landslide emergency management in Italy (Fig. 3): TLS, GB-InSAR, IRT.

The employed TLS is a Long Range and High Accuracy 3-D time-of-flight (model Riegl LMS-Z420i; RIEGL 2010). This device is able to

acquire the position of up to 12,000 points/s calculating the round-trip travelling time of the pulsed laser beam (near-infrared wavelength) from the instrument to the scanned object, with a maximum angular resolution of 0.008° , an accuracy of ± 10 mm (one s at 50 m range under RIEGL test conditions) and from a maximum distance of 800 m.

The applied GB-InSAR, is a system designed and implemented by the Joint Research Centre (JRC) of the European Commission and its spin-off company Ellegi-LiSALab. This device is able to acquire high resolution 2D displacement data every few tens of seconds, making it an invaluable tool for both early warning and characterization purposes. It operates automatically round-the-clock and in all-weather conditions, but the main constraint is probably the need for a



Fig. 3 a Case studies location; b Western Elba Island (unstable rock masses); c San Leo (collapsed rock cliff); d Santa Trada (planar slide in metamorphic weathered rocks)

connection to the electricity network since the system cannot practically operate with batteries, generators or solar panels.

The used thermal camera is a hand-held or tripod-mounted FLIR SC620 model, characterized by a focal plane array microbolometer sensor with a 640-by-480 pixel matrix (leading to a 13 cm spatial resolution considering the specific acquiring distance), capable of measuring electromagnetic radiation in the thermal infrared band between 7.5 and 13 μm (Long Wavelength IR band), with a thermal accuracy of $\pm 2^\circ\text{C}$ and a 0.65-mrad angular resolution. A built-in 3.2 Mpixel digital camera allowed the comparison between IR and photos taken in the visible range in order to improve the acquired thermograms interpretation.

3.1 Western Elba Island Coastline

The investigated area is located on the western hillside of Mount Capanne, overlooking the westernmost portion of the Elba Island coastline (Central Italy), along a 250 m stretch of the provincial roadway n° 25 (Fig. 3a, b). This roadway plays a key role in the Elba Island transit conditions, representing the only linear infrastructure connecting the villages located on the island western coastline, furthermore, being part of the Tuscan Archipelago National Park it has a panoramic relevance for tourism, the local population and authorities. This area is characterized by very steep rock slopes overlooking the roadway, which, due to its geostructural setting and degree of fracturing, in the recent years underwent the detachment of rock mass portions and rock debris, invading the roadway and in some occasions severely damaging its protection system (catchment nets and barriers). In order to define the risk scenarios for the roadway transportation security conditions, these instability occurrences were investigated through a methodology based on the integration of accurate geological and geomechanical field surveys and terrestrial remote sensing techniques, such as

TLS and IRT (Frodella and Morelli 2013; Gigli et al. 2014a). The final aim was to define the area 3D geo-structural and geomechanical rock mass characterization, detect the potentially more hazardous rock mass portions, calculate their volume and perform a detailed stability analysis. IRT surveys in particular were carried out in correspondence of rock mass most critical sectors, in order to detect thermal anomalies connected to open fractures, water seepage and moisture zones, validate the unstable block volume calculation, rapidly assess the hydraulic conditions along the more critical rock mass discontinuities, contributing together with the TLS semiautomatic analysis to a more detailed remote 3D geometrical and geomechanical characterization.

From a geological point of view, the study area is characterized by complex structural setting (Gigli et al. 2014a). Figure 4c shows the stereographic projection of the collected data: five main discontinuity sets were identified, JN3 set in particular includes high persistent decimetric-spaced discontinuity planes (=exfoliation joints, EJ), which represent slipping planes that isolate large rock mass portions (Fig. 4c). The obtained TLS 3-D surface model, obtained by merging the different point clouds, contributed to characterize the morphological variability of the investigated area: a rough morphology, characterized by creek erosion gullies isolating jutting rock mass portions, was revealed (Fig. 4a). Furthermore a semi-automatic geo-structural survey was performed by means of a Matlab tool (DiAna = Discontinuity Analysis; Gigli and Casagli 2011), on a limited sector of the rock mass not covered by nets, rock bolts, and fences. Figure 4d reports the poles of the semi-automatically extracted discontinuities (labeled from D1 to D7, and represented in 3D in Fig. 4b), which improved the rock mass structural characterization, adding two more discontinuity sets to the five detected by means of the traditional field survey. Given the geological setting of the investigated area, and the most

probable detected failure mechanism occurring (planar failure along JN3 discontinuity set), an iterative procedure was applied with the aim of identifying the maximum credible scenario. A Matlab routine was built for this purpose by moving on the 3-D surface a plane with the same orientation of JN3 set.

By selecting a volume threshold value of 1000 m³, three protruding rock masses were detected and labeled from north to south as M1, M2, and M3 (Fig. 4a). The latter masses for their considerable extension, overhanging position, and shape (mainly elongated along the direction of maximum slope) were identified as potential critical rock mass sectors with regards to instability mechanisms. M3 rock mass, in addition to the basal slipping plane, is also delimited southeastward from the stable portion of the rock slope by a second sub-vertical plane (belonging to JN2 set in Fig. 4c and D3 in Fig. 4d). The resulting rock masses volumes (expressed in

cubic meter) are 3706 (M1), 4359 (M2), and 1293 (M3). The obtained IRT surface temperature maps (thermograms), are represented by means of a color scale, in which the higher temperatures are displayed by the lighter colors, whereas the colder temperatures by the darker ones (Fig. 5). Warm thermal anomalies connected to air circulation were detected in correspondence of the open portions of the JN3 discontinuities delimiting the detected M1, M2, and M3 critical masses. The abovementioned discontinuities detected on the thermograms follow closely the EJ basal planes; this interpretation was strengthened by the comparison of the thermograms with the optical images that confirmed no evidence of water flow along the detected discontinuities. For these reasons, dry conditions were diagnosed for all M1, M2, and M3 basal slipping planes, and the absence of water pressure was considered in the stability analysis.

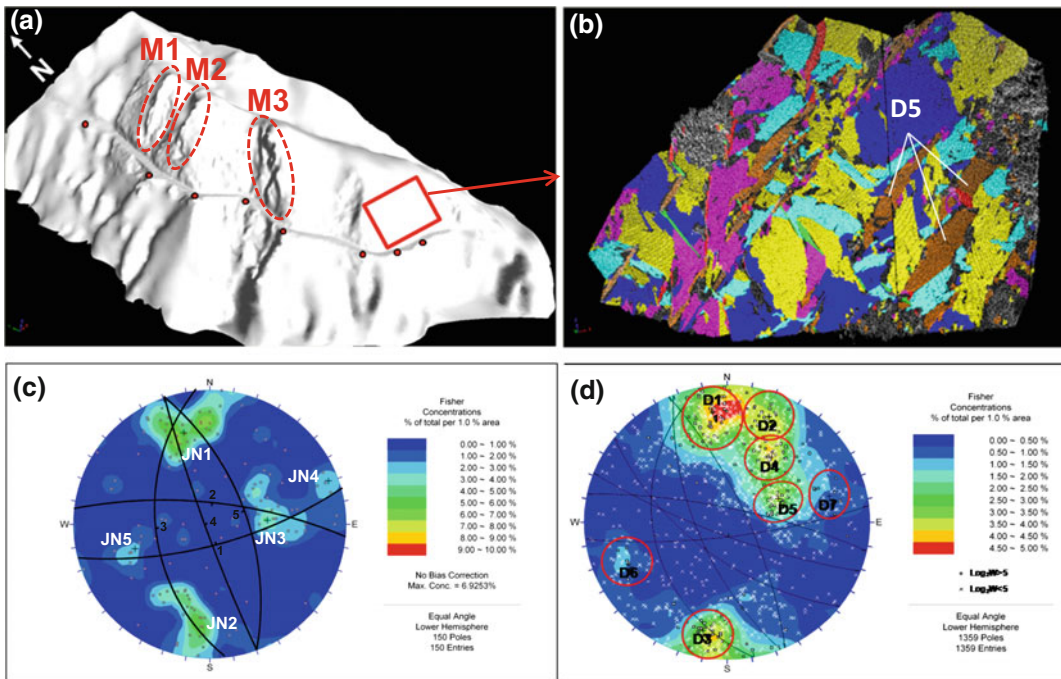


Fig. 4 a High-definition 3-D surface and maps of the investigated rock slope (a) (dots mark the different scan positions labeled from 1 to 8), while the square delimitates the sector where the semiautomatic geomechanical survey was carried out. b 3-D representation of all the

joint sets extracted from the point cloud selected sector. Stereographic projection of discontinuity poles and modal planes of the main sets collected in the investigated area through the traditional field surveys (c) and the semi-automatic analysis (d)

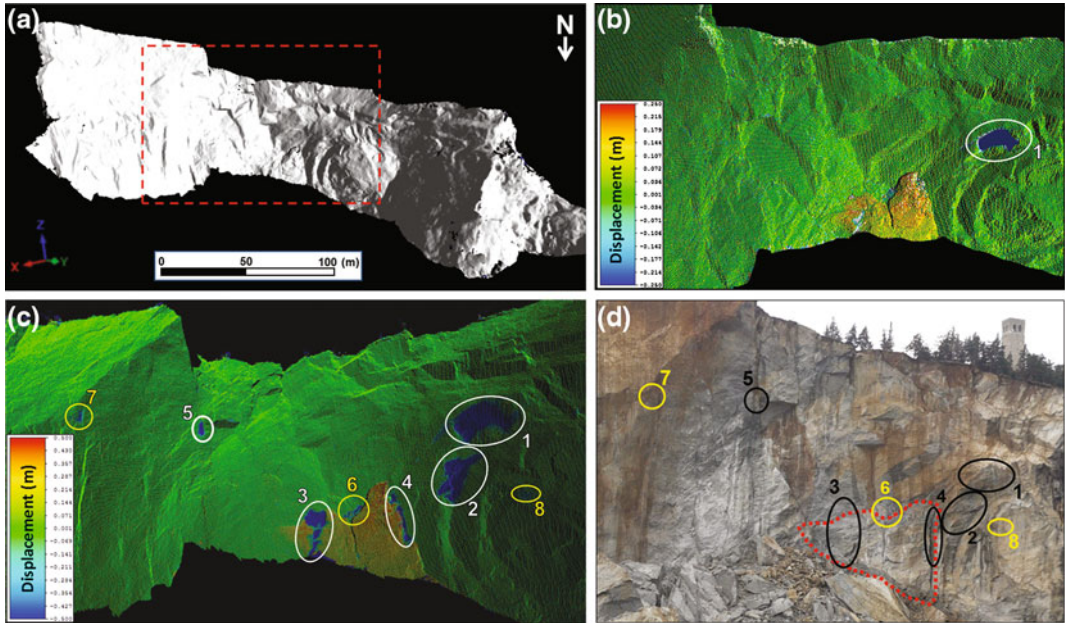


Fig. 5 Optical images of the unstable rock masses taken from the digital camera integrated in the laser scanner device from different scanning positions (**a** = M1; **c** = M2; **e** = M3); related 3-D digital model with the detected basal and lateral slipping planes (**b**, **d**, **f**), and mosaicked thermograms (**g** = M1, **h** = M2, and **i** = M3)

acquired around 1 p.m., November 2011. *Dotted lines* mark the basal slipping planes; *white squares* on the thermogram allow a comparison with the correspondent sectors in the optical images, acquired by the built-in digital camera

3.2 San Leo Rock Cliff

The town of San Leo, renowned for its medieval Fortress and Romanesque churches, is located in the southwestern sector of the Emilia Romagna Region (northern Italy) (Fig. 3a, c), on top of a limestone isolated rock massif overlying clayey slopes, which is historically affected by instability phenomena (Benedetti et al. 2013). On February 27th, 2014 an entire portion of the rock plate north-eastern sector collapsed, causing a huge rock fall of about 0.30 Mm^3 (Borgatti et al. 2015). Minor structural damages were reported in the town and a few buildings were evacuated as a precautionary measure. Although no fatalities occurred and the San Leo cultural heritage suffered no damages, this landslide event caused a consistent retreat of the cliff edge, and minor rock falls kept taking place on the newly formed rock wall, worsening this hazardous situation. For these reasons a GB-InSAR monitoring activity coupled with TLS surveys were carried

out, in order to manage the post-event emergency phase and evaluate the residual risk (Frodella et al. 2016). Furthermore IRT surveys were performed in order to integrate the TLS and GB-InSAR data in the analysis of the rock wall morphological and structural features.

In order to completely cover the intervention areas, four different laser scanning surveys (March 7th 2014, April 9th 2014, June 11th 2014 and December 8th 2014) were performed from different viewpoints. The 3D terrain model of the analysed rock wall sector revealed a rock wall surface, characterized by criticalities such as overhanging sectors, ledges and niches (Fig. 6a). 3-D temporal variations of the terrain model were detected by comparing sequential datasets acquired in the carried out different laser scanning surveys; the resulting 3-D rock wall temporal variations from March 7th 2014 to December 18th 2014 is shown in Fig. 6b, c. For each scanned point, the displacement vector component was determined perpendicularly to the local surface of

the 3D model of the former scan. The deformational field analysis provided evidence of an ongoing rock block toppling (with an estimated volume of 450 m^3), which is almost completely detached from the rock wall central sector (Fig. 6b, c). The latter displacement evolution reached values ranging from 12 cm (March 7th–April 9th comparison), to 25 cm (March 7th–June 11th comparison; Fig. 6b) and finally to about 50 cm (March 7th–December 18th comparison; Fig. 6c). The scan comparison also provided the detection of block fall (areas colored in blue in Fig. 6b, c) that took place during the laser scanning monitoring period. The detachment of rock blocks is in fact the mass movement of highest frequency and lowest magnitude in the rock wall monitored area. The major rock block detachment occurred in between the April 9th–June 11th TLS monitoring period, involving a 94 m^3 rock volume (oval 1 in Fig. 6c, d), whereas the rest took place in between June 11th and December 18th, involving consistent detachments (ranging from 66 to 10 m^3 in volume) and minor block falls (ranging from 2 to 1 m^3 in volume; yellow ovals in Fig. 6c, d).

On March 7th 2014, a GB-InSAR system was installed opposite to the north-eastern sector of the analyzed rock wall, for the real time monitoring of the residual movements of both the rock wall collapse-affected sector and the rock fall deposits. The employed radar system operates in the k_u -band (wavelength range of 2.5–1.67 cm; central frequency of 17.2 GHz and 200 MHz band width), and is capable of achieving a 3 m synthetic aperture in a 2 min scanning time. The TLS 3D model was merged with the GB-InSAR data obtaining a 3D GB-InSAR cumulative displacement map, which allowed to read detected LOS displacements directly on the observed scenario 3D representation, and therefore both to better localize the most critical areas, and compare the different techniques displacement data (Fig. 7a).

The GB-InSAR data acquired during the first monitoring year allowed us to assess a relative stability of the rock cliff and the town structures observed, and to detect critical areas, corresponding to: (i) a detensioned rock block located at the foot of the monitored rock wall central sector (confirming the TLS analysis of an

ongoing rock block toppling); and (ii) the rock fall deposits (metric and decametric size boulders and blocks in a coarse sandy-clayey matrix (maximum recorded cumulative displacement in the investigated area).

Infrared surface temperature maps collected on April 9th 2014 (following a period characterized by local intense rainfall) allowed to detect widespread seepage sectors in correspondence of a rock mass key discontinuity, corresponding to a high persistent normal fault dissecting the whole rock massif (oval 1 in Fig. 7b, c). In this geological, morphological and structural context discontinuities affected by seepage represent potential criticalities with respect to instability phenomena, as confirmed by minor seepage sectors (ovals 4 in Fig. 7b, c), which are located in correspondence of rock wall sectors affected by a widespread fracture network and block detachments (ovals 1–2 in Fig. 6c, d).

3.3 Santa Trada Landslide

The Santa Trada landslide (Calabria Region, Southern Italy; Del Ventisette et al. 2011) offers a good example of emergency management through the application of GB-InSAR in emergency conditions to assess the risk impending on a critical infrastructure. The landslide is a 100 m high, 90 m wide translational slide, developed in sand and conglomerates originating from metamorphic weathered rocks (Fig. 8); its thickness is estimated to be between 3 and 5 m. It occurred on 30th January 2009 after a period characterized by heavy rainfall (146.0 mm in December 2008 and 188.6 mm in January 2009) and its sudden movement threatened a viaduct sector along the A3 motorway, an important communication route connecting Salerno and Reggio Calabria. Two possible risk scenarios were consequently hypothesized:

- Progressive mobilization of small shallow landslides: the landslides could obstruct a minor road present at the foot of the slope. In this case probably the debris would not have concerned the motorway or its pillars;

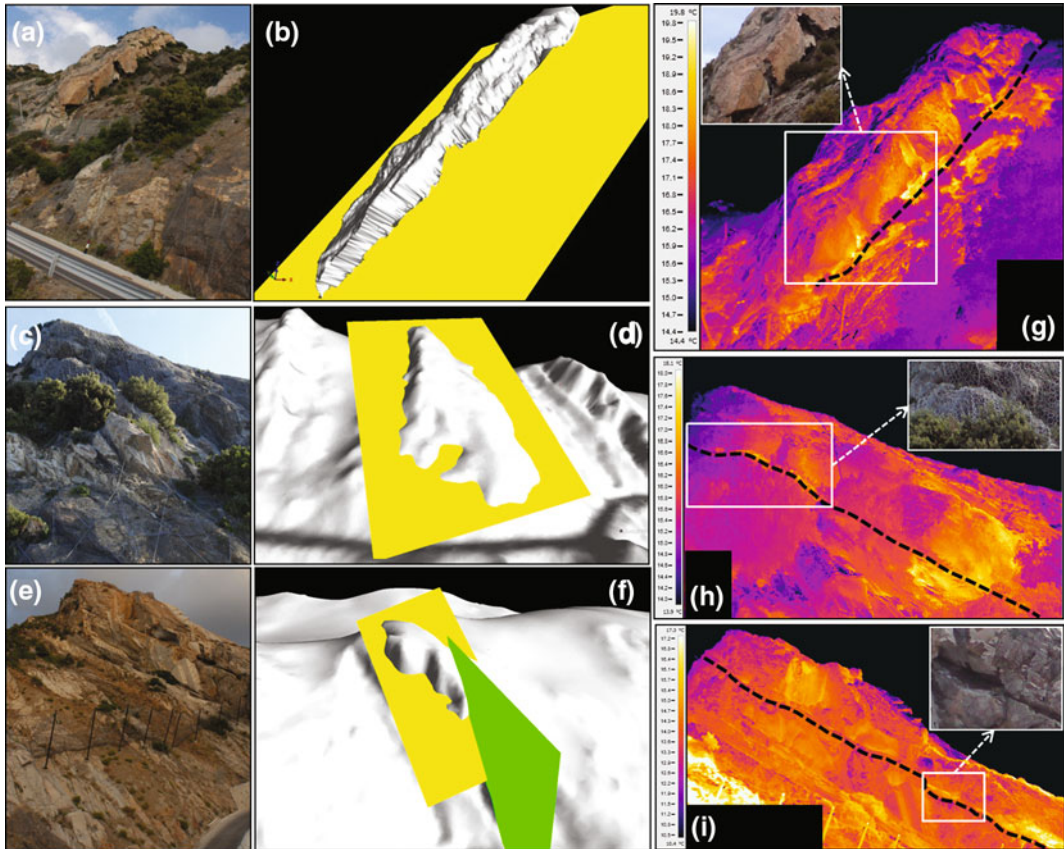


Fig. 6 High resolution 3D surface of the surveyed rock wall **a** (red dashed square corresponds to the area affected by rock block detachments). **b** Comparison between March 7th 2014 and April 9th scans: white oval showing the first monitored rock block detachment; orange-yellow areas enhance rock wall sector characterized by displacements. **c** Comparison between March

7th 2014 and December 18th scans, enhancing the occurred detached rock block sectors (in blue); yellow ovals enhance the minor block detachments. **d** Correspondent sectors in optical image (black ovals enhance major detachments); dashed line delimits the rock wall displaced sector

- Mobilization of the whole landslide: in this case, considering the estimated volume of several tens of thousands of cubic meters, the motorway pillars could have been affected by the failure. In addition, given the characteristics of the material involved and the geomorphology of the area, in case of collapse of the whole landslide an unstable dam on the Santa Trada seasonal stream (at the foot of the landslide) could have developed.

For safety reasons this tract of the motorway was closed to traffic. The GB-InSAR was a suitable and versatile tool to assess the actual

hazard of the landslide in order to enable the re-opening of the motorway.

On 31st January a ground-based had been installed. Already on 2nd February the motorway was partially reopened thanks to the first monitoring data. During the mid-term monitoring campaign (lasted until 24th April) two approaches for calculating the interferograms and displacement maps were adopted:

- Differential: the time span between the first and last image composing the interferogram is kept constant (e.g. 1 day) and the interferograms represent sequential moments (e.g.

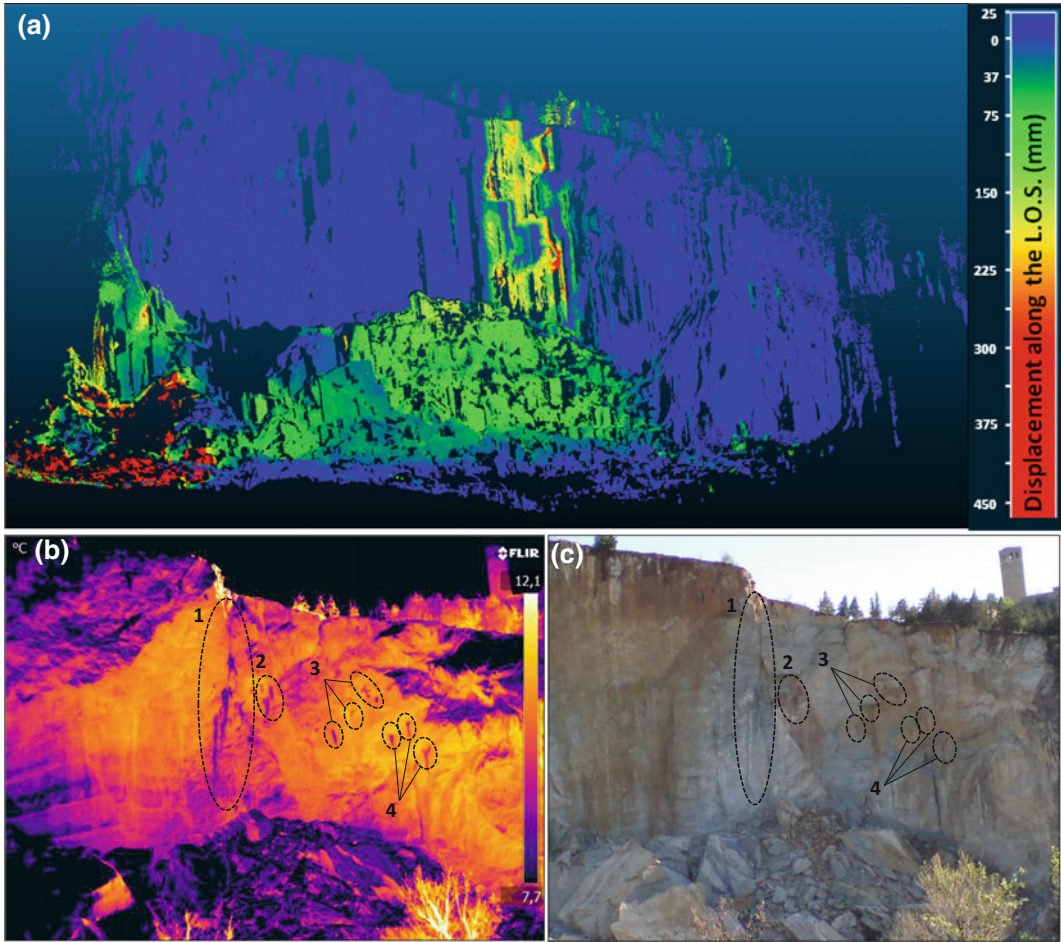


Fig. 7 GBInSAR and TLS data integration. **a** San Leo rock wall March 7th 2014–2015 3D GB-InSAR cumulative displacement map (after Frodella et al. 2016). **b** Thermogram acquired during April 9th 2014 and

c correspondent photo (see page sectors 1–4 are characterized by lower temperatures, due to local rock wall surface cooling caused by water evaporation)

day by day displacement). This approach is used in particular for kinematic analyses as it permits to identify acceleration phases because it enables to evaluate two comparable time periods.

- Incremental: the first image is taken as a reference and the interferograms are all calculated between the reference and the last image; in this way the time span is increasing with time. This approach is useful to evaluate the total cumulative displacement and to measure the displacement also in the slower portions of the landslide. Furthermore, it is

suitable for spatial analyses as the total extension of the unstable area can be assessed. On the other hand, long time intervals can cause phase ambiguity and loss of coherence. In fact, for Santa Trada landslide, thanks to the displacement maps provided by the GB-InSAR it has been possible to delimitate the area affected by the movement (Fig. 9) and to identify some temporal phases characterized by different activity levels and to assess the risk scenarios' temporal evolution.

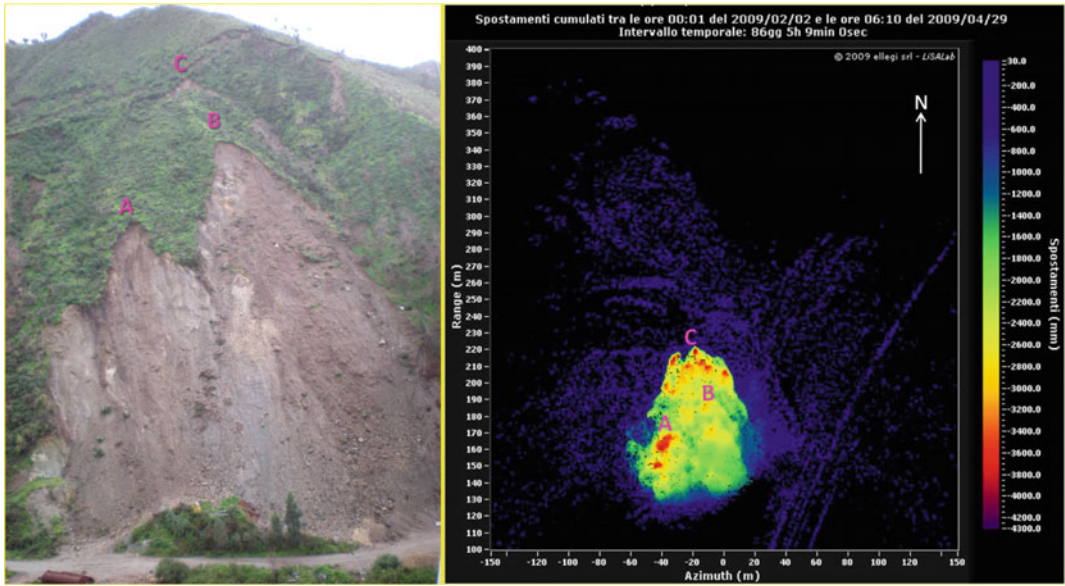


Fig. 8 *Left* Photo of the Santa Trada landslide from 1st February to 29th April 2009. The *letters* indicate the corresponding points between the two images
Right Cumulated displacement map calculated with incremental approach spanning from 2nd

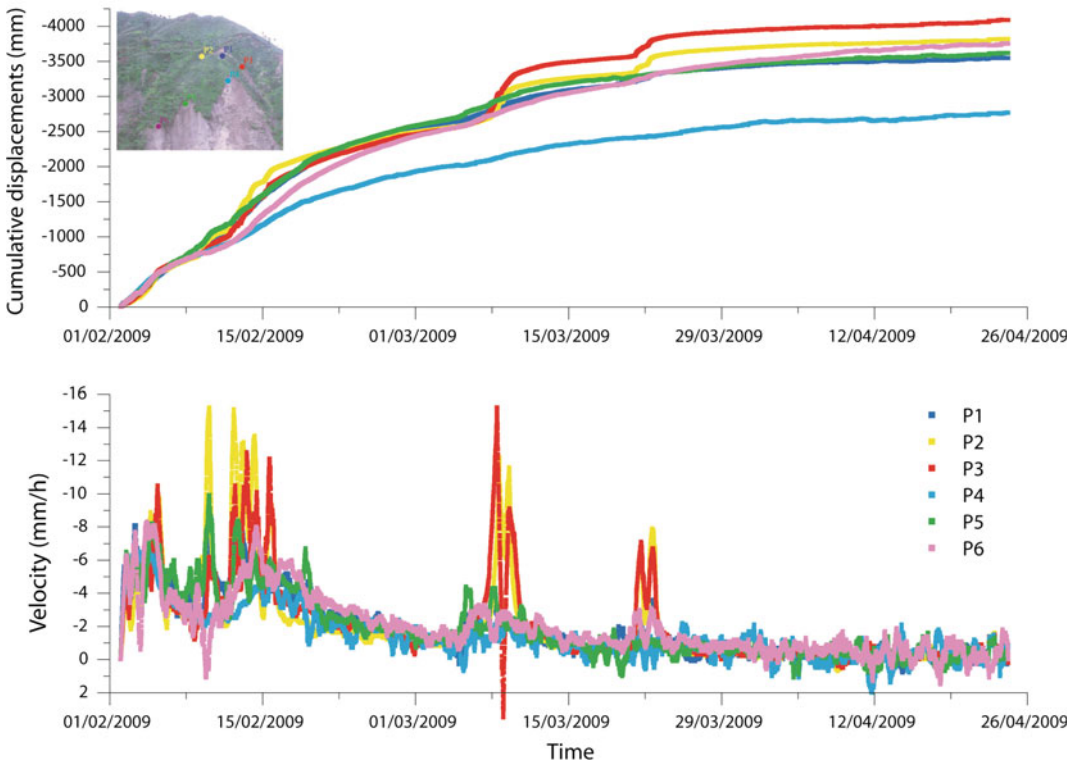


Fig. 9 Displacement and velocity time series of Santa Trada landslide obtained from a GB-InSAR (from Del Ventisette et al. 2011)

4 Discussion and Conclusion

Ground-based remote sensing refers to the science aimed at collecting Earth Observations by using non-contact techniques from terrestrial platforms (Lillesand et al. 2014). According to this general definition, a number of advanced sensors are available today, which may contribute differently to analyse and reduce the landslide risk (Qiao et al. 2013). Their application are usually categorized into three main groups (Mantovani et al. 1996; Scaioni et al. 2014):

- (i) recognition, mapping, classification and analysis;
- (ii) monitoring (continuous and periodical);
- (iii) hazard assessment, forecasting and early warning.

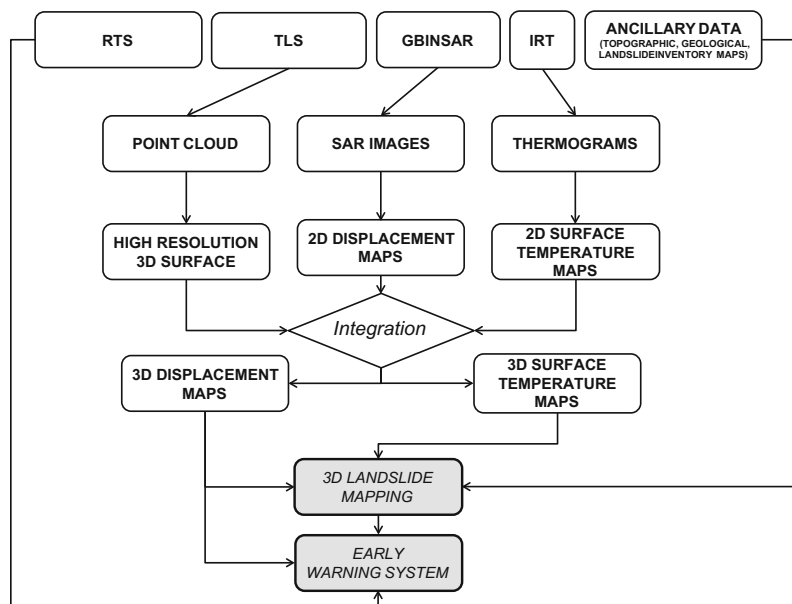
However, each domain could be further subdivided on the basis of the adopted sensor technology and the same sensors may be employed for more different purposes and activities (sometimes simultaneously and sometimes changing slightly their settings). In this paper, the main ground-based instruments used in the field of civil protection have been shown and in this framework some paradigmatic case studies have

been presented in order to show the synergic use of most of these analytic techniques (Fig. 10).

In western Elba Island, an integrated methodology based on traditional field and remote surveys such as terrestrial laser scanning and terrestrial infrared thermography was tested on a rock slope threatening a coastal panoramic roadway. The aim was to define susceptibility scenarios connected to rock slopes affected by periodical instability processes. In particular, the methodology was oriented to obtain an accurate three-dimensional rock mass characterization in order to detect the potentially more hazardous rock mass portions, calculate their volume, and collect all the required geomechanical and geometrical parameters to perform a detailed stability analysis. The proposed approach proved to be an effective tool in the field of emergency management, when it is often urgently necessary and gather all the required information (characterization and mapping) as fast as possible in dangerous environments.

In the San Leo rock cliff a monitoring system based on remote sensing techniques, such as radar interferometry, infrared thermography and terrestrial laser scanning, was planned in order to monitor the ground deformation and the residual risk of a rock wall affected by a huge sector

Fig. 10 Logic scheme of the presented case study methodologies



collapse. The analysed area is characterized by complex geomorphological and geometric features, different ongoing landslide processes with various state of activity. Each single employed monitoring technique can be considered not adequate for their intrinsic limitations. The combined use of the abovementioned techniques provided an effective monitoring system for landslide characterization and state of activity monitoring, thanks to the different instrument characteristics (LOS, range of detectable velocity, repetition time), which allowed to overcome the limitations of each single employed technique.

In the Santa Trada area, a GB-InSAR device was promptly installed in order to understand the temporal evolution of a landslide that seriously threatened the functionality and the safety of a strategic road infrastructure. This technique worked with all weather conditions and with a continuous surveillance for all the time of emergency, allowing the rapid assessment of the overall dynamics of the instable slope and related risks scenarios. This application was among the first to demonstrate the full effectiveness of this system in managing landslides emergencies since it greatly facilitated the intervention operations by designated authorities that aimed to restore a normal service in the shortest possible time after a precautionary closure of the motorway. It also

granted the possibility to acquire data during precipitations, which represent the most critical moment in stability terms; indeed, usually traditional monitoring instruments are not able to work in such conditions and to provide such useful information real-time, since they normally require a longer time for the installation and a direct access to the unstable and unsafe sites.

With all these cases study we show a brief overview of applications (individual or combined) which include all the above-mentioned categorized groups, from the identification to the early warning system. In view of these, their supporting literature and existing best practices at national and international level in the framework of Civil Protection (e.g., Caduff et al. 2015b; Calvello et al. 2015; Fekete et al. 2015), the most common fields of application can be extrapolated (Table 1).

This synthesis suggests that each instrument is usable in more than one application area and their effectiveness is certainly greater if coupled with other devices since usually proper settings does not allow having redundant information but rather a more complete evaluation. The absence of applications (red areas in the table) indicates that existing analytical techniques based on these instruments are still at a research level or, at most, in a testing phase on few cases of general

Table 1 Ground-based devices in the application fields of civil protection: green = convenience of use, red = no convenience of use

	CHARACTERIZATION AND MAPPING	PERIODICAL CHECK	CONTINUOUS MONITORING	EARLY WARNING
TLS				
DPW				
IRT				
GB-INSAR				
RTS				

Table 2 Evaluation of the effectiveness of existing ground-based techniques for different landslide types

Technique	Effectiveness				
	Slide	Topples/Falls	Flows	Lateral spreads	Complex mechanisms
TLS	High	High	High	High	High
DPW	High	High	Medium	Low	Medium
IRT	High	High	Medium	Low	Medium
GB-INSAR	High	Medium	Medium	High	High
RTS	High	High	High	High	High

interest. Because of a growing demand for effective Civil Protection procedures in pre- and post-disaster initiatives in landslide-prone areas, the purpose of researchers in the near future is to improve the investigative capacity of the such instruments and consequently to extend their fields of application. In fact, landslides managing in order to reduce vulnerability is currently considered more feasible (in terms of faster and extensive results) than governing all the natural conditions leading to instability, such as the spatial distribution of geology and geomorphology and the climatic influence. In such new global awareness we have extrapolated also the effectiveness of the performance of each ground-based technique with respect to the dynamics of landslide types (as defined by Cruden and Varnes 1996) (Table 2).

This evaluation can be considered a first crucial step towards the choice of the methodology to adopt which grants the best-quality results. These levels of effectiveness are complied if the effects of the techniques limitations (SafeLand 2012) are reduced to a minimum and if the movement speed of the observed scenario does not exceed the instrumental acquisition and processing times.

In conclusion, ground-based techniques have been recently interested by several technical and scientific improvements, providing for each instability process a wide range of equally effective solutions. Currently landslide analysis operators can select the most proper methodology with respect to their specific needs, which can be related to the different civil protection phases, technical issues, financial budget, environmental factors and specific features of the studied unstable slope. It should be also stressed

that all the listed techniques provide different kind of measurements (e.g. regarding single targets or widespread areas), that could be conveniently used in close cooperation in order to overcome each single intrinsic limitations and arrange effective action plans and management strategies.

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References

- Abellán A, Vilaplana JM, Martínez J (2006) Application of a long-range terrestrial laser scanner to a detailed rockfall study at Vall de Núria (Eastern pyrenees, Spain). *Eng Geol* 88:136–148
- Abellán A, Vilaplana JM, Calvet J, Garcia-Selles D, Asensio E (2011) Rockfall monitoring by Terrestrial Laser Scanning—case study of the basaltic rock face at Castellfollit de la Roca (Catalonia, Spain). *Nat Hazards Earth Syst Sci* 11:829–841
- Alexander DE (1993) *Natural disasters*. Springer Science & Business Media
- Bardi F, Frodella W, Ciampalini A, Bianchini S, Del Ventisette C, Gigli G, Fanti R, Moretti S, Basile G, Casagli N (2014) Integration between ground based and satellite SAR data in landslide mapping: The San Fratello case study. *Geomorphology* 223:45–60
- Baroň I, Bečkovský D, Miča L (2012) Application of infrared thermography for mapping open fractures in deep-seated rockslides and unstable cliffs. *Landslides* 1–13
- Benedetti G, Bernardi M, Borgatti L, Continelli F, Ghirelli M, Guerra C, Landuzzi A, Lucente CC, Marchi G (2013) San Leo: centuries of coexistence with landslides. In: Margottini C, Canuti P, Sassa K (eds) *Landslide Science and Practice*. Springer, Heidelberg, Germany 529–537
- Brunetti MT, Xiao Z, Komatsu G, Peruccacci S, Guzzetti F (2015) Terrestrial and extraterrestrial

- landslide size statistics. In: European planetary science congress 2015, 27 Sept–2 Oct 2015, Nantes, France. Copernicus. org/EPSC2015, id. EPSC2015-776 (10: 776)
- Caduff R, Schlunegger F, Kos A, Wiesmann A (2015a) A review of terrestrial radar interferometry for measuring surface change in the geosciences. *Earth Surf Proc Land* 40(2):208–228
- Caduff R, Wiesmann A, Bühler Y, Pielmeier C (2015b) Continuous monitoring of snowpack displacement at high spatial and temporal resolution with terrestrial radar interferometry. *Geophys Res Lett* 42(3):813–820
- Calvari S, Intrieri E, Di Traglia F, Bonaccorso A, Casagli N, Cristaldi A (2016) Monitoring crater-wall collapse at open-conduit volcanoes: the case study of the 12 January 2013 event at Stromboli. *Bull Volc* 78 (39):1–16
- Calvello M, d’Orsi RN, Piciullo L, Paes N, Magalhaes M, Lacerda WA (2015) The Rio de Janeiro early warning system for rainfall-induced landslides: analysis of performance for the years 2010–2013. *Int J Disaster Risk Reduction* 12:3–15
- Cardenal J, Mata E, Perez-Garcia JL, Delgado J, Andez M, Gonzalez A, Diaz-de-Teran JR (2008) Close range digital photogrammetry techniques applied to landslide monitoring. *Int Arch Photogrammetry, Remote Sens Spat Inf Sci* 37
- Casagli N, Farina P, Guerri L, Tarchi D, Fortuny J, Leva D, Nico G (2003) Preliminary results of SAR monitoring of the Sciara del Fuoco on the Stromboli volcano. In: International workshop “Occurrence and mechanisms of flow-like landslides in natural slopes and earthfills”, Sorrento, Italy, 14–16 May 2003, vol 2, pp 291–295
- Cruden DM, Varnes DJ (1996) Landslide types and processes. In *Landslides: investigation and Mitigation*, Sp. Rep. 247, Transportation Research Board, National Research Council, Turner AK, Schuster RL (ed) Washington DC: National Academy Press. 36–75
- Del Ventisette C, Intrieri E, Luzi G, Casagli N, Fanti R, Leva D (2011) Using ground based radar interferometry during emergency: the case of the A3 motorway (Calabria Region, Italy) threatened by a landslide. *Nat Hazards Earth Syst Sci* 11(9):2483–2495
- Di Traglia F, Del Ventisette C, Rosi M, Mugnai F, Intrieri E, Moretti S, Casagli N (2013) Ground-based InSAR reveals conduit pressurization pulses at Stromboli volcano. *Terra Nova* 25(3):192–198
- Di Traglia F, Intrieri E, Nolesini T, Bardi F, Del Ventisette C, Ferrigno F, Frangioni S, Frodella W, Gigli G, Lotti A, Tacconi Stefanelli C, Tanteri L, Leva D, Casagli N (2014a) The ground-based InSAR monitoring system at Stromboli volcano: linking changes in displacement rate and intensity of persistent volcanic activity. *Bull Volc* 76(2):1–18
- Di Traglia F, Nolesini T, Intrieri E, Mugnai F, Leva D, Rosi M, Casagli N (2014b) Review of ten years of volcano deformations recorded by the ground-based InSAR monitoring system at Stromboli volcano: a tool to mitigate volcano flank dynamics and intense volcanic activity. *Earth Sci Rev* 139:317–335
- Dilley M, Chen RS, Deichmann U (2005) Natural disaster hotspots: a global risk analysis. World Bank
- Fan YB, Yang SW, Xu LK, Li SH, Feng C, Liang BF (2016) Real-time monitoring instrument designed for the deformation and sliding period of colluvial landslides. *Bull Eng Geol Environ* 1–10
- Farina P, Leoni L, Babboni F, Coppi F, Mayer L, Ricci P (2011) IBIS-M, an innovative radar for monitoring slopes in open-pit mines. In: *Proceedings, slope stability 2011: international symposium on rock slope stability in open pit mining and civil engineering*, Vancouver (Canada), 18–21 Sept 2011
- Fekete A, Tzavella K, Armas I, Binner J, Garschagen M, Giupponi C et al (2015) Critical data source; tool or even infrastructure? Challenges of geographic information systems and remote sensing for disaster risk governance. *ISPRS Int J Geo-Inf* 4(4):1848–1869
- Ferrero AM, Forlani G, Roncella R, Voyat HI (2009) Advanced geostructural survey methods applied to rock mass characterization. *Rock Mech Rock Eng* 42:65–631
- Forlani G, Pinto L, Roncella R, Pagliari D (2014) Terrestrial photogrammetry without ground control points. *Earth Sci Inf* 7(2):71–81
- Franceschi M, Teza G, Preto N, Pesci A, Galgaro A, Girardi S (2009) Discrimination between marls and limestones using intensity data from terrestrial laser scanner. *ISPRS J Photogramm* 64:522–528
- Frodella W, Morelli S (2013) High-resolution 3D geomechanical characterization for the evaluation of rock-slide susceptibility scenarios. *Rendiconti Online della Società Geologica Italiana* 24:143–145. ISSN 2035-8008
- Frodella W, Morelli S, Fidolini F, Pazzi V, Fanti R (2014a) Geomorphology of the Rotolon landslide (Veneto Region, Italy). *J Maps* 10(3):394–401
- Frodella W, Morelli S, Gigli G, Casagli N (2014b) Contribution of infrared thermography to the slope instability characterization. In: *Proceedings of world landslide forum 3*, vol 4, 2–6 June 2014, Beijing, China, pp 144–147
- Frodella W, Fidolini F, Morelli S, Pazzi F (2015) Application of infrared thermography for landslide mapping: the Rotolon DSGDS case study. *Rend Online Soc Geol It* 35:144–147. Società Geologica Italiana, Roma 2015
- Frodella W, Ciampalini A, Gigli G, Lombardi L, Raspini F, Nocentini M, Scardigli C, Casagli N (2016) Synergic use of satellite and ground based remote sensing methods for monitoring the San Leo rock cliff (Northern Italy). *Geomorphology* 264:80–94
- Frohlich C, Mettenleiter M (2004) Terrestrial laser scanning: new perspectives in 3D surveying. In: Thies M, Koch B, Spiecker H, Weinacker H (eds) *Laser scanners for forest and landscape assessment*. *Int Arch Photogrammetry, Remote Sens Spatial Inf Sci* 36:8/W2

- Gigli G, Casagli N (2011) Semi-automatic extraction of rock mass structural data from high resolution LIDAR point clouds. *Int J Rock Mech Min Sci* 48:187–198
- Gigli G, Mugnai F, Leoni L, Casagli N (2009) Analysis of deformations in historic urban areas using terrestrial laser scanning. *Nat Hazards Earth Syst Sci* 9: 1759–1761
- Gigli G, Frodella W, Garfagnoli F, Mugnai F, Morelli S, Menna F, Casagli N (2014a) 3-D geomechanical rock mass characterization for the evaluation of rockslide susceptibility scenarios. *Landslides* 11(1):131–140
- Gigli G, Morelli S, Fornera S, Casagli N (2014b) Terrestrial laser scanner and geomechanical surveys for the rapid evaluation of rockfall susceptibility scenarios. *Landslides* 11(1):1–14
- Ghiglia DC, Romero LA (1994) Robust two-dimensional weighted and un-weighted phase unwrapping that uses fast transforms and iterative methods. *J Opt Soc Am* 11(1):107–117
- Giordan D, Allasia P, Manconi A, Baldo M, Santangelo M, Cardinali M, Corazza A, Albanese V, Lollino G, Guzzetti F (2013) Morphological and kinematic evolution of a large earthflow: The Montaguto landslide, southern Italy. *Geomorphology* 187:61–79
- Gopi S (2007) *Advanced surveying: total station, GIS and remote sensing*. Pearson Education India
- Grussenmeyer P, Landes T, Voegtler T, Ringle K (2008) Comparison methods of terrestrial laser scanning, photogrammetry and tacheometry data for recording of cultural heritage buildings. *ISPRS Arch Photogramm Remote Sens* 37:W5
- Kasperski J, Delacourt C, Allemand P, Potherat P, Jaud M, Varrel E (2010) Application of a terrestrial laser scanner (TLS) to the study of the Séchilienne landslide (Isère, France). *Remote Sens* 2:2785–2802
- Kjekstad O, Highland L (2009) Economic and social impacts of landslides. In: *Landslides—disaster risk reduction*. Springer, Berlin, pp 573–587
- Kvamme KL, Ermenwein EG, Markussen CJ (2006) Robotic total station for microtopographic mapping: an example from the Northern Great Plains. *Archaeol Prospection* 13(2):91–102
- Intrieri E, Gigli G, Mugnai F, Fanti R, Casagli N (2012) Design and implementation of a landslide early warning system. *Eng Geol* 147–148:124–136
- Intrieri E, Di Traglia F, Del Ventisette C, Gigli G, Mugnai F, Luzi G, Casagli N (2013) Flank instability of Stromboli volcano (Aeolian Islands, Southern Italy): integration of GB-InSAR and geomorphological observations. *Geomorphology* 201:60–69
- Intrieri E, Gigli G, Nocentini M, Lombardi L, Mugnai F, Casagli N (2015) Sinkhole monitoring and early warning: an experimental and successful GB-InSAR application. *Geomorphology* 241:304–314
- Lillesand T, Kiefer RW, Chipman J (2014) *Remote sensing and image interpretation*. Wiley, New York
- Maldaqe X (2001) *Theory and practice of infrared technology for non destructive testing*. Wiley, New York, 684 p
- Mantovani F, Soeters R, van Westen CJ (1996) Remote sensing techniques for landslide studies and hazard zonation in Europe. *Geomorphology* 15:213–225
- Morelli S, Segoni S, Manzo G, Ermini L, Catani F (2012) Urban planning, flood risk and public policy: the case of the Arno River, Firenze, Italy. *Appl Geogr* 34: 205–218
- Oppikofer T, Jaboyedoff M, Blikra L, Derron MH, Metzger R (2009) Characterization and monitoring of the Åknes rockslide using terrestrial laser scanning. *Nat Hazards Earth Syst Sci* 9:1003–1019
- Pesci A, Teza G (2008) Effects of surface irregularities on intensity data from laser scanning an experimental approach. *Ann Geophys-Italy* 51:839–848
- Pieraccini M, Casagli N, Luzi G, Tarchi D, Mecatti D, Noferini L, Atzeni C (2003) Landslide monitoring by ground-based radar interferometry: a field test in Valdarno (Italy). *Int J Remote Sens* 24(6):1385–1391
- Pratesi F, Nolesini T, Bianchini S, Leva D, Lombardi L, Fanti R, Casagli N (2015) Early warning GBInSAR-based method for monitoring Volterra (Tuscany, Italy) city walls. *IEEE J Sel Top Appl Earth Obs Remote Sens* 8(4):1753–1762
- Qiao G, Lu P, Scaioni M, Xu S, Tong S, Feng T, Wu H, Chen W, Tian Y, Wang W, Li R (2013) Landslide investigation with remote sensing and sensor network: from susceptibility mapping and scaled-down simulation towards in situ sensor network design. *Remote Sens* 5:4319–4346
- RIEGL (2010) Data sheet of long range & high accuracy 3D terrestrial laser scanner LMS- Z420i. http://www.riegl.com/uploads/tx_pxpriegldownloads/10_DataSheet_Z420i_03-05-2010.pdf
- Rosser NJ, Petley DN, Lim M, Dunning SA, Allison RJ (2005) Terrestrial laser scanning for monitoring the process of hard rock coastal cliff erosion. *Q J Eng Geol Hydrogeol* 38:363–375
- SafeLand (2012) *SafeLand-FP7, Deliverable 4.5, Evaluation report on innovative monitoring and remote sensing methods and future technology*, 280 p http://cordis.europa.eu/result/rcn/54948_en.html. Last accessed 10 May 2016
- Scaioni M, Longoni L, Melillo V, Papini M (2014) Remote sensing for landslide investigations: an overview of recent achievements and perspectives. *Remote Sens* 6(10):9600–9652
- Scaioni M, Feng T, Lu P, Qiao G, Tong X, Li R, Barazzetti L, Previtali M, Roncella R (2015) Close-range photogrammetric techniques for deformation measurement: applications to landslides. In: *Modern technologies for landslide monitoring and prediction*. Springer, Berlin, pp 13–41
- Severin J, Eberhardt E, Leoni L, Fortin S (2014) Development and application of a pseudo-3D pit slope displacement map derived from ground-based radar. *Eng Geol* 181:202–211
- Slob S, Hack HRGK, Feng Q, Röshoff K, Turner AK (2007) Fracture mapping using 3D laser scanning techniques. In: *Proceedings of the 11th congress of the*

- International Society for Rock Mechanics, Lisbon, Portugal, vol 1, pp 299–302
- Spampinato L, Calvari S, Oppenheimer C, Boschi E (2011) Volcano surveillance using infrared cameras. *Earth Sci Rev* 106:63–91
- Squarizoni C, Galgaro A, Teza G, Acosta CAT, Perino MA, Bucciari N (2008) Terrestrial laser scanner and infrared thermography in rock fall prone slope analysis. *Geophysical research abstracts* 10, EGU2008-A-09254, EGU General Assembly 2008
- Stavroulaki ME, Riveiro B, Drosopoulos GA, Solla M, Koutsianitis P, Stavroulakis GE (2016) Modelling and strength evaluation of masonry bridges using terrestrial photogrammetry and finite elements. *Adv Eng Softw*
- Tapete D, Casagli N, Luzi G, Fanti R, Gigli G, Leva D (2013) Integrating radar and laser-based remote sensing techniques for monitoring structural deformation of archaeological monuments. *J Archaeol Sci* 40 (1):176–189
- Tapete D, Morelli S, Fanti R, Casagli N (2015) Localising deformation along the elevation of linear structures: an experiment with space-borne InSAR and RTK GPS on the Roman Aqueducts in Rome, Italy. *Appl Geogr* 58:65–83
- Tarchi D, Casagli N, Fanti R, Leva D, Luzi G, Pasuto A, Pieraccini M, Silvano S (2003) Landslide monitoring by using ground-based SAR interferometry: an example of application to the Tessina landslide in Italy. *Eng Geol* 1(68):15–30
- Teza G, Marcato G, Castelli E, Galgaro A (2012) IRTROCK: a matlab toolbox for contactless recognition of surface and shallow weakness traces of a rock mass by infrared thermography. *Comput Geosci* 45:109–118
- Voegtle T, Schwab I, Landes T (2008) Influences of different materials on the measurements of a terrestrial laser scanner (TLS). In: *Proceedings of the XXI congress, The International Society for Photogrammetry and Remote Sensing, ISPRS2008*, vol 37, pp 1061–1066
- Wolter A, Stead D, Clague JJ (2014) A morphologic characterisation of the 1963 Vajont Slide, Italy, using long-range terrestrial photogrammetry. *Geomorphology* 206:147–164
- Wu JH, Lin HM, Lee DH, Fang SC (2005) Integrity assessment of rock mass behind the shotcreted slope using thermography. *Eng Geol* 80:164–173
- Zhang Z, Zheng S, Zhan Z (2004) Digital terrestrial photogrammetry with photo total station. In: *International archives of photogrammetry and remote sensing*, Istanbul, Turkey, pp 232–236