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GEOMORPHOLOGICAL EVOLUTION AND MONITORING OF SAN BERNARDINO-GUVANO COASTAL LANDSLIDE (EASTERN LIGURIA, ITALY)

Abstract: Raso E., Brandolini P., Faccini F., Realini E., Caldera S. & Firpo M., *Geomorphological evolution and monitoring of San Bernardino-Guvano landslide (Eastern Liguria, Italy).* (*IT ISSN 0391-9838, 2017).*

The San Bernardino-Guvano landslide is one of the wider slope mass movements located along the eastern Ligurian coast between Vernazza and Corniglia, Cinque Terre National Park. It is an ancient and complex landslide that has been studied since 1853, when a catastrophic event occurred. This paper aims to describe the geomorphological evolution and monitoring of this coastal landslide: both geological and geomorphological field surveys supported by airborne imagery were carried out, as well as bibliographical research about past geotechnical investigations and topographical monitoring; furthermore, a new single-frequency Global Navigation Satellite System (GNSS) low-cost monitoring started in October 2015. Structural geology heavily influences the stability of this coastal slope: a fault cuts the landslide area N-S, as well as low-angle thrust fault planes with NE dip direction. The slope is affected by landslides with different intensity and kinematic evolution, in particular rockfalls and debris avalanches along the scarp and right flank and earth flow along the central sector and at the slope toe. Man-made structures are relevant and they mainly consist of retaining walls, drainage channels, buildings, hiking trails, roads and railway infrastructures. Data obtained by GNSS receivers have shown remarkable displacements during the last year, according to the results of previous topographical and geotechnical monitoring campaigns. Deep analysis of GNSS data, together with the support and maintenance of the actual monitoring program, will allow a better comprehension of the slope stability condition, essential for supporting the design of proper risk reduction interventions.

Keywords: landslide, geomorphological hazard, monitoring activities, Cinque Terre, GNSS.

Riassunto: Raso E., Brandolini P., Faccini F., Realini E., Caldera S. & Firpo M. *Evoluzione geomorfologica e monitoraggio della frana costiera di San Bernardino-Guvano (Liguria orientale, Italia). (IT ISSN 0391-9838, 2017).*

La frana di San Bernardino-Guvano costituisce uno dei più estesi movimenti di massa osservabili lungo la costa ligure orientale tra Vernazza e Corniglia nell'ambito del Parco Nazionale delle Cinque Terre. È una frana antica, di genesi complessa, che è stata oggetto di studi sin dal 1853, quando avvenne un catastrofico evento di riattivazione. Questo contributo ha lo scopo di presentare l'evoluzione e le attività di monitoraggio di questa frana costiera: è stato condotto un rilevamento geologico-geomorfologico integrato con la fotointerpretazione di immagini aeree e supportato da una ricerca d'archivio delle precedenti indagini geotecniche e dei monitoraggi topografici svolti nell'area; inoltre è stata avviata una nuova campagna di monitoraggio tramite l'utilizzo di sensori GNSS (Global Navigation Satellite System) a partire dall'ottobre 2015. Le condizioni geologico-strutturali condizionano fortemente la stabilità di questo versante costiero: una faglia con direzione N-S taglia l'area di frana unitamente ad un piano di sovrascorrimento con basso angolo di inclinazione immergente verso NE. Il versante è interessato da movimenti franosi con differenti cinematismi e intensità, con la presenza in particolare di frane di crollo e di valanghe di detrito lungo la scarpata ed il fianco destro e di colate di terra lungo il settore centrale ed il piede del versante. Rilevante è l'interazione con le strutture antropiche, quali muri di contenimento, canali di drenaggio, edifici, sentieri escursionistici e infrastrutture stradali e ferroviarie. I dati ricavati dal monitoraggio GNSS hanno mostrato significativi valori di spostamento, in accordo con i risultati ottenuti durante le precedenti attività di monitoraggio topografico e geotecnico. Una profonda analisi dei dati raccolti unitamente ai futuri riscontri relativi al prosieguo della campagna di monitoraggio in atto consentiranno una migliore interpretazione delle condizioni di stabilità del versante, quale indispensabile supporto ad un'adeguata programmazione degli interventi di mitigazione del rischio geomorfologico.

Termini chiave: frana, pericolosità geomorfologica, attività di monitoraggio, Cinque Terre, GNSS.

INTRODUCTION

Research on landslides has increased in Italy and worldwide (Guzzetti, 2000; Crozier & Glade, 2006; Magri & *alii*, 2008; Salvati & *alii*, 2010; Corominas & *alii*, 2014) during the last decades. The Geotechnical Society Commission, on behalf of the United Nations and UNESCO, proposed a catalogue of the world's landslides (WP/WLI, 1993) and established guidelines for the standardized description of

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landslides and classification criteria. A recent important contribution in terms of classification of landslides is provided by Hungr & *alii* (2014).

With the National Law n. 267/1998, just enacted after the disastrous landslide event of Sarno (Campania, Southern Italy), an inventory map of landslides was realized with the aim of identifying and mapping landslides throughout all the country. Altogether 480,000 landslides have been recorded out of an area of 20,000 km^2, representing approximately 7% of the national territory (ISPRA, 2008).

Landslides are the most frequent geomorphological hazard in Italy and despite casualties and economic losses are less than those caused by earthquakes, an higher frequency of events has been detected since the early 2000s: only in Liguria Region, many landslides were triggered by heavy rainfall events, whose number is rising year after year, such as those of 2000, 2002, 2007, 2010, 2011, 2013 and 2014 (Guzzetti & *alii*, 2005; Brandolini & *alii*, 2005; Faccini & *alii*, 2005, 2015; Cevasco & *alii*, 2013, 2014; Galve & *alii*, 2015; Raso & *alii*).

Liguria Region presents geological, geomorphological, hydrological, climatic and anthropogenic features representing potential landslides predisposing factors: the Inventory of Italian Landslides (IFFI) highlights about 7,500 landslides in Liguria, approximately 8% of the whole national territory. Among these, about 20% are in state of activity and characterized by recent displacements.

The presence of ancient and recent landslides along the Ligurian coastal landscape is not very recurring, because of an intense erosive activity of sea waves and running waters; the effects of landslides are often modified by human activity and sometimes landforms associated with wide slope mass movements are confused with marine terraces (Fanucci & Nosengo, 1977). Coastal landslides therefore represent an interesting research topic for their influence on landscape and for their interaction with settlements and infrastructure; consequently, they play a key role in the geomorphological risk research.

The Ligurian coast is 345 km long and is characterized by 190 km of rocky coastline, 41 km of beaches and 114 km of artificial structures. Along its eastern stretch, some large coastal landslides are known in literature. They are characterized both by very slow/extremely slow kinematics (i.e. Rodalabia & Guvano; De Stefanis & *alii*, 1978) and by high intensity mechanisms, such as Monesteroli, the Batternara landslide between Riomaggiore and Manarola (Faccini & *alii*, 2015), along the "Via dell'Amore" and between Manarola and Corniglia ("Lama della Bansuola", below the village of Volastra). Under this aspect, the Cinque Terre can be considered as one of the most outstanding example of coastal landscape affected by high geomorphological risk, as dramatically confirmed by the catastrophic events of October 25th, 2011 (Brandolini & Cevasco, 2015; Raso & *alii*, 2016a, b).

The aim of this work is to evaluate the geomorphological evolution of the San Bernardino-Guvano area, located between Vernazza and Corniglia - Cinque Terre National Park (Eastern Liguria); for this purpose, bibliographical works dealing with the geological and geomorphological evolution of the study area and with past geotechnical and topographical monitoring campaigns were first examined; secondarily, detailed geological and geomorphological field surveys supported by airborne imagery were carried out, as well as a new single-frequency Global Navigation Satellite System (GNSS) low-cost monitoring campaign which started in October 2015.

Climate change and its consequences on rainfall regime are determining an increase in frequency of short and intense precipitation events. Such phenomena triggered several shallow landslides and caused diffuse land degradation widely distributed throughout the Cinque Terre catchments, consequently leading to a growth in sediment transport and destructive power of flash floods and landslides in periurban and rural areas (Pieri & *alii*, 2016; Brandolini & *alii*, 2016).

This, coupled with the presence of several exposed elements such as the Genova-Roma railway line, SP51 (Strada provinciale 51) County Road, the "Sentiero Verde-Azzurro" (SVA), a coastal trail very popular among hikers, and the village of San Bernardino at the top of the slope, produces a high level of geomorphological risk. The San Bernardino-Guvano landslide is therefore an interesting case study for the assessment of geomorphological hazard in order to mitigate geomorphological risk.

GENERAL OUTLINES

The S.Bernardino-Guvano coastal landslide is located in Eastern Liguria (NW Italy), within the Cinque Terre National Park (fig. 1), considered one of the most peculiar examples of a terraced coastal landscape in the Mediterranean region. In fact, during the last centuries most part of the slopes, up to 400-500 meters a.s.l., have been terraced with the purpose of cultivating olive groves and especially vineyards, creating a highly unusual, man-made coastal landscape fully integrated with the surrounding geomorphological environment (Terranova & *alii*, 2006). In some cases, such as in the presented case study, the terraces developed themselves along coastal landslides and degradation scarps (Brandolini, 2017).

Previous studies

The landslide of San Bernardino-Guvano is historically known from the second half of the nineteenth century, a few years before the start of technical investigations related to the construction of the Genova-Pisa railway.

First scientific research activity in this area was carried out by a pioneer geologist, Gerolamo Guidoni, who described in 1854 the catastrophic event concerning the reactivation of the ancient landslide affecting the slope below the village of San Bernardino the night between 26 and 27 December 1853 (Guidoni, 1854): the landslide crown was about 200 m large and caused the collapse of several buildings; remarkable displacement occurred until 1862 (Guidoni, 1902).

An extremely useful source of information about the landslide is represented by the project realized by the Kingdom of Italy's engineers in the middle of the XIX century

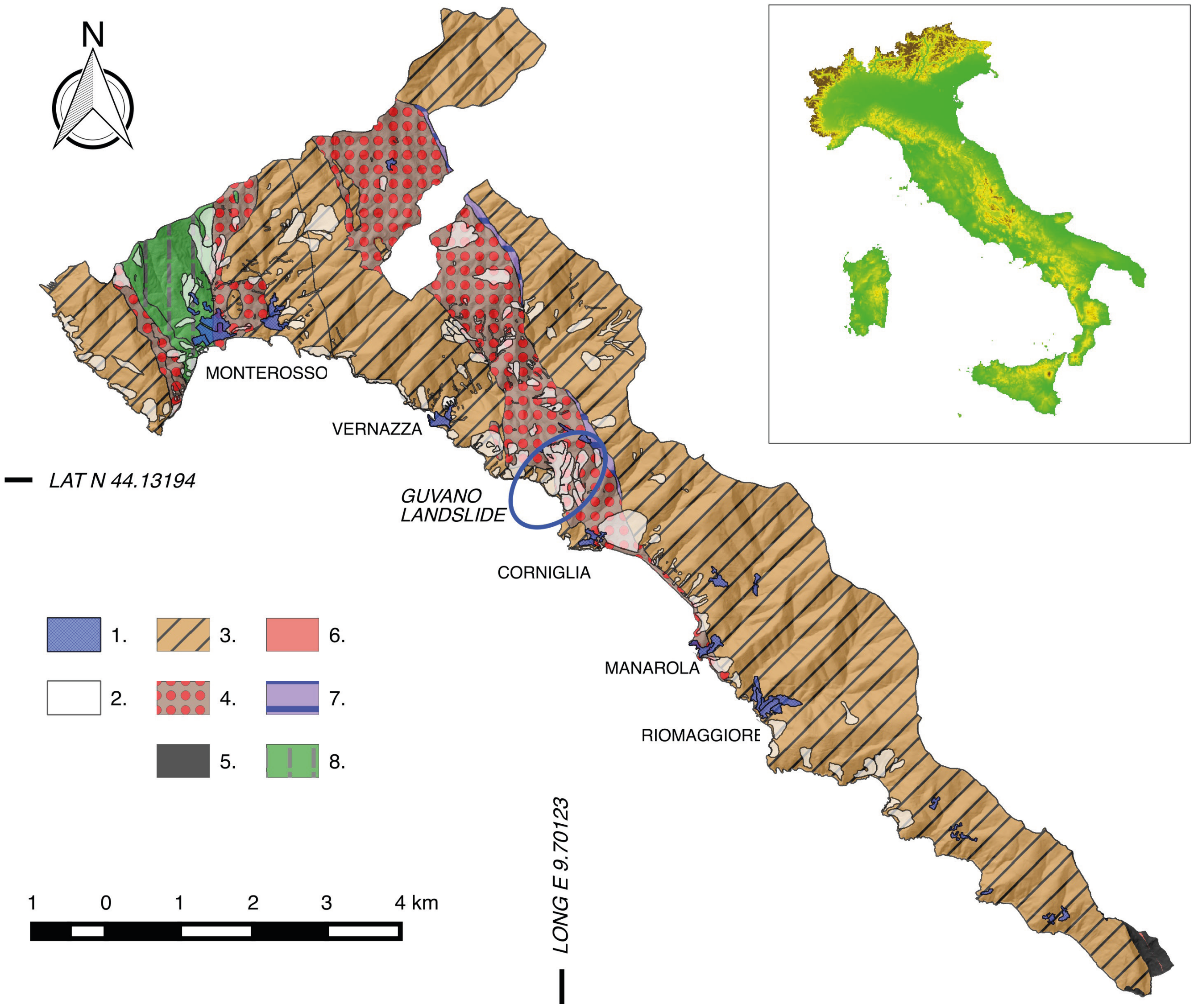

FIG. 1 - S. Bernardino - Guvano landslide location in the framework of geological sketch map of the Cinque Terre National Park. Legend: 1. Urban area: 2. Landslide; 3. Sandstones; 4. Shales; 5. Limestones; 6. Cherts; 7. Marls; 8. Ophiolites.

concerning the construction of the Sestri Levante - La Spezia railway line between 1865 and 1874 (Direzione Tecnica Governativa, 1880): in order to stabilize the landslide, a complex shallow and underground drainage system was realized, consisting in 26 galleries whose total length was 1129 m and 56 vertical wells with a total length of 709 m. Furthermore, a massive, 300 m long concrete and stone retaining wall was built along the landslide toe with the aim of protecting it by the erosional activity of sea waves (fig. 2).

In 1978 De Stefanis & *alii* realized the first geological and geomorphological map of the landslide area at a large scale, in which several geomorphological features (debris accumulations, edges of scarp, etc.) of the complex landslide have been distinguished, as well as their state of activity.

Terranova (1984), in the framework of the first Geomorphological Map of the Cinque Terre Area (scale 1:25,000) has presented an interesting geological-geomorphological sketch map of the Guvano Area in which different landslide source areas related to the bedrock composition were pointed out.

Federici & *alii* (2001) in the framework of the "Atlas of urban areas affected by landslides in Liguria" produced a very detailed geomorphological map at 1:5000 scale, based on the guidelines proposed by the Italian Geological Survey (Servizio Geologico Nazionale, 1994). Different kinematics (translational and flow types) of mass movement were pointed out and the main effects caused by landslide displacement and countermeasures to reduce it were described.

Cevasco (2007), within a wider analysis of rock mass instability phenomena affecting the Cinque Terre coastline, presented an updated synthesis of the Guvano landslide features, supported by a systems data set.

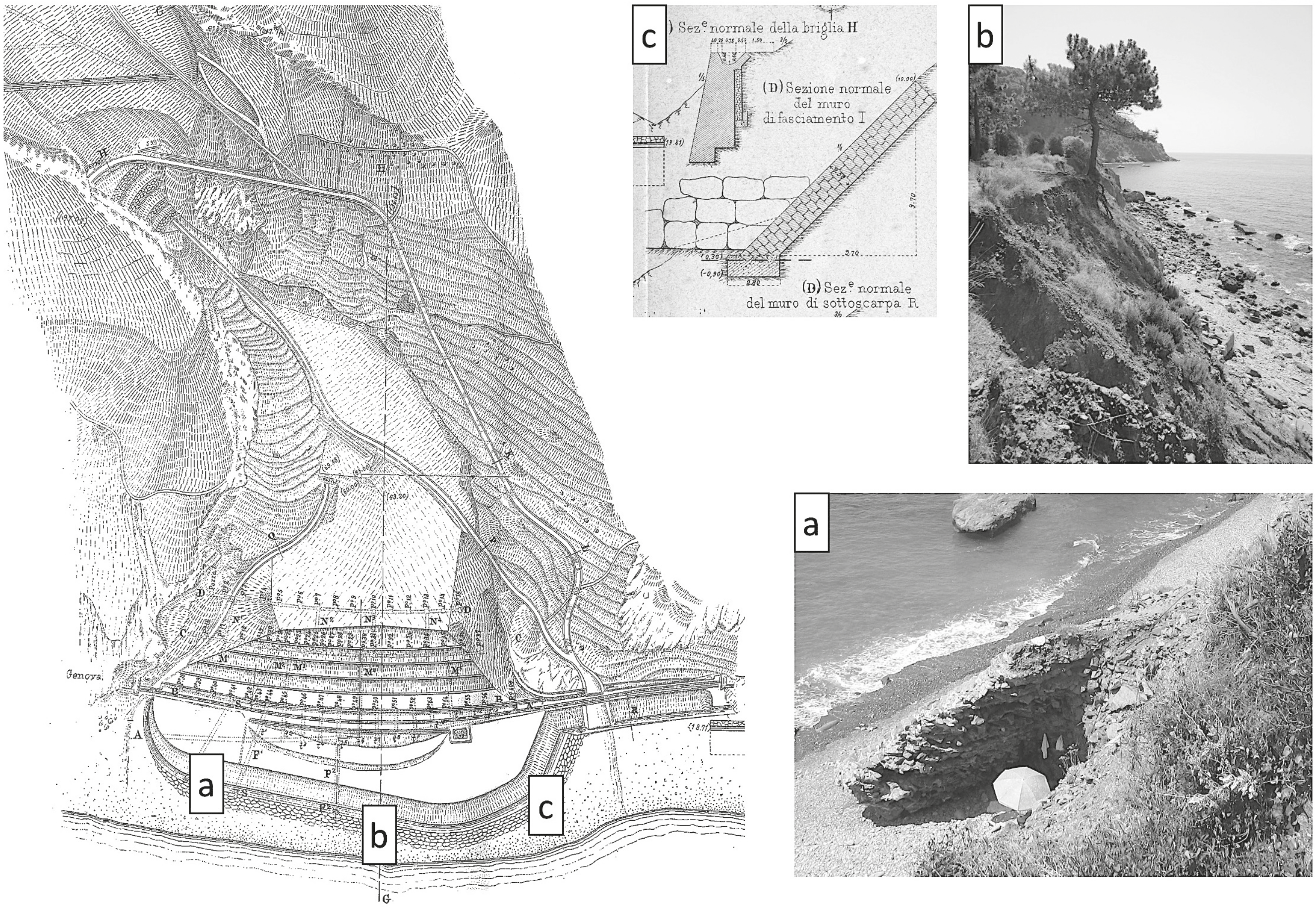

FIG. 2 - Interventions design to stabilize the S. Bernardino – Guvano landslide area realized by the "Ferrovie del Regno" Engineers (DIREZIONE TECNICA GOVERNATIVA, 1880): a) Ruins of the retaining wall (landslide toe); b) Active scarp due to sea wave erosion (landslide toe). c) retaining wall at the landslide toe.

Raggi & *alii* (2011), just after the dramatic flooding event of October 25th, 2011, published a series of geomorphological sketch maps of the Cinque Terre area providing a qualitative interpretation of the Guvano landslide body thickness through several geological cross sections.

At last, Cevasco & *alii* (2013) describe the geomorphological effects of October 25th, 2011 high-intensity rainfalls event, affecting a narrow area between Cinque Terre and the Magra Valley. A total rainfall amount of 539 mm/24 hrs was recorded by the Brugnato rain gauge, located approximately 10 km north of Vernazza, and a total rainfall amount of 382 mm/24 hrs was recorded along the coast by the Monterosso rain gauge, located 3 km northwest of Vernazza. In Monterosso, rainfall intensities of 90 mm/h, 195 mm/3 h and 350 mm/6 h were recorded between 9 and 15 UTC (A.R.P.A.L.-C.F.M.I.-P.C., 2012). This event caused the triggering of hundreds of shallow landslides and flooding phenomena mainly along the catchments of Monterosso and Vernazza (Cevasco & *alii*, 2014) and marginally also along the coastal slope between San Bernardino and Corniglia: these high-intensity landslides must be treated in a different way from the well known Guvano complex Landslide.

Previous geotechnical investigations and monitoring activities

In 2000, severe rockfall events affected part of the SP51 County Road under the landslide crown; after the road closure, in situ investigations and a topographical and geotechnical monitoring program were predisposed in order to obtain a detailed stratigraphy of the area.

Starting from June 2003 some field tests were carried out by the "Comunità Montana della Riviera Spezzina", followed by a 12 months monitoring program ended in June 2004 (Eptaconsult, 2004). Tests included the realization of 5 soil borings and laboratory analysis on disturbed samples (Eptaconsult, 2004); 4 borings were advanced adopting rotary core barrels to obtain rock and soil samples while one of them was advanced using a drill bit at the end for a faster advance; laboratory tests on disturbed soil samples were conducted to classify soils and determine their physical behavior.

Secondarily, four boreholes were cased with inclinometers and one with a piezometer: inclinometer probes were used in order to detect displacement along the boring length, while the groundwater level has been monitored along the piezometer equipped borehole and also along the 4 inclinometer boreholes.

A topographical monitoring was performed between June 2003 and June 2004 to detect the displacements along the landslide body: after 2004, the project was interrupted and there has not been any further investigation until today.

Sand and mud layers constitute the upper part of the sliding body while the underlying layers are composed of a heterogeneous mix of mud and silt with boulders and altered rock. The presence of marine sands at the bottom of the S3 and S4 boring holes, strengthen the hypothesis of the presence of a former beach already existing when the 1853 event occurred.

Half of the collected samples were classified as ML (low plasticity mud), while the other half was classified as CL (low to medium plasticity clays), according to the U.S.C.S. soil classification system. Fine-grained fractions were comprised in a range between 35 and 45%, and the clay contents were, in general, less than 20%. The coarse-grained fraction consisted of angular pebbles up to 15 cm in diameter. The Plasticity Index (PI) values were less than 15%, with an increase in the lower portion of the landslide body.

Groundwater level was registered from June 2003 until June 2004 between 6 and 9 m below the surface; water table fluctuations were relatively small and range between 2 and 3 m. Results obtained by the 2003-2004 topographical and geotechnical monitoring show displacement rates along the crown area and in the central sector of the right flank. Inclinometers show remarkable displacement rates at the slope toe, with the slip surface confirmed at 11 m of depth.

MATERIALS AND METHODS

Documents and notes describing slope instability phenomena affecting the San Bernardino-Guvano area were collected, as well as technical papers about railway works realized between the end of the XIX century and the beginning of the XX century along the lower portion of the landslide.

A multi-temporal cartographic comparison was realized to evaluate the morphological changes of the slope and the evolution of the landslide during the last two centuries. In particular, the *Stati Sardi di Terraferma* maps (1815-1822, scale 1:9,450) have been used, as well as the IGMI (Istituto Geografico Militare Italiano) maps dated 1878, 1904 and 1936 (scale 1:25,000), and two Regional Technical Maps (CTR, scale 1:25,000) dated 1994 and 2010.

Detailed geological and geomorphological surveys were carried out: the first one was focused on the relationship between tectonic and lithological features and landslide evolution. The latter was performed in order to detect the landslide features: in particular, it was focused both on typical landforms characterizing complex landslides (rock rotational slides/earth flows) and on areas characterized by high-intensity phenomena and possible first-failure landslides, i.e. crown area with a typical half-moon shape, overall concave and convex forms related to the landslide scarps and deposits, respectively, and the presence of back-tilted slope facets due to the rotational movements (Carlini & *alii*, 2016).

Field survey has been supported by photo interpretation of aerial images provided by Regione Liguria (1973, 1984 and 2007 aerial surveys) and by Regione Friuli-Venezia-Giulia Geological Service (November 2011), a few weeks after the October 25th, 2011 flooding event. Their analysis allows to detect a wide distribution of gravitational phenomena characterized by different intensity and kinematics. Preparatory and triggering factors affecting the whole slope were individuated in order to better estimate their relationship and influence with specific landslide types (Popescu, 2002). Standing on evaluations made through the analysis of geological and geomorphological features of the area and data obtained from field investigations, thickness of the sliding body could be verified and compared with previous evaluations.

In 2015, the Vernazza Municipality, together with Softeco S.r.l., GReD S.r.l. (Politecnico di Milano spin-off) and the Department of Earth, Environment and Life Sciences of University of Genova, started a new GNSS (Global Navigation Satellite System) monitoring program based low-cost technology.

A GNSS monitoring system is based on the continuous calculation of the position of a set of GNSS receivers permanently installed on an infrastructure or area to be monitored. To allow for measurements of deformation with millimeter-level accuracy, relative positioning is typically used (i.e., the positions of the moving nodes are known relatively to one or a set of stable nodes), by means of dual-frequency geodetic receivers. Such receivers, however, are costly (in the order of 10,000 € for the receiver alone, not counting the hardware deployment, data processing and maintenance costs), and this severely limits their actual application to operational landslide monitoring. The system used in this work uses low-cost single-frequency receivers (hardware cost: less than 2,000 € for each monitored point), with advanced observation processing that allows to reach a precision comparable to that of standard geodetic receivers (Caldera & *alii*, 2016). It's important to stress out that displacements are typically evaluated in two ways: single-shot or trend evaluation. The single-shot method consists in estimating the position of a monitoring point by processing a specific dataset collected over a short range of time (e.g. one hour, or one day). The trend is instead derived from a statistical analysis of single-shot position time series and provides a point-deformation model whose accuracy is estimated to be higher than the one of single-shot solutions.

Moreover, the extended use of low cost single-frequency GNSS receivers is possible in case of small-medium size landslides monitoring (a few hundreds of meters to 1 or 2 km) because it allows a relative positioning with short baselines (typically less than 5 km) which mitigates spatially correlated errors (such as ionospheric disturbances) and makes the use of L2 frequency unnecessary. Single-frequency receivers have been successfully used in the past for different landslide surveying tasks (Benoit & *alii*, 2015; Heunecke & *alii*, 2011).

The monitoring system based on low-cost receivers that was used in this study can therefore be described as a sum of two main components: data acquisition and processing

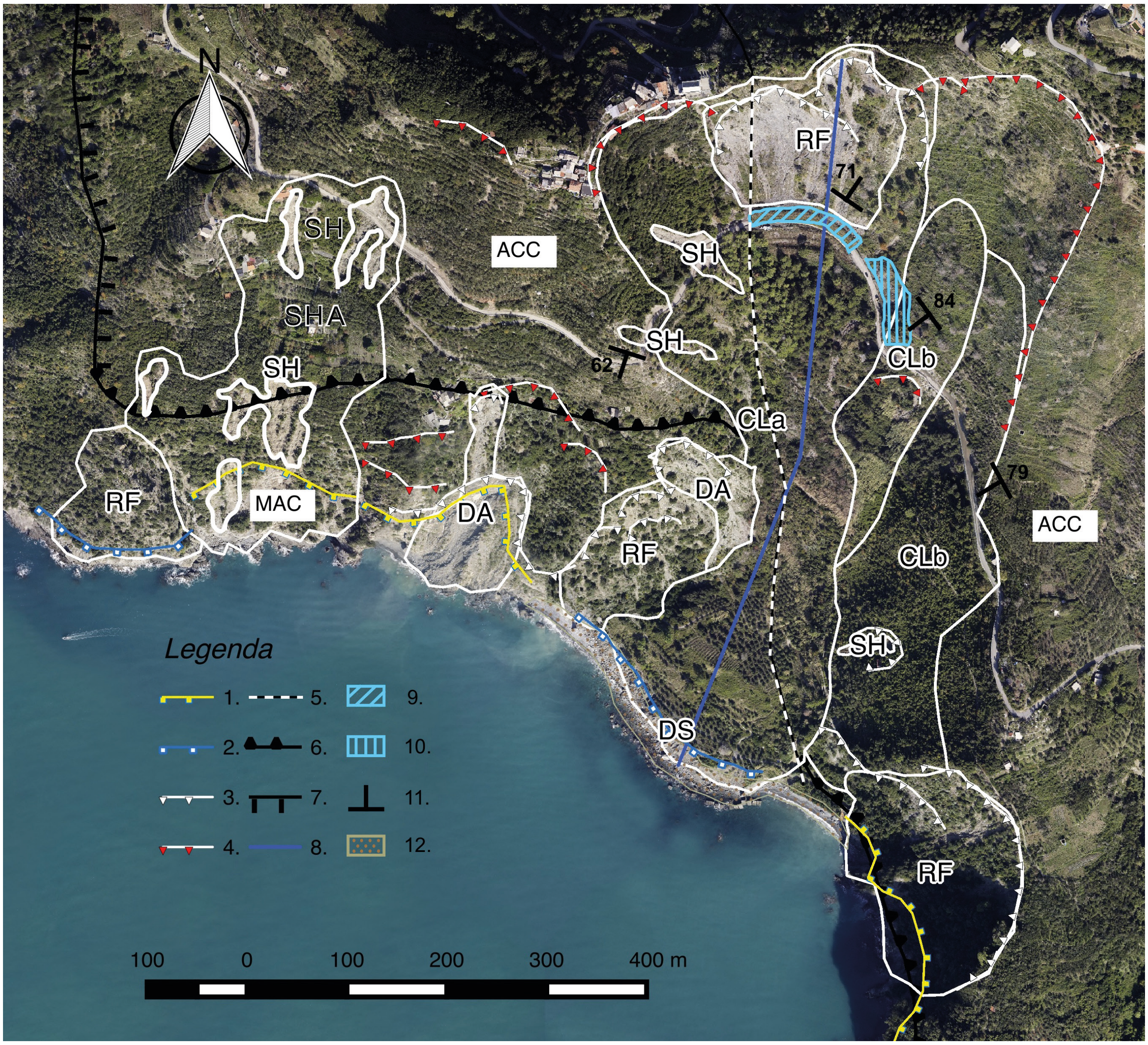

FIG. 3 - Geological and geomorphological sketch map: MAC. Sandstone; ACC. Shales and limestone; RF. Rockfalls; SH. Shallow landslides triggered by the October 25th, 2011 event; DA. Debris avalanches triggered by the October 25th, 2011 event; SHA. Area interested by several shallow landslides and locally dry stone walls collapsed; CL. Complex landslide: active (CLa), inactive (CLb); DS. Beach deposits; 1. Edge of active marine scarp > 25 m; 2. Edge of active marine scarp < 25 m; 3. Edge of active landslide scarp; 4. Edge of inactive landslide scarp. 5. N-S Fault; 6. Overthrust; 7. Normal fault. 8. Geological cross section. 9. Passive rockfall defence; 10. Active rockfall defence; 11. Bed attitude; 12. Beach deposit.

followed by trend or single-shot displacements analysis.

Data obtained by GNSS sensors have been compared with daily and cumulative rainfall amounts registered by the ARPAL (Agenzia Regionale per la Protezione dell'Ambiente Ligure) weather station located in Monterosso al Mare (SP), 2 km far from San Bernardino.

The GNSS technique has already been tested as a powerful tool in ground deformation analysis with high accuracy and reliability (Magri & *alii*, 2008; Benoit & *alii*, 2015). The main objective of this program is to detect displacements of the order of a few millimeters by relative positioning of low-cost receivers over a short baseline (about 2-3 km): the monitoring program has started in October 2015 when four GNSS sensors (also called GeoGuard Monitoring Units – GMU – because they were originally designed and developed by Softeco and GReD for the GeoGuard monitoring service) were positioned along the landslide body. The GMUs include low-cost single-frequency (L1) hardware for both receiver and antenna. The receiver module is a u-blox LEA-6T, providing GPS observations which are transferred by mobile connection to the control center (GeoGuard Cloud) and processed by a customized version of the free and open source software goGPS (Realini & Reguzzoni, 2013). Single-shot displacement data and trend analyses are then processed and managed by the GeoGuard Cloud, which send it to the end-user service interface.

RESULTS

Geological and geomorphological survey

The bedrock has a different composition in the lower and upper portion of the slope: the lower one is mainly composed of a turbiditic sandstone-siltstone flysch, with coarse and medium-grained sandstone beds and thin interbedded siltstones (Macigno Formation, MAC), belonging to the Tuscan Nappe Unit; the upper part, shales with limestones and silty sandstone turbidites (Canetolo shales and limestones Formation, ACC), marly limestones and calcarenitic turbidites (Groppo del Vescovo limestones Formation) and fine-grained sandstone turbidites (Ponte Bratica sandstones Formation) belonging to the Canetolo Unit (APAT, 2006). The Tuscan Nappe and the Canetolo Units are included in a wide overturned southwest-verging antiform fold. These units are bounded to the Northeast by a major normal fault (La Spezia Fault), beyond which the Ligurian Units outcrop (Federici & *alii*, 2001).

The area is characterized by the tectonic contact between the Canetolo shales and limestones and the Macigno sandstones and siltstones (De Stefanis & *alii*, 1978; APAT, 2006); the N-S fault surface is only visible in proximity of the landslide crown and along some ridge portions with no vegetation. Shales and limestones outcrop in proximity to the hamlet of San Bernardino and along the NE and SE sector of the studied area, while significant outcrops of sandstones and siltstones are detected along the NW sector close to the landslide crown and westward from the landslide toe (figg. 3, 4, 5).

A detailed record on bedrock outcrops indicates the rock strata dipping to SW (DIR°N 130°≈168°/INCL°50°≈80°) along both the left and right flank of the slope; a set of joints was found dipping to SE (DIR°N 55°≈60°/INCL°57°≈70°). Some measures were taken along the depletion area, where the ACC formation clearly outcrops, while some other outcrops (left flank) belong to the eastern portion of the relict S. Bernardino landslide. Degradation of rock mechanical properties due to fracturing promotes and controls large rock slope failures: in this case, such damage can be associated to the N-S fault line, associated joint planes and bedding planes detected during the geological survey. Furthermore, during rainy season, the joints provide infiltration channels for the rainwater into the inner slope (Xu & *alii*, 2016).

The main mechanism could be described as a retrogressive complex mass movement occurred along the

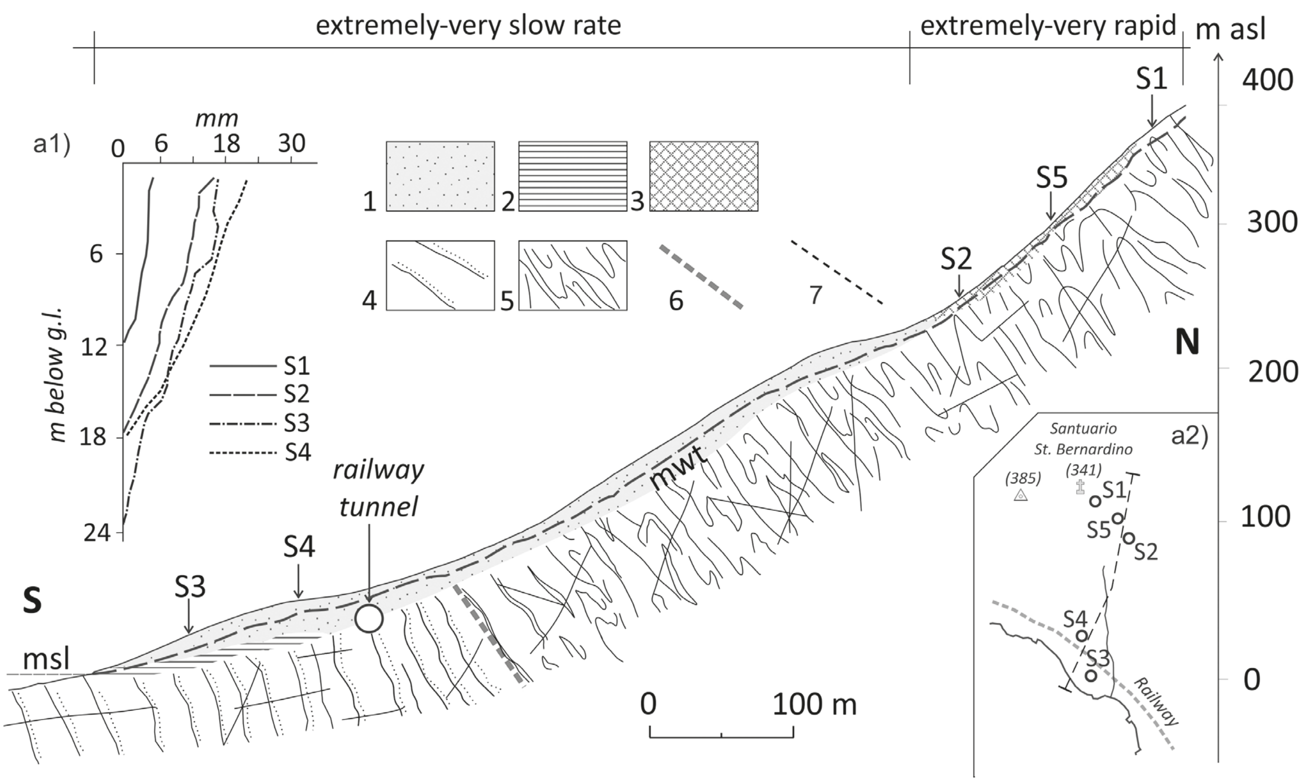

FIG. 4 - Geological cross section of S. Bernardino - Guvano landslide. 1. Medium/lower landslide body (silty and clayey sand); 2. Marine sands; 3. Upper landslide body (boulders and debris); 4. Sandstone (MAC); 5. Shales and limestone (ACC); 6. Fault; 7. Mean water table (mwt); a1: Inclinometer cumulative displacements profile during the 2003-2004 campaign time range; a2: Inset map showing borehole locations (S1-S5).

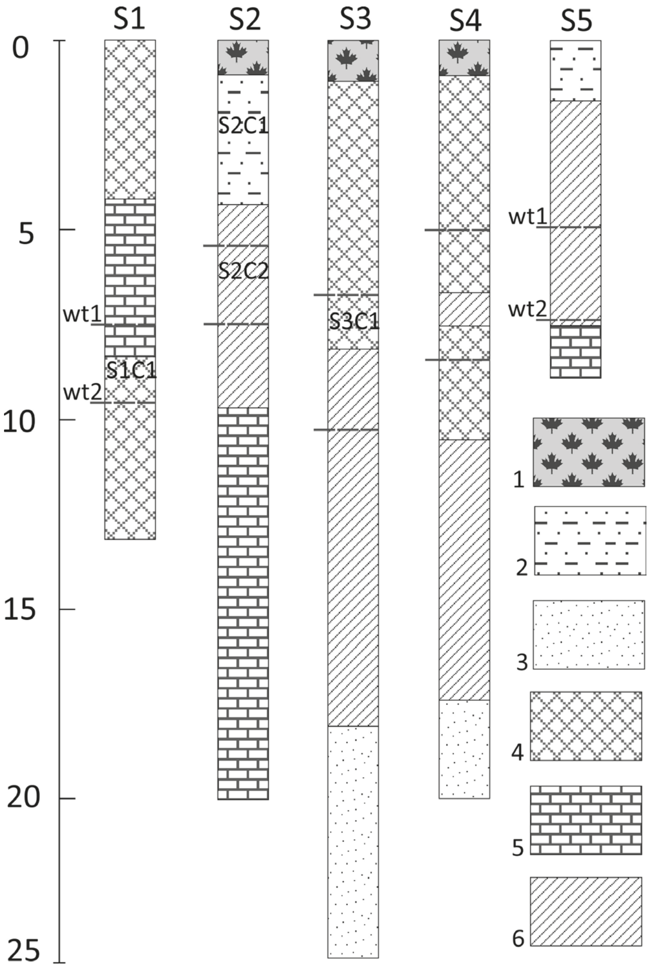

FIG. 5 - Borehole stratigraphies: 1. Organic soil; 2. Silty and clayey sands; 3. Marine sands; 4. Fractured shales with silty interlayers; 5. Shales and limestones; 6. Very fractured shales and limestones with silty interlayers. wt1-wt2: range between maximum and minimum water table values registered between 2003 and 2004. SC = Soil Sample (see Table 1 for further explanations).

coastal slope between the village of S. Bernardino (350 m a.s.l.) and the coastline, in correspondence of the tectonic contact between the two main lithological formations previously described; the 600 m long landslide crown is easily recognizable just below Case Fornaci hamlet. Between the main edge of scarp and the landslide toe in proximity to the shoreline, the total length of the landslide body is measured in 800 m. The upper portion has a width of 340 m, while a narrowing is detected along the middle portion (90 m), and again a spreading along the toe (235 m). On October 25th, 2011 heavy rainfalls have triggered several shallow landslides of limited extent and volume, located in areas characterized by high steepness rates. Rockfall events occurred along the eastern sector of the main edge of scarp and along the middle and lower portion of the right flank, where the Macigno sandstones are severely fractured and altered. From the middle to the lower portion of the slope, the landslide body shows a progressive width increase.

Various coastal landforms are detected in the area: erosional edges of scarp often more than 25 m high border the coastline between Vernazza and Corniglia, which is affected by several rockfalls and debris avalanches. The sea wave action at the landslide toe, mainly driven by south-western winds (Libeccio), has created a steep earth cliff composed by heterogeneous gravitational deposits and refills, also affected by a diffuse rill erosion.

A short stream flowing N-S along the landslide body is downcutting, especially along the lower and steeper sector between the SVA and the shoreline.

Several anthropic interventions have been carried out during the last two centuries: concrete and stone walls along the higher and medium portion of the slope, drainage channels, wells and trenches and a massive retaining wall surrounding the whole perimeter of the landslide toe were built by the Italian Railways in the middle of XIX century; concrete and natural boulders whose function was to reduce wave energy were subsequently added during the XX century. At present time, all human works are almost completely destroyed; in particular, the retaining wall was eroded by waves and the drainage channels now filled by debris and vegetation along the middle portion of the slope.

The main reason of the abandonment and lack of maintenance of these structures is because of the relocation of the railway line along a tunnel located 20 m North from the former railway tracks: since then, slope maintenance was no longer needed and erosional and gravitational processes kept growing in intensity (Stanchi & *alii*, 2012).

Landslide evolution in XIX-XXI Century

The present-day situation represents the last step of a complex slope evolution which started with an ancient gravitational movement involving a wider area. Actual evidences of that phase are the inactive edges of scarps and the presence of residual gravitational deposits on the western and eastern boundaries of the landslide area.

The complex slope dynamics affecting the area during the last 200 years can be reconstructed along six main phases (fig. 6).

1. Beginning of the XIX century: the slope under the S. Bernardino Church is a relict landslide cut by several streams with N-S direction. The lower portion of the slope is probably an inactive earth flow deposit. High rocky cliffs are detected on the western and eastern side of the slope.
2. End of XIX century: reactivation of the western portion of the relict landslide from S. Bernardino to the coastline: the movement has a N-S component. The description of the 1853 event (Guidoni, 1854) helps to identify it as a rock collapse. Another gravitational phenomenon (active rockfall scarp) of the South-eastern side of the Guvano Bay was probably generated by the construction of the Genova-Roma railway line at the end of the XIX century. The construction of drainage channels, horizontal and vertical wells took place, as well as the realization of a retaining wall enclosing the slope toe.
3. Beginning of the XX century: geomorphological dynamics is similar to the previous step, except for a

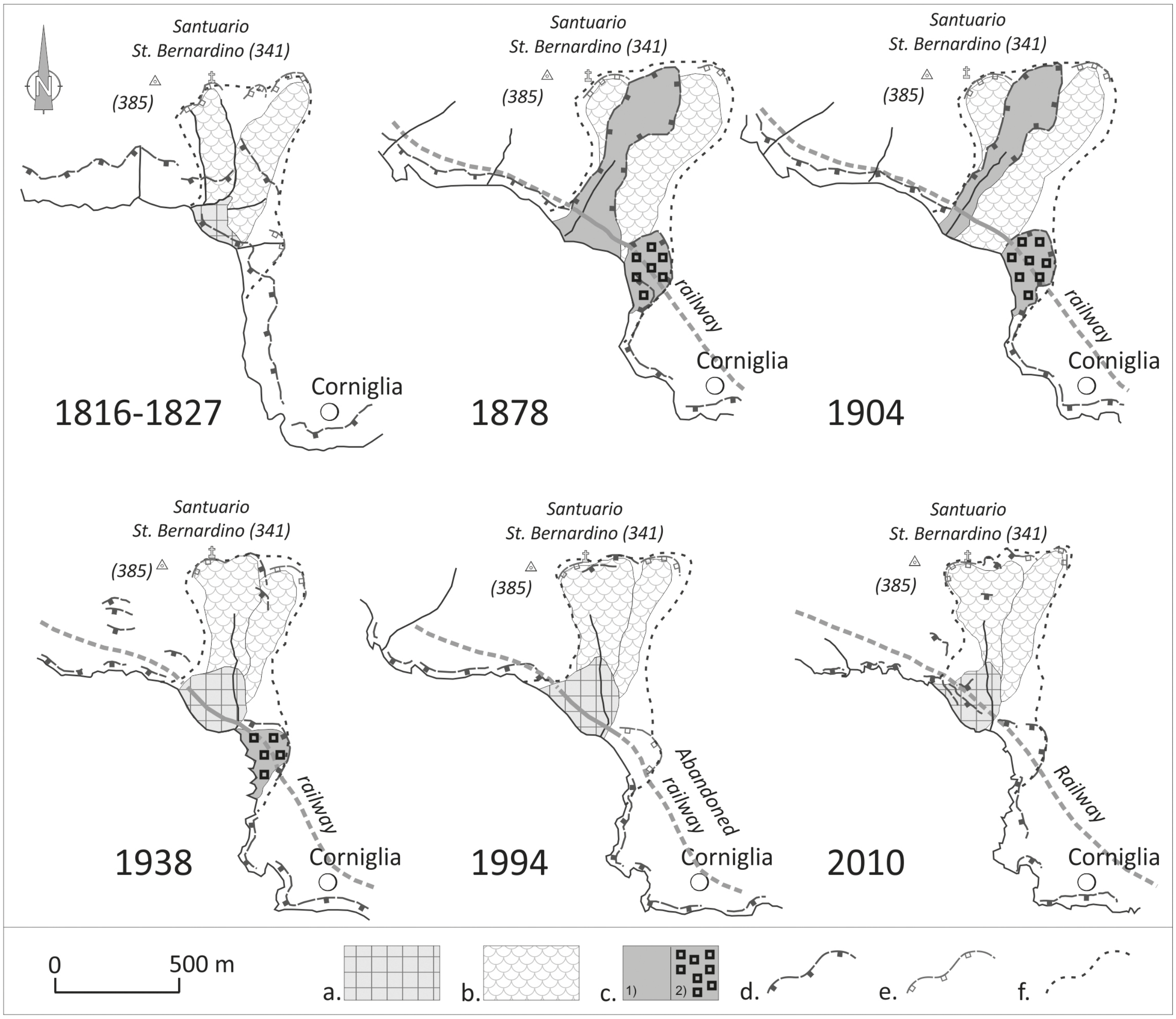

FIG. 6 - S. Bernardino - Guvano landslide evolution in the last two centuries: a. Talus flow; b. Complex landslide; c1. 1853 Landslide; c2. Rockfalls; d. Edge of active scarp; e. Edge of inactive scarp; f. Limit of ancient landslide.

reduction of the landslide width and the presence of a NE-SW oriented stream. Sea waves erosion rates are increasing.

4. Middle of the XX century: the 1853 landslide seems to be inactive at that time, while active and dormant scarps are present under S.Bernardino. The railway line is transferred along a tunnel carved 20 meters northward from the old tracks. The works realized at the end of the XX century experience a continuous degradation process.
5. End of the XX century: further slope modifications are detected as the realization of the SP51 County Road, the re-opening of the SVA, the complete abandonment of the retaining wall at the slope toe and of drainage wells and channels.
6. Beginning of the XXI century: the present day situation is illustrated in fig. 3: the main geomorphological evidences are the retreat of the active scarp under San Bernardino and the reactivation of the South-eastern active rockfall scarp. Geotechnical and topographical monitoring put in evidence the existence of displacement rates.

Monitoring activities

The data collected by the GMU allowed estimating continuous, high frequency 3D positions for a total of four sensing points. Hereafter only the results of the horizontal component, less noisy, are presented and discussed.

During this session, two GMU nodes (GUV3 and

GUV4) were acquiring observations without any loss, and one nodes (GUV2) worked discontinuously. One GMU node (GUV1) was set up on a bedrock outcrop to avoid small collapse effects and was used as reference for the other three sensors.

In order to ensure the stability of the references and to assess the real precision of the processing for site-specific acquisition conditions, the baseline between the fixed receivers is processed.

Time series of horizontal cumulative displacements at daily time resolution are computed for the GMU nodes working during the monitoring session, but only the March - September 2016 results has been reported on figure 7 since it includes data from all the sensors except GUV2.

A mesh of horizontal displacement rates (fig. 7) is obtained for a 10-months period (2015/12-2016/09) in which two GMU node (GUV1 – Sent.Azzurro and GUV4 – San Bernardino) have been acquiring data, and for a 7-months period (2016/04-2016/09) in which another GMU node (GUV3 - Uliveto) acquired data. The GUV2 (Muro Sostegno) sensor has had a few data transmission issues and has not worked adequately until now. The measured displacement rates show a good spatial heterogeneity. Gradients of displacement rates are observed in the north-south and east-west directions. The displacement rates increase from early-mid June to early July. Higher displacement rates are recorded in the lower part of the landslide (a total of 2.5 cm displacement towards S-SW registered by GUV3) than in the upper side (a total of 1.5 cm displacement towards S registered by GUV4).

DISCUSSION

The San Bernardino-Guvano landslide must be considered as a relict or at least reactivated ancient landslide, since its current situation represent the result of a sequence of gravitational events along different morphoclimatic conditions (Federici & *alii*, 2001), proven by several slope evidences and by landslide deposits detected under the mean sea level.

The primary factors which characterized this unstable slope condition are the geological and structural features and the neotectonic activities of Eastern Liguria coast. In particular, an extensional tectonics characterized by a set of high angle normal faults (NW-SE direction) and by a horst and graben structure have strongly affected this area starting from Upper Pliocene. Along these tectonic discontinuities, displacements occurred until 18,000 years b.p., while all the region comprised between Eastern Liguria and North-Western Tuscany was affected by tectonic uplift during the Pleistocene (Federici, 1980). Several strike-slip faults are NE-SW oriented, and deeply influenced the drainage pattern of Thyrrenian catchments.

A different approach was adopted to treat high intensity phenomena (often described as first failure mechanisms/ high speed landslides) and the complex Guvano landslide (low intensity and very slow to extremely slow movement) in order to evaluate which elements at risk are subject to these specific hazards in the whole area of San Bernardino-Guvano: quick landslides could affect the high number of hikers on the SVA trail of the Cinque Terre National Park, cars and pedestrian on the County road SP51, while low intensity movements endanger buildings and infrastructures close to the scarp area and the railway tunnel at the bottom of the slope (fig. 8).

High intensity phenomena

During the October 25th, 2011 rainfall events, a high number of shallow landslides, debris avalanches and debris - mud flows affected the Guvano area (fig. 3), causing localized but significant damages.

These phenomena, even with a lower destructive power compared to the ones occurring in the close villages of Monterosso al Mare and Vernazza, were triggered by heavy rainfall concentrated in a few hours: in the most part of cases, they were surveyed as shallow landslides made by fully saturated debris on a steep slope, without confinement in an established channel, and debris slides evolved into debris avalanches. These landslide types can be classified as extremely/very rapid shallow flows (speed range between 3 m/min and 5 m/s, Hungr & *alii*, 2014).

The role of the existing road and trail network cutting the landslide area as a preparatory factor of high intensity landslides (i.e. debris flows and shallow landslides) was determining.

The rockfall phenomena seems to be linked to the decay of shear strength of rock masses and discontinuities affected by deep weathering processes.

Low intensity phenomena

The San Bernardino-Guvano landslide can be considered as a very slow/extremely slow kinematic phenomenon (Hungr & *alii*, 2014). The main predisposal factor is to be found in the geological asset of the area: N-S direction fault between Macigno and Canetolo shales and limestones formation, both characterized by different geotechnical behavior, has been identified as the most important weakness factor affecting the area.

Standing on data from GNSS monitoring, displacement and strain rates show temporal variations and a total of three different flow regimes can be identified: April 2016 - mid-June 2016, mid-June 2016 - mid-July 2016 and mid-July 2016 - September 2016 (fig. 7). In order to investigate them, displacement rates are calculated and compared with the rainfall amount measured at Monterosso al Mare weather station (ARPAL).

The first regime corresponds to a period of rainfall average (60 days showing a total of 120 mm) in which scarce evidence of displacement has been recorded.

The second regime corresponds to the start of a reactivation of the sliding body: 1.75 cm towards SW from GUV3 and 1.5 cm towards SE from GUV4. The displacement is triggered by a consistent rainfall amount (200 mm in 15 days, from 01/06 to 15/06). The time lag between the sliding reactivation (20/06) and the start of heavy rainfall period (01/06) can be explained by the complex hydrology of the landslide with different response of the slope to rainfall.

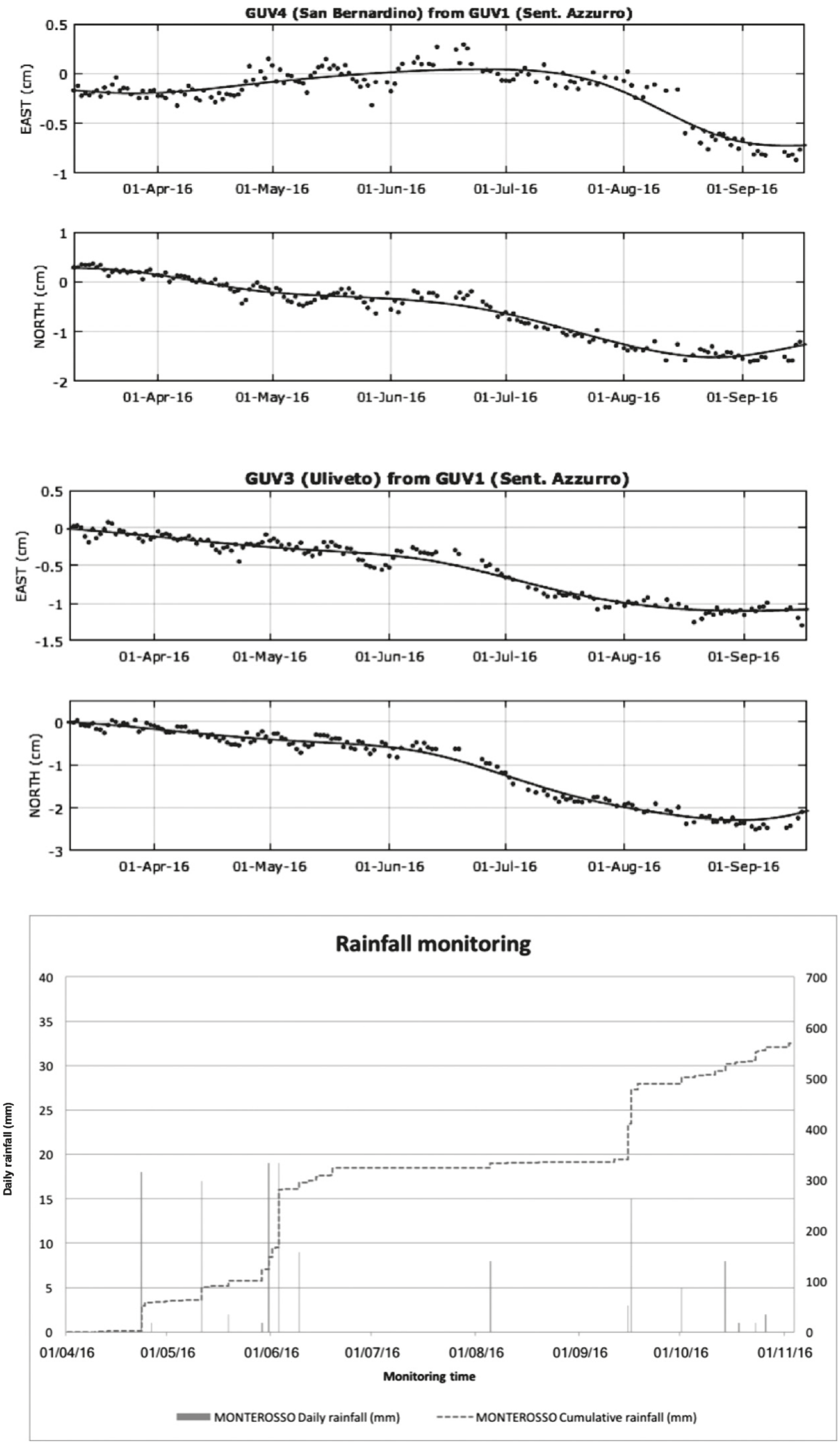

FIG. 7 - Monitoring results of daily rainfall level registered by Monterosso al Mare - ARPAL weather station and the ground displacement rate registered by GNSS sensors from March to September 2016.

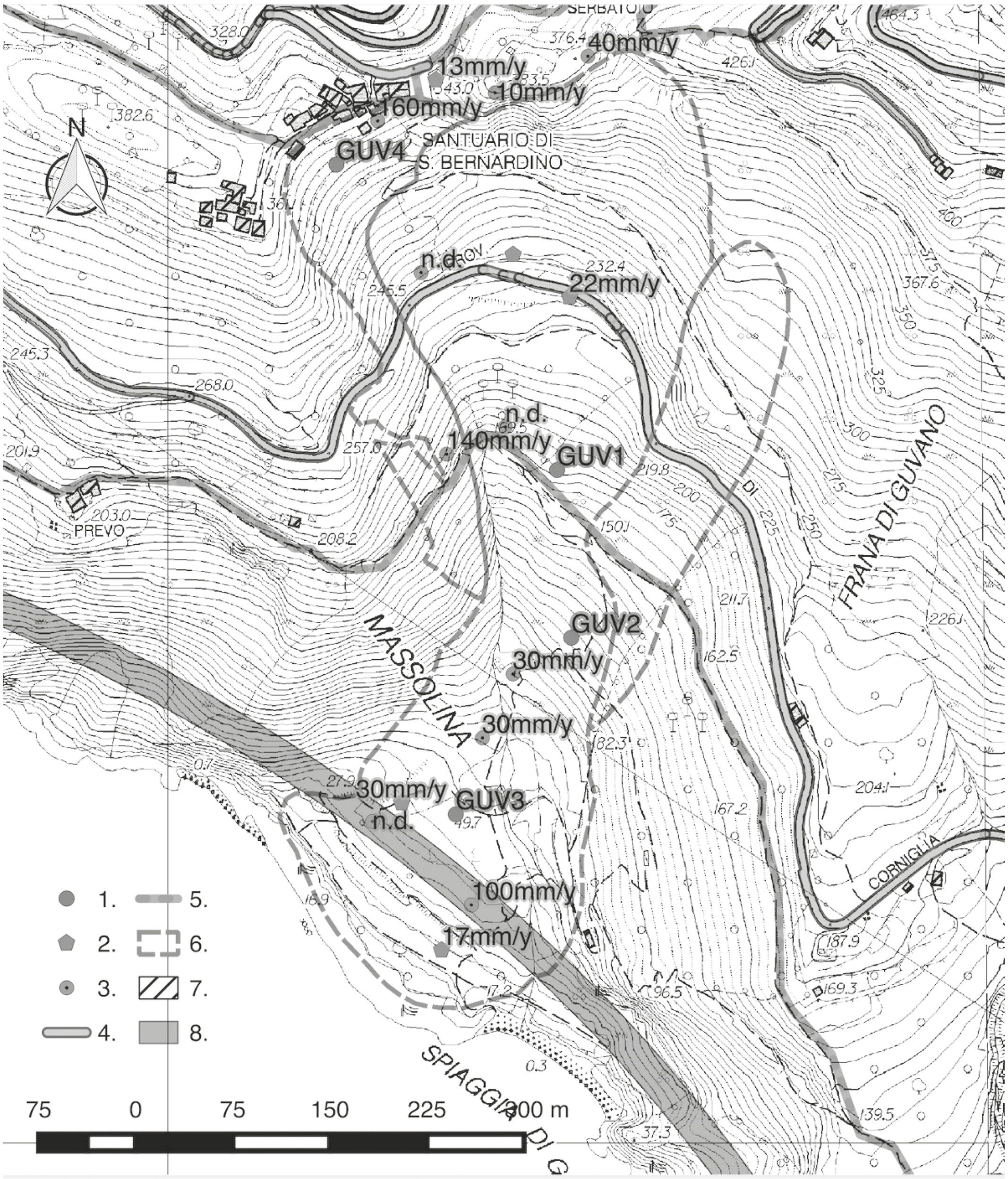

Fig. 8 - Slope dynamic sketch map: 1. GNSS sensors (2015-2016); 2. Inclinometers (2003-2004, after Eptaconsult s.c.r.l., 2004); 3. Topographic landmarks (2003-2004, after Eptaconsult s.c.r.l., 2004); 4. SP51 County Road; 5. SVA; 6. S. Bernardino-Guvano coastal landslide; 7. Urban areas; 8. Railway tunnel.

Tab. 1. Physical and mechanical parameters derived from laboratory tests during the 2003-2004 monitoring campaign (Eptaconsult, 2004). SC = Soil Sample; USCS classification: ML = silt, CL = low plasticity clay; S+G = sand + gravel fraction (percentage); M+C = silt + clay fraction (percentage); w_{nat} %: natural water content; LL % = Liquid limit (percentage); PI % = Plasticty Index (percentage); f’ (deg) = effective stress friction angle (degrees); C’ (kPa) = soil cohesion (KiloPascal); f_r (deg) = residual friction angle (degrees).

sample	USCS	S+G %	M+C %	w_{nat} %	LL %	PI %	f’ deg	C’ kPa	f'_r deg
S1C1	ML	57	43	5.7	30	7	34	13	22
S2C1	ML	65	35	4.3	29	5	39	28	25
S2C2	CL	60	40	8.9	30	10	37	16	22
S3C1	CL	56	44	14	33	16	24	8	16

The third rainfall regime is characterized by occasional precipitation (a total 40 mm recorded in two months) and shows a constant displacement rate at GUV3 (total of 0,75 cm towards South), while no relevant displacements have been recorded by GUV4 at the same time.

The displacement field is in agreement with previous knowledge (Eptaconsult, 2004), indicates a horizontal gradient of speed rates of 30mm/year.

Higher displacement rates registered by GUV3 sensor are directly related with residual strength: relationships between the j'r (residual friction angle) and soil property values are observable on table 1, where a direct correlation between the decreasing of j'r with increasing of Liquid Limit (LL), Plasticity Index (PI) and Clay Fraction (CF) (Kimura & *alii*, 2014) is evidenced.

Therefore, kinematics is mainly controlled by:

a) Rainfall regimes causing infiltration of precipitation and consequent changes in pore pressure and thus variations in excess shear stress controlling speed.
b) Intense landslide toe erosion caused by sea waves action, especially when generated by southwestern winds (Libeccio) which could reach a fetch length of 300 km and wave height up to 6 m.
c) Poor geotechnical properties especially along the middle-lower sector of the slope, where lower j'r coupled with higher LL, PI and CF values contribute to decrease the average residual strength of the sliding body.

CONCLUSIONS

The San Bernardino – Guvano area is therefore affected by landslides characterized by different size, geomaterials and failure speed: high intensity phenomena are concentrated along the road cuts and hiking trails, are triggered by intense and concentrated rainfall events and represent a threat for specific categories of elements at risk (e.g. hikers, cars, pedestrians); low intensity phenomena are here represented by the historical Guvano coastal landslide and in this case a different study approach was needed: on the basis of rainfall and surficial displacement monitoring from October 2015 to September 2016, the sliding body response to heavy rains and its effect on the slope movement were analyzed.

A landslide reactivation started at mid-June 2016 was observed after a prolonged rainfall period (200 mm cumulative rainfall along the same period) and the movement is still ongoing: the landslide is therefore to be classified as an active, extremely to very slow rotational slide.

Horizontal measures provided an accurate and precious feedback about the sliding body kinematics, while the vertical component of displacement has been affected by external, unmodeled geophysical effects that influence individual site positioning and depend also by the distance between base and rover stations: to reduce the RMSE (root mean squared error) affecting the positioning estimation (currently of the order of 1-5 mm), the baseline length is planned to be further shortened by installing a GNSS base station outside the landslide mass.

Since the activity of the landslide has been assessed through low-cost, GNSS monitoring, a network of wells equipped with piezometers and pressure-type water level gauges would be necessary to better understand the response of groundwater table and water pressure to heavy rainfalls and vertical infiltration of rainwater.

An alert system coupled with the 4 GNSS sensors would be extremely useful for a potential evacuation of the S. Bernardino village; further research will be carried out on the high intensity landslides affecting the SP51 County Road, the SVA and the relative elements at risk.

A proper risk mitigation program should be also carried out through adequate environmental policies considering also climatic change and its impact on rainfall regime. Restoring abandoned vineyard terraces and dry stone walls maintenance is mandatory to prevent effects caused by high intensity rainfall. In fact, terraced slopes are not only the main issue of Cinque Terre landscape but they represent moreover a fundamental factor to preserve geomorphological equilibrium modified along the centuries by human activities.

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