

SEISMICALLY INDUCED ACCELERATION OF DEEP-SEATED CREEP IN THE COMPLEX MONTE SARESANO LANDSLIDE

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EXTENDED ABSTRACT

La frana in roccia del Monte Saresano (Tavernola Bergamasca, BG, Lombardia), interessa un versante lungo cui attività di cava sono continuate per diversi decenni. Il dissesto è stato soggetto ad almeno tre riattivazioni storiche a partire dal 1900. Evidenze geomorfologiche, strutturali e geomeccaniche suggeriscono la presenza di un'instabilità che si estende verso monte ben più dell'attuale settore attivo. La pericolosità del fenomeno è legata alla attività sismica regionale e al disturbo antropico mentre l'elevato rischio è associato alla possibile propagazione verso valle e agli effetti generati da un impatto nel lago e alla conseguente onda anomala.

Nel febbraio 2021 una significativa accelerazione del movimento in seguito a un evento sismico di magnitudo locale ML = 2.2, circa 2 km a est del comune di Viadanica (BG) e circa 7 km a ovest del sito di frana. Le velocità di spostamento sono aumentate fino a 6.3-11.2 mm/gg immediatamente dopo l'evento, da un valore di fondo di circa 0.1-0.2 mm/gg, e fratture comparse lungo il perimetro del corpo di frana, interessando la viabilità. Successivamente a questa accelerazione, è seguita una fase di rallentamento progressivo, con debole influenza delle precipitazioni, limitata prevalentemente a movimenti superficiali.

Il presente studio integra i dati della rete di monitoraggio (attiva dal 2017), comprendente target ottici, ricevitori GNSS, estensimetri in foro, inclinometri, TDR, sonde multiparametriche e un sistema radar da terra. Una caratterizzazione geomeccanica dei materiali ha incluso prove di identificazione di materiali sciolti, prove triassiali e di taglio diretto sui materiali della zona di scorrimento basale, nonché prove di creep sul Calcare di Domaro. Le indagini composizionali (XRF, XRD, sezioni sottili) hanno definito le caratteristiche composizionali dei calcari e calcari marnosi.

L'integrazione di dati geofisici, stratigrafici e di monitoraggio ha evidenziato una dinamica complessa, caratterizzata da deformazioni distribuite lungo zone di taglio entro uno spessore significativo di brecce e ammasso roccioso fortemente danneggiato. Tali superfici di scorrimento isolano circa 2.6 milioni di m³, potenzialmente estendibili a 4.45 milioni di m³ se si include l'intero livello cataclastico basale (circa 10 metri). 50 stazioni di misura HVSR hanno consentito, la ricostruzione della profondità del corpo di frana mediante la calibrazione dei parametri nei punti dove stratigrafie e dati inclinometrici, erano disponibili.

Infine, la modellazione numerica tridimensionale agli Elementi Finiti ha consentito di analizzare l'evoluzione della stabilità del versante. Le analisi statiche e lo Strength Reduction Method hanno permesso di stimare i valori critici di coesione e angolo di attrito. I risultati numerici riproducono la profondità osservata della zona di scorrimento, suggerendo che una fratturazione diffusa e livelli cataclastici, derivanti da eventi di instabilità preistorici, e sfruttati sia durante le riattivazioni sia dalle perturbazioni antropiche, l'evoluzione recente della frana. L'evento sismico del febbraio 2021 ha agito come innesco per il settore del corpo di frana in condizioni critiche. Queste considerazioni supporteranno future strategie di mitigazione del rischio, nonché la progettazione e la validazione di interventi di stabilizzazione o più precisamente di riduzione dell'attività del fenomeno. Inoltre, nuovi dati provenienti dalla rete di monitoraggio e dalle prove geomeccaniche consentiranno lo sviluppo di modelli numerici più avanzati.

ABSTRACT

The Monte Saresano landslide (Tavernola Bergamasca, Italy), is a large rockslide (up to 4.5 million m³) along the slope of an old quarry, with at least three reactivation stages since 1900.

In February 2021, after a seismic event of ML=2.2 that occurred 2 km east of the municipality of Viadanica (BG) approximately 7 km west of the landslide site, the entire monitoring network has recorded a significant acceleration of the movement with displacement rate of 6.34-11.23 mm/day compared to 0.1-0.2 mm/day before the event.

This study uses a variety of approaches, through the analysis of monitoring data from a comprehensive monitoring network (active mostly since 2017), laboratory geomechanical characterization of the materials (UCS, TCS, BTS, LTS), compositional investigations (XRF, XRD, thin sections), geophysical and borehole data, has allowed the identification of 2.6 million m³ unstable mass, potentially extending to 4.45 million m³.

Using these results, a 3D Finite Element Analysis (FEA) was implemented to study the slope stability.

The numerical results, suggest the presence of widespread fracturing and severely weakened cataclastic levels developed from prehistorical activity. Such weakened planes have been reactivated by recent quarrying activities and the 2021 seismic event.

KEYWORDS: *rockslide, reactivation, low-magnitude earthquakes, integrated monitoring, geomechanics, long-term post-seismic creep, 3D Finite Element Analysis*

INTRODUCTION

Large rockslides characterized by continuous, slow, long-term activity, represent a critical risk for exposed areas, as they are highly sensitive to reactivation triggered by external perturbations. Consequently, it is fundamental to analyze these phenomena by collecting data on their geometries, geological and structural controls, current state of activity, and sensitivity to external factors (CHIGIRA, 1992; EVANS *et alii*, 2006). This generally requires extensive investigation and monitoring efforts, alongside the need to assess the susceptibility of these instabilities to human activities.

Earthquake-induced landslides are among the most hazardous secondary effects of strong seismicity in mountainous regions, and numerous previous events have shown their destructive capacity consequences (DELGADO *et alii*, 2011; LACROIX *et alii*, 2014; DELGADO *et alii*, 2015; GISCHIG *et alii*, 2015; LENTI *et alii*, 2015). The role of landslides as a key component of earthquake hazard has been long recognized, as demonstrated by the extensive body of literature devoted to seismic slope stability modeling approaches (JIBSON, 2011). However, for large, deep-seated landslides (volume > 100,000 m³), the use of simple index to represent seismic response may not provide sufficient information

to anticipate the probability of catastrophic failure (JIBSON, 2011).

In many deep-seated rockslides, deformation is governed by time-dependent processes that lead to progressive weakening of the rock mass and a persistent creep regime (CHIGIRA, 1992). Such rockslide may remain stable over long periods, and it can be temporarily modified by perturbations, including seismic shaking (KEEFER, 1984) and human activities. Indeed, monitoring studies have documented measurable displacement of creeping rock slopes to regional seismic events, even in the absence of catastrophic failure. These observations highlight the potentiality of seismic shaking to temporarily perturb ongoing time-dependent deformation processes in deep-seated instabilities. However, the mechanisms linking such perturbations to transient accelerations and the subsequent return to previous deformation rates are still not fully understood.

Assessing landslide hazard requires detailed information on landslide geometry, structural setting, and material properties, together with long-term monitoring capable of capturing both deformation regime and short-term responses. This is particularly challenging for deep-seated rockslides, where slip surfaces are often diffuse and located at depth within highly fractured and damaged rock masses (VAN ASCH, 1984).

This study focuses on the Monte Saresano rockslide, located in the Orobic Prealps along the western shore of Lake Iseo (Tavernola Bergamasca, northern Italy), which represents a well-instrumented natural laboratory for investigating long-term creep and its response to external perturbations. The slope experienced a marked acceleration in 2021 follow on a low-magnitude earthquake, superimposed on an already active slow-deformation regime. By integrating geological and geomorphological observations with long-term monitoring data, geophysical surveys, laboratory geomechanical tests, and three-dimensional numerical modelling, this paper aims to improve the understanding of the processes controlling creep-dominated deformation and seismic sensitivity in deep-seated rockslides.

Geological setting

The Tavernola-Monte Saresano area belongs to the Southern Alpine Domain, which represents the south-verging portion of the Alpine chain. This domain is characterized by a Paleozoic basement and a Permo-Mesozoic sedimentary cover, affected by fold and thrust systems.

The geological formations outcropping in the study area are (Fig. 1.a-b-c) (CASSINIS *et alii*, 2011):

- Domaro Limestone Formation (Upper – Lower Pliensbachian): pertains to the carbonate succession of the Sebino Basin, deposited in a basinal environment during the Lower Jurassic rifting phase. reaches a maximum thickness of approximately 300 m, thinning rapidly to the west.
- Villa Carcina Formation (Lower Toarcian – Aalenian):

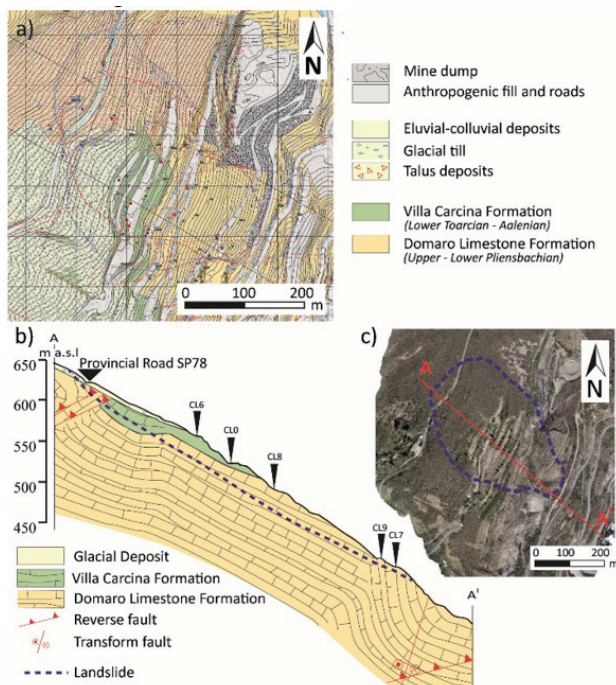


Fig. 1 - a) Geological map of the study area as from GEODES S.r.l. b) Geological cross-section A-A' crossing the Monte Saresano rockslide. c) Orthophoto showing the plan trace of section A-A' and the perimeter of the rockslide

in stratigraphic contact with the upper member of the DOM, it is composed of marls and grey calcareous marls, transitioning to coarse calcarenites and calcirudites with resedimented bioclasts. Total thickness of the formation ranges from 230 m to 270 m.

Mining activity

At the end of the 19th century, a large deposit of cement marl was identified along the slope of Monte Saresano, and the first industrial excavation and production plant were established. Between 1910 and 1935, quarrying activities underwent a major expansion, driven by the production of grey and white cement. Currently, the Ognoli quarry, located on the unstable slope, is inactive and activities are concentrated in the Ca' Bianca quarry, northwest of Monte Saresano, north of the Ognoli area. Here, excavation is carried out by blasting and hydraulic hammer excavators. The exploited rock belongs to the DOM (Domaro Limestone) and is characterized by an average CaCO_3 content of 72-75 %, SiO_2 of 20-22 %, Al_2O_3 of about 2% and MgO approximately 1 % (CASSINIS *et alii*, 2011). Digital Elevation Models (DEMs) of the slope were generated and analyzed by digitizing multiple topographic maps and processing recent surveys (1970, 1987, 2003, and 2013) (Fig. 2). A comparison of the DEMs indicates that excavation activities were mainly concentrated at higher elevations

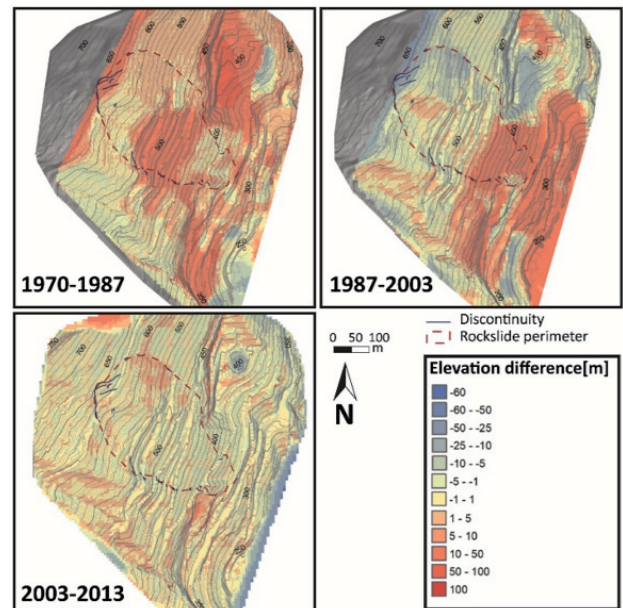


Fig. 2 - Topographic elevation changes derived from Different of Digital Elevation Models (DoD) analysis of DEMs for three quarrying activity period

during the 1970–1987 period, with an estimated excavated volume of approximately $3.5 \times 10^6 \text{ m}^3$. Between 1987–2003, excavation shifted toward the lower portion of the slope, with an estimated extracted volume of about $1.3 \times 10^6 \text{ m}^3$. In contrast, no significant topographic changes were detected during the 2003–2013 period (CASAGLI *et alii*, 2021). When quarrying was discontinued also because of slope instabilities past.

Historical instability events

As mentioned, throughout its history, the slope has been affected by several instability phenomena. The interpretation of the slope instability extending from the upper slopes of Monte Saresano (characterized by a rock scarp and an underlying talus deposit) down to the mid-slope, aerial photographs and topographic maps reveal a large where morphological evidence of movement is less distinct. Historical reports indicate the presence of fractures crossing unpaved roads at various elevations dating back to the early 20th century.

The first documented landslide occurred in the early 1950s, marked by the opening and closing of tension cracks between elevations of 510 and 520 m a.s.l. in the eastern sector (Fig. 4). Systematic monitoring of the “Ognoli Landslide” sector began in December 1970, following the detachment of approximately 40.000 m^3 of material between 363 and 670 m a.s.l. In 2010, a subsequent event involving an estimated volume of $20.000\text{-}25.000 \text{ m}^3$ occurred in the “Pinnacoli” area, at the toe of the Ognoli Landslide.

These movements preconditioned or probability were evidence of a regime of continuous, slow deformation. This trend

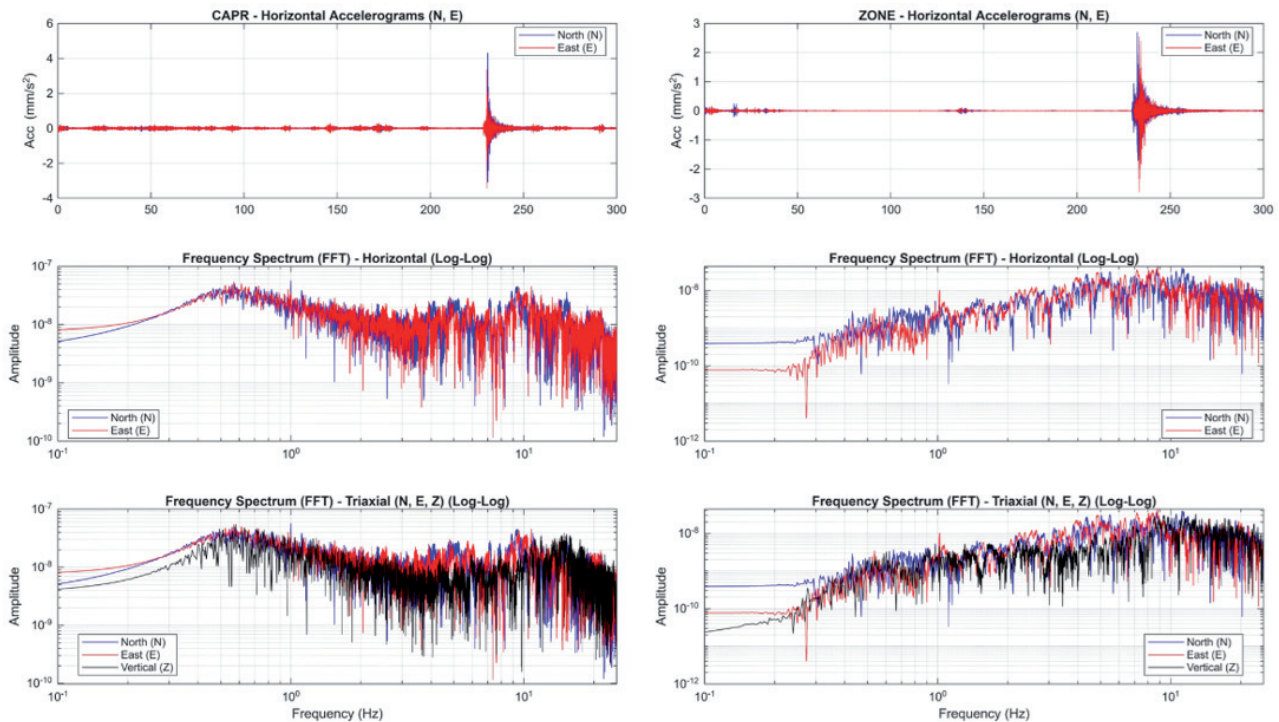


Fig. 3 - The ML 2.2 earthquake that occurred 2 km east of Viadanica (BG) on 16 February 2021 at 17:41:45 UTC, as recorded by the Capriolo (CAPR) and Zone (ZONE) seismic stations. a) Horizontal acceleration time histories. b) FFT of the horizontal ground motion components (N–E). c) FFT of the triaxial components (N–E–Z). The signals are characterized by very low amplitudes (PGA on the order of 10^{-4} g) and frequency content mainly concentrated in the ~1–10 Hz range, with limited energy at lower frequencies (<1 Hz). A slightly higher low-frequency contribution is observed in the E component. (data source: INGV)

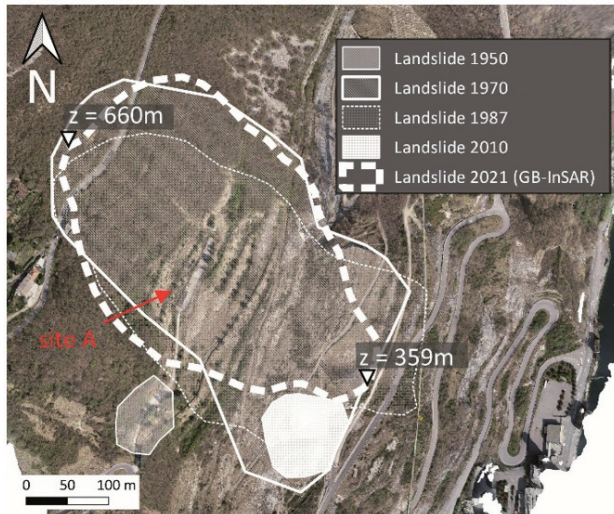


Fig. 4 - Orthophoto with the extent of the main instabilities recorded historically

persisted until 16 February 2021, when a ML 2.2 earthquake occurred approximately 2 km east of Viadanica (BG) and 7 km from Tavernola Bergamasca (Fig. 3). This seismic event triggered a marked acceleration in the displacement already rates recorded by the monitoring system at the site (Fig. 4).

Monitoring system

Given the persistent instabilities observed on the slope, a dense monitoring network was progressively established to define the spatial extent (both areal and at depth) of the mobilized mass and to track displacement rates. Initial monitoring activities began in 1970, when BROILI (1987) proposed and supervised the installation of crackmeters, multibase extensometers, and boreholes inspected via weighted probes to detect shear zone deformation (where the obstruction of the weight indicated borehole distortion and cracked shear zones).

The first modern instruments were installed in the 1990s (Surface Wire Extensometers), followed by the deployment of advanced supplementary systems, and the integration of existing instrumentation. Between May and June 2021, following the acceleration phase recorded in February 2021, a portion of the monitoring network (including surface wire extensometers, borehole extensometers, and inclinometers) was automated by equipping the instruments with electrical transducers and in-place probes for continuous data acquisition.

The monitoring system comprise the following instruments and installations (Fig. 5):

- Robotic Total Station (RTS) installed since June 2010, acquires the position of 56 optical prisms at hourly intervals.

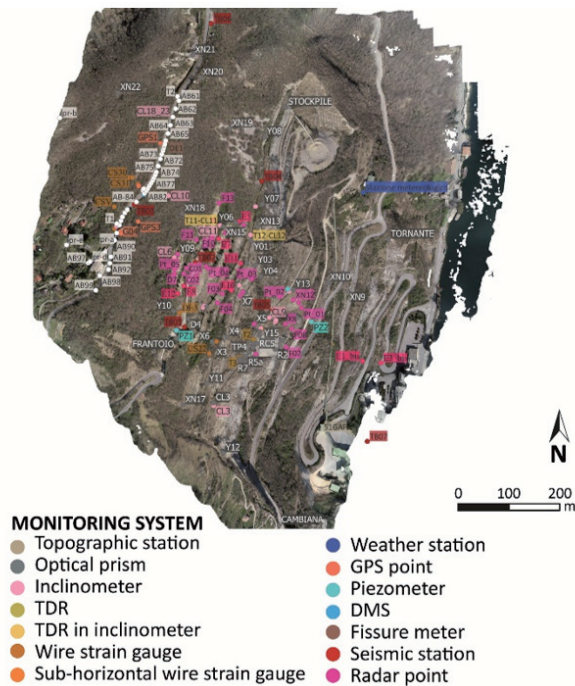


Fig. 5 - Orthophoto showing the location of the monitoring instrumentation

The number of prisms has been increased over the years to improve the spatial coverage of slope deformation.

- 42 levelling benchmarks (cornerstones) located along the SP78 road, monitored via monthly surveys.
- 20 inclinometer casings with depth ranging from 15 to 80 m provide manual measurements every two months, whereas some are equipped with fixed in-place probes for automatic continuous readings. Because of the long-term activity and the 2021 reactivation only three inclinometers remain active and measurable.
- 9 Time Domain Reflectometry (TDR) cables, 6 of which are coupled with inclinometer tubes.
- -8 sub-horizontal borehole extensometers (single-base or multi-base). Readings were initially taken monthly increasing to a weekly frequency starting in April 2004.
- 3 piezometers equipped with electrical sensors for continuous groundwater level monitoring.
- An 80m long multiparametric DMS column (CSG S.r.l.) located along the Provincial Road SP78. This system allows for remote access via dedicated software and simultaneously measures inclination, temperature, piezometric levels, and accelerometric events at 1 m depth intervals.
- 9 surface wire extensometers, installed in April 1990, originally read monthly, and automated since May 2021.
- A remote weather station providing continuous recording of air temperature and precipitation.

- 5 GPS-GNSS stations recording positions automatically every six hours.
- A surface crackmeter (DE1) installed along the valley side retaining wall of the SP78 road, featuring automatic readings and remote transmission.
- 7 microseismic stations installed in July 2021, allowing the collection of data on the landslide dynamic response to various stresses, including earthquakes, quarrying activities at the Ca' Bianca mine, and industrial operations of the cement plant.
- From September 2018 to January 2021, ten GB-InSAR (Ellegi S.r.l.) measurement campaigns were conducted with the station positioned at the mouth of the Rino stream. In February 2021, a LISALAB continuous Ground-Based Interferometric Synthetic Aperture Radar (GB-InSAR) station operated by Ellegi S.r.l. was installed next to the Tavernola municipal building.

While the analysis of the monitoring data allowed for the quantification of the volume mobilized during the acceleration phase of February 2021 (Fig. 7), they alone are insufficient to fully constrain the mechanisms linking the low-magnitude seismic perturbation to deep-seated slip, and to explain the processes responsible for the subsequent re-establishment of pre-event displacement rates.

METHODS AND RESULTS

To investigate the mechanisms controlling the post-seismic behaviour of the Monte Saresano landslide, an integrated methodological approach was adopted, combining laboratory geomechanical testing, geophysical investigations, borehole data, and three-dimensional finite element modelling.

Failure Surface Reconstruction

Stratigraphic logs from all available boreholes, alongside ground surface surveys and deep monitoring data, were utilized to reconstruct the 3D geometry of the failure surface.

This reconstruction was particularly challenging due to the significant thickness of the damaged rock mass and cataclastic zones identified in the cores, which made the precise localization of the sliding interface complex.

To improve the spatial resolution of the data points defining the failure zone (*i.e.*, the base of the active rockslide), a high-density HVSR (Horizontal-to-Vertical Spectral Ratio) (KANAI *et alii*, 1954; NOGOSHI & IGARASHI, 1971) monitoring campaign was conducted. Ambient noise measurements were acquired at 50 stations arranged on a grid covering both the active rockslide and the surrounding stable areas.

The depth estimation approach was based on a calibration procedure using 20 locations where borehole data were available to ground-truth the depth of the sliding surface. At these calibration points, the shear wave velocity (V_s) was back-calculated using the fundamental resonance frequency (f_0) derived

from HVSR and the known depth (H) from stratigraphy (using the relationship $V_s = 4 H f_0$) (NAKAMURA, 1989; NAKAMURA, 1996 a; NAKAMURA, 1996 b).

Subsequently, the calibrated velocity field was extrapolated to the nearest HVSR stations where no borehole data existed, allowing for the estimation of the failure depth at those locations. Finally, all depth data points were interpolated to generate the 3D surface using the mapped surface fractures as zero-depth constraints (Fig. 6).

The reconstructed failure surface allowed for the calculation, of the total active rockslide volume, which is estimated at approximately $2.13 \times 10^6 \text{ m}^3$.

In plan view (Fig. 6), the unstable mass is elongated, with its maximum width at the crown, gradually decreasing toward the toe. The toe of the landslide lies immediately above provincial road SP78 at an elevation of 362 m a.s.l. and is situated roughly 250 m above the lake shore.

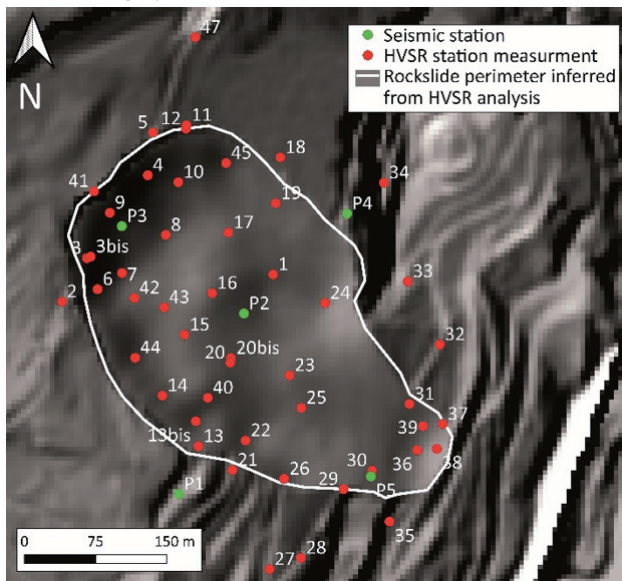


Fig. 6 - 2013 Digital Elevation Model (DEMs) excavated along the slip surface inferred from HVSR analysis

Monitoring time series

All instruments (topographic targets, inclinometers, TDR cables, extensometers, and GPS stations) recorded a slow but continuous deformation of the mobilized body over time, with displacement rates of a few millimeters per month.

Due to the February 2021 recent seismic acceleration, velocities increased from a rate of 0.1-0.2 mm/day to 6.3-11.2 mm/day, followed by a progressive deceleration phase that lasted approximately between March 2021 and February 2024 (Fig. 7.b).

Furthermore, the analysis of cumulative precipitation data shows no correlation between precipitation patterns and the observed acceleration phase. The increase in velocity in 2021 does not coincide with significant rainfall events, and

the cumulative rainfall curve remains uniform and constant throughout the period (Fig. 7.b). This indicates that the rapid acceleration phase was not caused by hydrologically factors.

Comparing the velocity during the steady state condition of different optical points, six groups were identified. According to these groups, the monitoring points are located within in the landslide to form a displacement magnitude field that decrease from the area close to the site A (Fig. 4) toward landslide toe (Fig.7.a-b).

Based on the analysis of displacement data recorded by the Robotic Total Station (RTS) for seven selected optical targets, the recent evolution history of the slope was divided into six stages according to kinematic response:

- Pre-2021 Event: Background velocity between 0.10-0.20 mm/day.
- 2021 Event: (20.02.2021 – 19.03.2021) Acceleration phase with velocity between 6.3-11.2 mm/day.
- Post-Event 1: (20.03.2021 – 19.06.2021) Deceleration phase with velocity between 1.57-2.88 mm/day.
- Post-Event 2: (19.06.2021 – 16.01.2022) Stabilization phase with velocity between 0.37-0.65 mm/day.
- Post-Event 3: (16.01.2022 – 23.02.2024) Long-term trend with velocity between 0.12-0.19 mm/day.
- Post-Event 4: (23.02.2024 – 01.12.2025) Recent trend with velocity between 0.16-0.30 mm/day.

The rockslide can be briefly summarized by considering the 2021 event as a rapid dynamic phase, followed by a slowing creep behaviour that characterizes all subsequent post-event phases.

GB-InSAR

Among the currently active monitoring instruments, one of the most significant for the landslide is a ground-based radar interferometric station (Ellegi S.r.l), installed close to the Tavernola Municipality building, previously positioned at the mouth of the Rino River until July 2021.

Initially, interferometric data were used for the planimetric delimitation of the mobilized body, as the instrument allows to determine, through systematic measurements, the displacements of significant areas of the slope characterized by electromagnetically reflective surfaces. By comparing the signal phases of two temporally separated acquisitions, from the same point, it is possible to derive the displacements of the points along the line-of-sight (LOS) direction.

As shown in Fig. 7, the boundaries between moving and stable areas are quite clear, especially in areas without vegetation.

The instrument also enables real-time analysis and monitoring of local movements, providing immediate information on slope behavior. A notable example occurred at the end of November 2025, when a portion of material above the site A area (Fig. 4) was mobilized during safety operations, allowing the evolution of the movement to be directly observed (Fig. 8).

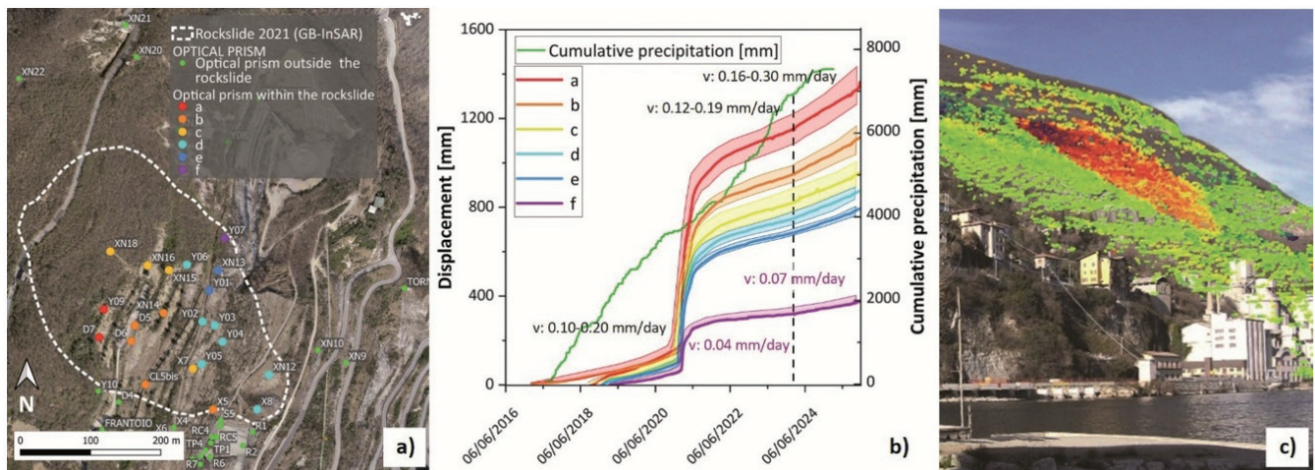


Fig. 7 - a) Orthophoto showing the positions of the optical prisms and the landslide perimeter; the optical sights within the landslide perimeter were grouped 6 families (a-f) with similar behavior. b) Displacement-time graph (Displacement [mm] vs. Date [dd.mm.yyyy]); the optical sights within the landslide perimeter were grouped into six families (a-f) with similar behavior. The cumulative rainfall curve is also reported and plotted on the left vertical axis. c) Cumulative displacement measured by radar interferometry (GB-InSAR) (Data source: Ellegi S.r.l.)

Geomechanical characterization

In order to identify the causes of variations in material behaviour, characterized by the alternation of slow creep phases and rapid dynamic phase, an experimental laboratory test campaign was conducted on intact rock specimens, samples from borehole cores at different depths.

The characterization of the rapid dynamic behaviour was carried out through 15 indirect tensile tests (Brazilian tests BTS), 9 uniaxial compression test (UCS) and 3 triaxial tests (TCS), under displacement-controlled conditions carried out on specimens with a diameter of 38 mm. The indirect tensile tests (Brazilian tests, BTS), performed according to ASTM D3967-23, did not show any variation in strength with depth, with stress tensile values ranging from 3.53 MPa to 16.94 MPa, and an average of 8.37 MPa.

Uniaxial compression tests (UCS) (ASTM D3148-02) were carried out using a GDS 250 kN VIS Axial Loading System and an Advantest 9 Rock – Sercomp 7 Rock.

All tested specimens exhibited high to extremely high strength, corresponding to Classes A and B in the DEERE & MILLER (1966) classification, with a maximum uniaxial compressive strength of 299.31 MPa and an extremely stiff mechanical response.

During the tests, two main failure modes were observed: an exploding type, characterized by violent fragmentation of the specimen, and a splitting type, marked by predominant longitudinal cracking (Fig. 9).

The multistage triaxial tests technique (ASTM D7012-23/ASTM D2664-04) used different confining pressures of 10 MPa, 20 MPa, 30 MPa, and 40 MPa. The results of axial and radial stresses were plotted on a normal stress–shear stress graph. The resulting Mohr-Coulomb failure, an average cohesion of 51 MPa and a friction angle of 37°. The friction angle and

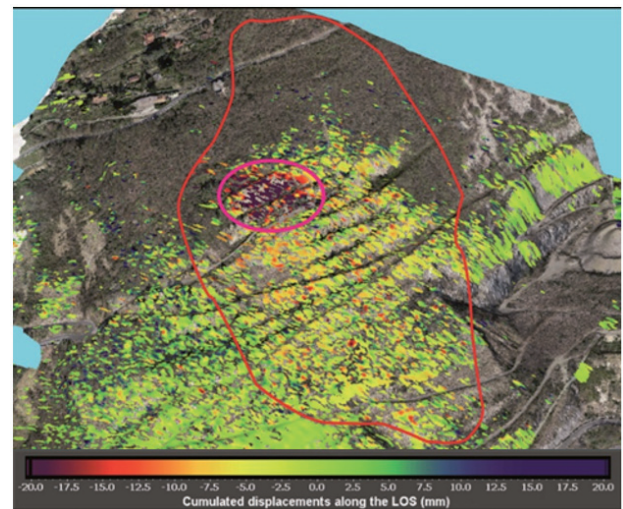


Fig. 8 - Cumulative displacement measured by ground base radar interferometry (GB-InSAR) for the period 01/11/2025 to 01/12/2025 (Data source: Ellegi S.r.l.) The red line represents the perimeter of the rockslide detected by radar in 2021. The acceleration recorded in the site A area in November 2025 is highlighted in purple

high cohesion suggest good mechanical performance, typical of compact rocks with brittle-to-friable behavior. Two creep tests were carried out to characterize behaviour under constant load over time. Due to the high variability observed in uniaxial tests, the first test was performed by applying incremental load steps, each followed by a period of constant load.

The test lasted a total of 96 days and ended with a highly explosive failure during the 230 kN loading step. Analyzing the displacement velocity rates for a sample of five stress steps (from 19 MPa to 209 MPa) highlights a gradual increase in displacement velocity (Fig. 10a).

Borehole	Depth of sampling [m]	Porosity [%]	σ_c [MPa]	E_{50} [GPa]	Poisson Ratio
CL18_23	2.85	0.53	94.3	23.6	0.14
CL19_23	3.10	3.59	146.2	12.4	0.33
CL21_23	3.35	1.89	193.8	17.2	0.33
CL21_23	3.60	1.07	61.6	15.9	-
S01_22	48.8	1.15	299.3	41.9	0.3
S01_22	62.25	1.18	207.1	59.9	0.37
S01_22	62.25	3.15	187.9	13.9	0.36
S01_22	66.80	1.81	73.1	48.6	0.1
S01_22	76.85	4.34	111.3	26.9	-

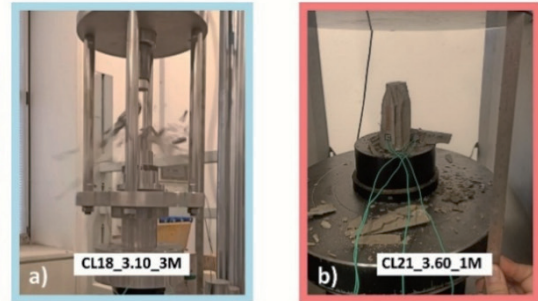


Fig. 9 - Table with results of UCS tests. The specimens highlighted in red they had a splitting type of breakage (a) and the specimens highlighted in blue had an explosive fragmenting breakage (b)

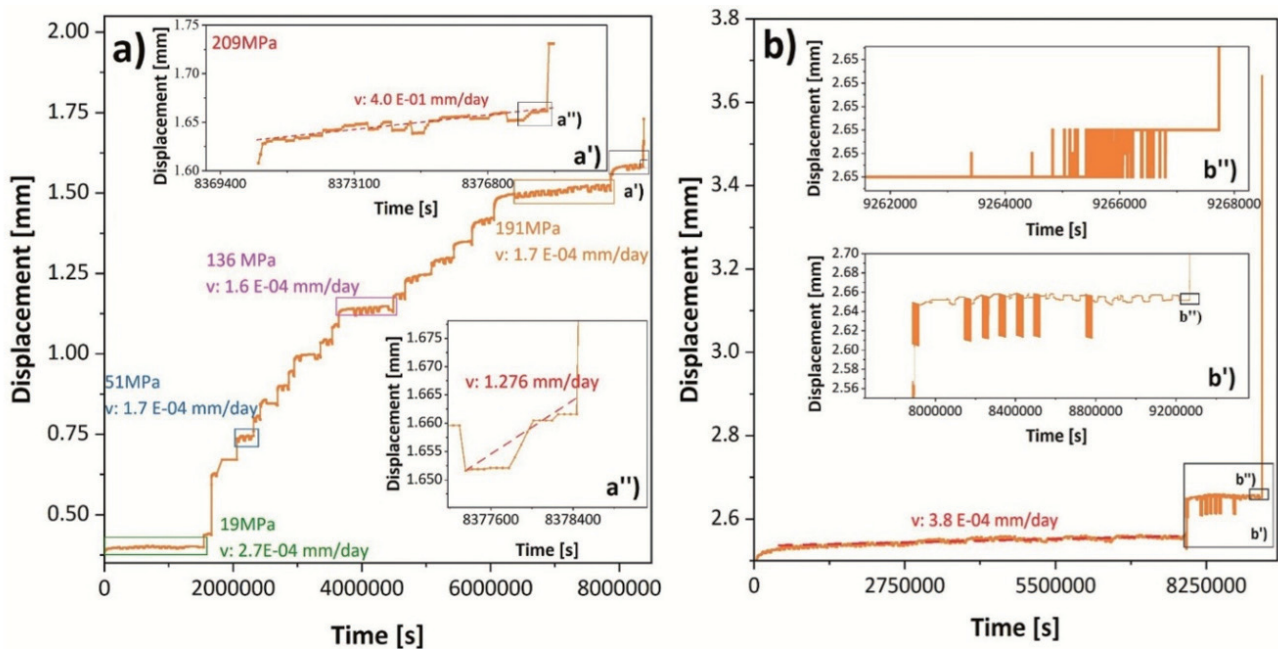


Fig. 10 - a) Creep experiment using load steps, with five selected load levels (between frame) with computed velocity. b) Creep experiment at constant load 240 kN. In b') the last portion of the test with the loading and unloading and in b'') the last fraction before the explosive fragmentation

The second creep test was performed by subjecting the specimen to a constant load of 240 kN for 92 days, after which it was subjected to 222 loading–unloading cycles (Fig. 10b). Each cycle consisted of unloading down to 230 kN for 5 minutes, followed by reloading to 240 kN in 5 minutes, and then maintaining a constant load of 240 kN for 10 minutes (Fig. 10b). After the completion of the cycles, the specimen was kept under a 240 kN constant load of until its explosive failure, which occurred 15 days after the cycling phase, resulting in a total test duration of 107 days. From the results obtained from both tests, it was not possible to clearly identify the three classical phases of a creep failure. This suggests that the micro-damage accumulation not sufficient to be detected by the testing machine (which primarily recorded thermal oscillations of the frame) until a critical threshold was reached, at which point the material rapidly collapsed, evolving into an explosive failure.

Finite element modelling

A Digital Elevation Model (DEM) incorporating the full thickness of the weak shear zone, developed by borehole stratigraphy and the HVSR results, intersecting with the topography of a 2013 DEM, providing a detailed representation of the potential failure geometry. The surfaces thus generated were imported into the MIDAS FEA software, where the finite element volumes and meshes were constructed. To enhance computational efficiency, the main volume was subdivided into two sub-volumes: the basal volume was assigned a coarser mesh to reduce the total number of elements, while the volume near the potentially unstable zone was meshed more finely to improve the accuracy of the results in the critical region.

For this reason, the volume was divided into three sub-volumes: a lower base with 16.166 nodes and 66.582 mesh elements with an element size of 40 m; an upper base with

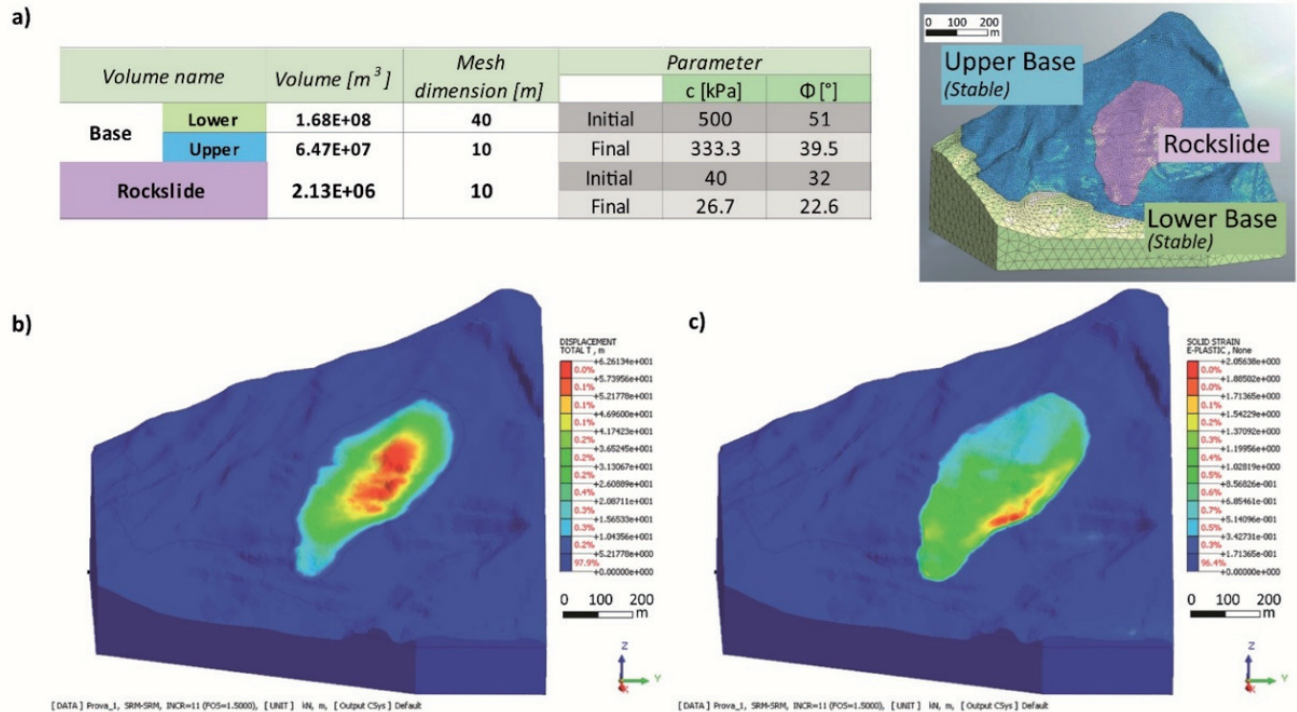


Fig. 11 - a) Summary table of input parameter values entered at the start of numerical processing and their values reduced after calculating the SRF for each volume of the model. b) Representation of the Total Displacement at the end of SRM processing. c) Representation of the Solid Plastic Strain at the end of modelling step

78.863 nodes and 417 .310 mesh elements with an element size of 10 m; and a rockslide volume with 3951 nodes and 15130 mesh elements with an element size of 10 m. All materials were modelled as isotropic and elastoplastic, described using the Mohr–Coulomb constitutive model. Boundary conditions, including constraints and gravitational loads, were applied to simulate the in-situ stress state of the slope. The factor of safety was estimated using the Strength Reduction Method (SRM), in which cohesion and friction coefficient are progressively reduced until the numerical model can no longer reach a stable equilibrium solution, thereby identifying the potential failure mechanism and the critical slip surface (Fig. 11a). Preliminary results highlight the location of plastic zones and emphasize the sensitivity of slope stability to variations in material parameters, providing a quantitative basis for further analysis and risk assessment (Fig. 11c). It is noteworthy that, in the representation of the total displacement, the central portion of the volume is predominantly mobilized, and its pattern appears consistent with the displacements observed in radar imagery (Fig. 11b).

CONCLUSION

This study shows that the Monte Saresano landslide can be interpreted as a deep-seated, structurally complex gravitational

system already close to critical equilibrium conditions before the event. The data indicate that the slope is affected by distributed deformation, extending down to a continuous and mechanically weakened cataclastic level.

The results demonstrate that the landslide body was already in a metastable equilibrium state where perturbation of a low-magnitude proximal seismic event (ML 2.2) was sufficient to induce a marked acceleration, without leading to a transition to rapid collapse. The subsequent return to near-background velocities suggests the establishment of a long-term post-seismic creep regime, controlled mainly by progressive damage processes. Highlighting how the seismic event influenced the behavior of the slope in the long term.

The integration of monitoring data, HVSR geophysical surveys, and stratigraphic information enabled a consistent reconstruction of the three-dimensional geometry of the slip surface, significantly reducing uncertainties in the depth and extent of the unstable volume. The results indicate that the shear surfaces are not localized along a single, well-defined plane, but instead develop within a zone of highly fractured and cataclastic rock, inherited from prehistoric instability phases and subsequently reactivated and exploited by both mining activity and seismic stresses.

Geomechanical test results indicate, despite the high strength of

intact limestones, a creep behaviour and brittle response suggesting that microscale level a damage accumulation over time, which plays a key role in controlling the landslide dynamics.

Three-dimensional numerical modelling simulates plastic deformation zones and the obtained displacement patterns agree with that observed by radar and topographic monitoring systems.

Overall, this study highlights that the Monte Saresano landslide is governed by a delicate balance between structural setting, accumulated damage, and external environmental drivers. This makes essential an integrated approach between experimental and numerical data for long-term to assess risk and design of mitigation strategies aimed at reducing landslide activity.

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