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SYSTEMATIC APPLICATION OF PHOTOMONITORING FOR LANDSLIDE SURVEILLANCE IN ITALY: FIRST RESULTS FROM THE GEOSCIENCES IR PROJECT

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EXTENDED ABSTRACT

Questo studio presenta i risultati della prima applicazione sistematica del fotomonitoraggio per la sorveglianza di frane su scala nazionale, condotta nell'ambito del progetto PNRR Infrastrutture di Ricerca (IR) "Geosciences IR". Tra gennaio 2024 e giugno 2025 sono stati monitorati tredici siti franosi distribuiti sul territorio italiano, rappresentativi di diverse tipologie di movimento: deformazioni gravitative profonde di versante (DGPV), colate in terra, crolli in roccia e falesie costiere. La rete di monitoraggio ha impiegato 15 camere, incluso un sistema UAV, implementando strategie differenziate sui 13 siti di studio: monitoraggio continuo con frequenza oraria (8 siti), campagne periodiche (5 siti) e analisi di immagini da webcam dei servizi geologici disponibili in archivi storici (2 siti). Le immagini acquisite sono state elaborate mediante il software IRIS (NHAZCA S.r.l.), applicando algoritmi di change detection per fenomeni rapidi e digital image correlation per deformazioni lente.

Il dataset generato comprende oltre 150,000 immagini (390 GB) acquisite lungo un range di distanze sensore-target da 50 m a oltre 1000 m. L'analisi mediante change detection ha identificato e catalogato 1235 cluster legati a fenomeni gravitativi, con dimensioni variabili su cinque ordini di grandezza (0,007-2080 m²). La digital image correlation ha quantificato spostamenti cumulativi su diverse scale temporali, da deformazioni estremamente lente caratteristiche delle DGPV fino a riattivazioni rapide documentate nelle colate in terra.

La validazione quantitativa, condotta presso il sito di Baldiola confrontando le serie temporali di spostamento ottenute dal fotomonitoraggio con misure geodetiche da stazione totale robotizzata, ha prodotto coefficienti di correlazione elevati ($r = 0,831-0,999$; media 0,966; $p<0,001$), dimostrando accuratezza comparabile alle tecniche geodetiche convenzionali. L'analisi delle correlazioni con variabili meteorologiche ha confermato meccanismi di innesco coerenti con quanto riportato in letteratura per fenomeni analoghi: precipitazioni per Baldiola. L'analisi DIC a La Saxe ha documentato pattern di accelerazione stagionale coerenti con meccanismi di fusione nivale precedentemente descritti per questo sito. A Poggio Baldi, l'acquisizione oraria ha permesso di documentare pattern precursori, con micro-crolli localizzati in prossimità spaziale e temporale rispetto a collassi maggiori, aprendo prospettive per lo sviluppo di sistemi di allertamento precoce.

L'analisi comparativa delle performance ha evidenziato la netta superiorità dei sistemi fissi rispetto ai monitoraggi periodici in termini di risoluzione temporale, complessità analitica e qualità dei risultati. I requisiti tecnici ottimali prevedono camere con risoluzione minima di 8 MP e alimentazione elettrica continua. Questo studio dimostra che il fotomonitoraggio è una tecnica matura e affidabile per applicazioni operative di sorveglianza franosa, in grado di fornire dati quantitativi con accuratezza confrontabile alle tecniche tradizionali a costi contenuti. La scalabilità dimostrata in termini di distanza sensore-target e la capacità di rilevamento multi-scala rendono il fotomonitoraggio uno strumento strategico per ampliare le reti di monitoraggio sul territorio nazionale, dove al 01/01/2026 solo circa 1.200 delle 636,000 frane censite IFFI risultano monitorate.

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ABSTRACT

This study presents results from the first systematic evaluation of Photomonitoring techniques for landslide surveillance at national scale, conducted within the PNRR "Geosciences IR" project. Between January 2024 and June 2025, thirteen landslide sites across Italy were monitored using 15 cameras, including a UAV system. Change detection analysis identified 1235 gravitational events spanning five orders of magnitude (0.007–2080 m²). Quantitative validation at Baldiola earthflow against robotic total station measurements yielded correlation coefficients of r = 0.831–0.999 (mean 0.966), demonstrating accuracy comparable to conventional geodetic techniques. Meteorological correlation analysis at Baldiola confirmed rainfall-triggered mechanisms (r > 0.973) consistent with previous studies, while seasonal acceleration patterns at La Saxe aligned with documented snowmelt-driven processes. Fixed camera installations demonstrated superiority over periodic monitoring approaches that suffer of changes in lighting conditions and large variations in the scene (*e.g.* snow or vegetation coverages). This study establishes Photomonitoring as a cost-effective technique for operational landslide surveillance.

Keywords: *Photomonitoring, landslide monitoring, image analysis, validation*

INTRODUCTION

The IFFI (Inventario dei fenomeni franosi in Italia) inventory catalogues over 636000 landslides across Italy, yet approximately 1200 are subject to systematic instrumental monitoring (Trigila *et alii*, 2021; ISPRA, 2023). This significant gap reflects the high costs of conventional monitoring approaches requiring expensive instrumentation, specialized personnel, and ongoing maintenance commitments (Scaioni *et alii*, 2014; Casagli *et alii*, 2017; Dei Cas *et alii*, 2022).

Photomonitoring exploits digital image processing algorithms applied to optical imagery for landslide surveillance. The technique encompasses two complementary approaches: change detection (CD) identifies pixel appearance or disappearance corresponding to discrete events such as rockfalls or debris movements, while digital image correlation (DIC) tracks pixel displacement patterns to quantify continuous surface movements (Mazzanti *et alii*, 2015; Cosentino *et alii*, 2024). Camera-based systems can be positioned at safe distances from unstable slopes while providing wide-area coverage from single monitoring points, representing a significant advantage over point-based instrumentation.

Previous studies demonstrated Photomonitoring effectiveness at individual sites. Travelletti *et alii* (2012) presented a low-cost methodology using normalized image correlation on the Super-Sauze landslide (French Alps), validating results against differential GPS. Stumpf *et alii* (2015) investigated multi-view photogrammetry accuracy for 3D surface reconstruction and change detection. Gance *et alii* (2014) developed target detection and tracking methods for characterizing landslide displacements from time-lapse imagery. Kromer *et alii* (2017) demonstrated rockfall detection capabilities using terrestrial laser scanning combined with optical imagery. Mastrantoni *et alii* (2024) developed an automatic Photomonitoring workflow for spatiotemporal evaluation of rockfall hazard at Poggio Baldi; the same research group further explored the integration of UAV photogrammetry and photomonitoring for rockfall hazard assessment along transportation infrastructure (Mastrantoni *et alii*, 2025). However, systematic evaluations across diverse geological contexts and monitoring strategies have remained lacking before the present study.

This research was conducted within Work Package 3.2 of the GeosciencesIR project, funded through PNRR Mission 4, with Sapienza University of Rome as key partner. The objectives were: (*i*) to assess Photomonitoring performance across different landslide typologies and geological settings throughout Italy; and (*ii*) where independent measurements were available, to quantitatively validate displacement accuracy and verify detection of established landslide-climate triggering relationships.

MONITORING NETWORK AND STUDY SITES

The monitoring network encompasses fifteen cameras on thirteen sites distributed across Italy, representing diverse mass movement typologies (Fig. 1a, Table 1). Site selection prioritized diversity in landslide mechanisms to ensure comprehensive evaluation of Photomonitoring capabilities across different geological and geomorphological contexts.

The Alpine environment includes six sites: Mont-de-la-Saxe deep seated gravitational slope deformation (DSGSD) (Courmayeur, province of Aosta, Valle d'Aosta region), monitored through historical webcam archives spanning 2014–2022; Gollone landslide (Acceglio, province of Cuneo, Piedmont region), a complex mass movement with active rockfall processes; Monte Rosa (Macugnaga, province of Verbano-Cusio-Ossola, Piedmont region) for high-altitude periglacial environments; Ruinon rockslide (Valfurfa, province of Sondrio, Lombardy region), monitored through regional webcam archives; Scaiùn landslide (Val Masino, province of Sondrio, Lombardy region); and Cercevesa DSGSD (Paularo, province of Udine, Friuli-Venezia Giulia region).

The Apennine environment contributes with four sites: Poggio Baldi (Santa Sofia, province of Forlì-Cesena, Emilia-Romagna region), a remote sensing natural laboratory managed by Sapienza University since 2021 and continuously monitored since approximately 2016 (Romeo *et alii*, 2021), hosting an active rockfall source within the Marnoso-Arenacea Formation; Baldiola earthflow (Montese, province of Modena, Emilia-Romagna

Site	Province	Lithology	Type	Strategy
Mont-de-la-Saxe	Aosta (AO)	Argillaceous schist	DSGSD, Complex	Archive
Gollone	Cuneo (CN)	Metavolcanic rocks, quartzitic conglomerates, dolomitic marbles, calcschists	Complex	Continuous
Monte Rosa	Verbania Cusio Ossola (VB)	Gneiss, schists	Fall/topple, rapid debris flow	Periodic
Ruinon	Sondrio (SO)	Metapelites, metabasites, marbles, glacial deposits, rock glacier formations	DSGSD	Archive
Scaiùn	Sondrio (SO)	Metamorphic rocks	Fall/topple	Continuous
Cercevesa	Udine (UD)	Limestones, mudstones	DSGSD	Continuous
Poggio Baldi	Forlì Cesena (FC)	Pelitic-arenaceous turbiditic sequences	Complex	Continuous
Baldiola	MO	Clay-sandstone alternations	Slow earth flow	Continuous
Torgiovannetto	Perugia (PG)	Limestone with clay interlayers	Fall/topple	Continuous
Acuto	Frosinone (FR)	Limestones	Fall/topple	Continuous
Castellaro	Genova (GE)	Clasts of marly limestone, calcareous sandstone, ophiolites, gneiss, granites, marly limestone beds intercalated with black schistose clay levels	Fall/topple	Periodic
Porto Empedocle	Agrigento (AG)	Sandy-clayey silts, marly sands, biocalcarenites, marly silty clays	Fall/topple	Periodic
Calvello	Potenza (PZ)	Clay shales, Calcarenites, marls	Slow earth flow	Continuous

Tab. 1 - Summary of monitored sites

region), one of the most active slow-moving landslides in the Northern Apennines with displacement rates reaching meters per day during reactivation phases; Torgiovannetto quarry (Assisi, province of Perugia, Umbria region); and Acuto field laboratory (Acuto, province of Frosinone, Latium region), dedicated to methodological development in limestone cliff environments.

Coastal environments are represented by Castellaro cliff at Camogli on the Portofino Promontory (province of Genova, Liguria region), a flysch sequence outcropping in a sub-vertical slope subject to episodic failures and marine erosion, and Porto Empedocle (province of Agrigento, Sicily region) with soft rock cliffs experiencing progressive erosion. The Appennine environment also extended to Southern Italy, represented by Calvello earthflow (province of Potenza, Basilicata region).

MATERIALS AND METHODS

The monitoring network employed five camera system types selected according to site-specific requirements including

Camera	Resolution	Sites	Field of View (°)	Mean distance (m)	GSD (cm/pixel)
FlatMesh 4G Senceive	6 MP	Scaiùn, Cercevesa, Calvello	35	250-400	4-17
Canon EOS R6 + TBOX	20 MP	Baldiola, Torgiovannetto	38	120-800	3-22
Timelapse Lab TLA8	12 MP	Poggio Baldi	40	~400	~9.5
MOBOTIX S74	8 MP	Acuto, Poggio Baldi,	30	50-400	0.8-4
MOBOTIX M73	8 MP	Gollone	8 - 30	1000	3.6-15.6
GigaPan Epic Pro V	24 MP (single frame)	Porto Empedocle, Monte Rosa	4.5 (single frame)	100-800	0.4-2
DJI Mini 2		Castellaro	83	50	3

Tab. 2 - Camera systems deployed in the monitoring network

accessibility, power availability, connectivity, and required spatial resolution (Fig. 1b,c and d, Table 2).

Sensor-target distances ranged from 50 m (Acuto) to approximately 1000 m (Gollone). Ground Sample Distance (GSD) values ranged from 0.8 cm/pixel at close-range installations to more than 25.0 cm/pixel at maximum distances. Drone surveys at Castellaro cliff utilized a DJI Mini 2 for orthophoto generation through Structure-from-Motion processing.

All image processing was performed using the IRIS software platform (NHAZCA S.r.l.; Cosentino *et alii*, 2024). Change Detection (CD) algorithms identify modifications between temporally separated images through pixel-by-pixel comparison based on the Structural Similarity Index (SSIM; Wang *et alii*, 2004), detecting appearance or disappearance of material corresponding to rockfalls, debris movements, or erosion processes. Detected changes are grouped into spatial clusters with dimensions computed from pixel counts and GSD values. Digital Image Correlation (DIC) quantifies continuous surface displacements through sub-pixel tracking of textural features across image sequences, generating displacement vectors for successfully tracked regions. The implementation employs the GeFolki optical flow algorithm (Brigot *et alii*, 2016) with iterative refinement. SSIM-based filtering was also applied for automated quality assessment, enabling systematic identification of frames suitable for quantitative analysis while excluding images affected by adverse weather, illumination changes, or camera displacement. All results are systematically uploaded to ISPRA's IdroGEO platform for nationwide dissemination to stakeholders (https://idrogeo.isprambiente.it).

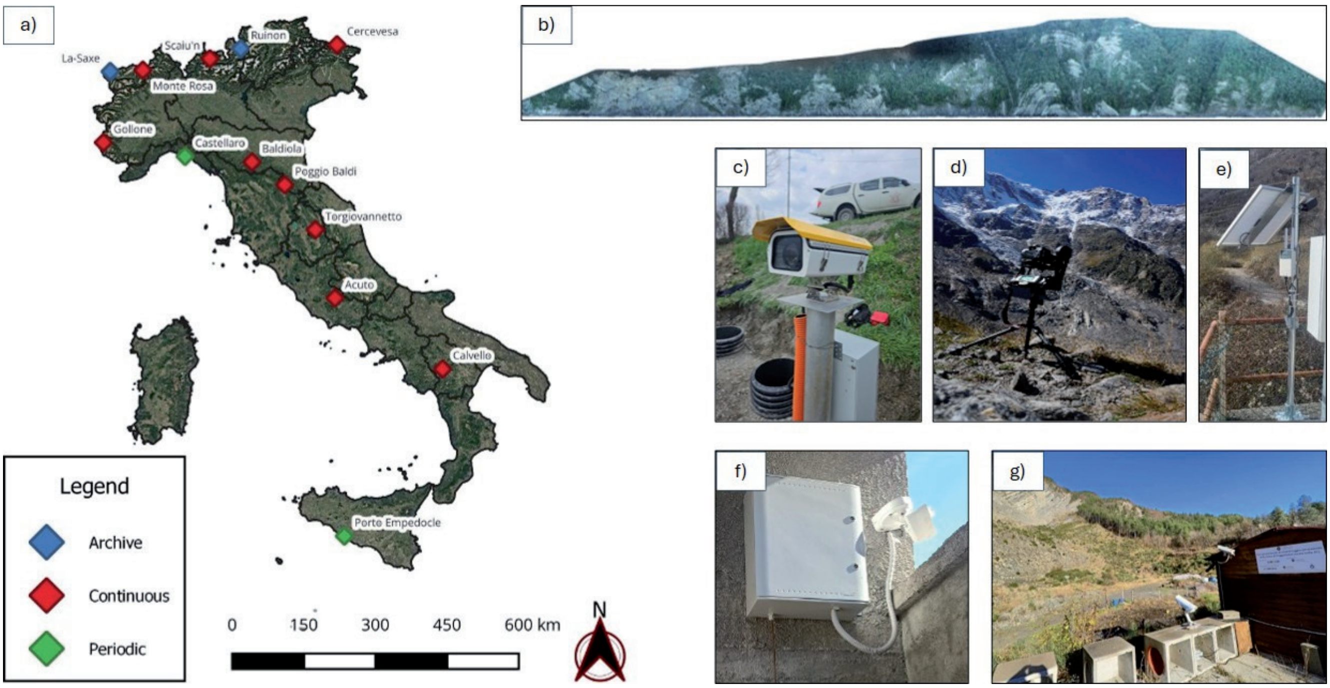

Fig. 1 - Photomonitoring network overview and camera systems deployed across Italy. (a) Location map of the thirteen monitoring sites, with symbols indicating monitoring strategy: archive-based (blue diamonds), continuous fixed installations (red diamonds), and periodic surveys (green diamonds). Landslide typologies are detailed in Table 1. (b) Orthophoto acquired through UAV survey at Castellaro cliff on November 17, 2023. (c) TBOX and Canon EOS R6 system installed at Baldiola earthflow. (d) GigaPan Epic Pro V robotic panoramic system during periodic survey at Monte Rosa. (e) FlatMesh 4G (Senceive) autonomous camera at Scaiùn. (f) MOBOTIX M73 dual-lens telephoto system at Gollone. (g) Timelapse Lab TLA8 camera at Poggio Baldi field laboratory

Quantitative validation was performed at Baldiola through comparison with robotic total station measurements operated by the University of Modena and Reggio Emilia (Lelli *et alii*, 2025). Statistical assessment employed Pearson correlation coefficients and coefficients of determination (R^2) on normalized displacement time series. Meteorological correlation analysis, performed at Baldiola and La-Saxe, utilized daily precipitation and snow depth records from nearby weather stations, with correlations computed on either normalized or cumulative displacement series depending on site-specific characteristics.

RESULTS AND DISCUSSION

The campaign generated over 150,000 images totalling approximately 390 GB over the 18-month observation period. Fixed camera installations contributed 67,655 images (217.4 GB). Network performance varied across sites: nine sites (Acuto, Camogli, Baldiola, Gollone, Poggio Baldi, La Saxe, Ruinon, Porto Empedocle, Cercevesa) achieved satisfactory to excellent results with consistent data acquisition and meaningful quantitative outputs; two sites (Torgiovannetto, Scaiùn) experienced significant operational challenges but still provided useful data; while two sites (Calvello, Monte Rosa) yielded only qualitative results or faced substantial limitations preventing quantitative analysis. Systematic CD analysis identified 1235 gravitational event clusters spanning five orders of magnitude (0.007–2080 m²). DIC extracted displacement time series revealing rates from cm/year to m/day. It is noteworthy that in two specific cases (Acuto and Poggio Baldi), the combination of a short sensor-target distance and high camera resolution allowed for the detection of very small areal changes at the centimetric scale. Although these sub-metric events may in some cases represent superficial weathering or raveling phenomena rather than true rockfalls, they share common characteristics with small-scale gravitational events and can potentially act as precursory indicators of larger failures, as documented at Poggio Baldi (see below). Therefore, for the purpose of this study, they were maintained in the overall cataloging of gravitational event clusters.

At Poggio Baldi, two monitoring systems were deployed approximately 350–400 m from the rockwall: a MOBOTIX S74 and a Timelapse Lab TLA8. The main MOBOTIX area investigated, the Region of Interest A (ROI A), covers the upper-right sector of the slope, characterized by alternating marl and sandstone units of the Marnoso-Arenacea Formation. CD analysis over 482 days (March 2024–June 2025) identified 958 rockfall events in ROI A, with GSD of 1.8–1.9 cm/pixel and dimensions from 12 cm² to approximately 14 m² (Fig. 2b).

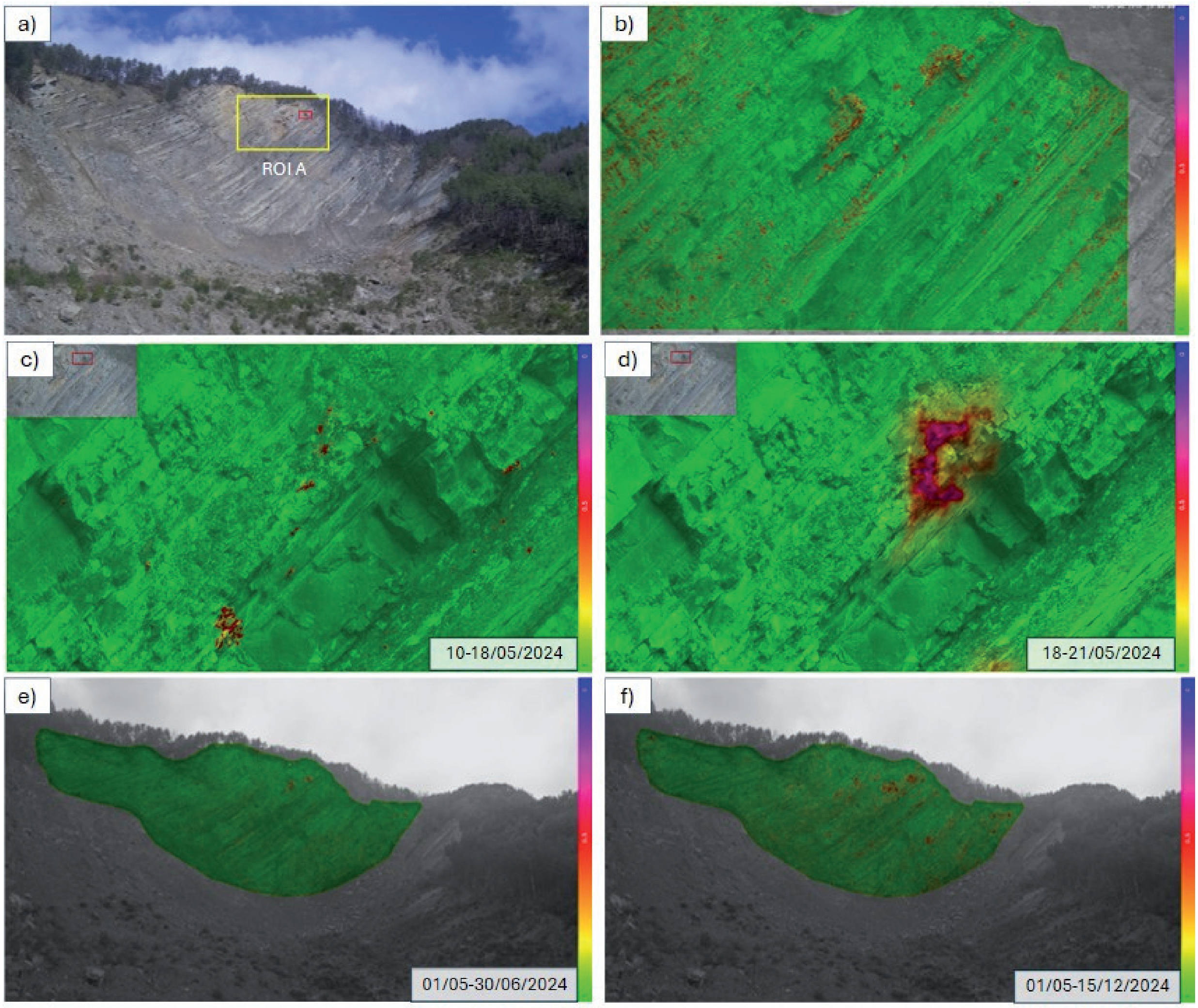

Fig. 2 - Poggio Baldi monitoring results. (a) TLA8 overview image; yellow box indicates MOBOTIX S74 ROI A, red box shows area detailed in (c,d); (b) Cumulative CD map showing 958 rockfall events in ROI A (May–July 2024); (c) Precursor rockfalls (May 10-18, 2024); (d) Major collapse (May 21, 2024) in same area as (c), demonstrating progressive failure; (e) TLA8 CD result (May 1–June 30, 2024); (f) TLA8 CD result (May 1–December 15, 2024) showing 115 total events

Fig. 3 - Poggio Baldi monitoring data on ISPRA's IdroGEO platform. CD analysis (November 25, 2024) uploaded to the national platform (Trigila et alii, 2026), showing detected gravitational events with spatial distribution. The interface allows consultation by the technical community, exemplifying the data dissemination workflow applied across all monitored sites

The most significant MOBOTIX activity occurred between May 7 and July 7, 2024. Several smaller events proved to be precursors of larger collapses, occurring in spatial and temporal proximity (hours to days) and consistently localized along margins or within eventual failure zones (Fig. 2c,d). The TLA8 system (Fig. 2a) provided complementary large-scale monitoring with coarser resolution (GSD ~5 cm/pixel, minimum detection threshold 0.036 m²) but broader coverage of the entire slope face. CD analysis identified 115 rockfall events over the May–December 2024 period (Fig. 2e-f). The systematic detection of precursor patterns across both monitoring systems supports the potential application of inverse velocity approaches (Fukuzono, 1985; Intrieri *et alii*, 2012) for failure prediction. Preliminary analyses applying such methods to TLA8-derived DIC displacement time series preceding documented failure events have demonstrated promising results; these methodological developments are currently under further investigation. A recent major failure event at the site is currently the subject of ongoing multi-technique investigation. All monitoring results are systematically uploaded to ISPRA's IdroGEO platform (Fig. 3), exemplifying the operational workflow for real-time data dissemination applied across all monitored sites, allowing consultation of recent events by the entire technical community.

At Gollone, a MOBOTIX M73 dual-lens system at approximately 1000 m distance captured over 9100 images (25 GB) over 16 months (February 2024–June 2025). The 8° telephoto lens achieved GSD of 3.6–3.9 cm/pixel. CD analysis detected 94 rockfall events: 44 fall events (mean 0.36 m², range 0.067–3.23 m²) and 50 debris events (mean 0.26 m², range 0.007–1.74 m²). Both types showed concentration in the 0.1–0.5 m² size class (59–60%), providing statistical data for magnitude-frequency analysis (Fig. 4). The minimum detectable size of 0.007 m² at 1000 m distance demonstrates the scalability of Photomonitoring at operational distances. On October 18, 2024, approximately a 2 m² block failure was captured in near-real-time: at 16:00 the detached block was visible mid-flight, while the 17:00 acquisition showed retrogressive failure evidence. The event rate of 0.010 events/hour over 374 observation days provides quantitative baseline for rockfall hazard intensity assessment, consistent with approaches described by Hungr *et alii* (1999) and Janeras *et alii* (2023).

At Baldiola, a Canon EOS R6 was installed approximately 500 m from the landslide toe, achieving GSD ranging from 6 to 22 cm/pixel depending on distance and local geometry. DIC analysis tracked displacement patterns across the earthflow body over 470 days (March 18, 2024 – June 30, 2025). Four monitoring points (TS_1 to TS_4) revealed significant spatial variability in landslide kinematics (Fig. 5). The most active sector (TS_1) recorded cumulative displacements reaching 120 m, while areas exhibiting lower apparent displacement (TS_4, 8.5 m total) reflect either different kinematic behavior or displacement components predominantly aligned with the optical axis. The DIC displacement field demonstrates the

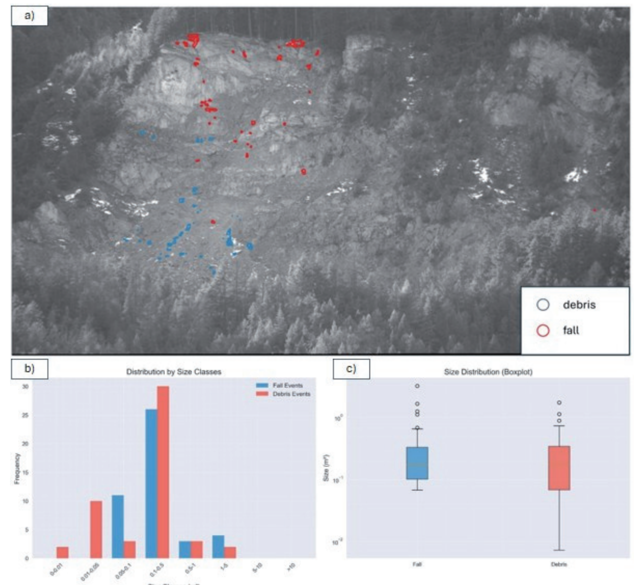

Fig. 4 - Gollone rockfall detection and statistical characterization over 16-month monitoring period (February 2024–June 2025, MOBOTIX M73 dual-lens system at ~1000 m distance, GSD 3.6–3.9 cm/pixel). (a) Spatial distribution of 94 detected gravitational events classified by mechanism: fall events (red circles, n=44, mean size 0.36 m²) and debris movement events (blue circles, n=50, mean size 0.26 m²); (b) Size-frequency distribution histogram showing concentration in the 0.1–0.5 m² size class (59-60% of events) for both event types, demonstrating detection capability at operational distances; (c) Boxplot comparison of size distributions showing similar median values and range for both event types, with minimum detected size of 0.007 m² at 1000 m distance

distinctive channelized morphology of the earthflow, with distinct kinematic zones showing variable activity levels across the landslide body and minimal displacement at the lateral margins.

Quantitative validation compared DIC-derived displacement time series against seven geodetic prisms monitored by robotic total station (Lelli *et alii*, 2025). Correlation analysis yielded coefficients from r = 0.831 to r = 0.999 (mean 0.966; Table 3), demonstrating accuracy comparable to conventional geodetic techniques. Lower correlations at some monitoring points likely reflect vegetation interference or significant displacement components aligned with the optical axis, representing inherent limitations of 2D measurement approaches.

Meteorological correlation at Baldiola revealed strong relationships with cumulative precipitation (r > 0.973), with 91 discrete acceleration events corresponding to daily precipitation thresholds of 31.3–46.8 mm/day. These results confirm triggering mechanisms consistent with hydrological thresholds documented in similar flysch environments throughout the Northern Apennines (Ronchetti *et alii*, 2009; Bogaard & Greco, 2018), demonstrating that Photomonitoring can effectively capture rainfall-displacement relationships essential for early warning applications.

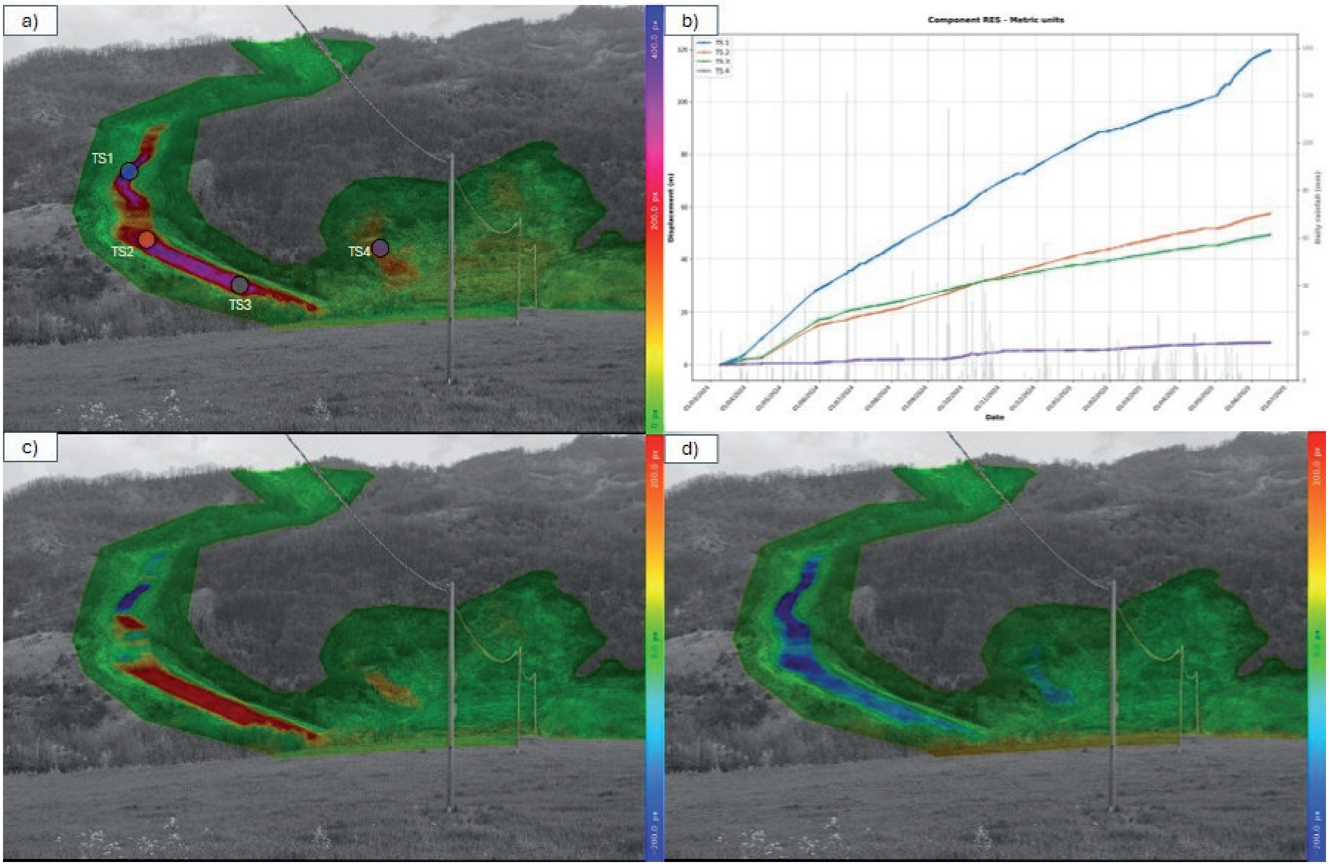

Fig. 5 - Baldiola earthflow DIC results (March 18, 2024 – June 30, 2025). (a) DIC displacement map (March 18, 2024 – April 1, 2025) with monitoring points (TS_1 to TS_4) showing maximum cumulative displacement of 120 m at TS_1; (b) Cumulative displacement time series (resultant component) from the four monitoring points, documenting significant spatial variability in earthflow kinematics; (c) East-West (horizontal) displacement component showing channelized flow pattern; (d) North-South (vertical) displacement component

Point	r-Pearson	p-value	R^2
BRC_M01	0.997	<0.001	0.995
BRC_M06	0.999	<0.001	0.997
BRC_M07	0.987	<0.001	0.973
BRC_M08	0.992	<0.001	0.984
BRC_M09	0.980	<0.001	0.960
BRC_M19	0.831	<0.001	0.690
BRC_M20	0.974	<0.001	0.944
Mean	**0.966**	-	**0.935**

Tab. 3 - Correlation analysis between Total Station and Photomonitoring

At La Saxe, DIC analysis of historical webcam archives (approximately 75,800 photographs, 93 GB) documented the evolution of the DSGSD following the major April 2014 activation event involving over 400,000 m³ of material (Crosta *et alii*, 2014). The archive was processed in two complementary phases: historical imagery (2014-2018, 630 filtered images from 72,000 through automated SSIM-based quality assessment, Fig. 6) and recent calibrated monitoring (October 2020-June 2022, GSD ~14 cm/pixel, Fig. 7). DIC analysis extracted displacement time series from ten monitoring points distributed across the landslide body (Fig. 6b), documenting variable displacement rates across different landslide sectors over the 2014-2018 period (Fig. 6c). The calibrated monitoring phase enabled precise quantification, with maximum cumulative displacement reaching approximately 2.4 m over 20 months (Fig. 7f).

Sequential DIC mapping reveals distinct spatial-temporal patterns, with enhanced displacement concentrated in the upper-central sector and progressive expansion during spring-summer periods (Fig. 7). These acceleration patterns align with snowmelt-triggered mechanisms documented in previous comprehensive studies on this well-characterized site (Crosta *et alii*, 2014), demonstrating Photomonitoring's capability to capture seasonal behavior in complex DSGSD systems.

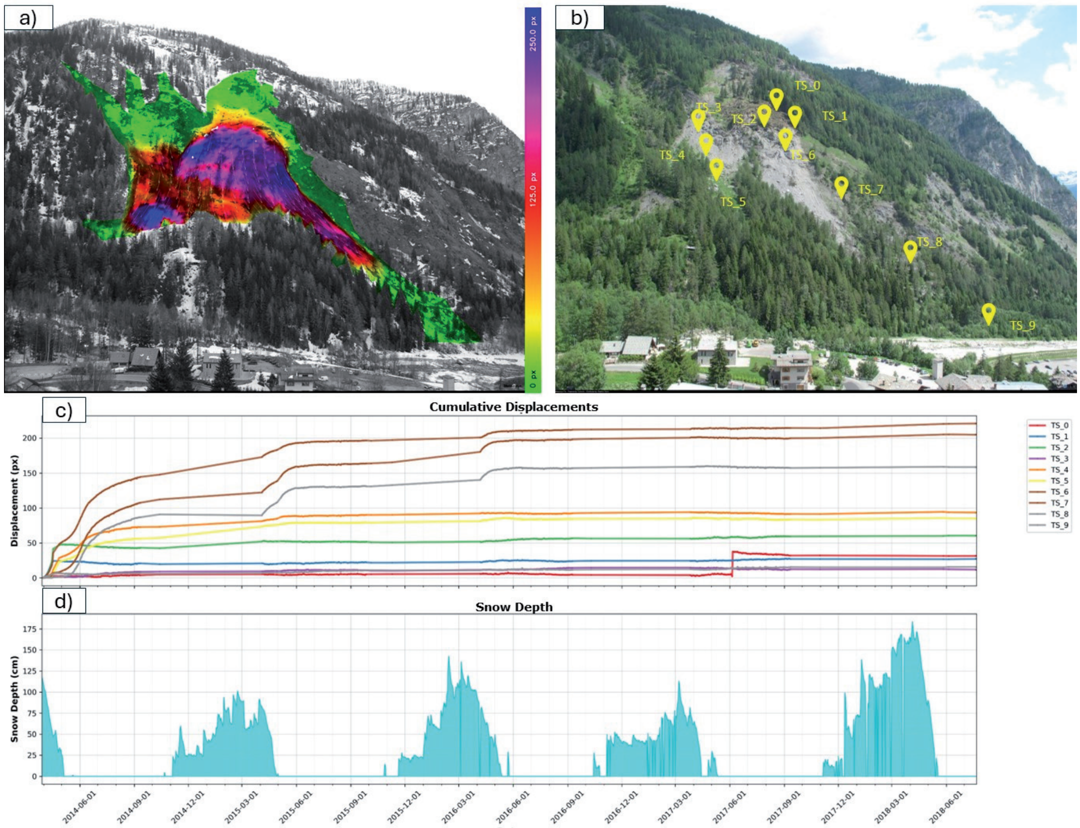

Fig. 6 - La Saxe DSGSD long-term monitoring through historical webcam archive analysis (2014-2018). (a) Cumulative DIC displacement map (March 2014–July 2018, 630 filtered images from 72,000 through automated SSIM-based quality assessment) showing post-activation deformation following the April 2014 event (>400,000 m³); (b) Landslide overview showing distribution of ten DIC tracking points (TS_0 to TS_9, yellow markers) across different landslide sectors; (c) Cumulative displacement time series extracted from DIC analysis showing variable movement rates ranging from ~20 to ~220 pixels across the monitored period; (d) Snow depth records from nearby weather station (2110 m a.s.l.) documenting seasonal snow cover variations

At Cercevesa, a FlatMesh 4G autonomous system operated continuously over 16 months at ~300 m distance (GSD 8 cm/pixel). DIC quantified extremely slow displacement rates characteristic of DSGSD phenomena (Fig. 8a), while CD identified 19 gravitational events including a 2.1 m² rockfall detachment zone (Fig. 8b), demonstrating dual monitoring capability for continuous slow deformation and discrete failure events in remote alpine settings. However, large noise arises from dense vegetation. At Castellaro cliff (Camogli, Portofino Promontory), four drone campaigns (November 2023–March 2025) generated high-resolution orthophotos (DJI Mini 2, GSD 3 cm/pixel) enabling systematic CD analysis across 1.9 km of coastal cliff (Fig. 8c). The analysis identified 29 gravitational events spanning 0.01–2080 m² (Fig. 8c-iii), with 62% concentrated in the 0.1–10 m² range demonstrating the UAV approach's effectiveness for periodic monitoring of coastal cliffs subject to episodic failures and marine erosion. The Acuto field laboratory achieved the highest spatial resolution in the network (GSD 0.8 cm/pixel) at 50–70 m distance, documenting 72 small events (48 on DX camera tower, 24 on SX camera rockwall) with sizes ranging 6.4-510.7 cm², demonstrating fine-scale gravitational event detection capabilities at this high resolution limestone cliff site. At Porto Empedocle, gigapixel imaging documented significant cliff recession in soft rock formations. At Ruinon, historical archive analysis (1348 photographs filtered to 32 high-quality images) enabled displacement quantification despite challenging dataset quality.

Several sites experienced operational challenges that compromised monitoring effectiveness. At Torgiovannetto, weak internet connectivity and inadequate solar power capacity resulted in only 146 operational days versus 302 days of system downtime, though 2 rockfall events were successfully detected including one creating a 2.0 m² detachment zone. At Scaiùn, progressive optical degradation after approximately one year of operation necessitated maintenance intervention, illustrating equipment reliability considerations for long-term deployments. At Calvello, suboptimal camera positioning compounded by connectivity constraints resulted in detection of predominantly

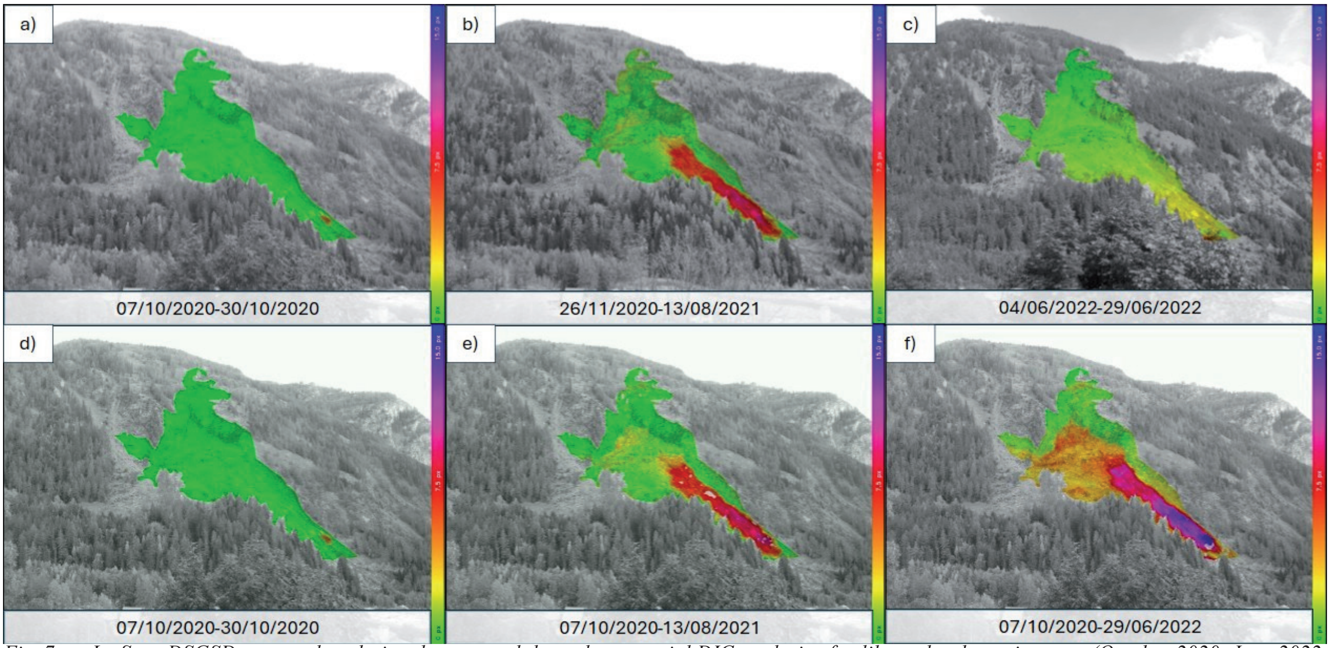

*Fig. 7 - La Saxe DSGSD temporal evolution documented through sequential DIC analysis of calibrated webcam imagery (October 2020–June 2022, GSD ~14 cm/pixel). Upper panels (a-c) show incremental displacement for specific time intervals: (a) baseline period (October 7-30, 2020); (b) winter-spring accumulation (October 2020-August 2021); (c) extended monitoring through June 2022. Lower panels (d-f) show cumulative displacement from baseline for the same time intervals, with maximum values exceeding 2.4 m concentrated in the upper-central sector. The spatial-temporal progression reveals enhanced displacement during spring-summer periods, with progressive expansion of the high-displacement zone consistent with snowmelt-triggered mechanisms documented in previous studies (*Crosta *et alii, 2014)*

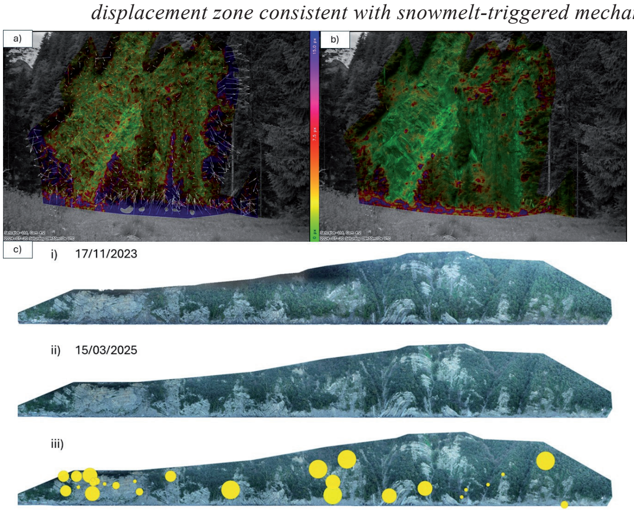

Fig. 8 - Monitoring results from additional sites. (a) Cercevesa DSGSD: DIC cumulative displacement map (February 2024–June 2025) with displacement vectors quantifying extremely slow deformation (3.6–14.0 cm/year); (b) Cercevesa: CD spatial distribution of 19 gravitational events including 2.1 m² rockfall niche; (c) Castellaro coastal cliff: drone-based monitoring showing (i) first orthophoto (November 17, 2023), (ii) last orthophoto obtained (March 15, 2025), and (iii) detected gravitational events (n=29, 0.01–2080 m²) along 1.9 km of cliff

secondary effects (vegetation dynamics, livestock disturbances) rather than primary earthflow displacement, highlighting the critical importance of comprehensive site feasibility assessment encompassing geometry, connectivity, accessibility, and maintenance logistics. At Monte Rosa, significant differences in environmental conditions (snow cover, lighting) between the 2023 and 2024 gigapixel surveys prevented quantitative CD analysis, emphasizing the limitations of periodic monitoring approaches compared to continuous fixed installations in highly remote alpine region, where fixed cameras should be preferred.

The technical requirements for reliable deployments include minimum 8 MP sensor resolution and continuous power supply. Sites relying solely on solar power experienced significant downtime during adverse weather periods. Several fundamental limitations must be acknowledged: single-camera systems provide only 2D displacement measurement, potentially underestimating magnitudes for movement components aligned with the optical axis (Sutton *et alii*, 2008); environmental factors including adverse weather, shadow variations, and vegetation growth create data gaps requiring systematic quality filtering; substantial data volumes (217 GB from fixed installations alone) demand significant computational resources and storage capacity for long-term monitoring programs.

CONCLUSIONS

This systematic evaluation across thirteen sites establishes Photomonitoring as a mature technique for operational landslide surveillance. Quantitative validation at Baldiola against robotic total station measurements confirms displacement accuracy comparable to conventional geodetic methods (r = 0.831–0.999, mean 0.966). The detection of 0.007 m² events at 1000 m distance at Gollone demonstrates remarkable operational scalability and the possibility of adopting custom lenses for specific monitoring purposes.

Meteorological correlation analysis at Baldiola (rainfall, r > 0.973) verifies the technique's capability to detect established triggering relationships, while seasonal acceleration patterns at La Saxe align with documented snowmelt-driven processes, demonstrating reliability for process-based landslide monitoring. The identification of precursor patterns at Poggio Baldi opens promising perspectives for early warning system development. In general, the Fixed camera and continuous monitoring approaches consistently outperformed periodic ones in temporal resolution, noise filtering, image quality, and reliability. Photomonitoring represents a strategic and cost effective pathway for expanding monitoring coverage across Italy, where currently approximately 1200 of 636,000 IFFI-catalogued landslides benefit from systematic instrumental monitoring.

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