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ABSTRACT

This deliverable summarizes the scientific research activities carried out in the period December 2023 – April 2024 by the Task 2.3.1 of the Work Package 2.3 inside the vertical spoke VS2 "Ground Instabilities" of the Extended Partnership RETURN.

The activities of the Task 2.3.1 have been devoted to the research and proposal of innovative sensors and solutions for the characterization and monitoring of ground instabilities. The different partners cooperating to the task have addressed various research topics based on their skills, experience, study targets and ongoing experimental activities. As a result, these proposed new methodologies cover a wide range of applications, from subaerial to submarine landslide studies. Additionally, a few proposals address innovative systems for the monitoring and early warning of sinkholes and subsidence.

The innovative proposals are categorized into novel sensors - NS (i.e., in case of need of complete technological development of the characterization/monitoring instrumentation), novel infrastructures - NI (i.e., in case of need of technological implementation of existing sensors), and novel applications - NA (i.e. in case of pioneering tests and experimental activities aimed at applying new approaches or technologically-ready instrumentations), offering a comprehensive approach to landslide monitoring and management.

The deliverable report is structured in an introductory overview of the innovation strategies gathered by the research group, followed by detailed technical sheets of the different novel sensors, infrastructures, and applications.

The obtained results lay the groundwork for the technological development strategies to be pursued by the vertical spoke VS2 in the upcoming months of the project.

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1. Introduction

This report summarizes the scientific research activities carried out in the period November 2023 – April 2024 by the **Task 2.3.1** "*Natural onshore and offshore field laboratories for remote and in-site monitoring of environmental forcings and deformation responses. Validation of cutting-edge sensors, technological devices, and techniques to identify and monitor precursor signals of ground instability, as well as the occurrence of ongoing deformations"* (hereinafter referred to as **TK1**) of the **Work Package 2.3** "*Monitoring & Modelling: toward a digital twin of ground instabilities effects*" (hereinafter referred to as **WP3**) inside the vertical spoke **VS2** "*Ground Instabilities"* of the Extended Partnership RETURN.

Following the Executive Working Plan of RETURN, which was delivered as Milestone 2.1 on 31 December 2022, the institutions cooperating to the WP3 and TK1 objectives are ENEA, OGS, POLITO, UNIBA, UNIBO, UNIFI, UNIGE, UNINA, UNIPA, UNIPD and UNIROMA1.

The recent activities of the task were devoted to the creation of an inventory of novel sensors and techniques for the characterization and monitoring of ground instabilities. The proposed new methodologies cover a wide range of applications, from subaerial to submarine landslides. Additionally, a few proposals address innovative systems for the monitoring and early warning of sinkholes and subsidence.

The task work was organized as follow:

1. Open call (including contributions from all the WPs of VS2) for innovative ideas addressing problems and solutions in landslide characterization and monitoring.
2. Inventory of the proposals to understand the targets of the solutions (subaerial landslides, submarine landslides, sinkholes, subsidence, liquefaction) and highlight the application areas that might further benefit from the technological development of the proposed sensors and technologies.
3. Classification of the proposed solutions into three main categories (novel sensors, novel infrastructures, and novel applications), rough indication of the present and future TRLs (Technological Readiness Levels) and of the potential cost of the development (if available and already estimated by the contributors).
4. Collection of detailed analyses related to the different proposed solutions including setting of the problems in landslide characterization and/or monitoring with the currently available methods, description of the proposed innovative solutions, expected outcomes and risk assessment.

The results are summarized in this deliverable report. After a brief overview of the collected innovative solutions and a detailed analysis of the related monitoring targets, the novel sensors and techniques are presented in detail, divided into three main categories (novel sensors, novel infrastructures, and novel techniques).

These outcomes lay the groundwork for the technological development strategies to be pursued by the vertical spoke VS2 in the upcoming months of the project. More specifically, some of the concept ideas contained herein could be placed at the basis of the development of prototypes of industrial interest by SME (Small-or Medium-Enterprises) based on Spoke's PNRR funding.

2. Overview of the novel sensors and techniques

The innovative solutions gathered by the different contributors to the TK objectives are summarized in Table 1. Each proposed idea is categorized through an ID (Nx) and the potential targets of investigation and/or monitoring are indicated.

Table 1. Inventory of innovative solutions for the characterization and monitoring of different types of ground instabilities. Subaerial landslides: SF = slow flows (earthflows), SS = slow slides (rotational and planar slides, soil slips), S = spreads (except liquefaction), SSD = slow slope deformations (rock/soil slope deformations, creep, DsGSD), RF=rapid flows (debris flows, mudflows), RS = rapid slides (rock slides, rock avalanches), FT = falls and topples (rock falls & rock topples). Subaerial landslides and sinkholes: S = slow and R = rapid. SUB = subsidence. Liquefaction is excluded from the potential effects since no proposal was collected to address this target.

Proposing Institution	ID	Short Description	Subaerial landslides							Submarine landslides		Sinkholes		SUB
			SF	SS	S	SSD	RF	RS	FT	S	R	S	R	
UNIBO	N1	*Seismic arrays to monitor shear wave velocity changes within the landslide*	X			X	X							
UNIPA	N2	*Monitoring system based on fiber optic technology to measure displacements of linear structures/infrastructures interacting with a landslide.*	X	X	X					X				X
SAPIENZA ENEA	N3	*High-resolution satellite imagery to depict landslide scar evolution at canyon head.*									X			
SAPIENZA	N5	*Acoustic monitoring trough sonar imaging of submarine slopes (SSMM – Submarine Slope Multibeam Monitoring).*								X	X			
POLITO	N6	*Automatic real-time microseismic data processing for early warning.*						X	X				X	
UNIBA	N7	*SAR interferometry coupled with multitemporal Lidar investigation by UAV and thermography to detect topographical changes as signal of upcoming processes.*		X										
SAPIENZA	N8	*PhotoMonitoring: displacement analysis (Digital Image Correlation, DIC) and change detection (CD) exploiting multi-platform multi-species optical images (satellite, UAV, ground-based; mobile).*	X	X		X	X	X	X		X			
OGS	N9	*GNSS cost-effective sensor for real-time monitoring of surface displacements within the landslide body.*		X		X								
UNINA	N10	*Triaxial velocimeters, rain gauge sensors, and neutral pressure for earth landslide monitoring.*	X			X								
UNIPA	N11	*Aerial/UAV/Lidar image processing and filtering for bathymetry reconstruction and imaging of the submerged morphologies (+ sample analysis).*								X	X			
UNIPA	N12	*Monitoring of coastal erosion: calculation, study and engineering modeling of longshore transport in order to determine the medium/long-term evolutionary trend of a coastal stretch.*								X	X			
POLITO	N13	*Remote connection to monitoring instruments to receive and consult data in real time in remote areas.*		X		X								

ENEA	N14	*Increasing the resolution of sensors from remote satellites, for cyclic, qualitative measurement or estimation of surface soil moisture in order to identify areas of water retention, at a geometric resolution congruent with DEMs in use.*					X							
UNIPA	N15	*Use of terrestrial laser scanner for evaluating the extent of movement of (existing) landslide phenomena as the intensity of rainfall events changes.*		X		X		X						
SAPIENZA	N16	*Development of an autonomous Unmanned Aerial System (UAS) platform able to perform Synthetic Aperture Radar (SAR) Interferometry and optical analysis.*	X	X	X		X	X	X		X	X		
UNIBA	N17	*Satellite data processing techniques for surveying subsidence phenomena by artificial SAR reflectors that increase the density and distribution of measurement points and allow for greater precision and reliability in monitoring.*												X
UNIBA	N18	*Infra-Red Thermography to monitoring discontinuities and rock mass portions that could be potentially considered as eventual precursory signs of the evolving instability of rocky cliffs and slopes.*	X						X					
UNINA	N19	*Early warning system to detect sinkhole-induced settlement based on Distributed Fiber Optic Systems (DFOS).*										X		
UNINA	N20	*Flexible and adaptive monitoring system in shallow slopes through tensio-inclinometer, specifically developed to measure suction changes and suction-induced deformation for early warning purpose.*	X			X	X							
UNINA	N21	*Upgrade of the weather station at the Pagani site with remote data transmission and installation of new sensors to measure suction and water content.*					X							
UNIGE	N22	*Implementation of an integrated monitoring system consisting of contact geotechnical sensors (i.e., automatic inclinometer probes and pore-water pressure transducers), rain gauges and geophysical sensors (i.e., seismological stations) for the coupled detection of displacements and their controlling factors.*		X										
SAPIENZA	N23	*Depth cameras.*					X	X	X					
SAPIENZA	N24	*Wireless network of sensors suitable for continuous monitoring of physical parameters (e.g., moisture, temperature) of soils and rocks subjected to intense thermal stress (both high and low T) with remote transmission, suitable for detecting both transient episodes and seasonal variability.*	X	X		X		X	X					

As already noted in previous deliverables (e.g. DV2.3.1 and DV2.3.3), a greater number of solutions was collected for the study of subaerial landslides (Figure 1), with the majority of proposals related to the characterization and monitoring of slow landslides (flows, slides and rock deformations). However, this disparity was to be expected given the much more complex nature of underwater investigation and monitoring. The significant number of proposals for submarine landslide monitoring solutions underscores the great research efforts aimed at filling knowledge gaps in this environment, ultimately striving towards comprehensive characterization and effective monitoring in all contexts.

By contrast, no innovative solutions are proposed for investigating or monitoring liquefaction and only a few ideas address the monitoring and early warning of sinkholes and subsidence.

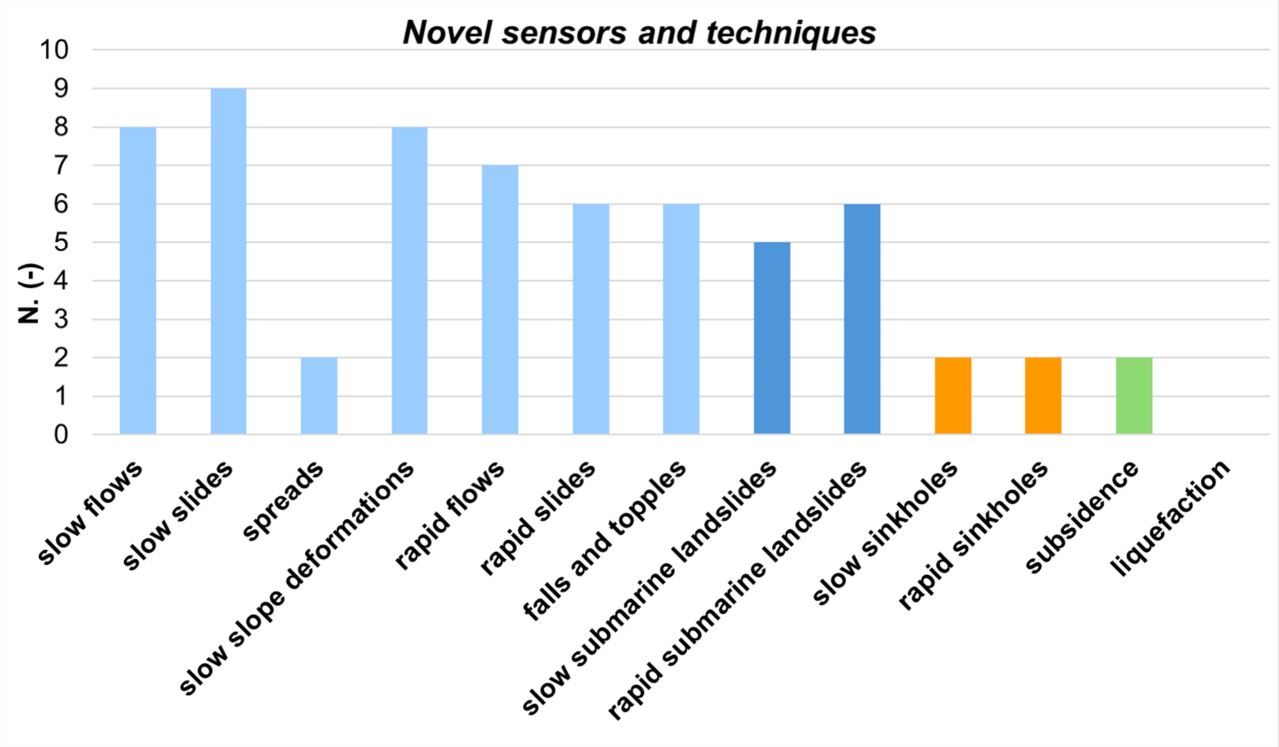

Figure 1. Potential targets of the proposed novel sensors and techniques.

The proposed solutions were further classified into three main categories:

1) **Novel Sensors (NS)**: new characterization/monitoring instrumentations that need complete technological development; at present, there are no commercially available systems of this kind.
2) **Novel Infrastructures (NI)**: the measuring sensors already exist or are commercially available, but need implementation in specific aspects, e.g., to work in a specific environment or in certain environmental conditions, to operate in near real-time, to be coupled with other sensors for a multiphysics measure, to operate from UAV (Unmanned Aerial Vehicles) platforms.
3) **Novel Techniques (NT)**: pioneering tests and experimental activities, also carried out in the framework of RETURN partnership, aimed at applying new approaches or technologically-ready instrumentations.

The classification of the different innovative solutions, together with a rough indication of their current TRL (Technological Readiness Level), possible target TRL and implementation costs, if available, are summarized in Table 2.

As further shown in Figure 2a, five solutions are related to the development of NS, ten solutions refer to NI and, in most cases, (12) the proposal is to apply already existing frontier methods of investigation and monitoring to landslides.

In general, there is a good balance between on-site novel instrumentation and non-contact (satellite/aerial/ground-based) sensors and technologies (Figure 2b). The TRLs are quite different and cover a wide range of development stages. As expected, they are generally low for the NS class and stay in the research field (e.g. technology concept formulated/experimental proof of concept). By contrast, the TRLs are very high for the NA class, involving sensors and techniques ready for the deployment phase (TRL > 7).

Table 2. Inventory of innovative solutions for the characterization and monitoring of different types of ground instabilities. Classification into Novel Sensors (NS), Novel Infrastructures (NI) and Novel Applications (NA).

ID	**NS**	**NI**	**NA**	**Current TRL**	**TRL advancement within Return? (if so, indicate the final TRL)**	**Indicative cost of the development**
N1			X	5	6	20-30 k€
N2		X	X	7-8	NO	*unknown*
N3			X	6	9	50-250K€
N5	X			2	4	100-300K€
N6		X		2	4	<2k€/station
N7		X		7	9	*unknown*
N8		X	X	7	9	*unknown*
N9	X	X		6	7	*unknown*
N10			X	3	5	*unknown*
N11			X	3	YES (NA)	*unknown*
N12			X	2	YES (NA)	*unknown*
N13		X		6	7	<2-3 k€/instrument
N14		X		3	NO	*unknown*
N15			X	8	NO	*unknown*
N16	X			2	9	100k€
N17		X		7	9	*unknown*
N18			X	5	6	*unknown*
N19			X	5 - 6	NO	50k€
N20		X	X	8	9	*unknown*
N21		X		8	9	*unknown*
N22			X	3	5	*unknown*
N23	X			3	6	5k€
N24	X			2	9	*unknown*

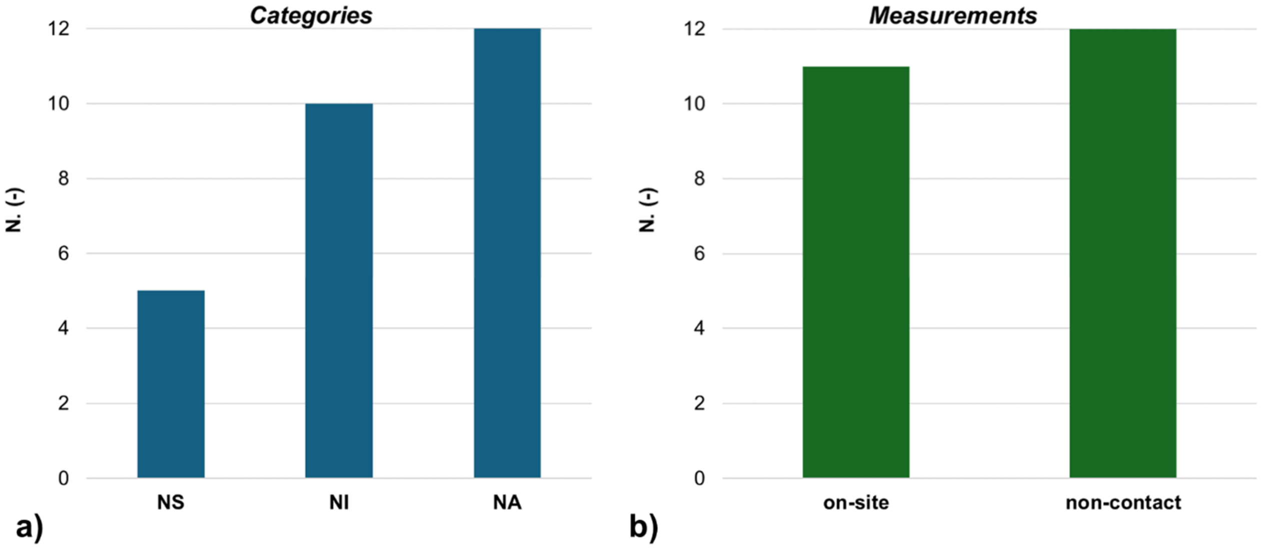

Figure 2. Classification of the innovative solutions: (a) Novel Sensors (NS), Novel Infrastructures (NI) and Novel Applications (NA). (b) On-site and non-contact solutions.

Other relevant outcomes of the inventory are:

1) Characterization and monitoring of the submarine environment can be implemented through different types of approaches (satellite/aerial/UAV image acquisition and processing, sonar imaging) also aimed at studying and quantifying costal erosion and processes for which there is a lack of knowledge and quantitative data.

2) In the subaerial environment, there is a strong need for remote control and transmission of the data from the monitoring sensors. This aspect might be a key point to put into operation effective early warning systems and further technological development is needed to achieve this goal.

3) Recurrent monitoring parameters for which new sensors and infrastructures are needed involve:
    a. Surface displacements in slow landslides;
    b. Water effects, from rainfall intensity to suction and pore-water pressure measurements in earth slides;
    c. Thermal effects, especially for rock slides, falls and toppling.

4) Geophysical parameters of the unstable volumes, with special focus on micro-seismicity and shear wave velocity modifications (e.g., 4 out of 24 proposed solutions involve implementation of passive seismic methods).

In the following, the different solutions are presented in detail and divided into the three main identified categories (NS, NI and NA).

3. NOVEL SENSORS

N5: Acoustic monitoring trough sonar imaging of submarine slopes (SSMM - Submarine Slope Multibeam Monitoring)

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Problem setting

"*If a landslide come as a surprise to the eyewitnesses, it would be more accurate to say that the observers failed to detect the phenomena which preceded the slide*" (Terzaghi, 1950). This is to say that despite other geohazards, landslides are preceded by precursors such as soil deformation; therefore the idea is to export the land monitoring systems (lisaSAR, GPS, lidar, laser, interferometric techniques, …) to the submarine realm, especially if we have recurring failure in a certain area and/or high-value infrastructure exposed to submarine landslide direct or indirect (tsunami) hazard. The idea is to build a system that in real-time will remotely monitor the seafloor by means of acoustic (sonar) methods that will be referred to in the text as SSMM (Seafloor Slope Multibeam Monitoring). It will not be a point-to-point measure of deformation but rather a scanning of a whole seafloor sector to depict its (unknown) changes in depth or precursory small failures.

State of the art

Currently, there are no technologies that allow for a frontal view of underwater slopes. The technology currently used to acquire bathymetric data (which therefore has an orthogonal view of the seabed) is multibeam acoustic systems. Multibeam acoustic technology utilizes a multi-beam echo sounder system to emit multiple sonar beams, enabling rapid and accurate mapping of the seafloor. Unlike traditional single-beam systems, multibeam systems provide high-resolution, three-dimensional images of the underwater terrain, capturing detailed information about depth and shape of the seabed. An important benefit of multibeam acoustic technology is its versatility. These systems can be mounted on various platforms, including ships, autonomous underwater vehicles (AUVs), and remotely operated vehicles (ROVs), allowing for flexibility in data collection across different marine environments. Considering this important property, the purpose of our innovative solution is to install a modified multibeam echo-sounder system on a mooring in the water column (Figure 3). The mooring technology, used in marine environments, consists of an anchoring system utilized to maintain a fixed position for a variety of submerged devices, instruments, or structures. These systems are composed of a cable or rope anchored to the seabed and kept buoyant by mooring buoys. A mooring can be designed to support a wide range of loads and can be configured according to the specific needs of the application. Moorings are widely employed to support oceanographic monitoring devices, climate observation instruments, underwater telecommunication systems, offshore drilling platforms, and much more.

Innovative solution

The SSMM is a system that should remotely monitor the seabed in real-time using acoustic (sonar) techniques installed on a mooring in front of a selected canyon head or instable slope (Figure 3). The SSMM system will scan every few seconds/minutes using a rotating transducer (like sector scanning or forward-looking sonars) (Figure 3). SSMM should stand below wave-base level, i.e. at water depth of some 50 m below wave base) to be stable enough to allow motion sensor to work (Figure 3). SSMM system should be located hundreds of meters above seafloor with a high viewpoint to illuminate the max possible area of the study site. The system may mount two transducers (one on each side) so that with current reversal it will always operate. Looking at whole slope and not at a single point, the system will discriminate between single gravity flow and overall or localized deformation of the slope, by analyzing the change in geometry of the observed backscatter point cloud. The expected deformation may have a vertical offset of decimeters/meters and horizontal deformation of meters/decameters. The system may have a passive rudder to align it parallel to the current and avoid/minimize rotation from one scan to one other (small rotation can be corrected by motion sensors or software). In fact, processing software should be able to automatically compare two successive DTMs (accepting limited transducer rotation or movement) to detect variation. In the extreme case one may accept the system to scan 360° and freely rotate and the software cross-correlate features for comparison (feasibility to be verified).

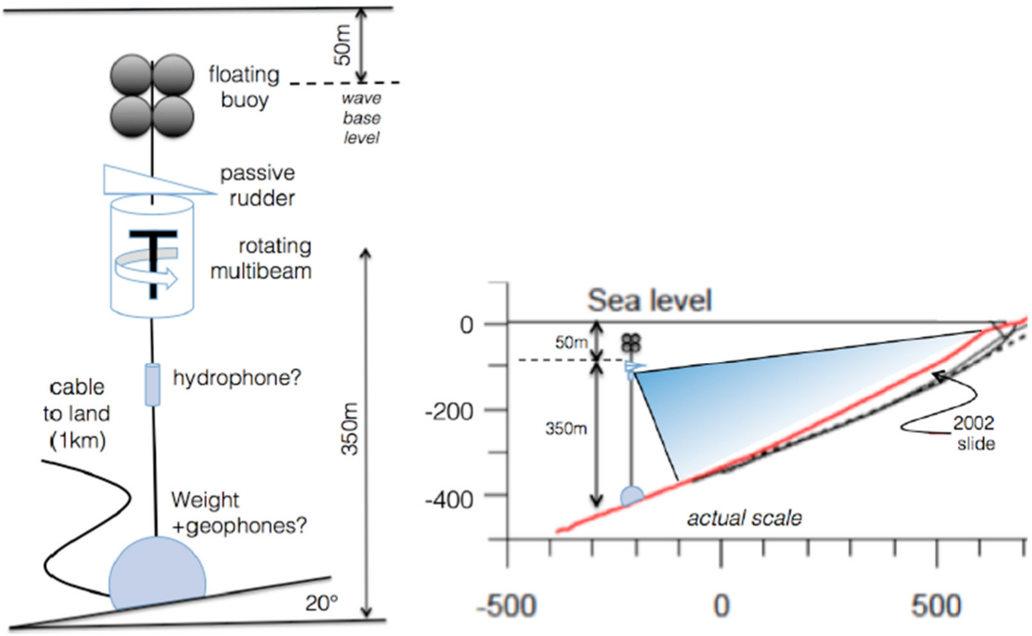
In conclusion, the SSMM system should:

a) Monitor a specific canyon head/submarine slope.
b) Have a real-time connection for power supply and data transmission (so allowing early-warning capability).
c) Resist rough weather conditions.
d) Possibly host ancillary sensors (hydrophones and geophones at seafloor).

This technology is the result of combining existing sensors and technologies; however, the feasibility of their assembly and software operation are purely conceptual. As mentioned, this technology is innovative, and the feasibility of its implementation is yet to be determined. For these reasons, its TRL is currently at 1-2. However, if the project proves feasible, we aim to demonstrate its feasibility in the underwater environment within this project and therefore achieve a TRL between 4-5.

The innovative nature of the SSMM system will offer groundbreaking solutions to underwater monitoring challenges. It incorporates leading-edge technology, ensuring accuracy and efficiency in data collection and analysis. The SSMM system has versatile applications in both industrial and scientific fields, from landslide and slope deformation detection to infrastructure monitoring and its potential for commercial patent signifies not only its value but also the opportunities it presents for further development commercialization.

The cost of the system is difficult to assess as it may imply re-design of existing instruments or a completely new development. The mooring system, marine engineering of sensors, setting up of software may, by itself, cost 100,000 to 300,000€, plus the instruments that may be likely triplicate the sum (bringing the gross total at about 1M€).



	Floating buoy-barge / no cable to land	Mooring /cable to land
advantages	1) possible subaerial monitoring 2) easy radio/GSM connection 3) upper possible viewpoint 4) no pressure resistent instrumentation	1) avoid waves 2) more stable platform 3) no energy limits 4) no data transmission problems
disadvantages	1) problem with severe storms 2) low stability of the platform for wave 3) needs battery recharge or solar power with power limit 4) threat from navigation	1) no subaerial monitoring 2) cable landing problematic (rocky coast) 3) a little lower viewpoint

Figure 3. Top left: Sketch of the SSMM system and its various components. Top right: Profile of an underwater slope and potential location of the SSMM system in the water column. Below: Table summarizing the potential advantages and disadvantages of a "floating buoy-barge" configuration or a "mooring" configuration.

Expected outcomes

The expected results are similar to those provided by subaerial monitoring system using electromagnetic waves (such as GBInSAR - Ground-Based Interferometric Synthetic Aperture Radar, Figure 4), providing near-real-time data that can be used to 1) define the pre-failure behavior of the slope; 2) precisely locate in time and space the occurrence of instability. This will enhance the capability to understand the preparing and triggering factors that are usually unknown, given the fact that only landslide scars are observed. This will help in hazard assessment implement mitigation measures as, unlike the technologies currently in use (MBES), the SSMM system may have a constant monitoring with real-time connection for early-warning capability.

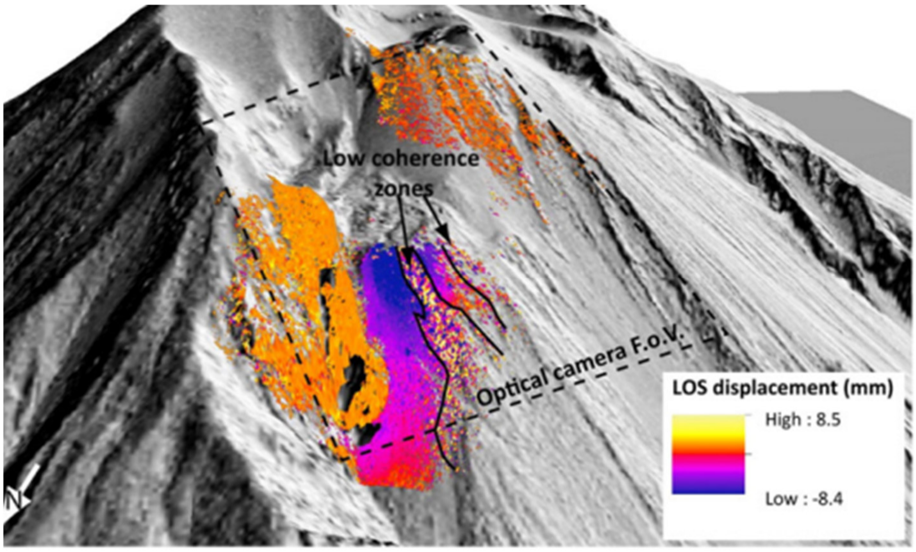


Figure 4. GBInSAR LOS displacement map revealing slope displacements (blue) related to the slope instability of the newly emplaced lava along the SdF (Sciara del Fuoco) slope on the Stromboli volcano. From Di Traglia et al. (2018).

Risk assessment

The weaknesses of the proposed SSMM system rely on the fact that this is an innovative solution for monitoring underwater slopes.

The primary weakness of the SSMM system is that it currently does not exist. This means that we are starting from scratch and the system needs to be fully conceived from the ground up. While we have a vision and a plan in place, bringing this system to life will require meticulous planning, extensive research, and collaborative efforts from experts in various fields.

Secondly, in situ feasibility experiments are essential. Real-world testing in underwater environments is crucial to understanding the challenges and limitations we may encounter, as well as refining the system to ensure its reliability and accuracy.

Lastly, cost may present a significant hurdle in the development and implementation of the SSMM system. Building and deploying advanced monitoring technology for underwater environments can be expensive, requiring investment, research facilities, and skilled personnel. Additionally, ongoing maintenance and operational costs must be considered to ensure the long-term sustainability of the system.

Despite these challenges, the realization of an effective SSMM system will enhance our understanding of underwater landslide and slope dynamics and contribute to the management of coastal hazards.

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N9: Implementation and test of cost-effective GNSS equipment to measure displacements on a known landslide body in real-time

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Problem setting

Monitoring landslides, particularly those located near populated areas, is crucial for developing early warning systems devoted to risk-management purposes. Most of the techniques deploy expensive monitoring systems, for instance sensors installed in situ, such as inclinometers and extensometers, or remote sensing techniques using ground-based sensors, such as ground-based interferometric synthetic aperture radars (GBInSAR), terrestrial laser scanner (TLS), or topographic measurements captured by robotic total stations (RTS) that can be hardly afforded by small municipalities in which landslide events often occur. The high cost of this type of equipment limits its application in monitoring especially when many measurement points, and therefore instruments, are required (as for landslide monitoring) or for those contexts in which there is a higher risk of instrument damage.

One promising solution is the use of cost-effective Global Navigation Satellite System (GNSS) sensors that can reduce the monitoring cost but can offer good performance, even in real-time, for detecting the landslide surface movement with the desired precision. Currently the use of this kind of equipment is oriented to near real-time applications when the GNSS data is elaborated in post-processing (Zuliani et al. 2022a) and the displacements of the measuring points, where the GNSS equipment is installed, are available with a delay of one hour. Furthermore, this kind of approach collects data from remote measuring GNSS stations, and the displacement calculus is made on a single centralized elaboration server. This solution unfortunately is not easily scalable because the calculus load, at the server side, grows with the number of remote sensors. The current GNSS cost-effective technologies may be improved and applied to monitor in real time ground instability, such as landslides. Additionally, it's viable to redistribute the processing workload of each sensor from the server side to the remote equipment where the sensors are situated. This capability allows the entire system to smoothly adjust to an expanding number of measurement points without overtaxing the server side.

State of the art

Monitoring active landslides in terms of displacements can efficiently support the definition of risk mitigation procedures and the implementation of early warning systems (Intrieri et al. 2012). Displacement can be detected from sensors installed directly on the landslide, or remotely sensed with ground, airborne, or satellite devices (Casagli et al. 2017). Monitoring systems can be used to understand the extension of phenomena and their kinematics (e.g., Frodella et al. 2018) but also to provide early warnings (Carlà et al. 2017) and, when implemented in real-time, to identify the variation and dynamics of landslides (Lombardi et al. 2017). Displacement data offer valuable insights into the dimensional and evolutionary parameters shaping conceptual models of landslides. This enables the assessment of landslide activity, evolution, triggering causes, and activation predisposition. Such information drives the selection of appropriate stabilization measures to mitigate landslide risks and supporting territorial planning and civil protection efforts. Moreover, the comprehension of the scale and dynamics of movement is pivotal for designing monitoring networks geared towards early warning systems. In this context, continuous and near-real-time data acquisition is imperative to establish thresholds for each sensor/instrument or to mathematically analyze displacement time series to predict potential failure times (see for details Intrieri et al. 2019).

In recent times, there has been a concerted effort to identify cost-effective solutions for minimizing instrumental expenses. Notably, innovations like wireless sensor networks (e.g., Intrieri et al. 2018; Mucchi et al. 2018) and single-frequency GNSS, encompassing the widely recognized Global Positioning System (GPS) sensors (e.g., Wang 2011; Zuliani et al. 2016; Šegina et al 2020; Rodriguez et al. 2021; Tunini et al. 2022; Zuliani et al. 2022a, b) have emerged as promising avenues.

A novel monitoring network leveraging single-frequency GPS sensors has been installed and it is currently managed by OGS in the in the Carnic Alps, North-Eastern Italy to monitor a landslide in the small village of Cazzaso in the Tolmezzo municipality (Zuliani et al. 2016; Zuliani et al. 2022a). Its primary aim is to highlight the system's innovative use of cost-effective GPS instrumentation while addressing the challenge of implementing efficient solutions for monitoring and early warning systems in critical infrastructures and unstable regions from hydrological point of view. The current system is operational but comes with some limitations. These limitations encompass a single-frequency and single-constellation receiver configuration, leading to reduced performance in areas with poor satellite coverage (e.g., densely vegetated slopes or limited lines of sight) or when only distant reference stations, usually belonging to regional GNSS permanent networks devoted to crustal deformation studies or cadastral services (Zuliani et al. 2018; Bragato et al. 2021), are accessible. Furthermore, it introduces a delay of one hour in displacement data provision. Additionally, the reliance on a single server for all processing tasks compromises the system's scalability potential.

Innovative solution

OGS has pioneered the development of LZER0, a highly adaptable GNSS platform recognized for its cost-effectiveness and versatility in various applications. As documented in Zuliani et al. 2022b, LZER0 transcends conventional surveying roles, extending its capabilities to encompass monitoring tasks. Integrated with the M8T single-frequency GNSS model from U-BLOX and complemented by a dedicated web portal for streamlined data visualization, LZER0 presents a holistic solution. GNSS data processing is facilitated through the RTKLIB software package, ensuring precise results accessible to end-users. By harnessing both real-time and post-processing RTKLIB engines, LZER0 excels in relative positioning mode. Its adaptability shines through in its successful deployment across diverse domains, including cadastral, monitoring, and automotive applications. This adaptability underscores LZER0's intuitive hardware and software interface, making it an ideal choice for research, educational, and professional endeavors with ease of deployment at its core.

In Zuliani et al. 2022b, a comparison was made between the results of monitoring a landslide in the municipality of Brugnera in North-Eastern Italy carried out both with LZER0, in real-time with data every second, and with a cost-effective commercial system, already used also for monitoring the Cazzaso landslide (Zuliani et al. 2022a), with post-processing calculation to produce a sample every hour. The encouraging results pushed OGS to develop an advanced LZER0 solution called LZER0 NET which implements the use of a new multi-frequency and multi-constellation chip from U-BLOX called ZED F9P (see Figure 5). The instrumentation has been replanned and redesigned and the hardware part is in production on a few dozen devices. Some components are currently being developed for the software management interface aimed at the instrument configuration and to the graphic display of the results. The device created overcomes some of the problems that emerged with the previous version (for example, the new system is full-GNSS and multi-frequency). This new potential must be tested in difficult environments (for example those covered by vegetation) and which exploit the multi-frequency GNSS signal (which makes it more performing even with reference stations up to a few dozen km away). We also want to verify whether the new scripts created for the LZER0 NET version improve the real-time calculation and post-processing mechanisms directly on the remote sensor. It is therefore proposed, once available, to install and test the LZER0 NET equipment on the Cazzaso landslide, which exposes the system to a particularly stimulating environment.

Figure 5. a) the first LZER0 prototype developed by OGS and used as the first sample to produce more pieces. b) The LZER0 Core Card (LLC) an electronic board developed by OGS mounting the U-BLOX ZED F9P GNSS chip receiver and included in the LZER0 NET device. c) part of the interface which is under development for LZER0 NET.

The current Technology Readiness Level (TRL) stands at 6, with the device having been designed and undergoing production in a limited quantity of units. Through rigorous testing and ongoing software refinement, we anticipate enhancing the robustness and reliability of the equipment, ultimately aiming to elevate its TRL to 7.

Expected outcomes

It is expected that the system created will be able to make the solution developed on the remote sensor available in real time, over the TCP/IP protocol (see a first prototype of interface in **Errore. L'origine riferimento non è stata trovata.**).

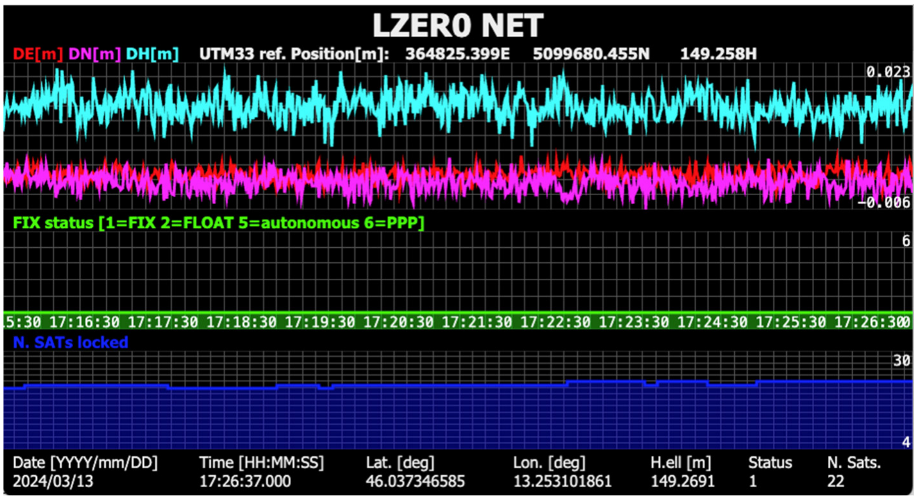

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Figure 6. The current web interface that displays the displacements produced by the LZER0 NET device. The interface needs to be redesigned to improve its performance and to be more reliable.

The solution includes the instrument coordinates updated at the rate of one measurement per second, the related uncertainties, the number of satellites used and the quality of the solution. The solution found will be able to provide displacements from a GNSS sensor that includes the best of the cost-effective GNSS technology currently available, with the advantage of having a solution available with an update rate of one second and therefore usable for early-warning applications. In addition, scalability will be guaranteed by the fact that the position calculation engine from GNSS data is created directly on the remote sensor, guaranteeing high scalability in anticipation of its use for extended monitoring systems including many measurement points.

Risk assessment

The development and testing of cost-effective GNSS equipment introduce challenges that are intricately tied to the reliability and stability of communication infrastructure. This becomes especially pronounced in remote or challenging environments, where access to a robust network connection is often limited or erratic. Such conditions amplify the risks associated with ensuring uninterrupted data transmission and reception, potentially impeding the effectiveness of the GNSS system. Consequently, we need to explore these challenges to fortify the equipment's resilience and performance in adverse conditions, ensuring its reliability across varied operational landscapes.

The automatic processing devoted to the real-time GNSS data-processing can be instable because of conflicts with different programs and services. All these issues must be tested in all possible combinations since data for early warning purposes carries additional risks. The main risk is the potential for false positives or false negatives in landslide predictions, which can lead to unnecessary countermeasures, or conversely, failure to issue warnings when necessary. To mitigate this risk, the automatic workflow should be customized, calibrated and validated on a monitoring window of at least 1 month for each monitoring site. The processing scheme should be re-adapted to the specific conditions of the new monitored sites.

A further point of weakness is the environmental factors such extreme vegetation cover that can severely affect the displacement measure. This issue can be partially solved using good GNSS antennas but with the constraint of keeping the costs moderately low to keep the whole equipment in the cost-effective class.

Furthermore, despite LZER0 NET's careful design to optimize power usage (such as the integration of a Raspberry Pi zero), the inclusion of batteries and solar panels for remote data transmission introduces potential risks related to battery longevity, maintenance, and overall performance. Inadequate battery management or oversight of power consumption can precipitate unforeseen system failures, resulting in data loss and operational interruptions.

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N16: Synthetic Aperture Radar (SAR) Interferometry from Autonomous Unmanned Aerial System (UAS) platform

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Problem setting

The aim is to develop an autonomous Unmanned Aerial System (UAS) platform equipped with Synthetic Aperture Radar (SAR) Interferometry for efficient monitoring of ground deformation. Combined with photogrammetry and DIC, it tackles instability phenomena in natural (landslides, volcanoes) and man-made environments (mines, cities, infrastructure).

Crucially, the autonomous UAS bridges the gap between:

- Space/airborne: Great for large areas but limited by cost and flexibility.
- Terrestrial: Cost-effective and high-frequency, but limited field of view.

This UAS excels where others struggle, offering high-quality data thanks to its autonomous, precise flight capabilities.

State of the art

Synthetic Aperture Radar (SAR) interferometry has established itself as a powerful and mature remote sensing technique. Its ability to measure minute displacements across multiple targets makes it highly valuable for monitoring ground deformation phenomena. A fundamental principle of SAR systems lies in exploiting the coordinated movement of paired antennas to generate high-resolution imagery of the observed area. Differential interferometry, employing the phase difference analysis between two captured images, allows for the retrieval of displacement information.

SAR sensors are currently deployed primarily within satellite and ground-based platforms. Satellite systems operating from orbits approximately 800 km above Earth provide interferometric displacement maps encompassing vast geographical regions. This technology facilitates long-term monitoring with revisit times typically ranging from several days to weeks and can illuminate areas spanning numerous square kilometers.

However, ground-based SAR (GBSAR) systems are more suitable for short-term, high-frequency monitoring of smaller areas, with sampling times potentially as brief as a few seconds (Pieraccini et al.,2019). GBSAR's primary limitation lies in image resolution, which is directly tied to the scan length. This stems from the system's reliance on the movement of antennas along a linear or circular mechanical guide.

Traditional SAR systems, whether spaceborne (orbital movement), airborne (flight path), or ground-based (mechanical guide), rely on specific movement mechanisms for image synthesis, each with inherent limitations. Spaceborne SAR suffers from extended revisit times (weeks to months). Conversely, ground-based SAR struggles with poor azimuth resolution, as angular resolution is directly linked to aperture length. UAS-borne SAR technology emerges as a potential solution to bridge the gap between these established monitoring methods.

As illustrated in Figure 7, UAS-borne SAR presents a compelling solution by effectively bridging the gap between satellite and terrestrial radar systems. This technology demonstrates the capability of performing extended scans (up to several squared kilometers) within a short timeframe (a few minutes). Several research groups and private companies are actively engaged in the development of UAS-borne SAR solutions (Brotzer et al., 2021; Xing et al., 2009; Hu et al., 2019; Xu et al., 2018; Essen et al., 2012; Xu et al., 2020; Moreira et al., 2019; Luebeck et al., 2020; Frey et al., 2019;

https://www.echoes-tech.it/tersa/ ; https://ars.upc.edu/projects/sar-in-drone ; https://www.imsar.com/wp-content/uploads/2019/10/nsp-3_datasheet_spreads.pdf ; https://www.echodyne.com/media/4qvkbwyx/echodyne-ts-echoflight.pdf ; https://gamma-rs.ch/uploads/media/Instruments_Info/GAMMA_L-Band_SAR_information_v1_4.pdf). Notably, recent research by Luebeck D. et al. (Moreira et al., 2019; Luebeck et al., 2020) and Frey O. et al. (https://www.echoes-tech.it/tersa/) has successfully demonstrated the application of differential interferometry using UAS-borne SAR platforms.

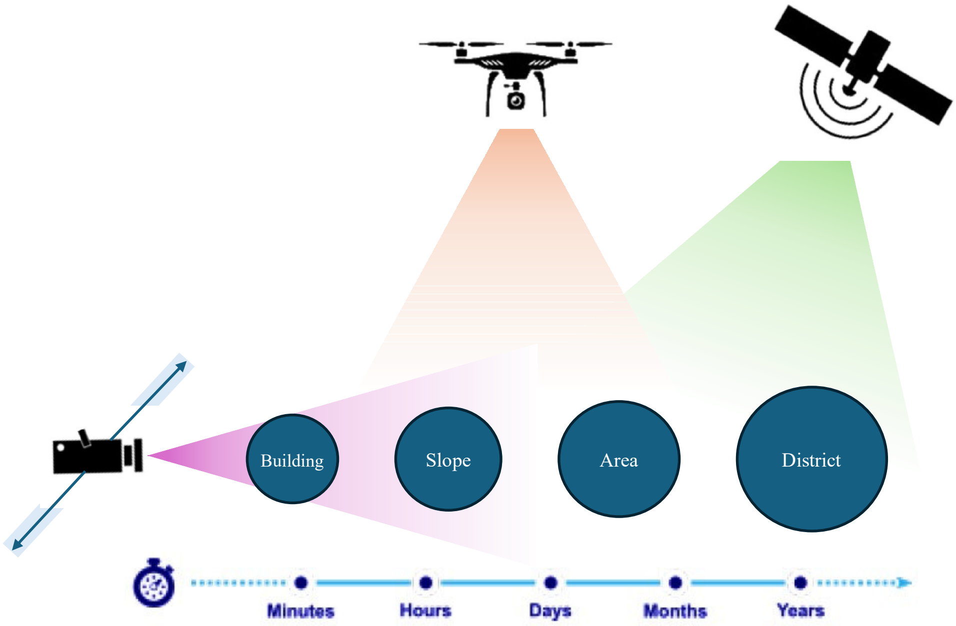

Figure 7. The UAS-borne SAR covers the gap between spaceborne and ground-based SAR monitoring systems.

Innovative solution

This project introduces a groundbreaking solution: an autonomous Unmanned Aerial System (UAS) platform specifically designed for high-precision Synthetic Aperture Radar (SAR) interferometry. This innovative technology addresses the limitations of existing monitoring methods by leveraging the unique capabilities of autonomous UAS flight and advanced data processing techniques.

Traditional monitoring methods, often reliant on satellites or ground-based installations, face challenges in achieving the precise and repeatable flight paths critical for high-quality SAR data. This autonomous UAS platform overcomes these limitations by employing advanced control algorithms. Precise positioning and attitude estimation are achieved through a combination of multiple sensors (RTK-GNSS, IMU) and sophisticated filtering algorithms. Furthermore, photogrammetry with fiducial markers can be integrated to push the boundaries of accuracy (Patel et al., 2021; Stamatescu et al., 2015; Li et al., 2004; Hazzat et al., 2015; Mráz et al., 2020; Whitaker et al., 2020).

The proposed system goes beyond basic autonomous flight. It utilizes Model Predictive Control (MPC) to optimize trajectory planning and account for external disturbances that can plague real-world environments (Kikuchi et al., 2018; Rawlings et al., 2009; Sun et al., 2017; Wenjie et al., 2018; Kang et al., 2009). This ensures even greater accuracy and data quality. Safety is paramount, and the autonomous UAS will be equipped with an advanced obstacle avoidance system utilizing sensors like radar, stereo cameras, or LiDAR (Muñoz et al., 2015; Yu et al., 2020)).

This innovative system doesn't stop SAR data acquisition. It seamlessly integrates SAR data with high-resolution imagery captured by onboard cameras. Techniques like Digital Image Correlation (DIC) can then be applied to both SAR and optical images, enabling the extraction of valuable displacement information for medium-long term monitoring applications. This combined approach offers superior accuracy and flexibility compared to traditional methods (Caporossi et al., 2013; Nakamura et al., 2007).

The current Technological Readiness Level (TRL) of this project is estimated to be 2 ("technology concept formulated"). With successful development, the TRL has the potential to reach 9 ("actual system proven in the operational environment"). This signifies a significant advancement, transforming the concept into a reliable and practical tool.

The development costs encompass both hardware and software components. A high-performance UAS platform capable of carrying a substantial payload (radar, cameras, sensors) is crucial. Advanced sensors (RTK-GNSS, IMU, LiDAR) are necessary for precise positioning and obstacle avoidance. Onboard and ground processing units will be required for real-time and post-mission data analysis. Software development will focus on flight control algorithms for autonomous operation, sensor fusion and data processing algorithms, and image processing and analysis software for SAR and optical data, including DIC integration.

A step forward for a custom development of the sensors will be needed in order to integrate the different technologies, systems and ancillary equipment aiming at reducing the weight and size of the overall sensor packet. This is a crucial step. The radar market is in fact offering many solutions at affordable prices but often such systems cannot be customized and easily integrated with other technologies. Also, most of such sensors and in particular radar technologies are based on evaluation kit and cannot provide high performance functionalities and high-quality data. Thus, it is fundamental to find a conjunction point between the development of the UAS platform and the payload. Thus, a significant portion of the cost will be associated with the development of a drone capable of lifting the necessary payload and the custom development of the payload. However, the potential benefits of this technology for various monitoring applications, such as landslide detection, infrastructure health assessment, and volcano monitoring, justify this investment. Furthermore, resources will be dedicated to the development of technological components with the potential for patenting or technology transfer for industrialization, potentially recouping some development costs.

This proposed autonomous UAS platform with dedicated custom payload for high-precision SAR interferometry represents a significant leap forward in environmental monitoring capabilities. By combining cutting-edge autonomous flight control, compact and innovative radar solutions, advanced data processing techniques, and sensor fusion, this technology offers unparalleled accuracy, flexibility, and cost-effectiveness. Further development efforts are warranted to unlock the full potential of this innovative solution and revolutionize the field of high-precision SAR interferometry.

Expected outcomes

This document outlines the anticipated outcomes and advantages of a groundbreaking autonomous Unmanned Aerial System (UAS) platform designed specifically for high-precision Synthetic Aperture Radar (SAR) interferometry. This innovative technology promises to revolutionize ground and structural deformation monitoring by surpassing the limitations of existing techniques.

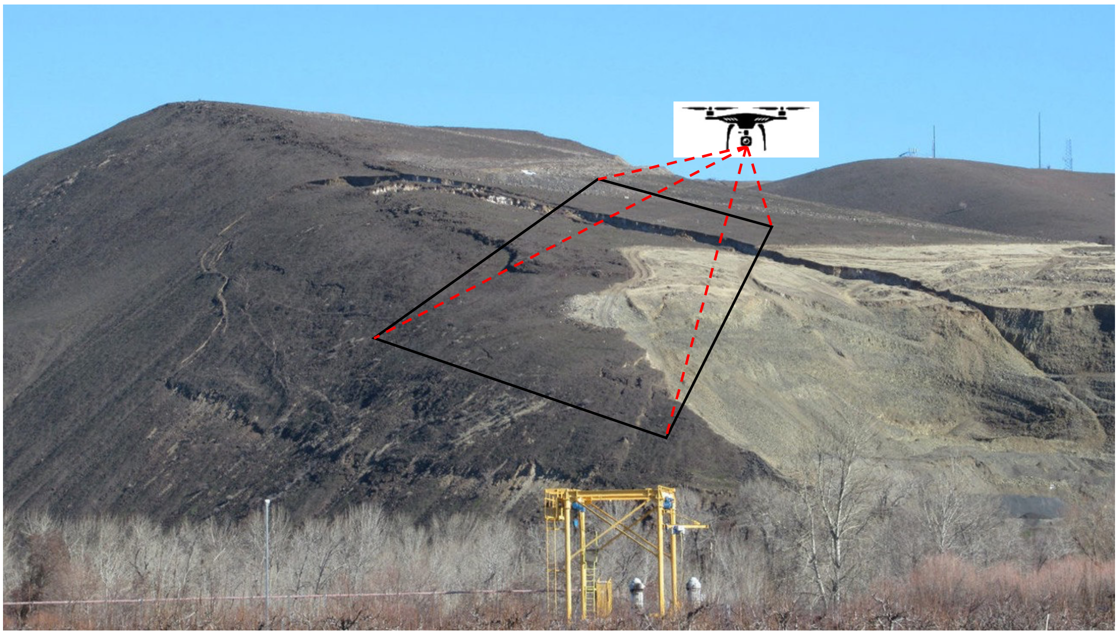

Figure 8. Rendering of a possible application on slope movements.

Enhanced Monitoring Capabilities and Data Acquisition

- **Detailed Slope Stability Analysis:** The system's ability to perform parallel, close-proximity flights over slopes facilitates the acquisition of high-resolution data. This detailed information empowers engineers and scientists with a deeper understanding of slope stability and associated risks. Furthermore, the platform's accessibility to areas previously deemed unreachable by traditional methods due to challenging terrain significantly expands the scope of possible monitoring applications (i.e., polarimetry and tomography for biomass estimation or vegetation index).
- **Rapid Large-Area Scans and Unimpeded Data Collection:** The UAS can scan vast areas (up to several squared kilometers) in a remarkably short timeframe, significantly outperforming the data collection capability of conventional ground-based methods. This acquisition capability is crucial for capturing dynamic events or establishing detailed baseline datasets for future comparisons. Additionally, unlike ground-based methods that can be hindered by obstacles, the UAS can navigate around natural obstructions, providing a more comprehensive view of the monitored area and ensuring complete data capture.
- **Superior Data Acquisition and Analysis:** This innovative system leverages the strengths of both differential interferometry and Digital Image Correlation (DIC) techniques. Differential interferometry offers highly accurate measurements of surface displacement, while DIC provides robust results by analyzing changes in image amplitude information. This powerful combination fosters a highly reliable monitoring system capable of delivering a more comprehensive understanding of ground movement.

Integration, Flexibility, and Targeted Testing

- **Unified Monitoring Platform:** Integrating differential SAR interferometry, photogrammetry, and DIC into a single UAS platform significantly improves monitoring performance, usability, and overall flexibility compared to separate monitoring techniques that require complex deployments and data fusion efforts. This streamlined approach reduces operational complexity and facilitates data analysis, leading to more efficient and cost-effective monitoring strategies.
- **Targeted Testing and Validation:** The selection of test sites will be based on specific criteria to ensure a thorough evaluation of the system's capabilities in various real-world scenarios:
    - Areas experiencing frequent ground or structural movements to assess the system's sensitivity to ongoing deformation.

    - Locations with existing complementary ground or satellite-based monitoring systems to facilitate data comparison and validation of the UAS-derived measurements.
    - Land cover with diverse optical and radar features to evaluate the system's performance across different environmental conditions.
- **Diverse Monitoring Scenarios:** The system is designed to function effectively in various challenging environments, expanding its applicability for real-world deployments:
    - Areas with mixed vegetation and bare terrain, where traditional methods might struggle to differentiate subtle changes due to limited data acquisition techniques.
    - Locations prone to frequent rockfalls and debris movement, requiring a monitoring system capable of capturing rapid changes and potential hazards.
    - Villages and urban areas susceptible to landslides at various rates (mm/year to meters/year), where early detection and monitoring of ground movement are critical for mitigating risks.

Broad Applications and Economic Potential

- **Infrastructure and Settlement Protection:** The system can be used for monitoring critical infrastructure such as bridges, dams, and pipelines, as well as protecting urban areas and villages from landslides and other ground instability phenomena. By providing real-time or near-real-time data on ground movement, the system can aid in early detection and mitigation efforts, potentially saving lives and infrastructure.
- **Coastal and Near-Shore Environment Monitoring:** The UAS platform can be utilized for detailed observation of coastal and near-shore environments, typically difficult to access and monitor using traditional methods such as boats or fixed monitoring stations. This includes mapping underwater features like underwater canyons and monitoring their evolution after storms, providing valuable data for coastal management and hazard mitigation strategies.
- **Economic Advantages:** This technology offers high economic potential for both equipment manufacturers and service providers. Manufacturers can benefit from the creation of a new generation of sophisticated UAS platforms specifically designed for high-precision SAR interferometry. Service companies and authorities involved in land management can leverage a system that integrates various sensors for comprehensive monitoring, expanding their capabilities beyond traditional optical inspections and offering more valuable data to clients. Furthermore, the potential for patenting technological components or technology transfer for industrialization creates additional economic opportunities.

This proposed autonomous UAS platform offers a transformative approach to ground and structural deformation monitoring. By combining its advanced capabilities with existing monitoring techniques, the system promises to revolutionize the field and provide valuable insights for various applications, ultimately leading to improved safety, infrastructure protection, and environmental management.

Risk assessment

During the development and application of Synthetic Aperture Radar (SAR) Interferometry from an Autonomous Unmanned Aerial System (UAS) platform in the field of Engineering Geology, it is crucial to carefully consider the potential risks and limitations associated with this innovative solution.

Among the risks that may arise during technological development is the critical issue of stabilizing the flight path of the UAS. The need to maintain a stable flight trajectory is essential to ensure the accuracy and reliability of SAR measurements; however, instability issues could compromise the quality of collected data.

Furthermore, it is important to consider challenges related to the payload of the UAS. The equipment required for SAR data collection may be subject to weight and size restrictions, impacting the UAS's ability to transport and operate efficiently.

Regarding limitations in practical application, it should be noted that the ability to measure ground deformations of a few millimeters per year may exceed the current capabilities of the instrument. This could limit the technology's utility for slowly occurring geological phenomena.

Additionally, the technology's sensitivity to weather conditions must be considered. The effectiveness of the UAS may be compromised by adverse conditions such as heavy rain, fog, or strong winds, which could affect the quality of collected data and operational safety.

Lastly, limitations regarding the size of objects to be monitored should be considered. The technology may encounter difficulties in analyzing large-scale geological phenomena, such as landslides or subsidence, due to restrictions on the scale of objects that can be accurately monitored.

Addressing these challenges requires a careful approach and comprehensive assessment of risks and limitations during the development and implementation of SAR Interferometry from a UAS platform.

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N23: Development of a high-range depth sensor coupled with optical camera for monitoring purposes

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Problem setting

Landslides pose a significant risk to life, property, and infrastructure worldwide. Effective monitoring and early warning systems are crucial for minimizing these risks. However, current monitoring solutions face several challenges, including limited spatial coverage, insufficient resolution to detect early signs of ground movement, and difficulty operating under various environmental conditions. There is a pressing need for advanced monitoring systems that can provide high-resolution, three-dimensional insights into ground instability and movement across extensive areas under diverse environmental conditions. Current depth sensing technologies, while invaluable for various applications, face significant limitations when it comes to maximum depth measurements and accuracy, particularly over long distances. These limitations become especially critical in the context of landslide monitoring, where the ability to accurately assess and predict ground movements over extensive areas can significantly impact risk management and safety measures.

The primary issues with existing depth cameras include:

Reduced Measurement Accuracy at Long Ranges: Most depth cameras are optimized for short to medium distances, typically not exceeding 20 meters. Beyond this range, the accuracy of depth measurements drops significantly. This decrease in accuracy is due to factors such as signal attenuation, scattering, and interference from environmental light sources, all of which can distort the depth information.

Environmental Constraints: The performance of depth cameras outdoors is further compromised by environmental conditions. Sunlight, for instance, can saturate the sensors of Time-of-Flight (ToF) cameras, leading to inaccurate depth data. Similarly, adverse weather conditions such as rain, fog, or heavy dust can scatter the signals used for depth measurement, reducing the system's overall reliability.

Limited Spatial Resolution: At greater distances, the spatial resolution of the depth data decreases, making it more challenging to detect small or subtle changes in the landscape that could indicate the early stages of a landslide. This limitation is a significant drawback for monitoring applications where detail is crucial for early warning systems.

These challenges underscore the need for a new approach to depth sensing that can offer enhanced accuracy and reliability for long-range monitoring applications, such as landslide detection and environmental assessment. Overcoming these limitations would represent a significant advancement in the field of remote sensing and hazard management.

State of the art

Recent advancements in remote sensing technologies have significantly improved landslide monitoring capabilities. Among these, depth cameras and high-resolution optical cameras have shown potential for detailed terrain analysis and change detection (Onoue et al., 2021). Standard digital cameras output images as a 2D grid of pixels. Each pixel has RGB values associated with it. Each attribute has a number from 0 to 255. Thousands to millions of pixels together create the kind of photographs we are all very familiar with. A depth camera on the other hand, has pixels which have a different numerical value associated with them, that number being the distance from the camera, or "depth." Some depth cameras have both an RGB and a depth system, which can give pixels with all four values, or RGBD (https://www.intelrealsense.com/beginners-guide-to-depth/; Tychola et al., 2022) (Figure 9). The output from a depth camera can be displayed in a variety of ways – in Figure 10, the colour image is shown side by side with the depth image, where each different colour in the depth map represents a different distance from the camera. In this case, cyan is closest to the camera, and red is furthest.

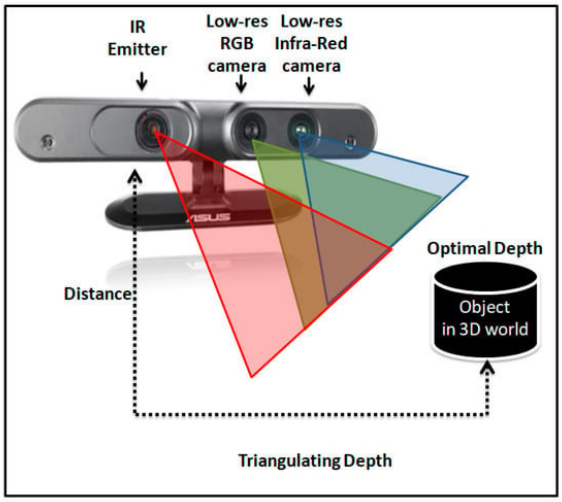

Figure 9. A standard low-range depth camera with its sensors (IR emitter, low-res RGB camera, and low-res infrared camera).

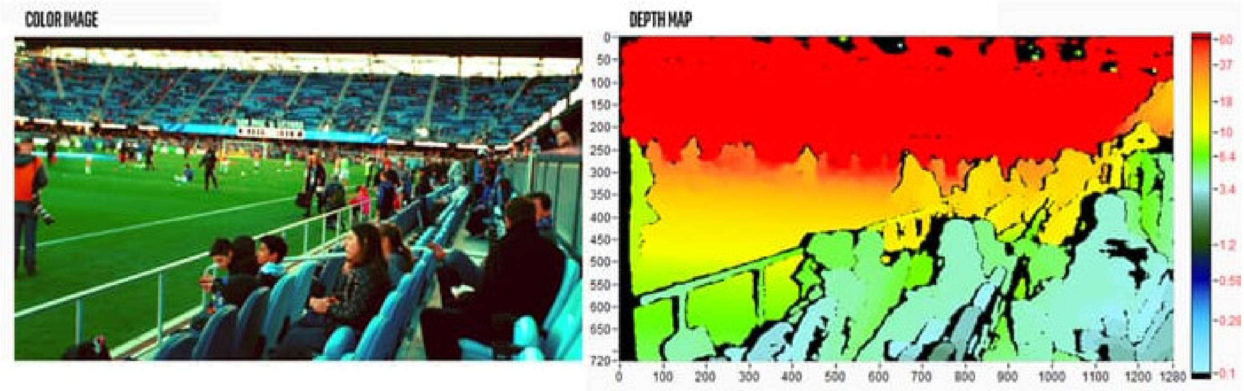

Figure 10.Example of a true-colour RGB image (left) and a RGBD image acquired by a standard depth camera (right).

There are a variety of different methods for calculating depth (e.g., structured light and coded light, stereo depth, and time of flight and LiDAR) all with different strengths and weaknesses and optimal operating conditions. All depth cameras give you the advantage of additional understanding about a scene, and more, it gives any device or system the ability to understand a scene in ways that don't require human intervention (Tychola et al., 2022; Langmann et al., 2012).

However, applications specifically focused on landslide monitoring are still underexplored. A review of the scientific literature reveals a gap in integrated, high-range depth sensing coupled with high-resolution optical imaging for real-time landslide detection and monitoring.

Innovative solution

The proposed system seeks to overcome the current limitations of depth camera technology for applications requiring long-range monitoring, such as landslide detection, by developing and integrating a high-range depth camera with a high-resolution optical camera. This integrated solution aims to leverage the strengths of both technologies to provide comprehensive, accurate, and real-time monitoring capabilities over large distances.

The system combines a depth camera, developed with potential in long-range depth sensing, with a high-resolution optical camera capable of capturing detailed visual information. The integration of these technologies is enhanced by advanced signal processing and image processing algorithms, designed to optimize depth accuracy and image clarity across various environmental conditions.

Key components of the innovative solution include:

- Adaptive signal enhancement: utilizes adaptive sensors and algorithms to enhance the camera's signal in outdoor and challenging light conditions, reducing noise and improving depth measurement accuracy.
- Environmental compensation: incorporates machine learning models trained on diverse environmental data to automatically adjust the depth sensing parameters and compensate for environmental factors such as sunlight, rain, and fog.
- Image-depth fusion: employs advanced image processing techniques to seamlessly fuse depth data with high-resolution optical images, providing a detailed 3D visualization of the monitored area.
- Real-time data analysis: integrates real-time data processing capabilities to immediately analyze depth and image data for early detection of ground movements or changes indicative of potential landslide risks.

The current Technology Readiness Level (TRL) of the proposed solution is estimated at TLR 3, where the concept has been formulated, and initial proof of concept has been demonstrated in a controlled environment. The integration of adaptive signal enhancement and environmental compensation algorithms, along with the image-depth fusion technique, remains in the early stages of development.

The development path toward TRL 6 involves several key phases:

- TRL 4-5: validation of technology components in a laboratory setting, focusing on the effectiveness of signal enhancement, environmental compensation, and image-depth fusion algorithms under simulated environmental conditions.
- TRL 6: demonstration of a prototype system in a relevant environment, such as a controlled outdoor area with variable lighting and weather conditions. This phase will also involve optimizing the system for real-time processing and analysis.

The development costs associated with advancing the technology from TRL 3 to TRL 6 are justified by the significant potential benefits of the integrated monitoring system. These benefits include enhanced safety and risk management in landslide-prone areas, reduced economic losses from landslide damage, and improved environmental monitoring capabilities. The investment in research and development will fund critical advancements in depth sensing technology, environmental adaptation algorithms, and real-time data processing capabilities, all of which are essential for achieving the desired level of accuracy and reliability in long-range monitoring applications.

Moreover, the proposed solution has the potential for broader applications beyond landslide monitoring, including infrastructure inspection, urban planning, and natural resource management, further justifying the development costs by opening up additional markets and revenue streams for the technology.

Expected outcomes

The proposed development of a new high-range depth camera integrated with a high-resolution optical camera aims to significantly improve landslide monitoring and magnitude estimates capabilities. This system is expected to offer:

- RGBD images: high-resolution and accurate depth measurements (Figure 11) combined with a RGB image enabling 3D change detection analysis and multi-temporal cross-sections (Figure 12).
- Enhanced detection capabilities: early detection of ground movements and rockfalls that may precede landslide, through detailed 3D mapping and high-resolution image change detection (Figure 12).
- Comprehensive coverage: ability to monitor extensive areas with high accuracy, surpassing the limitations of current depth systems.
- Real-time monitoring and alerting: providing real-time data to authorities and stakeholders, enabling faster response and mitigation actions.

Compared to available techniques, this integrated approach is expected to offer superior spatial resolution, range, and operational flexibility, contributing to more effective risk management and safety measures in landslide-prone areas.

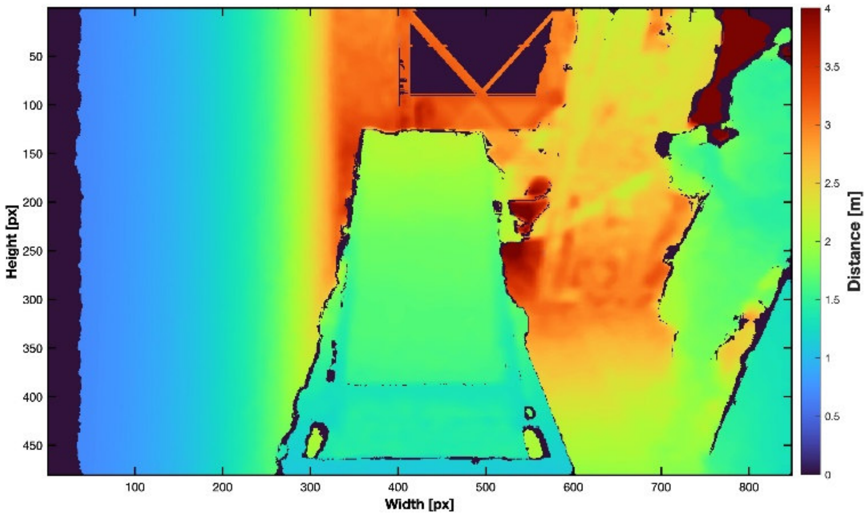

Figure 11. Laboratory test with a commercial depth camera measuring distances from the analogue slope model.

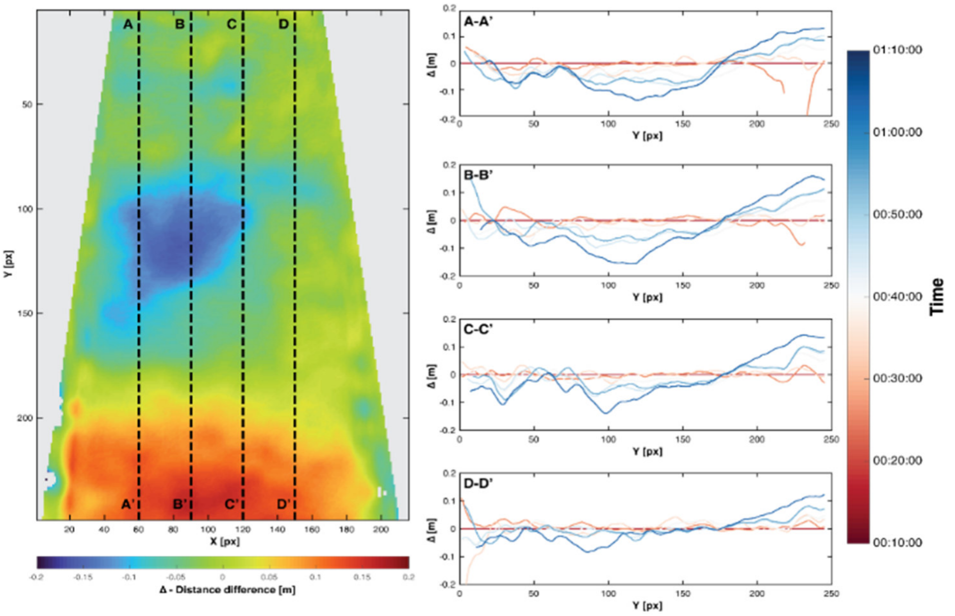

Figure 12.Laboratory test and potential results from multi-temporal depth monitoring of a human-controlled analogue slope model.

Risk assessment

The development and implementation of this advanced monitoring technology may involve potential risks and limitations:

- Technological complexity: At distances approaching or exceeding 20 meters, the resolution and accuracy of depth measurements tend to decrease. This is because the precision of depth data is inherently linked to the technology used (e.g., structured light, time-of-flight) and the camera's design. As the distance increases, the returned signal can become weaker or more distorted, leading to less precise depth estimations. Thus, reaching high distances while maintaining accuracy will be a challenge. Moreover, the integration of high-range depth sensing with high-resolution optical imaging requires sophisticated calibration and synchronization, posing challenges in system design and stability.
- Environmental constraints: the system's effectiveness may vary across different environments, with factors such as extreme weather, vegetation cover, and terrain type affecting performance.
- Field of View: the field of view (FOV) of a depth camera can also be a limiting factor for long-distance monitoring. A narrow FOV can restrict the area covered by the camera, necessitating the use of multiple cameras to monitor larger areas effectively. Conversely, a wide FOV can reduce the spatial resolution of the depth data, affecting the detail and usefulness of the information captured at greater distances.
- Reflectivity and absorption: the performance of depth cameras is influenced by the reflectivity and absorption characteristics of the objects and surfaces within their range. Dark, non-reflective surfaces can absorb the emitted signals (light), reducing the signal strength that returns to the camera and thereby decreasing the accuracy of depth measurements. This can be particularly challenging in natural environments, where the variety of materials and surface conditions can vary widely.
- System integration and data processing: integrating depth cameras into broader monitoring systems and processing the depth data effectively can be challenging, especially for long-distance applications. The data collected at these ranges may require more sophisticated algorithms to compensate for the aforementioned inaccuracies and environmental effects. Additionally, real-time processing and analysis of depth data can demand significant computational resources, especially when high-resolution depth information is required over large areas.

To mitigate these limitations, advancements in depth sensing technology and data processing algorithms are essential. Improvements might include more robust signal processing techniques, better noise reduction in outdoor conditions, and the development of sensors specifically designed for long-range depth measurement. Additionally, integrating depth cameras with other sensing technologies, such as high-resolution optical cameras or LIDAR, can provide complementary data that helps overcome some of the depth camera limitations, offering a more comprehensive monitoring solution.

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N24: Monitoring network of sensors for environmental and geotechnical monitoring in extreme temperatures

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Problem setting

Landslides are among the most relevant natural processes in the morphogenetic control of the landscape (Petley 2012), and, consequently, they represent an important hydrogeological risk factor (Sepúlveda et al., 2015). With over 600,000 identified events and approximately 8% of the national territory affected, landslides in Italy are the natural phenomena that have the greatest impact on the population, linear infrastructures, cultural assets, as well as the economic and productive system.

Tracking the landslide processes might be a significant challenge to improving our understanding of these phenomena and their evolutionary pattern, which is controlled by predisposition, preparatory and triggering factors *sensu* (Gunzburger et al., 2005).

Examining the slope's behavior in "extreme" natural circumstances, such as very high or low pressure or temperature, is particularly crucial within this framework. There are some specific events that may favor the occurrence of extreme conditions and, thus, of a peculiar stress regime on the gravitation process. This is for example the case of wildfires and frost events that are respectively able to induce very high and low temperatures on the air-rock/soil interface, as well as on the geotechnical system itself. Wildfire events are in fact one of the most relevant preparatory factors for shallow earth-landslides (AghaKouchak et al., 2020) (Fig. 1) since they are responsible for changes in the hydrologic and geomorphic response of watersheds. Similarly, the occurrence of freeze-thaw cycles can induce relevant accumulation of inelastic deformations within the rock-mass system, leading to permanent damage and, eventually, to slope collapses.

While more traditional remote-sensing analyses allow the indirect investigation of areas affected by such extreme phenomena, there are still few technologies able to *in situ* monitor a landslide system subjected to the same conditions. Even more true is the fact that most of the environmental and geotechnical monitoring solutions on the market are not tailor designed to work under extreme thermo-baric conditions, both in terms of their mechanics and data transmission.

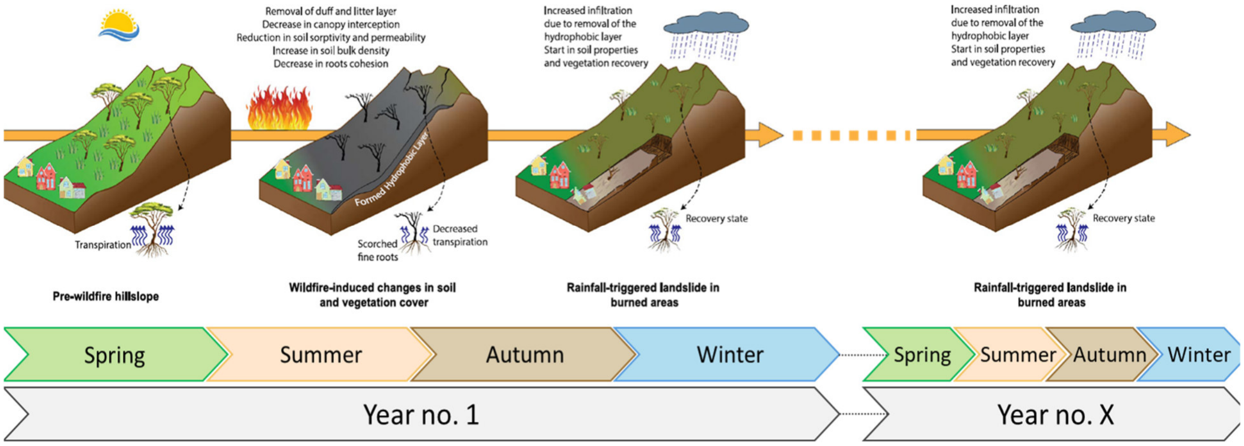

Figure 13.Example of a time-dependent cascading hazard in which the preparatory effects caused by wildfires on shallow landslides can last for some years (modified from (Abdollahi et al., 2023)).

State of the art

Several monitoring strategies are usually adopted for managing the landslide risk by employing sensors specifically aimed at analyzing the effects induced by natural and anthropic forcing that can negatively affect slope stability. Nevertheless, applications specifically focused on landslide monitoring under extreme conditions are still underexplored.

Different instruments have been developed to monitor the soil moisture, which is unequivocally recognized as one of the most important controlling factors of shallow landslides. However, the link between measured soil moisture, wildfire occurrence, and landslides activation has only recently been studied (Krueger et al., 2016). In particular, most of the studies where the application of these kinds of instruments has been tested are focused on the monitoring of the soil conditions before and after the wildfire event, and not during it. This aspect essentially depends on the logistical difficulty in which the instrument should work (i.e., very high temperatures) and, thus, on the high-level technological characteristics that it should feature.

The situation is similar for monitoring suites whose functionality is confronted with opposing thermal regimes (i.e., frost conditions).

A review of the scientific literature reveals a gap in the development of instruments able to work in extreme thermal conditions and transmitting data via a wireless data transmission network.

Innovative solution

The availability of nodal monitoring devices to be implemented in complex and integrated monitoring networks tailor-designed for slope stability assessment in extreme environmental conditions will pave the way for innovative applications. Within the context of geotechnical and environmental monitoring, the deployment of real-time nodal monitoring networks could provide invaluable information into evolving scenarios of slope instability, which are crucial for mitigating risks associated with natural hazards. For example, in wildfire-prone areas, such monitoring networks could have the ability to be equipped with a great variety of devices able to measure both environmental and soil- or rock mass-related quantities and parameters (e.g., air temperature, wind speed and direction, soil moisture and saturation, rock temperature, local displacements and deformations) providing real-time data and aiding in early detection of slope destabilization or preparation to instability. To point toward these applications, three prerequisites need to be met concerning nodal devices and monitoring networks:

i) measuring nodal devices must be enclosed in protective casings specifically designed for their application (high/low temperatures or high/low pressure environments);
ii) every node should be equipped with high-performance batteries and/or small footprint solar panels for uninterrupted power supply;
iii) all nodes should be able to communicate wirelessly with a central hub to avoid the presence of cables and enable real-time access and processing of monitoring multi parametric data.

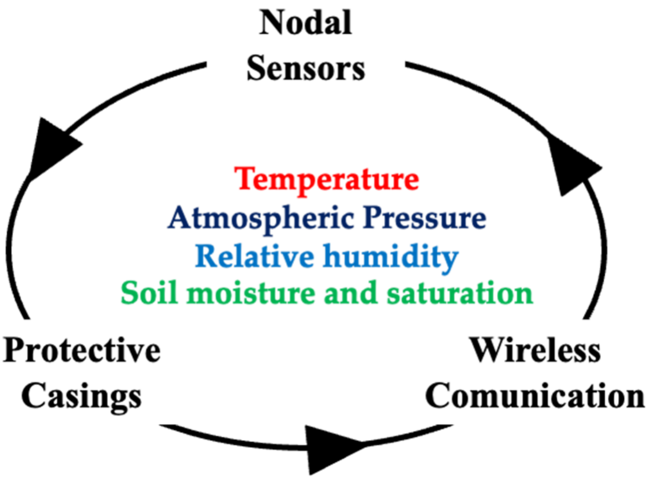

Figure 14.Monitoring system scheme.

Similarly, the application of such monitoring devices and networks could find applications in mountainous regions or environments characterized by freezing conditions. In fact, the absence of cables and the protective casings will allow them not only to endure harsh weather and climatic conditions, but also to continuously measure regardless of the environmental conditions, thus offering real-time and long-term monitoring dataset to investigate and prevent slope failures triggered by freeze-thaw cycles.

Moreover, in the framework of natural risk mitigation strategies (such as due to landslide events), these devices could integrate with autonomous systems for remote monitoring and decision-making, ensuring timely interventions to safeguard infrastructure and ecosystems in extreme conditions. Such innovative applications underscore the transformative potential of monitoring devices in enhancing resilience and disaster preparedness in multiple environmental contexts (i.e., volcanic areas, glaciers, wildfire-prone areas, high-mountainous regions).

Expected outcomes

The objectives and expected outcomes deriving from the proposed implementation of nodal devices in integrated monitoring networks for slope stability assessment in extreme environmental conditions are multiple:

- validate the functionality and durability of the protective casings ensuring their resistance to high/low temperatures or pressure variations;
- evaluate the feasibility and efficacy of high-performance batteries and/or solar panels integrated into each node to provide uninterrupted power supply for continuous monitoring operations;
- test the reliability and efficiency of wireless communication protocols between nodes and a central hub for enabling real-time access and processing of multiparametric monitoring data;

Expected outcomes also include demonstrating these monitoring networks' effectiveness in early detection of slope destabilization (particularly in wildfire-prone areas) and their capacity to provide crucial information for risk mitigation strategies. Furthermore, experimental activities employing such networks will aim to validate the adaptability of these systems to harsh natural environments (mountainous regions, volcanic areas and glaciers), ensuring continuous monitoring regardless of environmental challenges. Ultimately, the expected outcomes from these experimental activities will aim to highlight the potential of nodal monitoring devices in enhancing natural hazard preparedness.

Risk assessment

- However, the application of monitoring instruments able to work under extreme thermic conditions in the field of landslide monitoring must take into account a number of issues related to the meaning itself of the term "extreme". Solutions that can address these problems are proposed in Table 3.

Table 3. Proposed solutions.

Problem	**Solution**
- Very high or low temperatures can omit the sensor operability	- Development of protective casings to ensure the functionality of the instruments
- The sensor-data logger connection cables could be damaged, impairing the efficiency of the monitoring system	- The instruments must be designed wirelessly, as well as the transmission data system

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N2: Implementation of monitoring system based on fiber optic technology to measure displacements of linear structures/infrastructures (viaducts, water pipelines, etc.) interacting with a landslide body

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Problem setting

One of today's challenges involves monitoring and accurately assessing the landslides risk (in specific areas) and developing an effective early warning system to alert authorities and residents before potential landslide events occur. Gathering and analyzing data from fiber optic sensors to detect changes in ground conditions indicative of landslide mechanisms pose technical challenges. This includes the reliability and accuracy of sensor readings, as well as developing algorithms to interpret complex data patterns. Moreover, integrating fiber optic monitoring systems with existing landslide monitoring networks, as well as other sensor technologies and geospatial databases, presents interoperability and compatibility challenges that need to be addressed.

In the last years, the fiber optics system has been a technology with high performance to monitor both the displacement of ground instabilities and the efficiency of linear structures such as pipelines, roads, viaducts, aqueducts, etc. The prompt responsiveness of fiber optic sensors enables swift decision-making and proactive action planning, preempting the escalation of events. This technology facilitates real-time alerts concerning evolving conditions, obviating the need to await subsequent visual inspections, aerial surveys, or other forms of notification. Moreover, the fiber optic sensors facilitate the comprehensive monitoring of mitigation actions. Recent research shows that fiber optic sensors are a valuable tool to calibrate early warning systems based on rain thresholds, which are nowadays the most commonly utilized methods (Schenato et al. 2017).

The well-known experiences of the optical fiber system may be applied to the design of new systems able to monitor ground instability such as submarine landslides (slow and rapid), sinkholes (slow and rapid), and falls and topples landslides. Furthermore, the possibility of increasing the measuring range of strain (or cumulated displacements) with fiber-optic systems could widen the applicability of this technology in the field of landslides.

State of the art

Over the last six decades, Fiber Optic Sensing (FOS) has emerged as a key tool for improving and assessing structural robustness, operational effectiveness, safety protocols and longevity across a wide range of sectors including infrastructure, transportation, healthcare and beyond. Rooted in the principles of Optical Time Division Reflectometry (OTDR), FOS serves as a sophisticated measurement methodology originally developed to identify breaks within fiber optic transmission lines.

Fiber optic technology currently has a wide range of applications in the field of urban planning, with significant prospects for future developments. Fiber optic sensors are being deployed in various infrastructure areas such as buildings, water distribution networks and road systems, facilitating continuous monitoring to determine the impact of environmental factors on structural integrity. This proactive approach enables the pre-emptive detection of potential structural failures, thereby mitigating risks during both the construction phase and subsequent operational periods.

In recent years, fiber optics have attracted attention for their use in monitoring structural integrity and ground stability. A notable example of this application occurred when Aulakh et al. (2004) used an experimental configuration of a fiber optic system to monitor micro-deflections resulting from landslide activity. The fiber optic measurement and control methodology has also been applied to the management of deformation of large diameter pipes in predominantly granular soils, as demonstrated by Vorster et al. in 2006. Such investigations underline the robustness of the measurements, thereby highlighting the commendable reliability of the method in monitoring pipe behaviour, particularly in the context of pipe-soil interaction studies. Inaudi & Branko Glisic (2006) have further highlighted the distinctive attributes of fiber optic sensing within the domain of monitoring methodologies. Notably, these sensors facilitate the simultaneous measurement of temperature and strain across numerous points along elongated structures, such as pipelines. Moreover, their utility extends to detecting leaks, assessing operational parameters, and averting pipeline failures, particularly in regions susceptible to landslides, thus underscoring their multifaceted applications.

Optical Brillouin Time-Domain Reflectometry (BOTDR) represents a pioneering methodology enabling comprehensive strain profile measurements utilizing conventional optical fibers, as demonstrated by Soga et al. in 2008. This technique has demonstrated efficacy in monitoring excavations as well as subterranean structures, as evidenced by studies conducted by Hauswirth et al. in 2014 and Soga in 2014.

Further investigations employing this technology are directed towards monitoring the dynamics of landslide progression. For instance, in 2008, Iten et al. implemented optical fibers along a roadway bordering the St. Moritz landslide, effectively converting it into a macroscopic strain gauge. Subsequently, in 2011, Iten et al. provided the inaugural analysis outlining the design, experimentation, and assessment of optical sensors tailored for geotechnical monitoring purposes. In addition, in 2011, Ravet et al. advocated for the utilization of optical sensors in the surveillance of gas pipelines, particularly those traversing mountainous regions characterized by unstable terrain. In such locales, variations in soil structure between seasons, notably between winter and summer, escalate the risk of hazardous events.

Fiber optic sensors have emerged as indispensable tools in both engineering and scientific domains for deformation measurement. Presently, commercial sensor technologies exhibit the capability to discern strains within the microstrain range. Over the preceding decade, burgeoning demand from the engineering geology community has precipitated the enhancement and widespread adoption of fiber-optic technology. Nonetheless, rigorous testing of these sensors for ground motion detection remains scarce, as highlighted by Ivanov et al. in 2021.

A significant example of the application of this monitoring method is shown by Zhang et al. 2024. The authors studied a retrogressive landslide using the fiber optic system installed within the slope stabilizing piles. The results of this research are most significant indeed, the fiber optical technology can be a good in situ instrument to determine indirectly the geotechnical behaviour of stabilization works. Indeed, by analyzing the distributed strain measurements, it is possible to assess the sliding surfaces and compute the bending moment and shear force induced by the landslide movements on the piles.

Toward an extended use of monitoring systems based on fiber optic technology

Employing fiber optics for landslide monitoring represents a pioneering method that harnesses the unique properties of optical fibers to detect environmental alterations effectively. Fiber optic cables are strategically installed in the areas prone to landslides. These cables can be buried underground or placed along the surface depending on the terrain and the specific needs of the monitoring system. The fiber optic cables are equipped with DAS (Distributed Acoustic Sensing) technology, which allows them to detect disturbances along their length by measuring changes in acoustic signals. When the ground starts to move due to potential landslide activity, it generates subtle vibrations that are detected by the fiber optic cables. The data collected by the fiber optic cables are transmitted to a central monitoring station where sophisticated algorithms analyze the signals in real-time. These algorithms can distinguish between normal environmental noise and signals indicative of landslide activity. By continuously monitoring the acoustic signals along the fiber optic cables, the system can provide early warnings of potential landslide events. Alerts can be sent to relevant authorities and residents in the area, allowing them to take proactive measures to mitigate the risks. Finally, to provide a better understanding of changes in the territory, the monitoring system can be integrated with geospatial data. This allows for a better understanding of the dynamics of the landslide-prone area and more accurate risk assessments.

The concept entails employing a fiber optic cable within an economically feasible, real-time, and continuous monitoring framework. Installation of fiber optics can seamlessly coincide with the laying of underground pipelines, thereby facilitating the detection of potential pipeline leaks and ground displacements.

Ground movements can be effectively monitored utilizing fiber optics, particularly through the application of Brillouin Optical Time Domain Analysis (BOTDA). This sensing mechanism exhibits sensitivity to ground perturbations along the pipeline trajectory, attributable to various phenomena such as landslides, rockfalls, or seismic events. The strain imparted upon the fiber optic sensor positioned along the pipeline enables prompt identification and localization of such occurrences. Moreover, long-range fiber optic detection systems represent a valuable asset for monitoring ground settlements with precision.

BOTDA, leveraging stimulated Brillouin scattering (SBS) within single-mode fibers, operates on the principle of Brillouin scattered light encountering a frequency shift proportional to both temperature and strain fluctuations. This shift is discernible through the interaction between a pump lightwave (in pulse form) and a counter-propagating probe lightwave (continuous) within standard optical fibers. Typically, in ITU G.652 fibers at ambient temperature, the Brillouin frequency shift registers around 10.85 GHz at 1.55 µm, with strain and temperature coefficients measuring 0.05 MHz/°C and 1 MHz/°C, respectively (Ravet et al.2013). This linear correlation renders it a straightforward technique for detecting mechanical and thermal influences. Moreover, the pulsed nature of the pump lightwave facilitates precise localization via time-of-flight measurements and defines the spatial resolution through pulse duration.

According to Ravet et al. 2013 a possible monitoring system may consist of the following components: i) strain and temperature monitoring units, including remote signal regeneration modules and optical switches. Each of these units constitutes an optical node located in a pipeline node such as a pumping or compressor station; ii) Strain and Temperature Measurement Cables (SMC and TMC). The Temperature Measurement Cables may be used as communication between stations and control center; iii) data communication interface between monitoring units and the control centers including the use of a the TMC cable and iv) Monitoring software including measuring unit control, visualization, and configuration as well as alarming capabilities.

The BOTDA technique employed in geotechnical monitoring relies on measuring strain along a sensing fiber, often referred to as a strain measurement cable (SMC). Strain serves as the pivotal parameter for detecting landslide occurrences. Depending on the orientation of the pipeline and consequently the strain measurement cable (SMC), three directions of soil displacement can result in discernible increments in strain, as depicted in Figure 15.

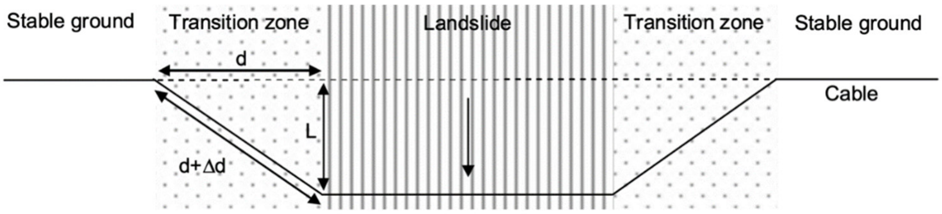

Figure 15.Lateral displacement of a pipeline due to a landslide (by Revet et al. 2013).

The cable deformation depends on the lateral displacement L and the strain ε is simply given by the following equation (Eq. 1):

$$\mathrm{e} = \frac{\Delta d}{d} = \sqrt{1 + (L/d)^2} - 1 \qquad \text{Eq. 1}$$

where *L/d* provides information on the magnitude of the cable displacement.

The monitoring system boasts the capability to detect a wide array of displacements, including combinations of longitudinal and lateral movements, owing to its high sensitivity in measuring strain-induced motions. Indeed, the vertical settlements push down the sensing cable similarly to the lateral displacement, inducing measurable elongation. The transfer of strain from the soil to the strain measurement cable is enhanced in correlation with the burial depth and soil compaction. Moreover, augmenting this transmission further can be achieved through the utilization of cable corrugation and/or ground anchors (Revet et al. 2013).

The actual TRL of this technology is between the 6 and the 7 level. In detail the technology several prototypes are built, and field tests are conducted to validate the performance of the system under realistic conditions. The test was carried out in landslide areas (rotational and planar slides, soil slips, earth flow, etc.) and the fiber optic monitoring system has been successfully demonstrated in real-world applications for landslide detection. However, the technology may be applied to another type of ground instabilities such as subsidence and submarine landslides.

Overall, the TRL of fiber optic monitoring systems applied to landslide detection can vary depending on the specific implementation and the level of maturity of the technology. As advancements continue and more applications are developed, the TRL of these systems is likely to increase, leading to wider adoption and integration into landslide monitoring and management practices. Indeed, monitoring networks may be established, and the system may be integrated into existing landslide risk management frameworks.

Expected outcomes

The fiber optic technology will be a real-time monitoring tool, enabling early detection of ground movement, precise and well-distributed measurement of strain and deformation, as well as continuous surveillance of at-risk areas. Moreover, the development of this system of monitoring may be used in submarine environment. Indeed, the development of fiber optic system will be useful to monitor the submarine landslides by providing real-time data on changes in seabed, enabling early detection of potential landslide events, and facilitating timely intervention to mitigate risks to underwater infrastructure and coastal communities. Additionally, the development of fiber optic systems will contribute to a deeper understanding of submarine landslide dynamics, leading to improved predictive models and more effective management strategies for mitigating the impacts of these geological hazards. In detail, submarine landslides can have significant environmental consequences, including the release of sediment and pollutants, disruption of marine habitats, and generation of tsunamis. Fiber optic monitoring systems will enable continuous surveillance of submarine slopes, allowing for early detection of landslide-induced environmental changes and timely intervention to mitigate adverse impacts on marine ecosystems and coastal communities.

Strengths, Weaknesses, Opportunities, and Threats assessment

To analyze potential advantages and/or limitations that might arise from the technological development/application of the proposed innovative solution a SWOT analysis was carried out (Table 4).

The fiber optic monitoring systems have a high initial setup cost which may be potentially limiting widespread implementation. This technology requires specialised expertise for its installation, calibration, and maintenance. Moreover, the limitations in coverage are linked particularly in challenging terrains or inaccessible areas.

Despite their weakness and threats the fiber optic monitoring systems exhibit several strengths and opportunities for enhancing ground instability detection. These include high sensitivity, enabling the detection of minute changes in strain, temperature, and acoustics, and facilitating early warning systems. Additionally, the distributed sensing capabilities of fiber optic cables provide comprehensive coverage over expansive areas, contributing to effective and extensive monitoring. Moreover, the ability for remote monitoring in real-time reduces the necessity for frequent physical inspections, enhancing efficiency and safety, especially in remote or hazardous environments. Furthermore, the integration of fiber optic data with other sensor data and geospatial information offers a holistic understanding of ground instabilities and their potential impact, allowing for informed decision-making and risk mitigation strategies. The reliability and accuracy of fiber optic monitoring systems ensure continuous surveillance, fostering proactive risk management practices.

Table 4. SWOT analysis of the fiber optic landslide monitoring system.

	Helpful	Harmful
Internal origin	**STRENGTHS** **High Sensitivity**: Fiber optic sensors can detect small changes in strain, temperature, and acoustics, allowing for early detection of ground instabilities. **Distributed Sensing**: Fiber optic cables enable distributed sensing over large areas, providing comprehensive coverage for monitoring ground conditions. **Remote Monitoring**: Fiber optic systems allow for real-time, remote monitoring, reducing the need for frequent physical inspections and enabling surveillance of remote or hazardous areas. **Data Integration**: Fiber optic data can be integrated with other sensor data and geospatial information, providing a comprehensive understanding of ground instabilities and their potential impact. **Reliability**: Fiber optic monitoring systems are reliable and accurate, providing continuous surveillance of ground conditions and enabling proactive risk mitigation.	**WEAKNESSES** **Initial Cost**: The initial setup cost of fiber optic monitoring systems can be high, including the installation of cables and sensor equipment. **Technical Complexity**: Fiber optic monitoring systems require specialized expertise for installation, calibration, and maintenance, which may pose challenges for some organizations. **Limited Coverage**: While fiber optic cables can cover large areas, there may still be limitations in coverage in certain terrains or inaccessible areas. **Data storage and management**: The high volume of data produced and the complexity of managing it.
External Origin	**OPPORTUNITIES** **Technological Advancements**: Ongoing advancements in fiber optic technology, such as improved sensor sensitivity, data processing capabilities and new materials, may enhance the effectiveness of monitoring systems in the field of landslide monitoring and involved infrastructures. **Expansion into New Markets:** Fiber optic monitoring systems have potential applications beyond traditional landslide monitoring, including in infrastructure monitoring, environmental monitoring, and industrial safety. **Partnerships and Collaborations**: Collaborations with research institutions, government agencies, and industry partners can facilitate the development and adoption of fiber optic monitoring solutions.	**THREATS** **Budget Constraints**: Budget constraints within organizations or government agencies may limit investment in fiber optic monitoring infrastructure and deployment. **Cybersecurity Risks**: Fiber optic systems are vulnerable to cybersecurity threats, including data breaches and hacking attacks, which may compromise the integrity and reliability of monitoring data.

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N6: Near real-time processing of passive seismic data for the early warning of landslides

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Problem setting

In the last decade, several case studies of passive seismic monitoring have been reported on landslides and potentially unstable rock masses. Different seismic parameters (i.e., resonance frequencies of the unstable compartments, seismic velocities and microseismicity) were found to highlight reversible and irreversible modifications over time. Reversible modifications are mainly linked to preparatory processes, with a thermal- and/or hydro-mechanical control on site stability driven by air temperature and precipitation rates. Irreversible modifications can be read as failure or reactivation precursors and be used for early-warning purposes. Differently from other monitoring techniques, passive seismic monitoring involves the recording of a huge amount of data. Ambient seismic noise is generally sampled at 200-500 Hz on each channel of the 3C receiver of each monitoring station for several months. Data acquisition and storage is highly power demanding, and the impact of data transmission might be even higher. As a consequence, remote transmission of the data is feasible only in sites equipped with connection to the electrical grid and a customized infrastructure for data storage and transmission. In remote stations, where the power supply relies only on the internal battery of the seismic station (possibly coupled with a solar panel) data are generally stored inside the acquisition unit and downloaded only in the case of on-site interventions. However, even when the data are available in near real-time, there is still a lack of automation in the processing of the passive seismic data. The consequence of both aspects is that generally data processing and intepretation is done much later than data acquisition, thus preventing a real application of the methods for early warning purposes.

To overcome this limitations a double approach should be pursued:

- Technological development of an energy-efficient low-cost system for data transmission and storage even from remote stations;
- Creation of an automatic workflow able to process the data as soon as they become available, with restitution of selected outputs linked to site stability.

State of the art

Several fruitful applications of ambient seismic noise and microseismicity analyses have been reported in the literature for the monitoring and quantification of preparatory processes (Colombero et al. 2021) and possible trigger precursors (Lévy et al. 2010; Mainsant et al. 2012; Bertello et al. 2018; Fiolleau et al. 2020). In unstable rock sites, the fundamental resonance frequency of the prone-to-fall compartment can be easily derived from the noise spectral content and tracked over time (Colombero et al. 2017). Similarly, the cross-correlation of ambient seismic noise simultaneously recorded at two stations gives an estimate of the seismic velocity variations between the two monitoring points (Colombero et al. 2018). The detection of irreversible drops in the resonance frequency values or negative velocity variations not correlated with air temperature and/or precipitation can be read as a precursor to failure. In parallel, the continuous ambient seismic noise record can contain impulsive events related to incipient fracturing, also called microseismic events. An increasing number of microseismic events is expected towards failure due to fracture propagation and growth (Amitrano et al. 2005). The microseismicity can be consequently tracked in time as a further and early-warning parameter. Besides the recognition of failure precursors, all the literature case studies on potentially unstable rock masses also highlighted significant reversible modifications in the seismic parameters driven by thermo- and hydro-mechanical preparatory processes acting at the daily and seasonal scale. The research approach is generally applied a posteriori, on several weeks or months of records. Here, we focus on the technological and methodological improvements needed to apply these methodologies in near real-time.

Innovative solution

Technological development of an energy-efficient low-cost system for data transmission and storage even from remote stations

The fist task involves the design of a system for passive seismic data transmission from remote monitoring stations (not connected to the national electrical grid) to an accessible computer/cloud in which the automatic data processing can be carried out in near-real time. A reliable, energy-efficient and low-cost infrastructure is needed on site. A wireless mesh network might be created in the monitored site to collect the data coming from the different sensors (generally deployed at distances of few tens of meters) equipped with on-purpose designed data transmitters. The data transmitters should be customized to be able to interrogate the storage units of different types of seismic stations. Between the available data formats, MiniSEED might be suitable for remote data transmission due to the compact but efficient data storage (approximately 60 Mb of data to be transmitted from each seismic station every day at 250-Hz sampling frequency). A power-autonomous central data collection point might be created on site for temporary data storage and further transmission to the processing center. To conserve power, the system could employ intermittent operation schedules, where stations activate only at predefined intervals for data transmission (e.g., every 12 or 24 hours) and be equipped with solar panels. An energy-efficient design and battery management systems would be crucial to ensure continuous operation and data transmission. The present TRL of this solution is 2 and might be raised to 4 within the RETURN partnership if a support for the technological development is given. The cost of the implementation might not exceed 1-2 k€ for monitoring point.

Creation of an automatic workflow able to process the data as soon as they become available, with restitution of selected outputs linked to site stability

When the data are transmitted to a computer/cloud that can be used for processing, an automatic processing workflow might be activated. The processing infrastructure should be able to periodically check for new files stored in a specific folder through a file system monitoring approach repeated at regular time intervals. If a new file is detected the automatic data processing workflow should be activated. The processing steps to be implemented and the output to be effectively delivered at the end of the procedure are still under investigation within RETURN activities. The present TRL of this solution is 2 and can reach 4 in the next months of the project, without additional costs for technological development.

Expected outcomes

Having an effective data transmission offers the advantage of processing the data in near real time if an automatic processing workflow is designed and implemented afterwards. In this way, passive seismic monitoring can really be used for early warning purposes to detect failure precursors. Monitoring systems equipped with passive seismic stations might become a more widespread monitoring technique. A carefully designed automatic procedure for data processing might simplify the processing and interpretation of passive seismic records, making them more user-friendly, understandable and accessible for end-users. Automated data processing will further ensure consistency and standardization in the analysis and presentation of the results, making it easier for end-users to interpret and compare information across different timeframes or locations. By automating repetitive tasks and data processing steps, the monitoring system will become more efficient, allowing end-users to focus on interpreting insights and taking action rather than navigating complex data processing procedures.

Risk assessment

The technological development of the passive seismic data transmission systems presents various risks linked to the reliability and stability of the communication infrastructure, particularly in remote or harsh environments where access to reliable network connectivity may be limited. Environmental factors such as extreme weather conditions can disrupt communication channels, leading to data transmission failures and system downtime. Moreover, the dependency on battery/solar panel power for remote data transmission systems introduces risks related to battery life, maintenance, and performance. Inadequate battery management or failure to account for power consumption can result in unexpected system failures, leading to data loss and operational disruptions.

The automatic processing of data for early warning purposes carries additional risks. The main risk is the potential for false positives or false negatives in landslide predictions, which can lead to unnecessary countermeasures, or conversely, failure to issue warnings when necessary. To mitigate this risk, the automatic workflow should be customized, calibrated and validated on a monitoring window of at least 1 month for each monitoring site. The processing scheme should be re-adapted to the specific conditions of new monitored sites.

Furthermore, technical failures or malfunctions in the sensors, data processing algorithms, or communication networks can compromise the timely delivery of warnings, reducing the system's effectiveness in mitigating landslide risks. Redundancy measures, such as backup systems and alternative communication channels, should be implemented to ensure the resilience of the early warning system in the face of technical failures or disruptions.

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N7: Integration of UAV based sensor and PSInSAR data to detect soil slips on Badlands

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Problem setting

Badlands are typical landforms on clayey, bare and sparsely vegetated slopes, developed on poorly consolidated deposits, characterized by high rates of erosion, due to water washout (Gallicchio et al., 2023). Erosion reduces the soil capacity to support life, leading to progressive simplification of the vegetation structures and a modification of the plant spatial distribution. High erosion rate implies high sediment transfer downstream due to weathering, surface flow-based processes, subsurface erosion, and mass wasting (Llena et al. 2020). Thus, badland runoff can trigger landslide movements that are difficult to predict. Then, detect precursory signs of the evolving instability due to described geomorphic processes can avoid potentially devastating consequences.

State of the art

The study of erosion rates and processes generally consists of in situ measurements, making use of various tools (e.g. erosion pins, profilometers, collectors and traps, gauging stations) or, recently, by topographical change detected on high-resolution DEM, derived from terrestrial laser scanning (TLS) or UAV Structure-from-Motion (SfM) (es. Marsico et al. 2021; Neugirg et al. 2016), and of indices derived from satellite optical imagery (es. Alatorre et al. 2009) Such approaches, however, are generally not integrated and then they present significant uncertainties, especially if there is a need to investigate large areas, over long periods.

Innovative solution

We propose to investigate erosion processes through integration of analysis, derived from UAV based sensor (lidar, L-band radiometer, thermography), rainfall, and satellite PSInSAR data (long time series of C-band Sentinel-1SAR images), on different test sites in the Basilicata region, in southern Italy.

The UAV based lidar allows to generate high-quality high-resolution multitemporal digital elevation models to detect topographical changes on slope, by putting together the advantages of both TLS and SfM techniques. The L-band radiometer allows to detect soil moisture on slope due to rain or vegetation, while the thermography lets to investigate the effects of the temperature variations and the solar radiation on the slope surface and joint behaviour. The multiple UAV based sensors allows to monitor the effect of weather on slope. This survey is low time spending and can be conducted frequently, even after a rainfall event.

Among the most recent methodologies, coherence measured on interferometric synthetic aperture radar (InSAR) has been recently proposed as a tool to observe badland soil erosion phenomena with high spatial and temporal resolution (Refice et al., 2022). Interferograms are formed between pairs of images with short temporal baselines, focusing in particular on combinations spanning up to 18 days (non-urban areas). Stacks of coherence images spanning fixed temporal baselines are processed separately and time series composed of the "cascaded" coherences were analysed, in correlation with corresponding time series of cumulated daily rainfall levels (daily rainfall measurements were collected from rain gauge stations located close to the test sites). In addition, each coherence time series is also fitted with a periodic function. From preliminary results, average coherence on badland areas is higher than on other nearby areas, either naturally vegetated (shrubs or Mediterranean scrub) or cultivated. Episodes of partial coherence loss on gullies appear temporally correlated with time series of precipitation cumulated over the time intervals between each InSAR pair.

The present TRL of this solution is 7 and can reach 9 during the project and there are no further costs for technological development.

Expected outcomes

The integration among the UAV based sensors aims to monitor the geomorphic processes and observe precursory signs of the instability on Badlands. The possibility to detect topographical changes, discontinuities and slope portions that could be potentially subjected to larger temperature and moisture content fluctuations allows to identify areas more susceptible to detachments and instabilities. Moreover, detection of the soil moisture and the temperature fluctuations on slope can aid to explore the impact of rainfall on spatial coherence since the climatic setting of our test site makes it difficult to analyze single rainfall events. However, our preliminary statistical analysis indicates that cumulated rainfall between SAR acquisition separated by short intervals (6 to 18 days) has a significant correlation with abrupt decreases in short-term InSAR coherence levels.

The same time series of InSAR coherences on cascaded short-baseline image pairs exhibit a different behaviour on other areas with crops or spontaneous vegetation: here, the correlation with rainfall is lower, and a seasonal trend is instead statistically significant. The spatial coincidence of high average temporal coherence levels with the areas characterized by clayey bare soils strongly suggests that we can actually observe with high spatial and temporal resolution badland soil erosion phenomena.

Risk assessment

Potential limitations could arise from the resolution of the source images and the construction of a model to explain the time series trend of the PS/DS.

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N13: In remote areas multi-parameter sensors for enhanced hydrodynamic monitoring with remote connectivity

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Problem setting

Remote mountainous areas are generally not easily accessible, and continuous groundwater monitoring data collection with suitable probes or data loggers is hampered by logistical problems, especially during the winter and spring months. Consequently, in many cases the only tools available to derive hydrogeological information about mountain spring recharge systems are datasets of discharge (Q), temperature (T) and electrical conductivity (EC) parameters directly on-site. Assessment of aquifer groundwater reserves based on these datasets has shown limitations, particularly with non-continuous data. Furthermore, without adequate instrumental maintenance activities, obtaining data in continuity over time would be difficult.

Therefore, continuous and long-term datasets of Q, EC and T are essential for accurate quantification and effective management of groundwater resources in mountainous regions. Given the importance of Alpine groundwater for drinking water, prudent investments are crucial to bring use in line with forecasts and sustainable development goals.

To overcome these limitations, one additions to conventional multi-parameter probes is proposed:

- The possibility of remote connection to the instrument to receive and consult data in real time even in places where the connection would be poor if not absent.

State of the art

Groundwater reserves assessment and forecasting in mountainous areas requires monitoring of both local meteorological conditions and groundwater parameters of springs (discharge (Q), temperature (T) and electrical conductivity (EC)). The reliability of the data depends on technical instrumentation such as multi-parameter probes and sensors. The integration of weather station sensors with spring discharge instruments provides a comprehensive understanding of how one set of parameters can have an impact on other results, defining consequential cause-and-effect relationships (Gizzi et al., 2020; Mondani et al., 2022). Continuous (hourly value) and long-term Q, EC and T values are, therefore, needed to properly quantify and to manage resources as well as the vulnerability and behavior of aquifer systems in response to snowmelt, rising temperature and heavy rainfall. These monitored sites can be chosen to lead analyses of instability mechanisms, since some of these springs could be located on slopes prone to landslide. The development of this type of analysis supports the understanding of the effects of climate change on water resources in mountain areas (Gizzi et al., 2022; Gizzi et al., 2023) and consequently on slow-moving landslides, like Deep Seated Gravitational Slope Deformation (DSGSD), involving large slope volumes.

Innovative solution

The possibility of remote connection to the instrument to receive and consult data in real time.

For this kind of solution, a system with an automatic processing workflow would need to be activated, which could be based, for instance, on the creation of a wireless network at the monitored site to collect data from the multi-parameter probe.

To preserve energy, the system could use intermittent operation schedules, where stations are activated for data transmission only at pre-defined intervals, and be equipped with solar panels.

Energy-efficient design and battery management systems would be essential to ensure continuous operation and data transmission.

The present TRL of this sensor implementation of data connectivity could be equivalent to 6 on a scale from 1 to 9 as per the TRL table and might be raised to 7 within the RETURN partnership.

Regarding the budget for this type of implementation, it will not exceed approximately 2 or 3 k€ per instrument.

Expected outcomes

An automated and efficient data transmission offers the advantage of being able to consult and process data in real time, avoiding the need to download data manually by going to the site, which can sometimes be a problem for logistical reasons.

Risk assessment

The data transmission system described would require a periodic check on the functionality of the various devices and a constant maintenance. Furthermore, possible malfunctions or disruption of the installed sensors should also be considered, which may be due to instrumental breakdown or as a consequences of extreme weather events.

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N14: High resolution satellite-derived soil moisture maps

Authors

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Problem setting

In mountainous terrain, rainfall-induced landslides pose a serious risk to people and infrastructure. Regional landslide early warning systems (LEWS) have proven to be a cost-efficient tool to inform the public about the imminent landslide danger. The main factor directly linked with the shallow landslides (debris-mud flows and debris avalanches) triggering is the soil moisture which depends not only on the rainfall intensity of the event, but also on the thermo-rainfall regime of the previous period. The soil moisture constitutes a preparatory process with variations in short (days-months) and long (months-years) cyclicity. Currently, regional monitoring systems are mainly based on rainfall data which refer to triggering thresholds defined on the basis of the correlation between rainfall and triggering of landslides occurred in the past. While ground-based soil moisture measurement stations can provide punctual information, the satellite images interpretation allows the production of soil moisture maps. Among the limitations of these products, there are the shallow character (first 10-20 cm from the surface) of the estimated soil moisture values and the rather low resolution of these products (cell size not less than 100m/1km /1°).

State of the art

Both scientific community and public administrations involved in defining mitigation and adaptation measures to landslide phenomena pay great attention to the monitoring and alarm systems connected to civil protection plans (Terlien, 1988; Aleotti, 2004; Guzzetti et alii, 2007; Cevasco et alii, 2010). In last decades, increasing attention is being paid to the use of technologies for estimating soil moisture data at different scale to improve LEWS (Segoni et al., 2018; Marino et al., 2020; Felsberg et al., 2021). As well as the recognition of the potential of in situ soil moisture measurements for regional LEWS (Ferrarezi et al., 2020; Wicki et al., 2020), satellite-derived soil moisture maps are recognized as capable of identifying triggering conditions and to develop prediction methods of shallow landslides (Bordoni et al., 2023)

Innovative solution

The development of technology for satellite-derived soil moisture maps production would be desirable to increase resolution (cell size dimension) and strengthen the ability to provide in-depth information.

Expected outcomes

Increasing the resolution of satellite-derived soil moisture maps can help strengthen the predictive capacity and accuracy of LEWS, reducing the number of false positives. Notable benefits can be expected in the two areas of triggering thresholds and source areas susceptibility maps. In particular:

- the rainfall triggering thresholds could be supported/integrated by data from the preparatory process consisting of soil humidity;
- soil moisture maps with an increased geometric resolution consistent with the DEMs in use (metric resolution) could be integrated with morphometric, lithological and land use parameters used in the source areas susceptibility maps, based on both statistical and deterministic approaches.

Risk assessment

No potential risks and limitations that might arise from the technological development/application of the proposed innovative solution are recognized.

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N17: Application of Sar reflectors to monitor subsidence

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Problem setting

The use of multi-temporal SAR interferometry has now represented a consolidated technique in the field of ground movement monitoring services supported by the ever-increasing availability of satellite data which guarantee improvements in terms of resolution and coverage over time spatial and temporal. For these reasons it is widely used to monitor the subsidence in the coastal areas since it is useful to assess Vertical Land Movements (VLMs). as reported in several studies (Aucelli et al., 2017; Bacques et al., 2018; Polcari et al., 2018; Anzidei et al., 2021; Scardino et al., 2022).

However, there are some limitations of the technique which still today represent critical obstacles for its greater diffusion and for a better accuracy of the results obtainable. Among these we can certainly mention the poor coverage of measurement points in extra-urban areas or in general the need to have measurements at specific points of an area or infrastructure.

State of the art

The Synthetic Aperture Radar Interferometry (InSAR) is a non-invasive technique (Tapete et al., 2012), suitable to monitor large areas of the Earth's surface at low cost, measuring the projection of the deformation vector onto the Line of Sight (LoS) direction. The latter is defined as the shortest path from a given point on ground to the SAR antenna and the interferogram represents the per-pixel phase difference between two SAR acquisitions. In general, an interferogram will contain both topographic and surface motion information. that can be obtained removing topographic component either using an external DEM (Massonnet et al., 1993).

Several multi-temporal InSAR techniques have been proposed, which exploit the redundancy offered by hundreds of image pairs. The output of these techniques, generally known as Persistent Scatterer Interferometry (PSI), is the mean ground velocity and time-series of relative ground displacements. The existing algorithms fall into two broad categories, namely the Permanent Scatterer (PS) (Ferretti et al., 2000) and the Small Baseline (SB) (Berardino et al., 2002) approaches, although more recently algorithms exploiting the basic principles of both methodologies have also been proposed (Crosetto et al., 2016).

The averaged interpolated LoS velocities, for PS in ascending ⟨V_A ⟩ and descending ⟨V_D ⟩ orbits obtained from the InSAR dataset need to be calibrated with the GNSS records (Avallone et al., 2016, Serpelloni et al., 2013; Devoti et al., 2017). GNSS data are processed following the procedures described in Serpelloni et al. (2022). For each GNSS station, the velocities in the LoS direction could be assessed, both in ascending and descending orbits,

Differences between InSAR and GNSS LoS projected velocities must be estimated in each GNSS station to assess the best fit among the two different datasets. Ascending and descending LoS PS InSAR data could be calibrated independently, applying a 2-D planar function with the best agreement between GNSS data and InSAR. This procedure is known from the literature (Farolfi et al., 2019; Anderlini et al., 2020) to provide satisfying results. From calibrated LoS PS InSAR data, it is possible to evaluate through trigonometric considerations the vertical component of the displacement from the original data. This value could be considered representative of Vertical Land Movements (VLMs),

Innovative solution

This proposal is aimed at the development of innovative satellite data processing techniques for monitoring ground caused by subsidence phenomena.

To improve measurements, the introduction of artificial coherent radar targets placed at points of interest represents a very interesting solution. These artificial targets are devices specifically designed to reflect radar waves in a consistent and predictable manner. Strategically positioned on unstable terrain or on infrastructure subject to risk of collapse, SAR reflectors allow to generate distinct and well-defined radar signals that can be used as reference points to measure ground movements or structural deformations over time.

The use of SAR reflectors increases the density and distribution of measurement points within the area of interest, allowing for greater precision and reliability in monitoring. Furthermore, SAR reflectors provide coherent and easily identifiable radar signals, simplifying data interpretation and analysis by operators. These artificial targets can be easily installed and positioned to cover specific areas of interest, allowing for greater flexibility in monitoring activities.

The present TRL of this solution is 7 and can reach 9 during the project and there are no further costs for technological development.

Expected outcomes

The increase of coverage of measurement points to assess subsidence is planned to:

- Analyze and evaluate the effectiveness of both active (e.g. radar transponders) and passive (e.g. corner reflectors) artificial SAR reflectors with particular reference to the precision and reliability of measurements.

- Explore the potential of artificial SAR reflectors with multi-directional and multi-band capabilities aimed at their use with reference to different satellite missions and different types of orbits (SSO/MIO).

- Evaluate the use of artificial SAR reflectors in monitoring specific points of critical land infrastructures (e.g. bridges, dams and buildings) in order to guarantee their safety and integrity.

Risk assessment

The artificial coherent radar targets are small boxes that must be left on terrain or on infrastructure at least the time interval between two SAR acquisitions used for interferometric processing. Despite the short temporal baselines, the targets could be stolen or damaged nullifying the survey.

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N20: Pre-failure suction-induced deformations for Landslides Early Warning Systems

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Problem setting

Many Landslides Early Warning Systems (LEWS) nowadays rely mainly on monitoring rainfall data, determining sometimes limitations in performance due to frequent false alarms triggered by rainfall thresholds exceeding. To enhance the accuracy of LEWS, monitoring of soil-based variables linked to the stress-strain response of the ground during intense rainfall events could be considered.

For this purpose, the potential of utilizing slope pre-failure deformation as an additional precursor to landslide initiation was investigated, combined with suction monitoring.
An innovative device developed called "tensioinclinometer" (Coppola et al., 2022) was designed to monitor suction and suction-induced deformation simultaneously. This device integrates a conventional tensiometer with an accelerometer mounted at the top of the tensiometer shaft to measure its inclination. Laboratory testing (Coppola et al., 2022) results demonstrate that detecting pre-failure deformation through the tilting of the tensiometer shaft is a viable indicator of imminent landslide occurrence.

State of the art

Recently, rainfall-triggered shallow landslides in coarse-grained volcanic fall deposits have converted into debris flows, causing huge damage and remarkable loss of life worldwide. These volcanic fall deposits are typically partially saturated and characterized by high suction and porosity values. Rainwater infiltration reduces suction, making such materials prone to rapid debris flow triggering.
Risk mitigation relies heavily on Landslide Early Warning Systems (LEWS). Given the rapidity of mass movement in landslides, alarms must be issued well before the trigger (UNISDR, 2006; Alfieri et al., 2012; Greco & Pagano, 2017).
LEWS effectiveness depends on specific landslide precursors and the model used to establish alarm thresholds. Most LEWS currently in operation primarily rely on rainfall as the only precursor variable, leading to conservative alarm thresholds setting and, therefore, an increase in false alarms number (Greco & Pagano, 2017; Intrieri et al., 2012; Sattele et al., 2015; Reder & Rianna, 2021). To enhance LEWS performance, the inclusion of additional precursor variables appears essential.
Failure initiation involves significant displacements within the mass above the failure surface due to high shear deformations near the failure surface (shear band). This phase may be preceded by diffuse shear and compressive plastic deformations above the failure surface, definable "pre-failure suction-induced deformations". Integrating pre-failure deformation with suction monitoring could enhance LEWS accuracy significantly. The approach here suggested investigates therefore the potential of suction and suction-induced pre-failure deformation as landslide precursors by using the tensioinclinometer.

Innovative solution

The tensioinclinometer cleverly merges a traditional tensiometer, which gauges pore-water pressure across both negative and positive ranges, with an accelerometer mounted on the top of the tensiometer shaft (Figure

16). This setup allows for the measurement of the inclination of the tensiometer shaft, serving as a reliable indicator of pre-failure deformation in landslide monitoring.

Pore-water pressure results more reliable precursor compared to volumetric water content. Silty volcanic slopes, typically lacking cohesion and featuring inclinations near the friction angle, often experience pore-water pressures triggering slope failures within a range of a few kilopascals, either negative or positive. Tensiometers guarantee accuracy to within 1 kPa and can effectively measure pore-water pressure across both ranges. This feature makes pore-water pressure data from tensiometers more effective indicators of rainfall-induced shallow landslides. Additionally, like water-content dielectric-based sensors, tensiometers require no maintenance (re-saturation) during wet periods. This lack of maintenance is not a drawback for tensiometers, especially considering their role in informing Early Warning Systems during crucial periods.

The use of tilting as a proxy variable for slope deformation was preferred over surface displacement measurements via methods such as total station, Global Positioning System (GPS), and photogrammetric techniques, as employed in other Landslide Early Warning Systems (LEWS) concepts (Barla and Antolini, 2016; Zhu et al., 2017). Total station measurements can be affected by adverse weather conditions that hinder the line of sight between the observer and the target. Similarly, rain may weaken GPS signals, while reduced visibility during rainy periods can compromise the quality of photographic images.

To facilitate easy maintenance or replacement, a metal box containing the accelerometer and electronics was securely attached to the tensiometer shaft using a clamping hook. This design allows for the swift removal of the metal box when needed. Furthermore, the metal box is engineered to be compatible with any commercial tensiometer, with cables from the tensiometers connecting to the chip extension via external sockets on the metal box.

The tensioinclinometer was engineered for wireless operation, powered by a battery and utilizing Wi-Fi for data transmission. All necessary electronics for measuring pore-water pressure, tilting, data storage, and data transmission are compactly housed on a semiconductor chip. Both the battery and semiconductor chip are housed within the metal box securely attached to the tensiometer shaft. This setup enables wireless monitoring of two crucial precursor variables within a single unit, providing an advantage over systems relying on separate elements connected by cables (as seen in approaches such as Yang et al., 2017). The wireless design offers rapid installation and/or replacement, while also reducing the risk of malfunction caused by cable damage from wildlife interference.

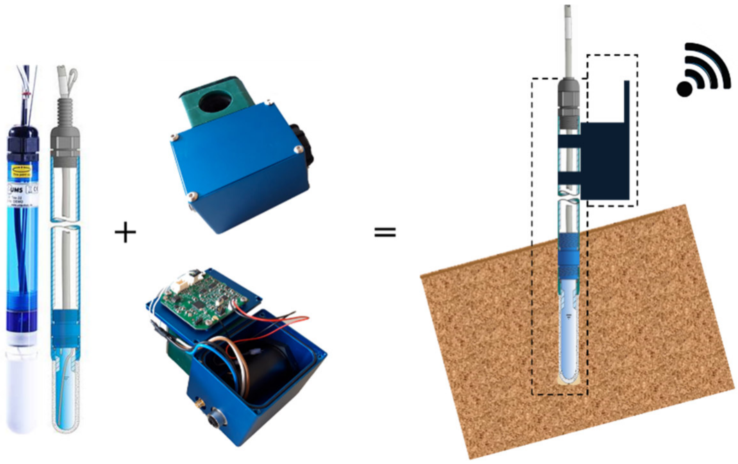

Figure 16.The tensioinclinometer.

The prototype firmware and management software were developed to operate in two distinct modes (Figure 17):

1. **Data Collection and Real-time Transmission (DC) Mode**: this mode facilitates real-time wireless data transfer (via Wi-Fi) immediately upon data acquisition. It is mainly used during rainy periods, when frequent

data transmission is necessary to inform the early warning system. However, it's worth noting that real-time transmission is the most energy-intensive mode and is therefore reserved for use only during wet periods.

2. **Data Logger (DL) Mode**: in this mode, data storage is prioritized, followed by wireless bulk data transmission upon remote request. DL mode is typically activated during dry periods when real-time data transmission is not necessary. To conserve battery energy, data are acquired at a lower sampling rate, stored in non-volatile memory onboard, and transmitted periodically in bulk upon user demand.

In both operation modes, if a period of 10 minutes between acquisitions is considered, it can be stated that the battery is meticulously designed with a conservative approach, ensuring longevity that can span several years before requiring replacement. However, to prevent memory saturation, it's suggested to download the data logged onboard at least once a year. This routine maintenance ensures that the memory does not become full, thereby maintaining the device's optimal functionality.

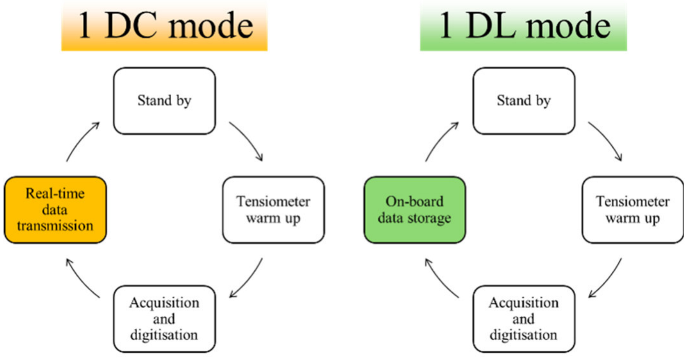

Figure 17.Operation modes.

Each tensio-inclinometer sends data to a collector node via Wi-Fi, either in real-time (DC mode) or in bulk on-demand (DL mode). Prior research has shown that Wi-Fi transmission functions properly even during rainfall (Biansoongnern et al., 2016). The collector node is configured to relay this data to a remote computer via a wired network to ensure the reliability of data transmission for the early-warning system. For this purpose, the collector node features a USB port, enabling either direct connection to a laptop or connection to the wired network via a USB-to-Ethernet adapter. The management software also generates a CSV file containing diagnostic information for various components such as temperature and battery level. Each metal box wirelessly communicates with a collector node, which is physically connected to a PC via a USB interface.

Expected outcomes

Expected results from the application of the proposed monitoring systems will consist in the evolution of the monitored physical variables, in different positions along the landslides. Whereas properly acquired and interpreted, data from the suggested monitoring system could be useful for defining alert and alarm thresholds, within the framework of an early warning system. This assumption derives from laboratory tests carried out to verify if suction-induced deformation is adequately captured by tilting evolution. This point appears crucial in designing LEWS monitoring systems because measuring the rotation of a tensiometer shaft installed in the slope (with the added benefit of suction measurement) is considerably simpler than setting of displacement monitoring system which is typically expensive and difficult to install and manage (Uchimura et al., 2015). Moreover, techniques for monitoring displacements often become highly inaccurate during persistent rainfall conditions, which are precisely the conditions expected when the LEWS is operational. In contrast, the tensioinclinometer is anticipated to operate reliably even under adverse weather conditions.

Risk assessment

The proposed solution shows notable advantages but, at the same time may suffer some limitations.

The main advantages derive from the ease of installation, management, and maintenance of the system. This means that the system is more accessible and requires fewer resources in terms of time and money to be implemented and maintained. Easy installation reduces upfront costs and the time needed to get the system up and running.

Limitations are essentially related to the nature of the installation site. For instance, in the case of open slopes, there's a likelihood of localized damage to the instrument due to the presence of grazing animals.

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N21: Upgrade of monitoring system for Flow Like-Landslides prediction

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Problem setting

Flow-like landslides pose significant threats to human life due to the difficulty in recognizing their pre-failure phase and the rapid downward movement of soil debris during the post-failure phase. Rainwater infiltration is considered to be one of the mechanisms that lead or predispose the whole slope to failure by reducing matric suction in unsaturated soils or causing an increase in pore water pressure in the saturated slope, thus reducing the shear strength. Additionally, local topographic features influence the occurrence of flow-like landslides, which can manifest in partially or completely saturated slopes, depending on factors such as slope angle (Pirone et al., 2015).

The effects of antecedent rainfalls may be considered as predisposing factors to these types of landslides. These effects can be taken into account through current in situ measurements of soil state, in terms of matric suction and volumetric water content. It is noteworthy that the impact of heavy rainfall on slope stability heavily depends on initial hydraulic conditions in the subsoil prior to the event. Therefore, seasonal variations in soil matric suction and volumetric water content reflect critical periods for landslide triggering (Pirone et al., 2015).
Field monitoring not only provides data on predisposing factors but also offers a dataset for calibrating and validating numerical models, aiding in the comprehension and prediction of shallow slip triggering.

State of the art

Matric suction coupled with volumetric water content are commonly considered as good precursors for the onset of flowslides and debris flows.

The analysis of field data from long-term monitoring in granular deposits susceptible to flowslides is a well-explored topic in the literature. Springman et al. 2013 found out the bi-seasonal hydrological response of a slope monitored in Toesseng, Switzerland, where the smallest 'factor of safety' is attained after the wetter winter months. Papa et al., 2013 presented monitoring data over six years collected at a test site in Monteforte Irpino in Southern Italy. Also, Damiano et al., 2012 described the slow seasonal fluctuations of soil suction and water content collected at a test site in Cervinara, in Campania Region, essentially related to the long-term precipitation sequence. As regards the response to short heavy rainfall, Comegna et al., 2016 tried to carry out a framework to interpret the hydrological slope response to rainstorms paying attention to the role of current hydraulic condition in the subsoil. Nevertheless, approaches that use field observations of the state of the subsoil to predict slope response under short heavy rainfalls are still lacking.

New infrastructure (NI)

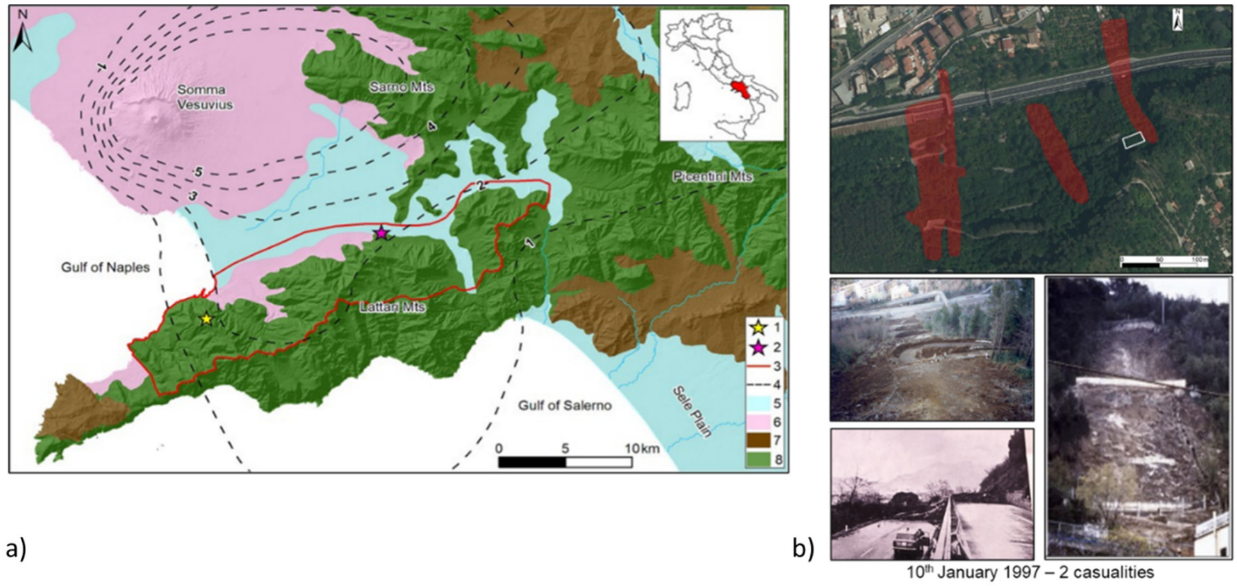
A prototype monitoring system aimed at predicting the triggering of flow-like landslides has already been established at the Test Site of Pagani (SA). An upgrade is proposed for the following reasons:

- Testing cheaper sensors to instrument a wider area at a lower cost;
- Evaluating more innovative sensors for integration into an IoT system;
- Measuring the profile of volumetric water content by installing multilevel probes to determine the water volume storage and its seasonal oscillations.

The test site of Pagani

The test site is located at the area of Pagani (SA), 35 km South-East from Naples, in a site where some debris flows have occurred in the past (Fig.1a, b). The stratigraphic setting consists of a 2 m deep succession of thin air-fall pyroclastic soil layers covering a fractured carbonate bedrock (Santo et al., 2021). Bottom upward in the considered section (Fig. 2c), the succession includes: discontinuous clayey-rich pyroclastic fall (C3-C2+C3), 20–60 cm thick silty sands (C1), overlaid by brown silty sands rich in pumices (A2), which have a thickness of 30–130 cm. The top soil consists of a highly weathered vegetated volcanic ash (A1); its thickness spans from 20 to 80 cm, with a mean value around 35 cm. The average slope angle is 35°.

The instrumentation consists of four tensiometers (for direct measurements of soil suction), four TDR probes (for indirect measurements of volumetric water content), and four thermometer soil probes (for soil temperature), installed at the same depth (Fig.2c). Matric suction and volumetric water content are being measured hourly since November, 2020. The site is also equipped with a rain gauge that records rainfall every ten minutes (Fig. 2d). The pyroclastic cover is partially saturated over the entire year.



10th January 1997 – 2 casualities

Figure 18.a) Geological setting of the Lattari Mts. with ashfall dispersion axes: 1) Faito Test Site; 2) Pagani test site; 3) Northern-slope affected by flowslides; 4) Dispersion axis of eruptions; 5) Alluvial deposits; 6) Pyroclastic deposits; 7) Flysch deposits; 8) Limestones. b) Area involved by historical flow like-landslides; c) effects of flow-like landslides of 10th January 1997.

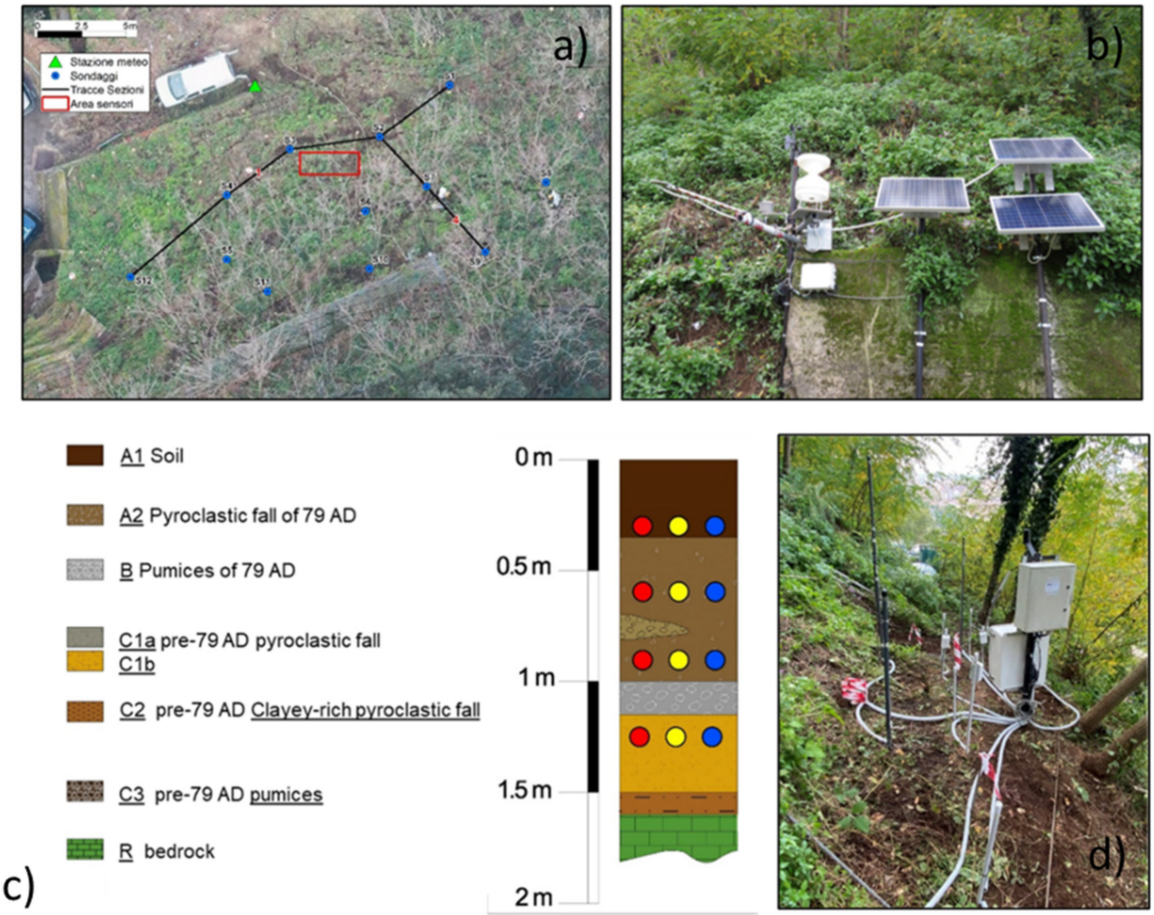


Figure 19.a) Location of the boreholes in the Test site; b) Meteorological station; c) simplified soil profile with indication of tensiometers (red symbol); TDR probes (yellow sensors) and soil thermometers (blue symbol); d) photo of the installed instrumentation.

Upgrade of the monitoring system

In order to test the effectiveness of cheaper sensors, the monitoring system can be upgraded by installing:

- sensors for indirect measurements of matric suction;
- capacitive sensors for indirect measurements of volumetric water content;
- traditional tensiometers to calibrate the sensors measuring matric suction.

Once tested, the goal is to instrument a large area and implement field measurements in Early Warning System.

The sensors for indirect measurements of matric suction typically measure the dielectric permittivity of a solid matrix to determine the water content of the solid matrix which corresponds to the water content of the surrounding soil. The relationship between water content and matric potential, known as the soil moisture characteristic curve of the solid matrix, is used to calculate the soil matric suction. The effectiveness of this sensor type hinges on establishing a precise calibration curve correlating the dielectric permittivity of a solid matrix with the matric suction of the surrounding soil, as measured by traditional tensiometers. These sensors are preferred due to their low maintenance requirements and ability to measure suctions higher than 70-80 kPa, which is the upper limit achieved by traditional tensiometers, beyond which desaturation and cavitation occur. Additionally, their minimal power requirements make them ideal for battery-powered IoT systems.

The soil moisture sensors usually measure the dielectric permittivity of the soil to obtain its volumetric water content. As the dielectric constant of water is significantly greater than that of air or soil minerals, the dielectric constant of soil is a sensitive measure of the quantity of void water. These sensors are based on capacitance techniques using a single narrowband frequency method (usually 70 MHz). These sensors are relatively inexpensive, easy to operate, and low-power, but may be less accurate for soils with a relatively high bulk electrical conductivity (Tarantino et al., 2008). Also in this case, the calibration functions are necessary to obtain reliable measurements.

Expected outcomes

The expected outcomes from integrating the existing monitoring system are as follows:

- Design of a low-cost remote transmission monitoring system for variables predisposing to the triggering of flow-like landslides;
- Validation of measurements obtained from sensors against those obtained from traditional instruments;
- Acquisition of hourly measurements for the development of physically-based rainfall thresholds for flow-like landslide initiation.

Regarding to rainfall thresholds, more reliable predictions and associated alarm systems may be obtained through physically based predictive approaches that account for the geotechnical soil parameters influencing the trigger. This monitoring system is designed to develop physically based rainfall thresholds for predicting shallow slip initiation through field monitoring that captures the short-term response of an unsaturated slope to individual rainstorms.

Risk assessment

In case the sensors to be integrated into the monitoring system in question do not function or do not show suitable resolution, measurements obtained from traditional instruments will be available. If the weather station were to experience malfunctions, it will be possible to download meteorological data from the Civil Protection weather station, installed near the test site.

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5. NOVEL APPLICATIONS

N1: Monitoring surface-wave velocity changes within landslide body using seismic arrays

Authors

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Problem setting

Field observations indicate that earthflows may exhibit a significant increase in water content during mobilization (e.g., Hutchinson et al., 1974), thus dramatically changing their consistency. It follows that the detection as a function of time of this change of mechanical behavior can have a potential impact for early warning purposes. Seismic methods can be used to monitor the landslide evolution in this framework: in particular, continuous measurement of surface-wave velocity can be used as an indicator of the loss of stiffness (or fluidization) of the material affected by the movement. In the last decade, only some studies have dealt with seismic monitoring of soft-soil landslides (such as earthflow and mudflows) and, in particular, focusing on detecting surface-wave velocity changes within active landslide body. This form is based on an experiment of this type, i.e., the one performed by Bertello et al. (2018): in this case, the continuous monitoring of the Rayleigh-wave velocity was carried out using an acquisition system compatible with the capabilities of the datalogger and the available power supply. In particular, the seismic array was set up with four 4.5 Hz geophones and the acquisition length, performed in passive mode (i.e., based on the acquisition of the ambient vibration wavefield), was limited to 2 min every 1 hour. These limitations, which affect the accuracy of the measurements, are combined with the fact that the instrumentation was placed directly on the unstable area: this type of installation could lead to alterations to the relative distances between sensors over time, as well as to the damage of the instrumentation (cables and sensors).

State of the art

As stated previously, only some studies dealt with surface-wave monitoring on soft-soil landslides. This document aims to provide new insights and ideas to improve the monitoring capabilities of the experiments carried out by Bertello et al. (2018). In this work, using the passive seismic continuous monitoring described previously, the authors highlight decreases of Rayleigh wave velocities of the order of 30% of the initial value a few days before the rapid movement of the landslide material (Fig. 1).
A similar work on an earthflow was carried out by Mainsant et al. (2012): these authors performed continuous measurements of surface-wave velocities using two seismometers placed in stable ground on both sides of the landslides, providing in this way the average Rayleigh velocity values across the investigated section. Using this setting, these authors avoided placing the sensors inside the unstable material and the acquisition system can operate even when the earthflow is rapidly moving; on the other hand, the use of this instrument layout can provide a significant overestimation of the velocity values if the signal propagation is not aligned with the sensor line. Finally, also Mainsant et al. (2012) identified a decrease of Rayleigh wave velocities (in this case of the order of 7% of the initial value) a few days before the failure.

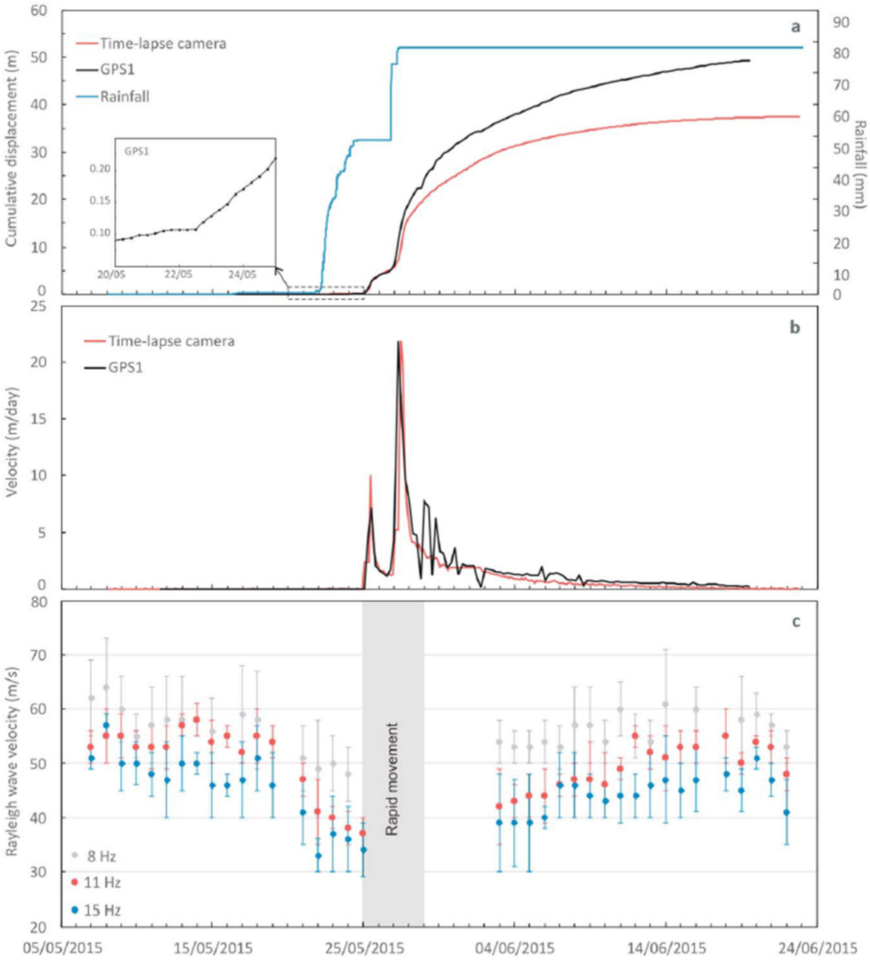

Figure 20.Comparison between (a) rainfall and cumulative displacement, (b) displacement rate, and (c) Rayleigh velocity measured by the monitoring system before and after the landslide reactivation (from Bertello et al., 2018).

Innovative solution

Given what has been described previously, the installation type proposed by Mainsant et al (2012) seems to be the most functional one from a practical point of view. To improve the quality and accuracy of the results of this passive seismic monitoring, we propose to increase the sensor number to be positioned on the two sides of the landslide body. In this way, a greater range of wavelengths can be sampled and a larger data redundancy can be exploited; moreover, with this setting, the ambient vibration wavefield can be sampled with a wider azimuthal coverage, thus decreasing the probability of overestimating the Rayleigh wave velocity values. To perform this analysis, we propose the use of sensors with a sampling frequency of at least 200 Hz, low power consumption (with autonomous power supply), and equipped with a reliable GPS receiver.

Despite the greater practicality of the first type of layout, the array installation directly on the unstable material may not be completely discarded: in fact, this can be used as calibration or comparison for the "external" array analysis (at least in the phases before the mobilization of the landslide). However, also this configuration should be appropriately modified to improve the quality of the results. In particular, this can be done by (1) combining active and passive mode acquisition to improve the dispersion curve at high-frequency ranges (for example, using an automatic hammer controlled by the datalogger that hits the ground during the measurement session); (2) using more geophones to ensure an adequate data redundancy.

The present TRL of the described solutions is 5 and might be raised to 6 within the RETURN partnership if a support for technological development is given. The cost of the implementation should not exceed 20000-30000 €.

Expected outcomes

As stated before, the expected outcomes of the proposed solutions will be in terms of quality and accuracy improvement of the estimates of Rayleigh wave velocity values. This is a crucial point of the procedure since a significant velocity change can be defined as such if this is greater than the associated standard deviation. Moreover, a better definition of the velocity values as a function of the frequency (and therefore of the depth), which could be obtained by exploiting the sampling of different wavelength intervals, would allow us to understand more precisely the subsoil portion subjected to loss of stiffness.

Finally, a further improvement of the procedure can be obtained by combining geophysical data with geotechnical sensors (e.g., with conventional dielectric sensors) to monitor the water content of the material.

Risk assessment

An important limitation if the installation is done only on the stable sides of the landslide is that the landslide deposit depth must be compatible with the minimum wavelength sampled by the array: this obviously depends on the sensor minimum distance. In view of this, as an object of analysis, deep and narrow landslides are preferable to wide and shallow ones.

Another important aspect to take into account is the data transmission. In fact, passive seismic monitoring involves the recordings of a huge amount of data and the remote transmission of these acquisitions (which can potentially last for several months) requires a high power demanding and the presence at the investigation site of a very performing mobile network connection, which is not always guaranteed especially in locations far from urban areas. To deal with this limitation, the most effective solution is to create an algorithm able to process on-site the data relating to a certain time interval and to transmit only the surface-wave dispersion curve values.

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N3: Use of high-resolution satellite imagery to depict landslide scar evolution at canyon head.

Authors

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Problem setting

Submarine morphologies are usually detected by acoustic waves (namely multibeam sonar echosounders) because light does not penetrate water. However, in shallow water, depending on transparency, light may detect features down to meters or tens of meters (Austin and Petzold, 1981) (Figure 21). Marine geohazards is an increasing issue for coastal infrastructures and communities, as they may be threatened by tsunamis, submarine landslides, shallow water eruptions. One of the main marine geohazards is the retrogressive erosion of the head of submarine canyons. The latter are very large features, carving the continental margins for tens or hundreds of kilometers, connecting the bathyal plain to the coastal environment. The canyon head naturally evolves retrogressively (i.e. upslope) by submarine landslides at the headscarp that are often tsunamigenic. So, during their evolution, canyon heads may reach the very nearshore environment. In the Mediterranean Sea, there are at least two very well-known events that caused tsunamis due to submarine landslides occurring at canyon head: i) in 1977 at Gioia Tauro (Southern Italy) during harbor construction (Colantoni et al., 1992) and in 1979 during the seaward expansion of the Nice airport (Cote d'Azur, France, Ioualalen et al, 2010). If these events are well known because of the impact of the tsunami waves on coastal infrastructures and communities, the phenomenon is unperceived when it does not generate tsunami. Therefore, such events (that may mine infrastructure of evolve in larger events) are often underestimated. This is of paramount relevance in the Mediterranean Sea, where active geology produces narrow continental shelves, high seismicity, and diffuse gravitational instability at the seafloor. In this context, feature detection algorithms have the potential to be applied to satellite images to depict canyon head geometry and detect its possible variation. Nowadays feature detection methods are improving thanks to new algorithms and submarine instability research may take profit of it.

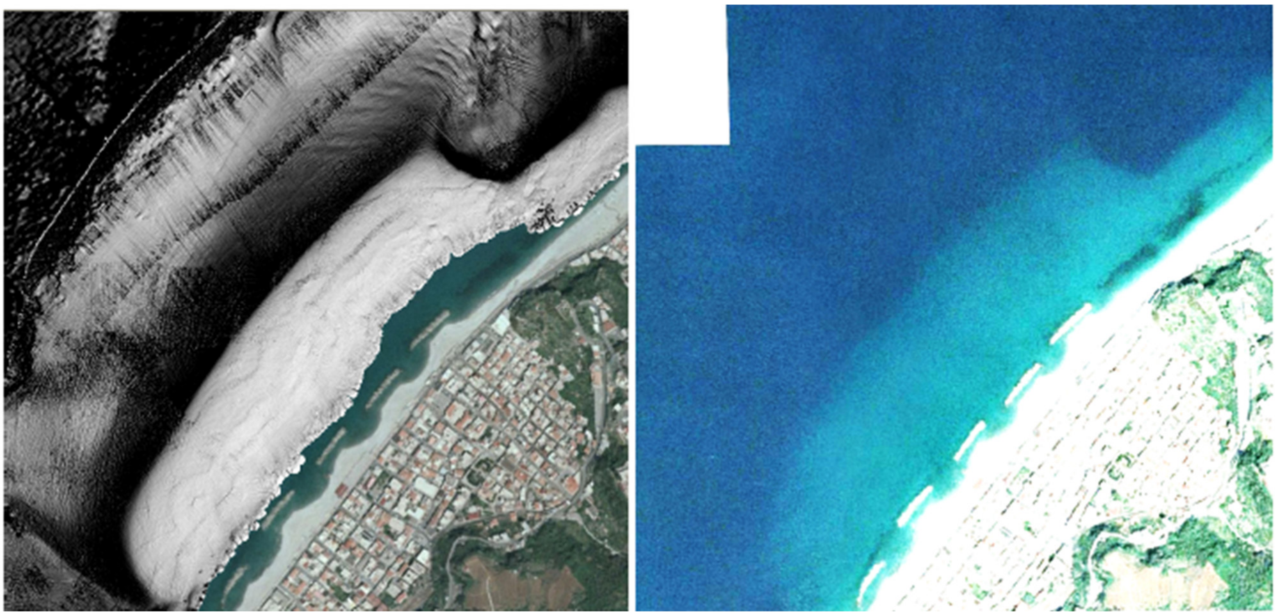

Figure 21.To the left multibeam echosounder data showing a depositional terrace very close to the coastline, carved by a canyon head. To the right: satellite image (contrast enhanced) of the same area, where the change in color depicts the sharp slope break.

State of the art

Satellite constellations capture detailed multispectral images of the Earth's surface, providing invaluable data for various applications such as environmental monitoring, urban planning, and disaster management. Satellites like WorldView-2 (with a revisit frequency of 1.1 days) allow for the acquisition of images with spatial resolution of 0.3-0.5-1 m. Moreover, WorldView-2, with its "Coastal Blue" band, improves water penetration and measurement accuracy. Such sensors are well suitable for the proposed study that, it is worth to say, does not measure bathymetry (a different filed in multispectral satellite processing) but only depict the change-in-color feature produced by the slope break of the canyon head.

For feature detection, various methods are implemented and compared to achieve the best result. Nowadays feature detection methods are maturing very rapidly and thanks to deep learning, new algorithms, and models. For instance, methods such as SSD, YOLO, R-CNN, Fast R-CNN, Faster R-CNN are among the state of art models, and they are able to deliver high accuracy and reasonable processing speed for a wide variety of applications.

Innovative solution

Monitoring of canyon heads with satellite observation can be an incredible powerful tool to highlight ongoing processes and assess the evolution of these very specific and hazardous features, up to provide an early warning system. In fact, satellite images are produced by several (and increasing in number) satellite constellations. The return time of the satellites is generally in the order of days, and this would allow, to compare the position of the head of the canyons at a very short time interval, up to use this surveillance as an early warning system for submarine instability in shallow water.

To do so, the specific aspect of this initiative (all to be explored) should encompass:

1) Individuation of canyons head or landslide scars very close to the coast.
2) a proper image processing to highlight the change in color due to sharp changes in bathymetry.
3) an automatic feature reconnaissance (object detection algorithm), extraction and comparison with previous acquisition, to quantify and precisely locate in time and space the headscarp retreat.

Nowadays, automatic object recognition on satellite imagery is a common practice for the prevention of natural disasters such as flooding and fires, socio-economic service delivery, and general urban and rural planning and management. Our proposal relies on the application of this existing technique in the nearshore environment for a purpose that has never been implemented: the detection of breaks in slope coinciding with canyon heads or landslide scars.

Since this technology exists and proved to be effective in other contexts but has never been applied to the recognition of bathymetric variations in nearshore environments, we assume a possible 6 TRL.

The aspiration is that, through the integration of good image processing and the application of object detection algorithms on them, the TRL will rise to 9.

Figure 22. In the upper image the color change is produced by a sharp slope break with a sudden depth increase (similar to Figure 21). In the central image the difference in color has been mapped by a dashed white line. In the lower image multibeam echosounder data defines the morpho-bathymetry of the area, where active erosion is going on, as witnessed by the arcuate bedforms at the center of the channels. The red dashed line defines the slope break. The difference between the two lines highlights the occurrence of a small submarine landslide between the two surveys. Note the short distance from the coast (up to less than 100m) and the presence of houses, main roads and railroad threatened by coastal erosion and eventually by tsunamis produced by large submarine landslides. Instead, the small landslide highlighted by the comparison between the two surveys was un-noticed. Problems due to coastline erosion is witnessed by artificial blocks emplaced at the shoreline in the lower left corner of the image, where the canyon head is closer to the shore.

The costs supposed for the application of the described technology strongly depends on the advancements required (i.e. resolution of images, number of frequencies to be analyzed, use of specifically designed algorithms etc.) and may range from 50k€ to 250 k€.

Expected outcomes

What is expected is to obtain a fully automatic system that, through the recognition of specific features (canyon heads), monitors their spatial variation over time.

Given the fact that submarine landslides in shallow water are quite frequent and in some cases destructive, our proposal has an important purpose of advancing the knowledge on this type of submarine ground instabilities in the context of mitigate natural disasters.

In fac at present, the definition of preparatory factors and triggers for submarine landslides is highly speculative as there are not time constrain and pre-failure data. Currently, this definition is based on residual bathymetric maps that depict changes in seafloor topography (i.e., landslides), which are then associated with possible events (such as earthquakes, storms, or significant sediment transport by rivers following floods). However, establishing a cause-effect connection is, as specified, highly speculative if there is no direct evidence that submarine landslides occur immediately after such triggering events. Through this technology it would be possible to define the time of occurrence of a given mass wasting and directly associate it with specific atmospheric, geological, or oceanographic phenomena, thus providing insights into the factors controlling submarine gravitational instability.

The advantages respct to the acoustic techniques currently used depict landslide scar evolution are: 1) the higher frequency of data acquisitions that is obtained through satellites; 2) the lower costs as satellite data are order of magnitude lower than acquisitions through MBES (multibeam) systems; 3) the possibility to obtain data in very shallow water that is very difficult (and extremely time consuming) with acoustic techniques.

Risk assessment

Multispectral and optical imaging accuracy is strictly connected to environmental conditions, such as the presence of clouds, water turbidity, sea state, sunlight reflection of sea surface etc, that can compromise the quality of images. For this reason, only a limited number of images will be selected.

Of course, many problems have to be taken into account, such as other features that may mimic canyon head (e.g. seagrass meadows, turbidity plumes) but the ambiguity may be overcame by the repetitive nature of the monitoring and the comparison with MBES data.

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N8: PhotoMonitoring: Revolutionizing Landslide Monitoring in Integrating Optical Analysis and Citizen Science for Enhanced Risk

Problem setting

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Problem setting

Landslides represent a critical threat throughout Italy, affecting populations, infrastructure, cultural heritage, and economic activities. With over 600,000 recorded incidents and approximately 8% of the national territory at risk, the impact of landslides is anticipated to escalate in the coming years. This is particularly true for certain types of landslides, exacerbated by the increasing frequency of extreme weather events (Calvello et al., 2018; Gariano et al., 2016; Mazzanti et al., 2017).

Current monitoring techniques, including piezometers, extensometers, and inclinometers, face several limitations and effective landslide monitoring necessitates:

- **Limited Spatial Coverage:** Traditional, point-based monitoring methods may not comprehensively cover the entirety of landslide areas, especially for extensive or complex movements.
- **Invasive Installation:** The installation of certain sensors can alter the natural behaviour of landslides or may require specialized skills, making the process intrusive.
- **Cost and Maintenance:** The deployment and upkeep of a dense network of sensors over vast areas are both costly and labour-intensive.
- **High Spatial Coverage:** Techniques capable of capturing movements across entire landslide areas are essential for thorough understanding and analysis.
- **Non-invasive Approach:** Preferably, monitoring methods should minimize physical disturbance to the landslides.
- **Cost-effectiveness and Scalability:** Solutions that are economical to deploy and maintain, particularly over large expanses, are vital.

PhotoMonitoring, employing Digital Image Correlation (DIC) and Change Detection (CD) techniques on multi-platform, multispectral optical imagery, emerges as a promising alternative to overcome the drawbacks of existing methods (Mazza et al., 2023a; Travelletti et al., 2012).

This approach offers:

- **Non-invasive Monitoring:** By analyzing remotely acquired images, PhotoMonitoring eliminates the need for physical sensor installations, thereby reducing disturbance to the landslide.
- **Extensive Spatial Coverage:** The use of multispectral imagery, sourced from satellites, UAVs, and ground-based or mobile platforms, ensures detailed coverage across entire landslide regions.

- **Scalability and Cost-efficiency:** Leveraging readily available imagery and advanced processing techniques, PhotoMonitoring presents a scalable and potentially more cost-effective option compared to traditional monitoring methods.

The shortcomings of existing techniques underscore the urgent need for innovative and enhanced monitoring solutions. The application of DIC and CD on multispectral imagery, coupled with a Citizen Science approach, introduces a non-invasive, comprehensive, and potentially more affordable strategy for landslide monitoring. This novel approach is poised to significantly improve our understanding of landslide dynamics, enable more effective risk management, and ultimately, enhance public safety and infrastructure resilience.

State of the art

Landslides, characterized by the downward movement of rock, earth, or debris on a slope, significantly threaten communities and infrastructure globally. These catastrophic events can result in loss of life, extensive property damage, and disruption of vital services, underscoring the need for effective monitoring strategies to mitigate hazards and ensure public safety.

Traditional monitoring methods have predominantly relied on in-situ sensors, such as piezometers, extensometers, and inclinometers (Mazzanti et al., 2017; Guerriero et al., 2020; Mazzanti et al., 2020). Despite their utility, these approaches face limitations, including:

- **Limited Spatial Coverage:** In-situ sensors provide data at specific points, often failing to encompass the full extent of landslide areas, particularly in cases of large or complex movements.
- **Invasive Installation:** The installation of some sensors can disturb the landslide area or require specialized knowledge, potentially altering the behaviour of the landslide itself.
- **Cost and Maintenance:** Establishing and maintaining a comprehensive sensor network over extensive landslide zones is both costly and labour-intensive.

The advent of remote sensing technologies, combined with advanced image processing algorithms, has revolutionized the landscape of landslide monitoring (Mazzanti et al., 2020; Caporossi et al., 2018; Arza-García et al., 2022).

These technologies offer:

- **Enhanced Spatial Coverage:** Remote sensing enables data capture over vast areas, offering a holistic view of landslide dynamics beyond the capabilities of point-based methods.
- **Cost-Effectiveness:** The use of satellite or aerial imagery for monitoring presents a more economical alternative to the extensive deployment and upkeep of in-situ sensor networks.
- **Repeatability and Trend Analysis:** Periodic observations from remote sensing facilitate the monitoring of changes over time, aiding in the identification of emerging landslide patterns.

PhotoMonitoring (PM), leveraging Digital Image Correlation (DIC) and Change Detection (CD) on multi-platform, multispectral optical imagery, represents a forefront application in this field. DIC and CD techniques analyze sequential images to quantify surface displacements and map changes over time, respectively. Utilizing imagery from diverse sources, such as satellites, UAVs, and ground-based cameras, PM proposes a non-invasive, comprehensive, and potentially more affordable solution for landslide monitoring (Mugnai et al., 2022; Manconi et al., 2018).

Recent studies have validated the effectiveness of DIC and CD across various platforms, highlighting:

- **Satellite Imagery for High-Precision Monitoring:** Research exemplified by (Manconi et al., 2018) illustrates the capability for broad-scale, precise monitoring using satellite data.
- **UAV Platforms for Detailed Analysis:** Works by (Mugnai et al., 2022) underscore the utility of UAV-acquired imagery and DIC for in-depth examination of rapidly evolving local areas.
- **Multi-Platform Approach for Comprehensive Change Detection:** (Cosentino et al., 2023; Mazza et al., 2023b) emphasizes the advantage of integrating data from multiple sources to achieve a fuller understanding of landslide evolution.

Despite its potential, remote sensing-based monitoring faces challenges, including data quality, privacy concerns, and liability issues, which must be addressed to harness its full capabilities effectively.

Citizen Science applications augment landslide monitoring by expanding data collection networks and validating remotely sensed data, thus enhancing the accuracy and reliability of monitoring efforts. However, addressing the associated challenges of data quality validation, privacy, and liability is imperative for the efficacy of this collaborative approach (Zaharia et al., 2023). By embracing remote sensing, image analysis methodologies, and Citizen Science, stakeholdersst can significantly improve our understanding of landslide dynamics and community resilience against these natural hazards. Ongoing research and innovation are crucial for developing robust monitoring frameworks that effectively mitigate landslide risks and protect vulnerable populations and infrastructure. Yet, realizing the full potential of these approaches necessitates further exploration and optimization, promising a future where effective monitoring and mitigation of landslides safeguard communities worldwide.

Innovative solution

In the field of geosciences, the advent of Artificial Intelligence (AI) and Deep Learning has opened avenues for sophisticated analysis of environmental phenomena that were previously inconceivable. Specifically, in the context of landslide monitoring, the application of these technologies has the potential to dramatically enhance the accuracy and timeliness of detection and analysis. The innovative solution proposed here entails the development of a robust image analysis system utilizing specialized AI and Deep Learning algorithms tailored for Change Detection (CD) and displacement analysis derived from optical imagery. This system aims to address the limitations posed by traditional monitoring methods, such as spatial coverage gaps, the invasive nature of sensor installations, and financial burdens associated with extensive sensor networks.

The current Technology Readiness Level (TRL) for PhotoMonitoring (PM) techniques stands at a TRL of 6, indicating that the technologies are well-established and proven in relevant environments. However, the integration of AI and Deep Learning for CD and displacement analysis from optical images is presently at a TRL of 3, reflecting its conceptual and developmental stage. The proposed advancements aim to elevate the TRL of this integrated system by refining the algorithms for practical deployment in diverse terrain and weather conditions.

Developing an image analysis system that integrates AI and Deep Learning necessitates a multidisciplinary effort, combining expertise in geotechnical engineering, software development, data science, and remote sensing. The system would be trained on extensive datasets of geological features and landslide occurrences, enabling it to identify subtle changes in the landscape indicative of potential landslide activity. By applying Deep Learning techniques, the system could analyze displacement vectors with a precision previously unattainable, thereby providing detailed assessments of landslide risks in near-real-time.

The financial implications of advancing the TRL of this solution are significant, encompassing the costs of algorithm development, training on large datasets, system testing in varied environments, and the creation of a user-friendly interface. These costs, however, are justifiable when considering the potential for a more comprehensive and less invasive monitoring system. The high sensitivity and broad spatial coverage provided by AI-driven analysis would lead to more effective early warning systems, potentially saving millions in infrastructure damage and invaluable human lives.

All of this extraordinary potential is also connected to the statistics related to the optical sensor market. The optical sensor market has grown significantly in recent years, achieving an estimated value of $1.93 billion in 2021. Projections indicate that by 2030, this sector may grow to a value of $7.02 billion, with total CMOS image sensor shipments increasing from 6.7 billion units in 2020 to approximately 13.5 billion units in 2025. This significant evolution is due to several key factors. In the first place, the continuous technological progress of optical sensors has made it possible to use them even in extremely adverse environments and in sectors that are constantly evolving and innovating. The amazing thing is that by 2023, it is estimated that an average of 4.7 billion photos will be taken per day worldwide, an incredible total of 1.81 trillion images per year. This high flexibility has contributed to significant market growth, especially given the exponential increase in the use of mobile devices for photography. Currently, 92.5% of photos are taken with smartphones, while only 7% are captured with traditional cameras or other platforms.

Conventional monitoring methods that rely on in-situ sensors often face challenges related to their spatial reach, intrusive nature, and cost efficiency. In response, a sophisticated alternative is proposed: a mobile application that synergizes Citizen Science with advanced PhotoMonitoring (PM) methodologies to amplify the efficacy of monitoring practices. This solution seeks to merge the prowess of AI and Deep Learning for analytical processes with the widespread availability of optical sensors found in contemporary smartphones. By integrating this innovative technology with Citizen Science initiatives, there's an opportunity to significantly expand the data reservoir, tapping into the widespread use of smartphones to crowdsource information on landslides. While Citizen Science is not the central focus of this innovation, it provides a crucial means of gathering ground-level data, which can serve to validate and refine the AI system's predictive accuracy. This application is poised to unify the proven concepts of PhotoMonitoring at TRL 6 with cutting-edge AI and Deep Learning data processing techniques within an accessible smartphone interface at TRL 3, all under the umbrella of Citizen Science engagement.

The application's design and functionality include:

- **Intuitive Image Capture:** Guiding users in capturing high-quality, geo-tagged images ensures consistency for effective analysis.
- **Streamlined Reporting:** Enabling users to report landslide observations facilitates comprehensive analysis and risk assessment.
- **Interactive Data Visualization:** Providing real-time updates on landslide activity through interactive maps fosters user engagement and community participation.
  Data validation and quality control measures ensure accuracy and reliability:
- **User Training and Education:** Equipping users with proper data collection techniques minimizes errors and improves consistency.
- **Image Filtering and Validation:** Automated techniques filter out irrelevant images, while cross-validation with other monitoring systems enhances data reliability.
  Investment in app development, data management infrastructure, and user training is crucial:
- **App Development:** Expertise in software engineering is required to build a user-friendly app with robust functionalities.
- **Data Management Infrastructure:** Secure server infrastructure is crucial for storing and managing citizen-collected data securely.
- **User Training:** Developing educational materials and conducting workshops promote widespread adoption of the app.

Figure 23: Innovation in Landslide Monitoring: A Citizen Science application turns smartphones into monitoring tools for advanced and participatory environmental surveillance.

Broadly, PhotoMonitoring leverages optical and multispectral sensors to extract critical information on terrestrial changes via digital image processing (DIP). It functions across a spectrum of spatial and temporal dimensions, rendering it exceptionally suitable for analyzing surface deformation. Various monitoring systems, ranging from low-frequency to near real-time and even real-time applications, play a significant role in early detection and hazard evaluation. The proposed enhancements in PhotoMonitoring techniques promise to deliver both visual and quantitative insights across different frequencies, ensuring adaptability to diverse monitoring contexts. Moreover, the vast archive of imagery already captured and the proliferation of smartphone photography signal a transformative potential for a mobile app designed for data gathering and analysis. This app, enriched by Citizen Science participation, could significantly reform landslide monitoring practices. Such technological progress, underscored by its cost efficiency, immediacy of data acquisition, and expansive coverage, stands to validate the investment required for its development.

Expected outcomes

The adaptability of the PM solution positions it as a versatile tool capable of meeting diverse requirements across emergency knowledge acquisition, control, and monitoring applications. Particularly in monitoring, PM stands out for its potential in developing Early Warning Systems for geological hazards, offering a balance between a wide-reaching sensitivity of measurements and user accessibility. Its exceptional adaptability, underscored by the integration of data from various sources such as satellites, Unmanned Aerial Vehicles (UAVs), ground and mobile sensors (through Citizen Science Monitoring), renders PM applicable across a broad spectrum of real-world contexts. This includes both experimental settings and natural environments, enhancing our capability to monitor and understand environmental dynamics comprehensively.

A critical advantage of PM lies in its cost-effectiveness and non-intrusiveness. Compared to traditional monitoring techniques, PM presents a more accessible and user-friendly option, significantly lowering the barriers to implementing monitoring strategies in geologically high-risk areas. These areas are often challenging for both residents and technical personnel to access. The broader implication of adopting PM techniques is the potential for a more widespread monitoring coverage, which can enhance environmental control and contribute to a deeper understanding of natural processes and landslide risk assessments.

Long-Term Benefits:

Despite initial investments, the long-term benefits of PM outweigh the costs, promising a transformative impact on landslide monitoring and risk management:

- **Increased Spatial Coverage:** Leveraging Citizen Science for data collection allows for extensive geographical coverage, surpassing traditional sensor networks' limitations. This approach promises a comprehensive understanding of landslide activities, especially beneficial for remote and hard-to-reach areas.
- **Cost-Effectiveness:** Utilizing readily available technology, such as smartphones, eliminates the necessity for expensive, in-situ sensor networks, significantly reducing the financial burden of monitoring infrastructure deployment and maintenance.
- **Real-Time Monitoring:** The capability for frequent image captures by citizen scientists enables near real-time monitoring of landslides, facilitating rapid detection of emerging risks and the implementation of timely mitigation measures.
- **Enhanced Public Awareness:** By engaging the community in the monitoring process, PM not only increases awareness of landslide hazards but also cultivates a collective responsibility towards landslide prevention and mitigation efforts.

Risk assessment

The deployment of PhotoMonitoring (PM) in geoscience applications necessitates a thorough consideration of various site-specific environmental factors that may compromise the analysis's quality. These factors can significantly impact the accuracy and reliability of data collected through PM, potentially leading to misinterpretations of geological phenomena or the overlooking of critical warning signs for natural hazards like landslides.

Challenges and Mitigation Strategies:

- **Misaligned Images:** The variability in sensor positioning over time can lead to misaligned images, complicating the analysis and interpretation of temporal changes in the monitored area.
  - **Solution:** Implementation of advanced image co-registration algorithms that automatically adjust and align images over time ensures consistent analysis despite sensor positional variations. This method enhances the accuracy of change detection and displacement measurements.
- **Lighting Variation:** Changes in lighting conditions due to the Earth's rotation, cloud cover, and other atmospheric variations can affect the visual consistency of images, making it challenging to compare and analyze them effectively.
  - **Solution:** Pre-processing techniques, including radiometric image corrections, can normalize lighting variations across images, ensuring that comparisons are based on changes in the terrain rather than differences in illumination.
- **Environmental Disturbances:** Factors such as fog, rain, snow, and other weather-related conditions can obscure or distort the imagery, leading to inaccurate analyses or missed detections of landslide indicators.

  - **Solution:** Utilizing imagery in spectral bands beyond the visible spectrum can mitigate the impact of environmental disturbances. For example, infrared and thermal bands can penetrate certain atmospheric conditions better than visible light, offering clearer views of the earth's surface under adverse weather conditions. Additionally, incorporating redundant sensors can provide backup data when primary sensors are compromised.
- **Undesirable Movements:** Wind-induced movements, along with the transit of vehicles, animals, and other non-geological movements, can introduce noise into the data, complicating the distinction between environmental changes and these irrelevant movements.
  - **Solution:** Post-processing filters, such as analysis masks, can be employed to isolate the geological changes of interest from the background noise caused by wind, fauna, and human activities. This selective analysis ensures that the focus remains on detecting and monitoring relevant geological changes without interference from extraneous movements.
- **Lack of Citizen Science Engagement:** A fundamental challenge in harnessing Citizen Science for landslide monitoring through PM is the absence of a widespread culture that values and promotes public participation in scientific research. This gap can limit the quantity and quality of data collected, thereby affecting the comprehensiveness and effectiveness of monitoring efforts.
  - **Solution:** Developing and implementing comprehensive educational and outreach programs aimed at raising public awareness about the significance of their contribution to geoscience research and landslide monitoring is crucial. These programs should focus on educating the community about the basics of landslide risks, the importance of their observations, and how to accurately collect and report data using available technologies. Furthermore, providing easy-to-use tools and platforms that facilitate public participation without requiring specialized knowledge can significantly enhance engagement levels.
  - **Engagement Platforms:** Creating interactive platforms and mobile applications that are user-friendly and engaging for the general public can encourage participation. These platforms can offer tutorials, real-time feedback, and gamification elements to educate and motivate citizens to contribute regularly.
  - **Collaboration with Local Authorities and Organizations:** Partnerships with local governments, schools, and community organizations can play a vital role in promoting Citizen Science. By integrating landslide monitoring into community programs and educational curriculums, a culture of active participation and awareness can be fostered.
  - **Recognition and Incentivization:** Acknowledging the contributions of citizen scientists through recognition programs, certificates, and tangible rewards can motivate sustained engagement. Public acknowledgement of the critical role these contributions play in enhancing landslide monitoring and risk assessment efforts can empower and encourage community members to participate actively.

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N10: Application of conventional sensors and triaxial velocimeters for a better understanding of slow flow behavior

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Problem setting

Slow flows, commonly described as earthflows, occur in many hilly and mountainous areas of the world. Although their long-term evolution is mainly characterized by slow intermittent movement controlled by pore pressure fluctuation at the landslide base (Iverson, 2000, 2005; Shulz et al., 2009) under specific conditions, unexpected accelerations might occur promoting catastrophic slope failure. Such events can result in extensive damage to settlements. In the last decades, a number of studies have documented significant acceleration of slow flows and related effects on buildings and infrastructures, underlining the need for a better understanding of conditions and processes driving the transition between ordinary intermittent movement and extraordinary surging accelerations (Guerriero et al., 2014, 2017). Several studies have identified the association of hydrologic forcing (i.e. prolonged and/or intense rainfall), the loss of drainage pathways due to landslide deformation, and the availability of new mobilized sediments in the source area as potential concurring factors promoting this behavioral transition. A common feature of slow flows is the presence of a significant fraction of fine grained (i.e. clay) materials that can control the rheology of the system and the available resistance along the sliding surface (van Asch et al., 2006). A recent study, identifying material viscosity as a diagnostic parameter of solid-fluid transition in landslides, has shown that clayey soils originated in flow-like landslides can exhibit a yield-stress fluid behavior associated with a bifurcation in viscosity and water content deviation from the Atterberg liquid limit might control mechanics of the system at solid-fluid transition (Carrière et al., 2018). In addition, a significant drop in shear wave velocity has been identified to be associated to slow flow mobilization and potential surge development, indicating a significant increase of porosity and consequently water content that might control the solid-fluid transition (Berti et al., 2018). Shear wave velocity change in relation to slow flow seasonal behavior has been documented by Berti et al. (2018), which observed a drop in shear wave velocity during seasonal reactivation of a slow flow, and by Maresca et al. (2022), which observed an increase in shear wave velocity associated to slow flow deceleration after surge in relation to summer drought. On this basis, the application of arrays of conventional sensor such as wire extensometer and pore pressure transducer, commonly employed to acquire surface displacement and pore pressure at the landside base, in association to daily estimation of shear wave velocity based on ambient seismic noise completed using triaxial velocimeters, can contribute to acquire data depicting slow flow behavior in terms of kinematics and both boundary/material conditions consequently improve our capabilities of documenting the process. Furthermore, considering the observation that slow flow reactivation triggered by entrainment of new material in the source zone can propagate as a kinematic wave from the head toward the toe, the use of multiple monitoring arrays can contribute to the description of this process.

State of the art

Slow flow behavior, in terms of kinematics and potential controlling factors, has been documented by many authors using data acquired through either discrete surveys and/or continuous monitoring. For instance, Coe et al. (2003) used repeated GPS measurements at selected location and data acquired through wire extensometer to quantify surface movement of the Slumgullion landslide in southwestern Colorado. Shulz et al. (2009) used a multi-sensors monitoring station equipped with three vibrating wire piezometers, four tensiometers, an air-temperature sensor, a rain gage and a wire extensometer, to identify relations between hydrology and velocity at the Slumgullion landslide. Berti and Simoni (2010) developed an array of hydrologic and deformational sensors consisting in multiple pore pressure transducers, shallow tensiometers and moisture contents sensor, a rain gage and a wire extensometer to describe landslide response to transient pore pressure change due to rainfall infiltration. Guerriero et al. (2017) used repeated GPS measurements and geophysical surveys to monitor surface movement and quantify sediment discharge along the Mount Pizzuto landslide in southern Italy. Documentation of change in material properties (and potentially mechanism: slide to flow) associated to slow flow acceleration/reactivation and deceleration after surge has been documented by a limited number of authors. For instance, Berti et al. (2018) documented shear wave velocity drop associated to slow flow acceleration using repeated geophysical surveys based on the multichannel analysis of surface waves (MASW) and the refraction microtremors (ReMi) techniques. With the aim of investigating the solid-to-fluid transition that can occur in rapid earthflows, Berti et al. (2022) present a methodological approach based on the combination of periodic measurements of Rayleigh wave velocities to evaluate the change of stiffness with time of the landslide material, and laboratory tests as Atterberg limits, fall cone and edometric tests in order to derive empirical correlations between geophysical and geotechnical properties. Maresca et al. (2022) used repeated recordings of ambient seismic noise through a triaxial velocimeter and the HVSR method to obtain field evidence of seasonal landslide material property change. Although conventional multi-sensors systems suitable to the description of slow flow kinematics and controlling factors have been widely applied, and systems and techniques to estimate temporal change in shear wave velocity based on repeated measurements have been adopted at selected locations, application of combination of these monitoring techniques are limited. If we consider the need for tracking the kinematics and factors controlling movement as well as material properties/mechanism change from both temporal and spatial point of view (i.e. slow flow reactivation propagation along the landslide), spatial arrays of multi-sensors and combined systems are still being developing and testing.

Innovative solution

The solution proposed to derive data for a better description of slow flow behaviour in terms of kinematics, factors controlling movement and change in material properties/mechanism consist in the development of a monitoring network consisting of five multi-sensors monitoring stations. Of these stations, four will be installed within the landslide area and a station will be installed outside from the landslide area. Each monitoring station installed inside the landslide area will consist of a datalogger powered by a battery, solar panel and regulator, and equipped with multiple sensors. Especially, a range extended wire extensometer (~7 m range), a pore pressure transducer (0 – 2 bar range) and a 4.5 Hz (+/-5%) triaxial compact velocimeter (Fig. 1) coupled with a GPS sensor for timing synchronization (Fig. 2) will be installed. The station installed outside from the landslide area will consist of a datalogger powered by a battery, solar panel and regulator, and equipped with a 4.5 Hz (+/-5%) triaxial compact velocimeter (Fig. 1) coupled with a GPS sensor for timing synchronization (Fig. 3) and a rain gage, temperature sensor and air pressure sensor. All of the stations will be equipped with a 4G Modem allowing for data transfer. The significance of the solution will be enhanced by the installation scheme that consider a longitudinal array of monitoring stations able to directly measure surface displacement and pore water pressure at the landslide base and provide daily data for estimating shear wave velocity through inversion of the HVSR curve based on the Rayleigh wave ellipticity. In this way, a potential reactivation and/or acceleration will be registered in terms of different parameters at different distance from the landslide head allowing for a potential interpretation of the process. Climatic monitoring data acquired outside from the landslide will form a basis for interpreting relation between hydrologic forcing and landslide response. The overall cost of the system for each of the two selected configurations will range from ~9000 to ~6500€, respectively. With these instruments, a Technology

Readiness Level (TRL) increase from level 3 of research (experimental Proof of Concept) to level 5 of development (technology validated in relevant environment) can be expected.

Figure 23.Three-channel data logger and GPS sensor.

Figure 24. Triaxial compact velocimeter.

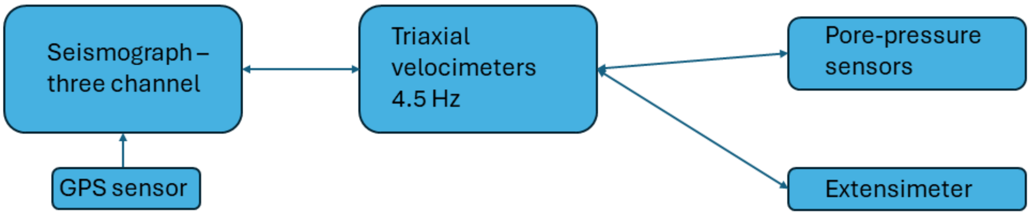

Figure 25. First monitoring system configuration.

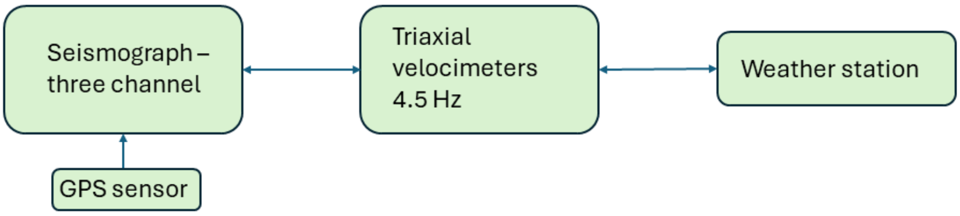

Figure 26. Second monitoring system configuration.

Expected outcomes

Expected results from the application of the proposed monitoring systems will consist in time series depicting the evolution of monitored parameters during the reference period such as surface displacement at different positions along the landslide, pore pressure measured along the landslide basal slip surface at different position along the landslide consistent with those of acquisition of surface displacement data. If obtained and interpreted correctly, the data derived from this application may contribute to the development of guidelines for other future uses of these monitoring systems. Further results will be represented by triaxial ambient seismic noise records at each installed monitoring station (inside and outside from the selected landslide) that will form a basis for deriving HVSR curves and Rayleigh wave ellipticity curves that will be inverted to derive a daily estimate of the shear wave velocity. The need for estimating shear wave velocity inside and outside from the monitored landslide is related to the need for a reference that might guide interpretation of small change in the shear wave velocity not strictly related to landslide movement. Result from the monitoring station installed outside from the landslide will consist in multiple time series depicting rainfall intensity, air temperature and air pressure change.

Risk assessment

The installation of the system will be completed in a remote area of southern Italy in which previous wildfire events have occurred so it cannot be excluded potential damage of the system by wildfire and/or eventual vandalization. The use of a properly dimensioned solar power system should guarantee a permanent operation of the system but, due to the potential presence of persistent snow cover in specific period of the year, temporal suspension in data acquisition might occur. The estimation of shear wave velocity through the selected Rayleigh wave ellipticity based inversion method might be affected by significant uncertainty.

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N11: Bathymetric data of white data area obtained from optical images.

Authors

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Problem setting

Marine area investigation to acquire bathymetry data, have limitations linked to work operations themselves. Medium size ships utilized cannot approach the coastal area both for safety reasons and for maneuvering difficulties. This is less problematic when using smaller ships but, equally, it is difficult to acquire bathymetric data from operative area up to the coastline (white data area).

State of the art

To obtain data of white data areas we study a new methodology based on optical images. To extract the bathymetry from optical images, we use a simplified version of the original radiative transfer equation from Jain and Miller (1977). This equation is expressed in terms of reflectance. In this context, R_0 (−) represents the reflectance just beneath the water surface, while R_∞ (−) denotes the reflectance value for a water column of infinite depth. R_b (−) is the radiance at the bottom, K_d (in units of m^-1) is the diffuse attenuation coefficient, and z is the water depth. All parameters, except for depth, are wavelength-dependent.

$$R_0(\lambda_i) = R_\infty(\lambda_i) + \left[R_b(\lambda_i) - R_\infty(\lambda_i)\right] \cdot e^{(-2K_d z)} \qquad (1)$$

The equation was initially calibrated using bathymetry data obtained by multibeam sonar in a portion near the study area. After calibration, it was then applied to derive the bathymetry of the entire study area. However, its applicability is limited to the maximum depth at which the reflectance is considered to be invariant with the depth and takes on the reflectance value of a water column of infinite depth.

Innovative solution

This technique aims to be able to obtain an indirect method to obtain submerged beach and internal continental shelf bathymetric data in order to be able to have continuous monitoring of this dynamic environment. This is of great importance for different scientific and social purposes. The current TRL is: Research 3: experimental proof of concept.

Expected outcomes

Actually there is not a validated and recognized methodology utilized to obtain the purpose we have described.

Our methodology have an error range that can be improved.

Risk assessment

The limits of this new methodology are:

- Data error range;

- resolution of bathymetric data obtained.

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Jain, S.G. and Miller, J.R., (1977). Algebraic expression for the diffuse irradiance reflectivity of water from the two-flow model, Appl. Opt., 16 (1), 202-204

N12: Novel multidisciplinary technique aimed at the study of coastal erosion

Authors

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Problem setting

This multidisciplinary study aims to analyse the coastal erosion problem, linked to the estimate of sediments rate taken care by the longshore current and its actual availability for the sedimentary balance of a beach. This linked to the presence of possible submerged morphologies that may or may not favour the persistence of these sediments along the coast.

State of the art

Up to now there are no techniques capable of providing continuous and spatially distributed measurement of longhshore current sediment transfer, a fact of considerable interest if we think of the anthropic structures present along the shores, and the coast erosional problems. This multidisciplinary study aims to evaluate, at the regional scale, the possibility of borrowing some techniques that are often used in fluvial contexts (e.g., geomorphological approach), to estimate the quantity of sediment that are deposited to the coast.

Innovative solution

The study of morphological changes of a river channel, linked to erosion-deposition processes, taking place in the riverbed, is a topic of current interest in relation not only to the morphometric variations of the fluvial features (e.g., active channel width, area of sediment bars) and the sedimentary balance of the whole relative hydrographic basin but also in relation to the role of the sediment load transferred downstream up to the near shore area.

These sediments constitute the solid transport that is pushed towards the coast and poured into the sea, representing a crucial sedimentary contribution to the beaches volumetric balance. The quantitative estimate of the volume of this fluvial load is currently achievable through robust approaches such as the morphological method grounded in the continuity principle applied to river sediments. To define the transport rates at selected locations (e.g., the river mouth) over a given time period, the method requires to measure the erosion and sedimentation volumes, which can be calculated using repeated Digital Elevation Models (DEM)and deriving a DEM of Difference (DoD) (Vericat et al., 2017; Capito et al., 2023). The coastal sedimentary balance is function of both the sediment load provided by rivers and the quantity of sediment transported by the longshore currents that move parallel to the coastline. For this reason, it is crucial to assess the impact of coastal erosion considering both the sediment input from the hydrographic basins and the longshore transport. The current TRL is Research 2: Technology concept formulated. It's potential development is Research 3: experimental proof of concept.

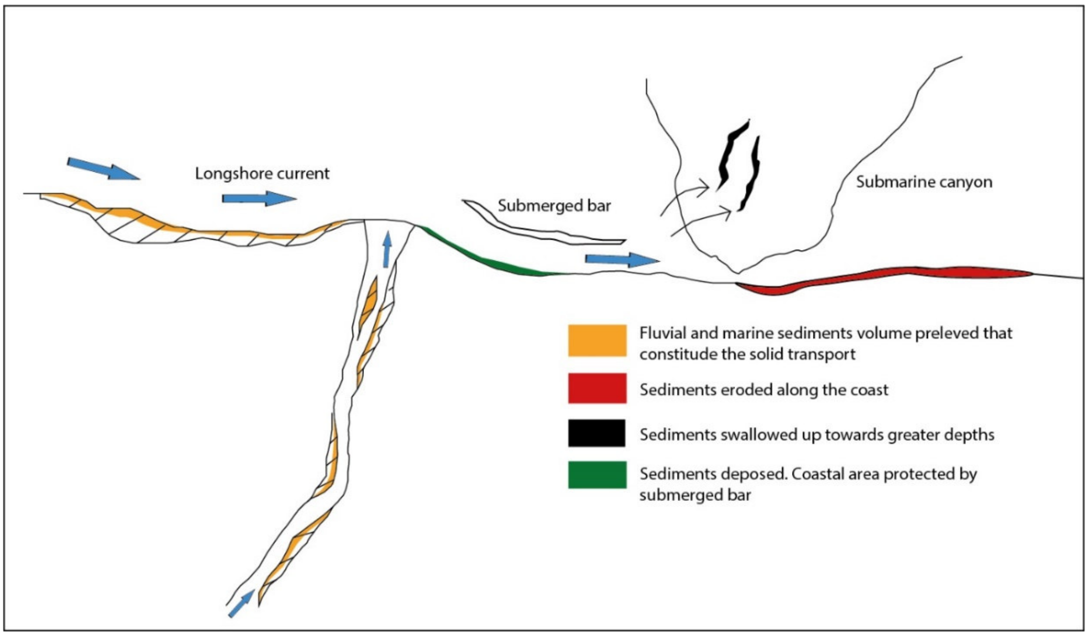

Figure 27.Coastal erosion scheme.

Expected outcomes

Study and calculation of sediments longshore currents rate and longshore transport engineering modeling in order to determine the medium/long term evolutionary trend of a coastal sector with respect to the problem of coastal erosion.

Risk assessment

This multidisciplinary study does not presuppose the creation of a new instrument and therefore has no financial costs to bear. It is based solely on the fusion of several scientific techniques to achieve the objective. This study could have as its limit the possibility of an exact estimate of the volume of sediment transported by longshore currents which would be dispersed in the case of submerged structures that favor its dispersion, and transported along the coast as material available for natural nourishment of the coast itself. Obviously, with due experimentation, this data can also be improved.

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N15: Use of the terrestrial laser scanner for the evaluation of relationships between DGPV system evolution and rainfall intensity.

Authors

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Problem setting

Deep Slope Gravitational Deformation (DGPV) phenomena, which are characterized by a very low deformation speed, are frequently coupled with more rapid phenomena such as rockfall landslide (with tilting of blocks) and surficial flows. In light of this, the monitoring of this geomorphological system could be very complex: the interpretation of the observed deformational system must consider the different degrees of rooting (substrate or blocks in deformations) of the monitoring vertices, as well as the plano-altimetric variability and the dynamic range of the movements themselves to measure (Pappalardo et al., 2021).

This deformational system, which is characterized by different landslide typologies (from surficial to very deep phenomena), and by different types of lithotecnical units with different rheology, could stand and react to rainfall (as preparatory or trigger factor) in different ways.

The Scopello landslide is one of the most significant cases of Deep Gravitational Deformations of Slopes in Sicily. The geological setting of the area is characterized by more/less regular and thick slab made of platform carbonatic rocks (Panormide platform units), which overlies a ductile clayey/sandy marly substratum (Catalano et al., 2013), result of the continental collision since Middle Miocene. The whole slab/substratum stack was segmented by the mio-pliocenic inverse high-angle faults and the pleistocenic normal faults.

The main deep-seated phenomena are strictly connected to the presence of faults, which result in several retrogressive/progressive pure landslide scarps. At the same time, while the main deep-seated dynamics evolve with very low velocities (mm/cm per year), surface gravitational processes have strongly modelled scarps and blocks (falls and toppling) and the marly clayey substratum (rotational slides and flows).

Figure 28.The Scopello DGPV landslide area (from sx to dx: location, field images, PAI ex-post map).

State of the art

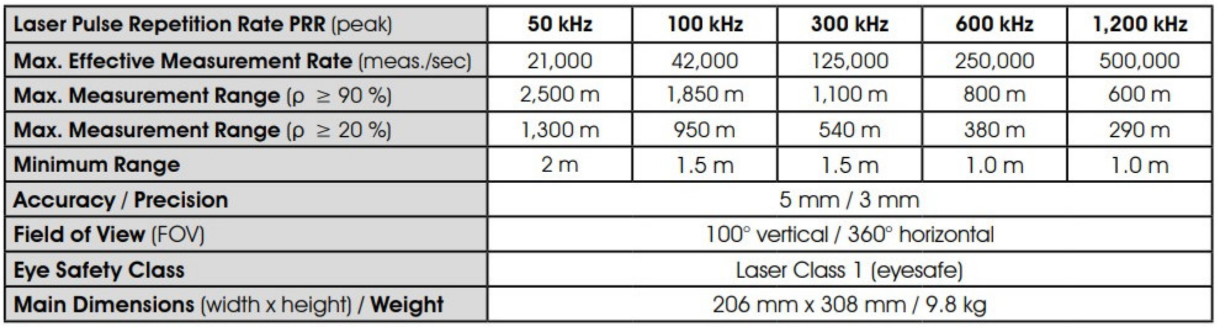
The mosaic of landforms in the Scopello area was studied with different integrated investigations, from geological and geomorphological field surveys to digital terrain models and aerophotogrammetric analyses, from Infrared Thermography surveys to DInSAR interferometry and acquisition of GNSS measurements Infrared Thermography surveys (Agnesi et al. 2006, 2015; Cappadonia et al. 2019; Di Maggio et al. 2014; Pappalardo et. al. 2021). To our knowledge, only Pappalardo et al. 2021 have investigated the rainfall effect for the Scopello landslides, focusing their research only on the activation of February 2005 (a large earth/debris flow, which laterally activated slab/rock slides and lateral spreads on the carbonate blocks in the right flank).

Innovative solution

The 3D terrestrial laser scanner (TLS) has been proposed as an alternative technique to perform geomechanical analysis remotely. TLS devices provide high-resolution point clouds of the detected surfaces to obtain 3D geometry of the mass surface. Applicated to the landslide characterization, the TLS analysis allows us to obtain a 3D view of the phenomenon, with high accuracy in identifying the discontinuity surfaces, fractures, and displaced volume. At the same time, the small size of the machine, together with the speed of data acquisition and elaboration, which are predominantly automated procedures, promote the recurrent use of the instrument to study the evolution of phenomena. The TLS is a well-known tool and widely adopted in several tasks of slope instability analysis (e.g., Oppikofer et al. 2009; Gigli and Casagli 2011; Squarzoni et al. 2008; Fanti et al. 2013) but the application to DGPV landslides is quite rare.

For the study area, we want to produce repeated and recurring TLS measurements to detect and monitor potential surficial or deep landslide activation/evolution. At the same time, the analysis of rainfall patterns will allow us to identify the role of rain with respect to landslide activation/evolution to discriminate the threshold factor as preparatory to triggering.

The TLS that will be used for the project is a RIEGL VZ-2000i, with a maximum measurement range of 2.5 km, pulse repetition rate PRR of 1.2 MHz, online waveform processing, multiple target capability, camera integrated, WI-FI and 3G/4G LTE technology, and laser class 1 (see Fig. 2 for other details).



Laser Pulse Repetition Rate PRR (peak)	**50 kHz**	**100 kHz**	**300 kHz**	**600 kHz**	**1,200 kHz**
Max. Effective Measurement Rate (meas./sec)	21,000	42,000	125,000	250,000	500,000
Max. Measurement Range (ρ ≥ 90 %)	2,500 m	1,850 m	1,100 m	800 m	600 m
Max. Measurement Range (ρ ≥ 20 %)	1,300 m	950 m	540 m	380 m	290 m
Minimum Range	2 m	1.5 m	1.5 m	1.0 m	1.0 m
Accuracy / Precision	5 mm / 3 mm				
Field of View (FOV)	100° vertical / 360° horizontal				
Eye Safety Class	Laser Class 1 (eyesafe)				
Main Dimensions (width x height) / **Weight**	206 mm x 308 mm / 9.8 kg				

Figure 29.Main characteristics of the RIEGL VZ-2000i.

Expected outcomes

The proposed application aims to define the relationships between rainfall intensity and landslide activation/evolution. In particular, for the study area, we want to discriminate the role of rainfalls from preparatory to triggering, both for deep and surficial landslides. To achieve this goal, we need to high-resolution 3D view of the study sector, with repeated and recurrent measurements.

The use of TLS technology allows us to obtain in a smart, fast, and efficient way high-resolution 3D reconstruction and to decide when, where and how to realize the measurements. As a consequence, we can program the measurements before, during, and after a specific intense rainfall or seasonal rainfall. This possibility allows us to obtain pre-, during and post-scenarios in order to better understand the rainfall role as preparatory or triggering factor, for the different landslide types of the study area.

Risk assessment

The evaluation of rainfall's role in landslide activation/evolution is a mandatory aim for the definition of landslide risk in a specific area. Differ landslide risk scenarios could be proposed according to the specific rainfall pattern, which could be defined as a preparatory or triggering threshold, also for different types of landslides. This assessment provides to define areas more susceptible to the activation/evolution of a specific landslide, supporting smart, accurate, and efficient territorial planning and management in case of rainfall strain.

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N18: Application of Infra-Red Thermography to rocky cliffs

Authors

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Problem setting

The need for the application of Infra-Red Thermography to the monitoring of rocky cliffs and landslide slopes is related to the necessity of improving monitoring capabilities of thermography to detect eventual precursory signs of the evolving instability of rocky cliffs and slopes. Therefore, the idea is to investigate through the application of the specific technique to real case studies if the same technique can be used also for real-time and alert monitoring. The solution will be applied to a coastal rocky cliff portion along the Apulian South-Adriatic coastline and a large earthflow body active in the Southern Apennine.

State of the art

There are recent applications that are worthy to be mentioned in this field, discussing about potentialities and limitations of the same monitoring technique, as for example: Marmoni et al. (2020), Melis et al. (2020), Mineo et al. (2015).

Innovative solution

The innovative solution is represented by the attempt to detect precursory signs of the upcoming instability within rock masses prone to failure that are generally characterized by brittle failure processes. The solution will adopt thermal surveys repeated at different time steps in order to investigate the effects of the seasonal temperature variations and the solar radiation on the rock surface and joint behaviour. The results will be integrated with digital LiDAR surveys aimed at reconstructing the geometry of the rock cliff and landslide body.

The present TRL of this solution is 5 and can reach 6 during the project and there are no further costs for technological development.

Expected outcomes

Possible outcomes from the application of the technique to the monitoring of rocky cliffs are represented by the possibility to detect discontinuities and rock mass portions that could be potentially subjected to larger temperature fluctuations and, as a consequence, could be considered as areas more susceptible to detachments and instabilities. The main advantage with respect to the available monitoring techniques could be represented by the opportunity to define precursory signs with respect to failure processes that are generally strongly brittle, so that monitoring techniques based on contact devices (as for example extensometers) are not very useful to detect upcoming failure and to provide alert messages. Another advantage is represented by the possibility to monitor large rock surface areas, rather than local points, as with traditional contact devices.

Risk assessment

Difficulty of measuring ground deformations of a few millimetres.

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Marmoni, G.R., Fiorucci, M., Grechi, G., Martino, S., (2020). Modelling the thermos-mechanical effects in a rock quarry wall induced by near-surface temperature fluctuations. Int. J. Rock Mech & Min. Sci., 134, 104440.

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N19: Distributed fiber optic system for sinkhole detection

Authors

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Problem setting

Sinkholes are a common geohazard consisting of a hole or depression formed in the ground surface due to the subsurface collapse of a cavity (Jennings et al., 1965). They are commonly caused by the dissolution of carbonate rocks such as limestone, dolomites, gypsum or chalk (Cooper et al., 2011), but can also be caused by the collapse of human-made structures such as old mine shafts (Brady & Brown, 1993) or buried pits in urban areas, in many cases due to erosion from leaking utility lines. In the built environment, sinkholes have the potential to cause severe damage to infrastructure, and in some cases lead to casualties. Sinkholes can develop over long periods (slow sinkholes), thus allowing ground deformation to be measured well before their eventual collapse (Chang & Hanssen, 2014). A range of methods have been explored, aiming to measure ground settlements to detect possible sinkhole formation sufficiently in advance. For example, electrical resistivity imaging (Van Schoor, 2002; Youssef et al., 2012), two-dimensional (2D) full seismic waveform tomography (Tran et al., 2013), multi-temporal interferometric synthetic aperture radar (InSAR) (Chang & Hanssen, 2014) or thermal far-infrared imagining (Lee et al., 2016). However, these techniques cannot accommodate the temporal frequency needed while also offering large area coverage with sufficient sampling resolution (Möller et al., 2022); as a result, there are limitations to wide-scale adoption in practice.

Distributed fiber optic sensing (DFOS) technologies are well suited to identify sinkholes where the potential location is unknown, especially for monitoring long linear infrastructures, such as roads or railways, as they can be laid in continuous lines. An additional advantage is that they can provide subsurface deformation measurements, which would allow the identification of a sinkhole before its effects are evident at the soil surface.

State of the art

Pioneer full-scale experiments on the use of fiber-optic sensors for sinkhole detection in sands were carried out by Villard & Briançon (2008). A 2 m wide and 0·5 m depth void was simulated with inflatable balloons, and monitoring was carried out with 1 m spaced fiber Bragg gratings (FBGs) incorporated in a fibre-optic cable, woven in a geosynthetic sheet. In their study, the focus was on the evaluation of strain developed into the geotextile. They showed that the fiber-optic sensor was able to pick up strain from the beginning of the balloons' deflation, with geosynthetics placed directly above the balloons. Similar tests, using distributed fiber-optic sensors were performed a year later by Belli et al. (2009). In this case fiber-optic strains were retrieved based on Brillouin scattering with a spatial resolution of 1 m. Three different fiber-optic sensors were used, both independently and as part of a geogrid, in order to study the sensitivity of the sensors in detecting soil settlements. A recent development in sinkhole detection relies on the use of fiber-optic cables, included in the earthwork during construction, sometimes within the use of a geogrid, to monitor ground displacements (Guan et al., 2013, 2015; Klar et al., 2014; Zhang et al., 2016; Inaudi, 2017). This is particularly suitable for long linear infrastructure, such as railways or roads. Lanticq et al. (2009) performed a full-scale test, simulating the formation of two voids 2.1 m wide and 2 m deep, sufficiently spaced to avoid interference. A cable 2 mm in diameter containing eight optical fibers was analyzed with Brillouin optical time-domain reflectometry (BOTDR) and optical frequency-domain reflectometry (OFDR), to study the efficacy of both technologies in detecting soil strains. Potentialities and limitation of fiber-optic sensors for sinkhole detections have been discussed by Gutierrez et al. 2023, that carried out a field trial application of distributed optical fiber sensors to sinkhole monitoring using Brillouin Optical Time Domain Analysis (BOTDA).

Innovative solution

A typical distributed fiber-optic sensing system (DFOS) is made of two components: an optical fiber cable and an optical fiber analyzer. Unlike traditional sensors that rely on discrete sensors measuring at pre-determined points, distributed sensing uses the whole optical fiber as a sensing element. The sensor is simply a standard and inexpensive telecommunications optical fiber with which strain or temperature can be measured at any given time at several thousand points over distances spanning kilometers (Kechavarzi et al. 2016), depending on the commercial optic analyzer used (e.g. Neubrescope NBX-7020, Luna ODiSi 6100, Omnisens Vision Dual, etc., Fig. 32). An optical fiber is a cylindrical structure that transmits light along its axis and is essentially made of three parts: a core that carries the light is surrounded by cladding with a lower refractive index, the latter surrounded by a buffer coating that protect the brittle fiber. The core is usually made of pure silicon dioxide (SiO_2) or polymethyl methacrylate (acrylic glass) and has a slightly higher refractive index compared to the cladding in order to allow the light travelling in the core to be reflected at the core-cladding interface.

Figure 30.Commercial fiber-optic analyzer.

DFOS technology enables continuous, real-time measurements along the entire length of a fiber optic cable. When light travels in an optical fiber, it can either propagate in the desired direction or travel in the opposite direction after being reflected, where the latter is called backscattered light (Fig. 33). Three types of light scattering exist: the Rayleigh scattering, occurring when the frequency of the transmitted light equals that of the backscattered light; the Brillouin scattering, that produces a shift in frequency caused by an interaction between the propagating optical pulse and the acoustic waves propagating in the silica fiber; the Raman scattering, due to an energy exchange between the photons and the fibre atoms, that produces new photons with lower (Stokes components) or higher (Anti-Stokes components) energy. Distributed fiber optic sensing technique (DFOS) takes advantage of this phenomena because the strain and temperature, to which the fiber is subjected, influence the properties of light travelling throughout the fiber.

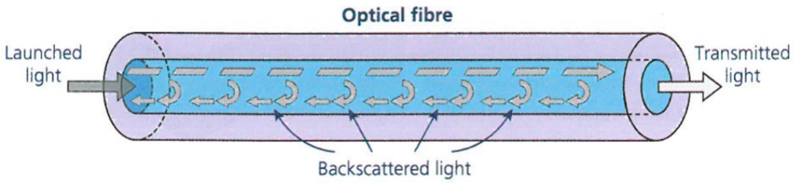

Figure 31.Backscattered light in fiber optic (after Kechavarzi et al, 2016).

Changes of the fiber refractive index caused by an external perturbation, like strain or temperature change, cause shifts in the local spectral frequency of the Rayleigh backscatter. Moreover, a time shift of the Rayleigh backscatter is produced by the cumulative changes in the refractive index. Such spectral and temporal shifts can be measured by performing a cross-correlation on the backscattered light signals in the time-domain (OTDR) or in the frequency-domain (OFDR) and scaled to return distributed temperature or strain measurements (Güemes et al., 2010).

On the other hand, the frequency of the Brillouin peak is directly proportional to the acoustic velocity and refractive index, both function of the local temperature and strain. It shifts linearly with changes in longitudinal strain and temperature in the fiber core (Kechavarzi et al. 2016):

$$\Delta\nu_b = C_\varepsilon \cdot \Delta\varepsilon + C_T \cdot \Delta T \qquad (1)$$

C_ε and C_T slightly vary around values of 500 MHz/% and 1 MHz/◦C, respectively, for standard telecommunication single mode fibres and at the operating wavelength of 1550 nm as generally used with Brillouin Optical Time Domain Reflectometry (BOTDR). Their value can be obtained by accurate calibration.

Another sensing method called Brillouin Optical Time Domain Analysis (BOTDA) can be used, that generally achieve larger accuracy than BOTDR. It requires analyzing the power difference between a pulse (*pump*) light and a continuous (*probe*) light that are sent in opposite direction each one from one end of the optical fiber, thus stimulating the Brillouin scattering (SBS). However, this technique has a potential risk of being unsuitable in case of fibre breakage during installation and monitoring.

Both BOTDA and Rayleigh OTDR can be used for accurate measurements of FO strains (±1 to ±5 με), but with very different sensing length (> 1000 m for BOTDA, < 50 m for Rayleigh OTDR) and spatial resolution (0.1 to 1 m for BOTDA, < 0.65 m for Rayleigh OTDR). Möller et al (2022) and Gao et al. (2023a,b) demonstrated in laboratory environment that DFOS measurements using Rayleigh OTDR would display a large signature strain profile if located anywhere within 0.5D of the sinkhole centerline (D being a characteristic horizontal span of the sinkhole), but display a much attenuated signal when located at or beyond 0.75D. Their results also demonstrate better accuracy for cables laid closer to the soil surface, where the horizontal ground movements are higher. This provides ground for further refinement in operational environment on how to lay fiber-optic cables to obtain efficient early warning, as well as for the interpretation of the measured strain to predict both the sinkhole size and affected 'damage' zone at the ground surface.

The use of DFOS sensors for sinkhole detection can be associated to a TRL = 5 to 6, since the technology has been at least validated, if not demonstrated, in relevant environment. A system prototype demonstration in operational environment (TRL = 7), mentioned in the next section, should not require large additional efforts.

Expected outcomes

The early formation of a sinkhole can be detected using the DFOS data: the sinkhole location can be identified using the center of the signature strain profile, and the approximate width can be estimated using the distance between the points of maximum slope on the fitted double modified Gaussian distribution of the DFOS data. From this, the ultimate surface damage zone can then be predicted (Möller et al, 2022; Della Ragione et al., 2023a, b).

Compared to other established techniques, adopted for sinkhole detection (i.e. seismic wave propagation, ground penetrating radar, InSAR), DFOS offer some advantages. The most relevant are that data can be acquired with high temporal frequency and that even small deformations can be measured along a continuous line with a high spatial resolution (‘distributed sensing’). Furthermore, the cost of the sensor itself (the fiber-optic cable) is extremely low (about € 0.10 per meter).

Unfortunately, the initial cost of the optical analyzer is currently still quite high (no less than € 50k). However, the increasing use of DFOS for different monitoring purposes let envisage a progressive and fast reduction of the access cost for this technology.

Applications in operational environment should explore the improved efficiency of sinkhole detection and sizing that can be obtained by using a combination of cables instead of a single cable, laid into a series of lines or grids to enable more accurate sensing of the sinkhole location in the horizontal plane.

Furthermore, the possibility of using this DFOS technique in combination with differential interferometric synthetic aperture radar (DInSAR) technology (both satellite- and ground-based) should also be investigated for this purpose.

Risk assessment

The proposed solution may suffer limitation to its use due to the initial cost of the monitoring system that is mainly related to the purchase of the interrogator. As mentioned before, a cost reduction may likely occur in the next future, which will mitigate this risk.

Moreover, expert knowledge is needed to reliably install and maintain the fiber-optic system, that may limit their use, primarily by the perception of a complex interpretation of measurements. Professionals in charge of interpreting and using DFOS results, such as geotechnical engineers, will likely intensify their collaboration with optical engineers and sensor industry partners to reduce this risk as low as reasonably possible.

BOTDA technology, that requires closed loop cables for stimulating Brillouin scatter, may be unsuitable in case of fibre breakage during installation and monitoring; however, this is not the case of Rayleigh OTDR or BOTDR, that may operate on open cables.

Finally, a large amount of data is produced by a distributed sensor system, which requires storage capacity and efficient archive interrogation. Therefore, data storage and management procedures must be developed and improved for large scale application.

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N22: Coupling ground-based geotechnical sensors and seismological stations for monitoring slow moving landslides

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Problem setting

The fields of research regarding landslides can be highly interdisciplinary, involving many experts, such as geologists, geomorphologists, geophysics and geotechnical engineers. Among the approaches aimed at investigating slope mass movements and their dynamics, those combining geotechnical and geophysical methods are commonly used. The complementariness between geotechnical and geophysical techniques is exploited to investigate landslides since long time (Jongmans & Garambois 2007). In recent decades, the technological development has led to significant advancements in equipment (e.g., automatic sensors), data collection (e.g., high-frequency acquisitions over long periods) along with data processing techniques. Accordingly, approaches coupling geotechnical and geophysical methods are increasingly being used by researchers for monitoring enabling a better understanding of landslide behavior (Whiteley et al., 2019 and references therein). Recent experiences from literature showed that the coupling of geotechnical and geophysical monitoring methods can provide sound insights into the kinematic behavior of reactivated and slow-moving landslides driven by rainfall (Brückl et al. 2013; Palis et al. 2017; Zoppè et al. 2015). Failure in these landslides develop along single or multiple pre-existing levels of weakness. Despite their low velocity, these slope instabilities can have considerable impacts on the built environment but, in some cases, they can exhibit paroxysmic phases leading to more severe consequences. In the context of slow landslide monitoring, geotechnical instruments allow direct measurement of ground displacements and geo-environmental factors driving their dynamics (e.g., groundwater) while geophysical devices can detect changes in the landslide mass by surveying physical parameters (e.g., elastic parameters, resistivity) or by capturing signals that may be generated by processes within the landslide body (e.g., failure events) (Pecoraro et al. 2019; Chae et al., 2017; Whiteley et al., 2019). However, new experimental applications implementing the integration of geophysical and multiple-parametric geotechnical systems can provide further useful contributes to the advancement in this field. On this basis, the employment of hydro-geotechnical sensors such as rain gauges, automatic inclinometer probes and pore-water pressure transducers in association with geophysical sensors (i.e., seismological stations) can have considerable potential in monitoring slowly deforming slopes.

State of the art

The integration of geotechnical and geophysical methods for landslide monitoring has become more common in the last years. Recent literature shows the use of conventional in-situ ground-based monitoring of rainfall, displacement and hydrogeological items in conjunction with the acquisition of geophysical signals generated artificially (i.e., active methods) or naturally (i.e., passive methods) (Whiteley et al., 2019). Some authors successfully attempted to correlate data from seismic recording instruments, like seismometers, with ground-based monitoring data acquired from traditional devices such as rain gauges, extensometers or GNSS antennas (Gomberg et al. 2011; Walter et al. 2013). Interestingly, some studies revealed an increase in seismic activity which was attributed to the endogenous landslide activity (e.g., subsurface movements) correlated to brittle failure of the landslide material. For example, by recording seismic signals through seismometers installed over a deep-seated landslide, Brückl et al. (2013) noted increases in seismic activity up to 1.5 months prior to the development of the slope deformations, which occurred simultaneously with snowmelt phases. Other authors noticed increases in seismic activity as a result of increased precipitation (Zoppè et al. 2015; Palis et al. 2017). However, as recently claimed by Whiteley et al. (2019), key advances for future developments in this field of research will increasingly arise from new applications of multiparametric monitoring geotechnical methods combined with geophysical techniques.

Innovative solution

The proposal presented herein involves the implementation of an integrated landslide monitoring system consisting of i) contact ground-based geotechnical sensors (i.e., automatic inclinometer probes and pore-water pressure transducers), ii) rainfall measurements and iii) passive geophysical sensors (i.e., seismic stations). This monitoring network will be installed at a site affected by an active slow-moving landslide. This site is already currently equipped with automatic hydrological and geotechnical monitoring sensors. The monitoring framework will be further implemented through the installation of two semi-permanent seismic stations. Fixed automatic inclinometer probes and piezometric sensors are currently installed inside boreholes at the main failure depths detected within the landslide volume. The automatic inclinometer probes monitor continuously horizontal displacements by means of Hall element sensors that measure the inclination of the casing tube with respect to the vertical. The accuracy of tilt angle readings is 0.5% in ±10° full-range scale, producing errors in displacement measurements of approximately ±0.1 mm, while the pore-water pressure sensors have an accuracy of 0.25% of full scale. Rainfall levels are measured by a tilting bucket rain gauge installed at the landslide head. Each instrument is connected to a datalogger for measurement acquisitions, is powered by a photovoltaic panel and includes a wireless device for transferring measured data. The seismic station to be installed over the landslide area is composed by an integrated triaxial MEMS accelerometer and an high quality triaxial velocimeter made of three geophones with a flat bandpass from 4.5 Hz up to 100 Hz, synchronously sampled at 24 bit with a dynamic range that exceeds 120 dB. The seismic stations are built to operate outdoors, powered by a backup-battery and equipped with both a solar panel and 4G Modem for continuous and real-time data transfer. The proposed monitoring network therefore lends itself to the jointed detection of displacements along with their controlling factors and of geophysical signals originated from endogenous or exogenous sources. Moreover, the acquisition of geophysical data could be helpful in detecting the formation and progression of precursory failure conditions allowing for better interpreting the linkages between the different predisposing, preparatory and triggering factors driving the landslide kinematic behaviour. The indicative costs for each deployed instrument are the following: automatic inclinometer probe ≈800€, pore-water pressure transducer ≈300€, rain gauge station ≈700€, of the seismic station is around 2,500€. With the proposed monitoring framework, the Technology Readiness Level (TRL) is expected to increase from the 3rd level of research (i.e., experimental Proof of Concept) to the 5th level of development (i.e., technology validated in relevant environment).

Expected outcomes

The proposal of monitoring network will allow the simultaneous acquisition of monitoring time-series related to rainfall, ground water regime, subsurface displacements and endogenous seismic activity related to the active landslide dynamics if any. The complete set of monitoring data could provide information on the landslide kinematic behavior, for example highlighting the potential conditions driving the initiation of acceleration phases and thus providing clues for the recognition of precursory failure conditions. Indeed, the comparison between hydro-geotechnical and geophysical data could allow to establish correlations between the preparatory factors and the complex processes leading to the occurrence of slope movements. Eventually, the outcomes of the application could contribute to a better understanding of slow-moving landslide behavior and might be of interest in the field of early warning system development.

Risk assessment

The proposed monitoring approach will be implemented at an active slow-moving landslide located in eastern Liguria (NW Italy). Since each deployed instrument is equipped with a solar power system, a continuous data acquisition should be expected. Notwithstanding, potential interruptions in data collection due to technical problems and malfunctions or deriving from power supply interruptions due to extreme weather conditions could occur. The seismic stations will be installed in private places across the landslide area, thus potential damage due to vandalism should be minimized. Potential technical-scientific uncertainties may be related to the interpretation of geophysical data in conjunction with subsurface displacement data. Specifically, subsurface movements could occur in the absence of notable seismic events, such those associated to mechanisms of viscous creep rather than frictional/brittle failure deformation, thus representing a possible limitation.

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6. Conclusions and further perspectives

The novel sensors and techniques for investigation and monitoring of different types of ground instabilities were gathered in this report by all the partners contributing to the TK1 of WP3 (VS2). Many of the proposed solutions offer enhanced precision and accuracy, real-time data acquisition and early warning capabilities, crucial aspects for risk mitigation.

The main results of the work can be summarized as follows:

- **Novel sensors and infrastructures** to enhance investigation and monitoring capabilities in different environments might be reached through further **technological development**.
- **Cutting-edge technologies and recently developed systems** are starting to be **tailored and applied to landslide investigation and monitoring** with the goal to improve knowledge and quantification of the ongoing processing, also in an early-warning perspective.

The solutions included in the **novel sensors** highlight:

- The need of technological innovation for the development of sensors capable of operating in challenging environments such as the marine domain.
- The cost-effectiveness of the new technologies as a key aspect to widespread the monitored sites and parameters (e.g. displacements and temperatures).
- Unmanned Aerial Systems (UAS) for non-contact measurements as significant advancement in the ability to collect data in remote or inaccessible areas, enhancing the understanding of landslide dynamics and facilitating timely interventions.

Novel infrastructures have several main goals:

- Remote connection/remote transmission of data, needed for near real-time monitoring and early warning. In addition, automation is a key aspect for the methods requiring deep data processing and decision making processes.
- Design, development and testing of multisensory/multiplatform systems for non-contact measurements.
- Design, development and testing of flexible and adaptive monitoring systems for on-site multiphysics monitoring.

Novel applications involve the testing of cutting-edge techniques that are starting to be applied to landslide monitoring and characterization, with particular reference to:

- fiber optic systems;
- integration of passive seismics measurements to detect failure precursors and internal modifications in the unstable bodies;
- novel techniques for the investigation and monitoring of the marine environment;
- implementation of existing monitoring systems with a multiphysical and multiparametric approach.

In summary, our research underscores the importance of continued investment and collaboration in the development and implementation of cutting-edge technologies and infrastructures for landslide monitoring and mitigation. Only through concerted efforts can we effectively address the challenges posed by landslides and build a safer and more resilient future.