ITINERIS

# Integrated platform for ground deformation observation and forecasting

Finanziato dall'Unione europea
NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani
PIANO NAZIONALE DI RIPRESA E RESILIENZA

| | |
|---|---|
| **Deliverable number:** | D7.5 |
| **Work package:** | WP7 - Geosphere/Landsurface |
| **Intermediate Objective:** | IO7.7 |
| **Deliverable type:** | X Document, report |
| | ☐ Websites, patent filings, videos, etc. |
| | ☐ Other: please specify ............................................ |
| **Dissemination level:** | X Public |
| | ☐ Restricted |
| **Estimated delivery (bimester):** | B14 |
| **Actual delivery date:** | 21/02/2025 |
| **Author(s) (Partner-OU):** | Giovanni Gigli, Tommaso Beni, Elena Benedetta Masi, Massimiliano Nocentini, Luca Lombardi, Istvan Szakolczai, Tommaso Carlà, Maryam Esmaeili, Nicolò Brilli, Veronica Tofani (UNIFI-CPC) |
| **Reviewed by:** | ITINERIS Executive Board |
| **Note:** | |

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System - CUP B53C22002150006 (D.D. n. 130/2022)
Funded by EU - Next Generation EU
Mission 4 “Education and Research” - Component 2: “From research to business” -
Investment 3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”

# Table of contents

# 1. INTRODUCTION

ATLAS (Advanced Technologies for Landslides) is a research infrastructure established to develop leading-edge methodologies for the prevention and management of ground instabilities. It aims to reduce hydrogeological risk through innovative research activities, leveraging state-of-the-art instruments as a pivotal component. Recognized as a medium-priority research infrastructure, ATLAS is included in the National Research Infrastructure Plan (PNIR) 2021-2027 of the Italian Ministry of Research.

The infrastructure includes key entities such as:

- The Civil Protection Center of the University of Florence: an operational structure of the National Service of Civil Protection (pursuant to Article 13 of the Civil Protection Code, D.Lgs. 1/2018) and recognized as a center of competence by the Civil Protection Department since 2018;
- The UNESCO Chair for Prevention and Sustainable Management of Geohydrological Hazards: established at the University of Florence in 2016, it is the first UNESCO Chair in Italy dedicated to applied research in geohydrological hazards;
- The Department of Earth Sciences (DST): renowned nationally and internationally for excellence in scientific research and relations in Earth Sciences, it is one of the 180 departments of excellence selected by the Ministry of Research (MUR).

ATLAS is closely associated with the International Consortium on Landslides (ICL), a network of 89 research institutes across 34 countries that promotes landslide research to benefit society and the environment. The mission of ATLAS is to promote research and technological development in hydrogeological risk prevention and management, supporting actions and policies for risk reduction.

ATLAS contributes to the ITINERIS project within the Work Package 7 (WP7 - Geosphere and Landsurface). In particular it is responsible for Activity 7.6 - Integrated platform for surface movements monitoring. This activity aims at developing an integrated platform constituted by a number of advanced surveying and monitoring devices, as well as an early warning tool to visualize and share data for emergency management, including the output from hazard forecasting models in a multi-scale perspective.

In this framework, the Integrated Platform for Ground Deformation Observation and Forecasting has been accomplished through the following core activities, described in the following sections:

- Employment of innovative technologies for surveying, monitoring and mitigating geo-hydrological events;
- Implementation of early warning systems;
- Development of landslide forecast models.

A test site was also set up in the Friuli Venezia Giulia Region, where many of the advanced technologies specifically purchased and implemented for the project are being applied and tested.

## 2. INNOVATIVE TECHNOLOGIES FOR LANDSLIDE SURVEYING AND MONITORING

The Civil Protection Center provides technical and scientific support to the Department of Civil Protection and other entities of the National Civil Protection Service for the rapid assessment of conditions of imminent danger for public and private safety, in relation to emergency situations connected to hydrogeological risk events, providing operational indications for the mitigation of residual risk. In the context of emergencies arising from natural or man-made disasters, the Center carries out and organizes inspections for the rapid assessment on the field of conditions of danger and risk. It also promptly acquires data and information, providing the necessary interpretation, for the mapping and characterization of areas with ongoing or impending disasters, in order to allow the rapid assessment of event scenarios and risk scenarios.

To this purpose, through ATLAS, the CPC develops and strengthens the cross-platform emergency infrastructure to support search, rescue and emergency management activities by integrating multi-parametric collection and monitoring systems suitable for managing natural and man-made emergencies, even in extreme environmental conditions.

The advanced multi-sensor instrumentation available at ATLAS is listed at the following link: https://www.ri-atlas.unifi.it/vp-9-instruments.html

The latter has recently been integrated with new devices specifically acquired for the ITINERIS project, as listed below:

*Survey and monitoring:*
- Laser scanner for UAV YellowScan Mapper+, maximum distance 230 m, acquisition speed 240,000 pts/s;
- Long-range 3D laser scanner RIEGL VZ 2000i, maximum distance 2500 m, acquisition speed 500,000 pts/s;
- Mobile laser scanner GEOSLAM ZEB-HORIZON RT, maximum distance 120 m, acquisition speed 640,000 pts/s;
- Wireless sensor network with crack gauges, wire extensometers, biaxial inclinometers and Weather stations.

*Localization and mapping:*
- Wireless GNSS network.

*Bathymetry and underwater inspection:*
- Automated STOK AUV underwater ROV with an operational depth up to 60 m, equipped with a camera, scam sonar system, and multibeam.

*Rapid prototyping:*
- Fortus 450 printer with a build volume of 406 x 355 x 406 mm.

*Unmanned aerial veichel (UAV):*
- Fixed-wing drone Trinity Pro with a payload of 1 kg.

*Thermal sensor:*
- FLIR T1020 thermal camera;
- FLIR A70 29° thermal sensor;
- FLIR A70 51° Science Kit thermal sensor.

*RADAR sensor:*
- LiSAMobile interferometer ground-based radar with synthetic aperture 1.3 m;
- LiSAMobile interferometer ground-based radar with synthetic aperture 3.0 m;
- Doppler radar.

*Multi- iper-spectral sensors:*

- 1x UAV Camera Iperspettrale Specim AFX17 (900-1700 nm);
- 1x UAV Camera Iperspettrale Specim AFX10 (400-1000 nm).

In the last months all these instruments have been tested in the field across different environmental contexts and for various study, analysis, and monitoring scenarios that align with ATLAS' core competencies. The knowledge, practice, and workflow related to well-established sensors such as LiDAR and ground-based radar (GBInSAR) have been enhanced with additional data types, including point clouds acquired using the SLAM technique. The latter instrumentation consists of a mobile laser scanning system, the GeoSLAM ZEB-HORIZON RT, that allows to dynamically and continuously reconstruct the surrounding environment.

Table 1 reports all the field tests conducted in recent months to test the instrumentation acquired by the infrastructure with ITINERIS funds. The idea of testing the instrumentation in very different environments stems from the fact that the instability phenomena typically studied and monitored by the ATLAS infrastructure, together with the Civil Protection Center of the University of Florence, the UNESCO Chair for Prevention and Sustainable Management of Geohydrological Hazards and the Department of Earth Sciences (DST) - primarily landslides and subsidence phenomena—often affect mixed environments where both natural and anthropogenic elements coexist. It is precisely the combination of anthropogenic features and potential hazards that defines the risk to be assessed.

*Table 1 – Summary of the field testing activities and the instruments used. The Passo della Morte case study is highlighted in blue, as it represents the main case study of the ATLaS-ITINERIS project. Acronyms: IN/OUT = indoor/outdoor; HM = historical monument; MLS = GeoSLAM ZEB-HORIZON; TLS = RIEGL VZ-2000i; EXT = extensometers; TILT = tiltmeters*

| | *IN/OUT* | *HM* | *GNSS* | *EXT* | *TILT* | *MLS* | *TLS* | *GBInSAR* |
|---|---|---|---|---|---|---|---|---|
| Quarry - La Spezia | IN/OUT | | x | | | x | | |
| Celsa Quarry | OUT | | x | | | x | x | |
| Vesuvio | OUT | | x | | | x | | |
| Specola Museum | IN | x | | | | x | x | |
| Siele Mine | OUT | | x | | | x | x | |
| Temperino Mine | IN/OUT | | x | | | x | x | |
| Passo della Morte | IN/OUT | | x | x | x | x | x | x |
| Palazzo Pitti | OUT | x | x | | | x | | |

Therefore, creating environments that include the geometric characterization of different scenarios allows us to define reliable survey procedures, adapting them to the specific instability phenomenon to be prevented, studied, monitored, or, if it has already occurred, mitigated.

The importance of geometric characterization of environments is that all modeling and in-depth studies for the assessment and characterization of geohazards require two- and three-dimensional representations of the investigated scenario that need to be as accurate and updated as possible.

For example, conducting numerical modeling of stress and strain in rock masses for underground activities, such as mining and quarrying, requires both underground and surface three-dimensional models (Figure 1a) to construct critical cross-sections for site stability analysis. In natural or anthropogenic surficial environments, such as an open-pit quarry or a riverbed (Figure 1b-c), a georeferenced three-dimensional model is essential for simulating rockfall trajectories, embankment failures, and other geological hazards. Similarly, in the field of cultural heritage monitoring, a three-dimensional model of both interior and exterior spaces is necessary to visualize potential hazardous elements. These digital models can also be integrated with additional data from other surveys (geotechnical and geophysical) to enhance analysis and decision-making.

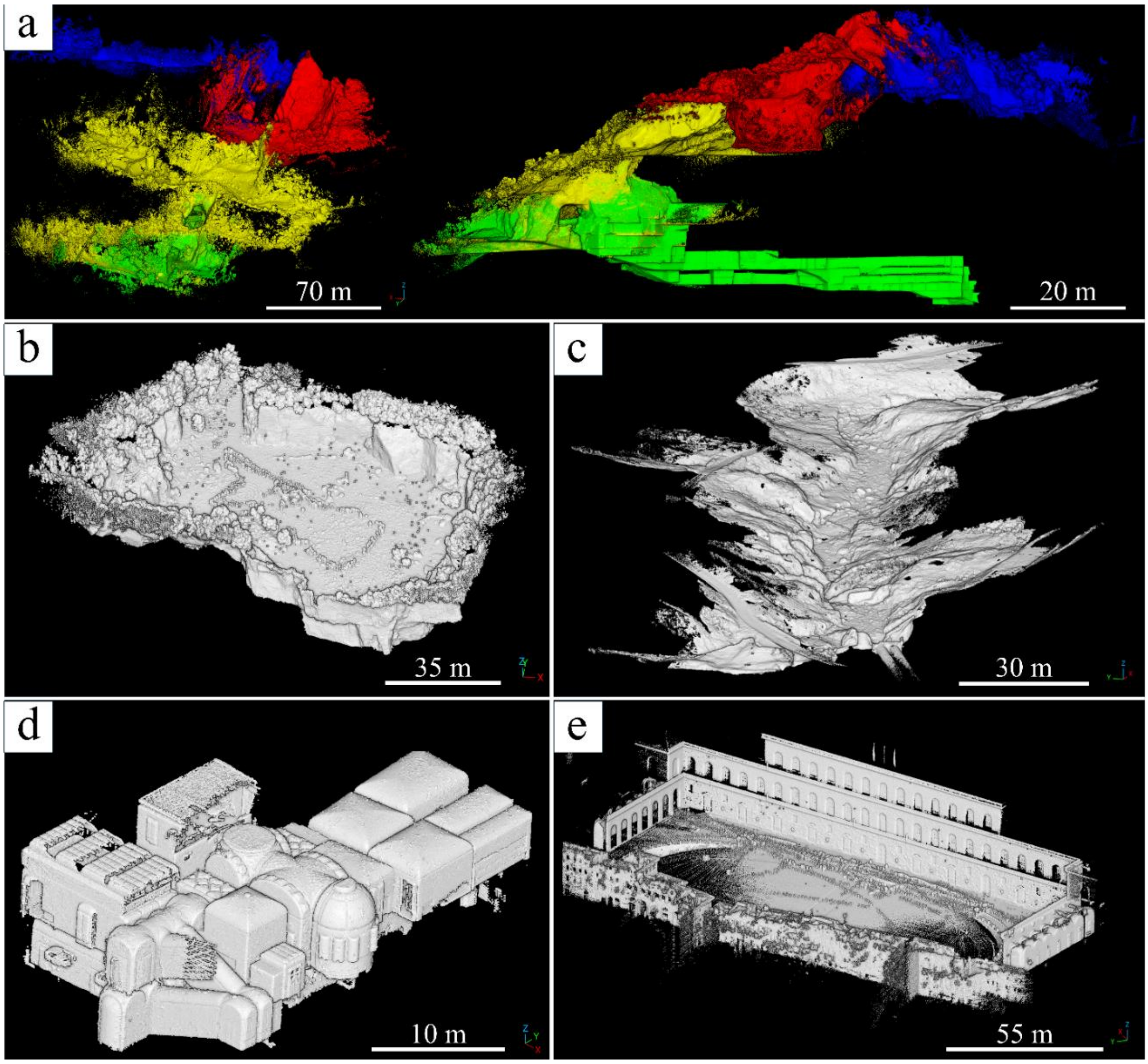


*Figure 1 - Examples of LiDAR surveys conducted with the MLS and TLS to evaluate the reliability of the instruments acquired by ATLaS IR within the ITINERIS project. a) Colored point cloud of an ornamental stone quarry (Porto Venere, Italy) featuring both underground and surface environments; colors represent the SLAM surveys required to cover the study area. In b) and c) white point clouds depicting outdoor sites: a surface marble quarry (Celsa Quarry, Italy) and a riverbed (Siele Mine, Italy), respectively; in d) and e) point clouds from cultural heritage surveys, representing the indoor spaces of the Specola Museum (Florence, Italy) and the façade of Palazzo Pitti, respectively (Florence, Italy). All these models were georeferenced using a GNSS system*

# 3. MONITORING AND EARLY WARNING PLATFORM

In landslide-prone areas, risk mitigation often faces challenges related to financial resources, environmental impact, and logistical issues. This is especially true for structural countermeasures, which aim to mitigate risk by reducing the probability of failure (e.g., bolts, anchors, piles), preventing the landslide from reaching elements at risk (e.g., barriers, ditches, retaining walls), or reinforcing existing buildings. Alternatively, early warning systems (EWSs) offer a cost-effective way to reduce risk with minimal environmental and financial impact. In some cases—such as when a landslide is too large to be stabilized—EWSs may be the only viable solution.

Various definitions of EWSs exist in literature. Medina-Cetina and Nadim (2008) describe them as "monitoring devices designed to avoid, or at least minimize, the impact of a threat on humans, property, the environment, or even more fundamental aspects like livelihoods." Similarly, the United Nations International Strategy for Disaster Reduction (UNISDR, 2009) defines them as "the set of capacities needed to generate and disseminate timely and meaningful warning information, enabling individuals, communities, and organizations threatened by a hazard to prepare and act appropriately, reducing the risk of harm or loss."

Thus, EWS function as risk mitigation tools by reducing exposure, particularly for people, by ensuring they evacuate hazardous areas in anticipation of an imminent collapse.

Thus, in parallel with all activities related to the purchase and testing of new surveying and monitoring instruments, one of the main goals of the ATLAS RI within the ITINERIS project is to implement a data-sharing platform well-matched with all outputs generated by the survey and monitoring instruments in use (Figure 2). This represents a rather complex challenge due to the heterogeneity of the data managed by the infrastructure in the context of landslide and geohazard monitoring and characterization. Many of the datasets are continuously acquired and updated over time at user-defined intervals. Often, they do not consist of standalone data packages but rather dynamic datasets that evolve with ongoing measurements. Considering this, the ATLAS platform must be capable of handling both two-dimensional and three-dimensional data, encompassing raster and/or vector objects, displacement time series, interferograms acquired from both ground-based and satellite sensors, as well as point clouds and meshes. Beyond ensuring compatibility with the various data (and metadata) formats, another key challenge is making the uploaded datasets accessible, navigable and downloadable given that the total data volume reaches terabytes or more.

mb_tile prova
Opacità: 100%
Workspace: unifitest1
Legenda: 🟦

uploadVulcanoOrt
Opacità: 100%
Workspace: unifitest1
Legenda: 🟦

temperature
Opacità: 100%

*Figure 2 - General view of the monitoring and early warning platform (draft version).*

All the aforementioned developments should also align with the FAIR principles promoted within the ITINERIS project. This implies that, moving forward, the ATLAS infrastructure will establish a data steward role. This figure will facilitate interaction with both national and international infrastructures on the same FAIR Implementation Community (FIC), enabling the development of a data-sharing environment that adheres to the FAIR guiding principles (Wilkinson et al. 2016). Additionally, ATLAS will ensure the preparation of a FAIR Implementation Profile (FIP), documenting compliance with these principles for its research products and datasets.

At this stage of the ITINERIS project, the platform is under test and will be available by May 2025. Some of the main key reference specifications used for its development are outlined below.

*The platform is designed to ensure:*

- Multi-user access with differentiated profiles and categories;
- The ability to create a customized dashboard for each user profile;
- Compatibility with smartphones and tablets.
- Autonomous uploading of major data types, including raster, vector, point clouds, and meshes;
- 2D and 3D data visualization;
- Real-time uploading and visualization of monitoring data;
- Customizable graph creation by combining data from different sensors
- Graphing not only displacement but also velocity, acceleration, and the inverse of velocity (useful for landslide time of failure prediction).
- Drawing lines, areas, and points for coordinate, length, and area calculations;
- Extracting profiles from meshes;
- Drawing inclined lines on 2D profiles to estimate landslide runout distances;
- Integration of predictive algorithms (see following Section)

A major milestone for the platform is its evolution into a comprehensive system for data storage, visualization, and analysis, as well as an early warning tool. The system therefore aims to:

- Define alert thresholds for real-time monitoring data, allowing for the configuration of combined thresholds that trigger alerts based on simultaneous exceedances across different sensors and/or multiple sensors of the same type;
- Notify users of threshold exceedances via email and Sms.

These specifications lay the foundation for a comprehensive, multi-functional platform capable of supporting advanced geohazard monitoring and analysis as well as emergency management.

# 4. LANDSLIDE FORECASTING MODELS

A key development related to Early Warning activities within the ITINERIS project, is the real time employment of specific forecasting algorithms developed by the ATLAS research group, such as LAMPO, HIRESSS AND MACUMBA.

These algorithms, which are described in the following sections, have been intensively revised and rewritten with the aim of integrating their results into the Monitoring and Early Warning Platform, in order to be able to use them in real time in the management phases of an emergency.

## 4.1 Lampo

The software LAMPO (Landslide Assessment through Multi-Parameter Observation) is part of a research program developed by the Center for Civil Protection of the University of Florence and aims at predicting the time of failure (ToF) of landslides.

LAMPO allows the analysis of displacement time series from different monitoring systems, each characterized by a different acquisition frequency, measurement unit and geometric component. The main innovation of LAMPO is that it allows predictions to be updated in real-time as new monitoring data is acquired and, most importantly, that these predictions can be made simultaneously for multiple time series, for multiple monitoring systems, using multiple prediction methods and testing a variety of different model parameters. This allows us to no longer have a single prediction per site, but a cloud of dozens of predictions that will condense around what is considered the most likely time of failure (ToF). The size and thus the dispersion of the cloud allows also an estimate of the reliability of the prediction, a useful parameter for decision makers.

LAMPO is deployed as a web application capable of automatically updating the time series of a given measurement site (on which several devices can be active), allowing their visualization and processing, and finally providing the ToF prediction through a probabilistic approach to increase the reliability of the prediction.

Through an account and monitoring site management system, it is possible to create a page for each monitored site and provide differentiated access to interested users (Civil Protection, local authorities, etc.).

In addition, a module for the visualization of data and subsequent processing by a forecasting algorithm using the methods of Saito and Fukuzono and the application of noise reduction filters has also been created.

These methods are based on displacement measurements and refer to the physical theory of creep, according to which any material subjected to constant stress over a long period of time exhibits a characteristic deformation before eventually evolving into a rupture. This deformation is usually divided into three phases: a first phase characterized by deceleration, a second phase characterized by a constant velocity, and a third phase characterized by an acceleration. This can lead to a new equilibrium state if the short acceleration is followed by a deceleration, or to collapse if the acceleration takes on an exponential course instead (Figure 3).

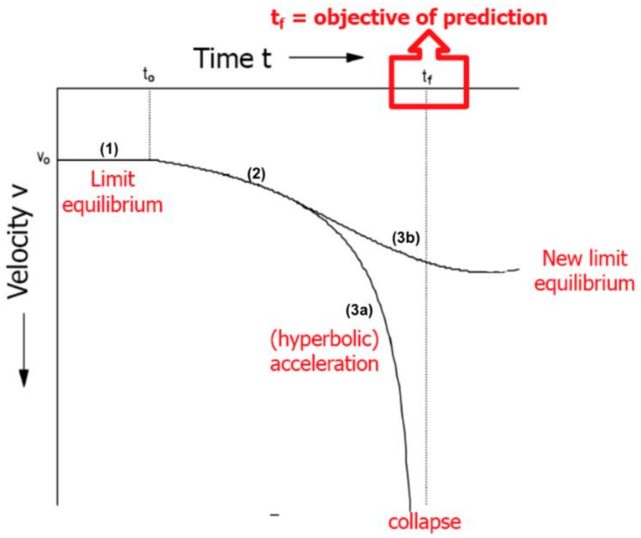


*Figure 3 - Diagram of a material subjected to constant stress over time, distinguishing the three phases of deformation (creep): (1) primary phase, (2) secondary phase of increasing velocity at constant rate and (3) tertiary phase.*

For the main purpose of identifying the ToF before collapse, various methods have been developed, of which the most widely used and reliable are those of Saito (1969) and Fukozono (1985). These methods, which were derived and developed graphically, can also be interpreted by equations so that they can be implemented in spreadsheets and algorithms.

For the Fukuzono method, the algorithm that enables the calculation of the ToF is as follows:

$$ToF = \frac{t_2(\Lambda_1) - t_1(\Lambda_2)}{\Lambda_1 - \Lambda_2}$$

where Λ1 and Λ2 are the inverse of the speed calculated at time $t_1$ and $t_2$, respectively.

The algorithm that enables the calculation of ToF using the Saito method is as follows:

$$ToF = \frac{t_2^2 - t_1 t_3}{2t_2 - (\mathrm{t}_1 + \mathrm{t}_3)}$$

where $t_1$, $t_2$, $t_3$ are three points in time on the displacement curve, so that the displacement recorded at $t_2$ must be at the intermediate point of the cumulative displacement recorded between $t_1$ and $t_3$.

The concept of LAMPO is to repeatedly calculate the ToF for each new measurement in order to increase the reliability of the prediction.

For each new measurement acquired by the monitoring instrument, a new time series is created consisting of the acquisition time ($t_1$) and each subsequent measurement time (t, time of prediction). Based on these two-time values and the corresponding displacement measurements, the ToF prediction can be performed using a special formula (Saito or Fukozono). By collecting measurements and blocking each value of $t_1$ (to create a separate time series for each $t_1$), up to thousands of predictions can be created. These are displayed in the prediction graph as time series with a different color for each $t_1$ (Figure 4). Reducing the noise, thickening the prediction cloud and/or aligning the predictions can increase confidence in the ToF prediction.

As already highlighted, the graphical representation of the data (the prediction graph) and the ability to display the mean and standard deviation of the predictions are of particular importance. It is also possible to apply filters.

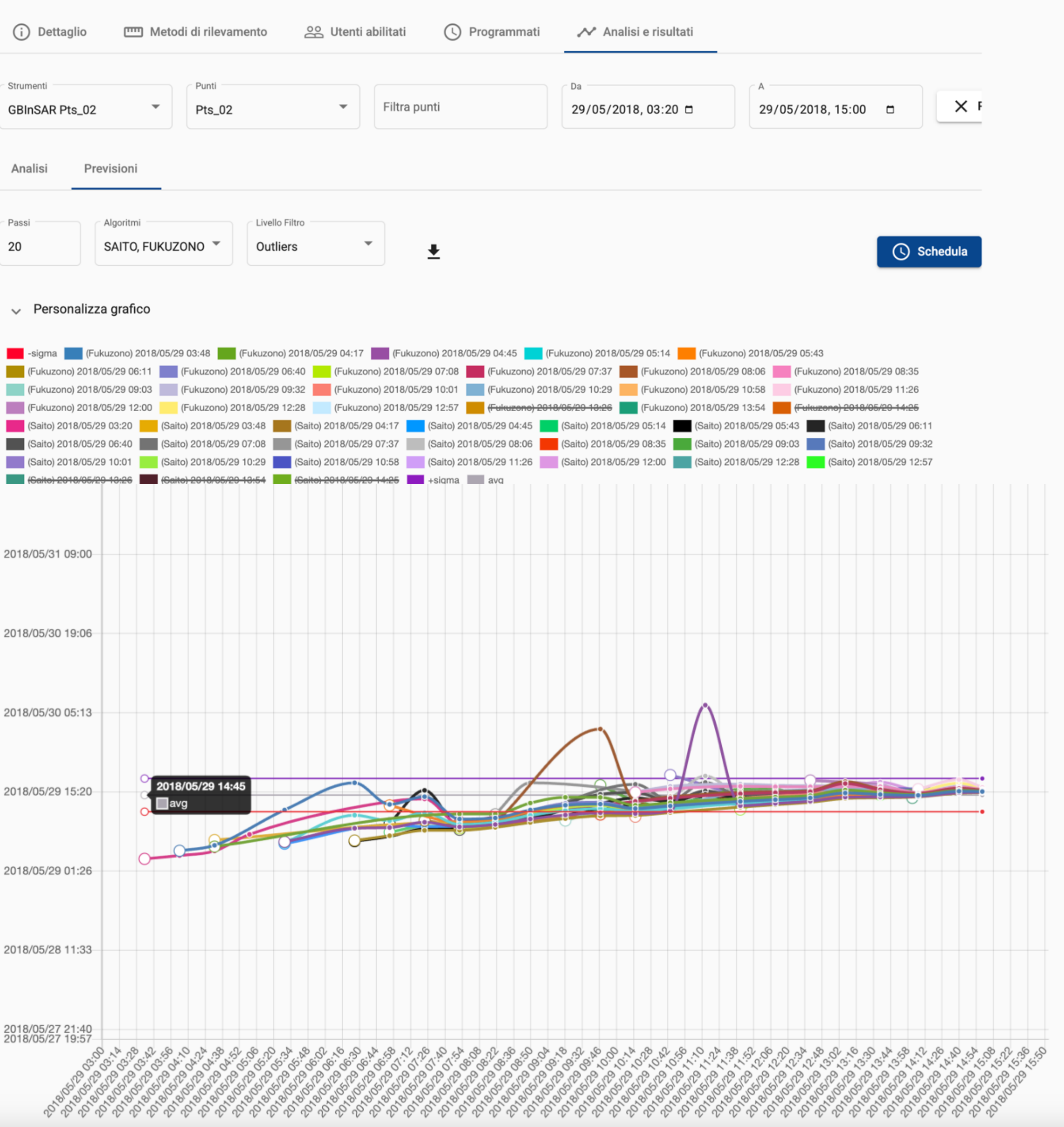
These can also be downloaded directly as a spreadsheet for further analysis.

For the ITINERISS Project, further developments of LAMPO were specifically carried out with new integrations for an automatic import of monitoring data and a real-time export of forecast results. These results will be finally implemented in the ATLAS research infrastructure platform.

Regarding the optimizations of the current LAMPO application, flexible data import has been provided to allow faster and smoother channeling of data from different monitoring systems. The files that can be imported into LAMPO are available in CSV format, as a text file (TXT) or as a shapefile (SHP). The SHP format is converted to CSV. It is possible to specify the correspondence between rows and columns of the file and the separator format so that the data is imported correctly into the application without any external formatting. It is also possible to see whether the data has been imported correctly via a special button.

It is also possible to display and download four graphs (Figure 5) that show, for the selected time interval, the displacement curve, the velocity curve, the reciprocal of the velocity and the ratio between velocity and acceleration. It is possible to set a moving average, which reduces noise and makes the data less scattered.

The R2 value of the regression line is also provided to allow a quantitative assessment of the reliability of the prediction.



Dettaglio | Metodi di rilevamento | Utenti abilitati | Programmati | Analisi e risultati

Strumenti: GBInSAR Pts_02
Punti: Pts_02
Filtra punti
Da: 29/05/2018, 03:20
A: 29/05/2018, 15:00

Analisi | Previsioni

Passi: 20
Algoritmi: SAITO, FUKUZONO
Livello Filtro: Outliers

Schedula

Personalizza grafico

*Figure 4 - Prediction graph for the Gallivaggio landslide. Note the prediction results (ToF) for a fixed interval from 03:20 on 29/05/2018 to 15:00 on 29/05/2018. The collapse occurred at 16:32. The series can be displayed with different colors for each $t_1$ used to calculate the ToF with the Saito and Fukuzono algorithms. The step size is 20, and the outliers are filtered out. A clear alignment of the predictions and a reduction in noise, an indicator of a possible collapse, can be seen. The average forecast in this case is 29/05/2018 at 14:45.*

*Figure 5 - Diagrams implemented in LAMPO.*

In the graph of the inverse velocity, the visualization of the regression line and its extension to the x-axis has been implemented to allow a prediction of the ToF by the graphical Fukuzono method (INV). This graphical method has a physical explanation for the creep. Namely, it is assumed that the velocity tends towards infinity on the instant of failure. It is therefore assumed that the reciprocal of the velocity tends towards zero until the moment of failure, where the velocity is infinite, and the reciprocal is 1/infinity and therefore 0 due to convention.

Therefore, the prediction of the ToF by the graphical INV method consists of assigning a prediction of the ToF to the intersection of the regression line with the x-axis (Figure 6). An estimate of the reliability of the prediction is provided by the R2 of this regression line.

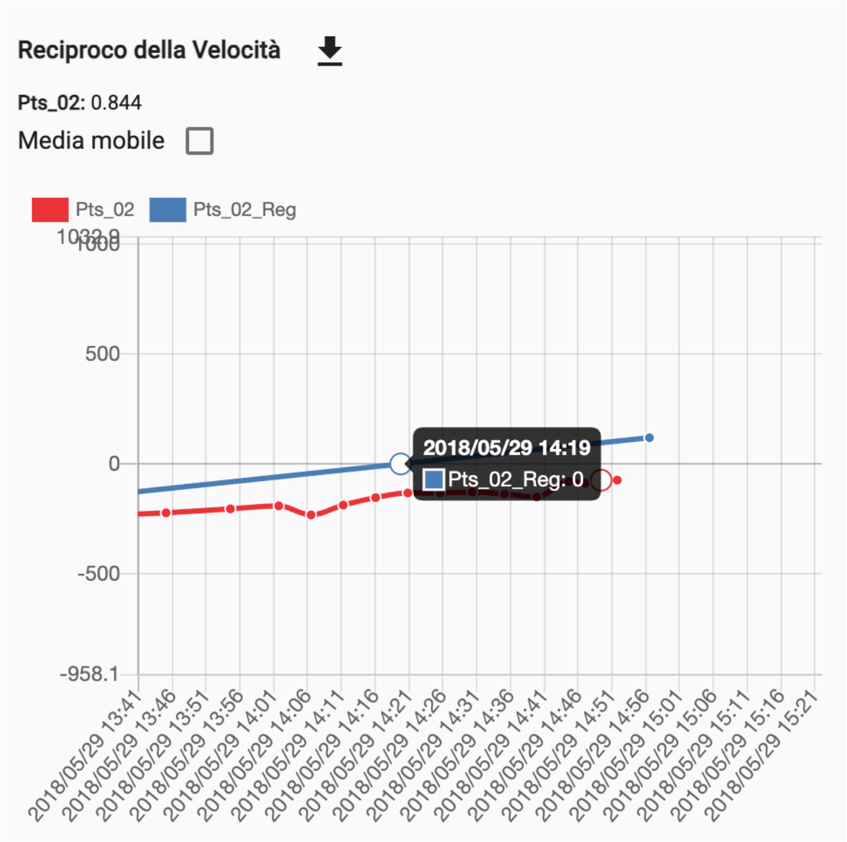


*Figure 6 - Graphical method according to Fukuzono (INV). The estimate of the ToF in this case is 29/05/2018 at 14:19. The reliability of this prediction is indicated by the R2, which in this case is 0.84.*

The ability to set a moving average has also been implemented to reduce noise and obtain a higher R2, thus increasing confidence in the forecast.

All charts are interactive and can be downloaded in Excel format.

The ability to schedule forecasts has been added to obtain ToF forecast analysis in real time as new data is recorded. This is done automatically in real time and makes it possible to obtain an estimate of the expected failure with an estimate of the forecast certainty. The results, sent to the defined reference path of the FTP server, indicate the quality of the prediction - explained as the R2 value of the inverse velocity regression line - and the average of the predictions for the set algorithm (in date and time format) as well as the measure of deviation from the expected ToF (d, in days). This value is understood as the difference between the current date and the average of the predictions.

In order to map the forecast results, it is also possible to enter the coordinates of each measurement point through a specific module.

## 4.2 HIRESSS (High Resolution Slope Stability Simulator)

The deterministic model HIRESSS (High Resolution Slope Stability Simulator, Rossi et al. 2013) developed by the research group at the Civil Protection Center provides real-time stability analysis over large areas with spatial resolutions of 20 meters or less and temporal resolutions of less than one hour (Figure 7). To achieve the necessary computational speed, the stability simulator is designed to maximize the computational power of multiprocessor supercomputers.

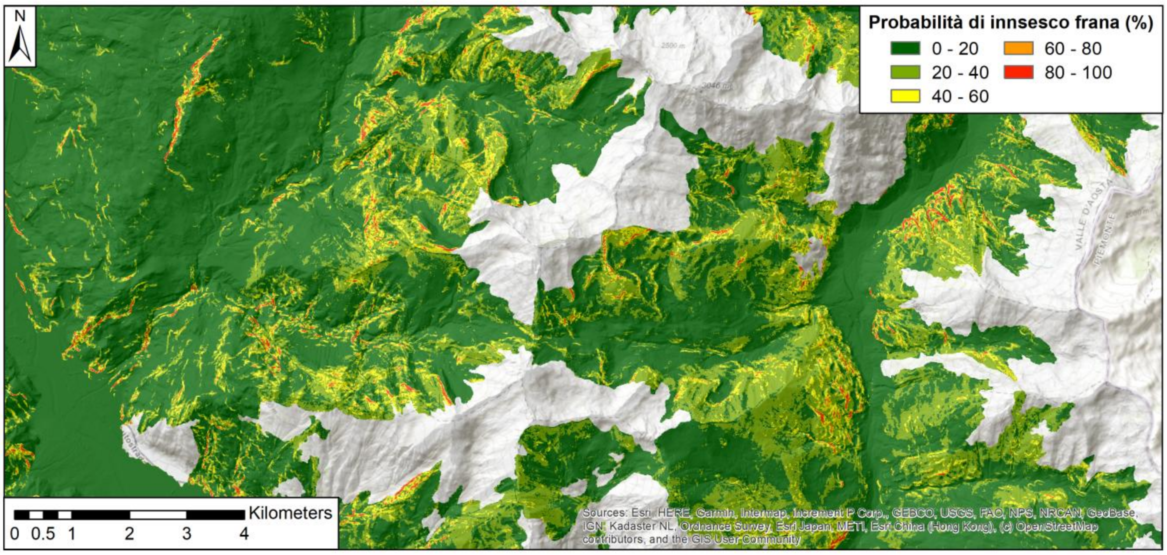


*Figure 7 - Example of the resulting map of the distributed landslide trigger probability (probability safety factor < 1.2) produced by the HIRESSS model. Detail of the landslide trigger probability map for an hourly precipitation step in April 2009 in Alert Area B of the Aosta Valley.*

The deterministic model is structured into two different modules: one hydrological module that models the distribution of interstitial pressures in the soil during the event, and a stability module that allows the determination of the safety factor (Figure 8).

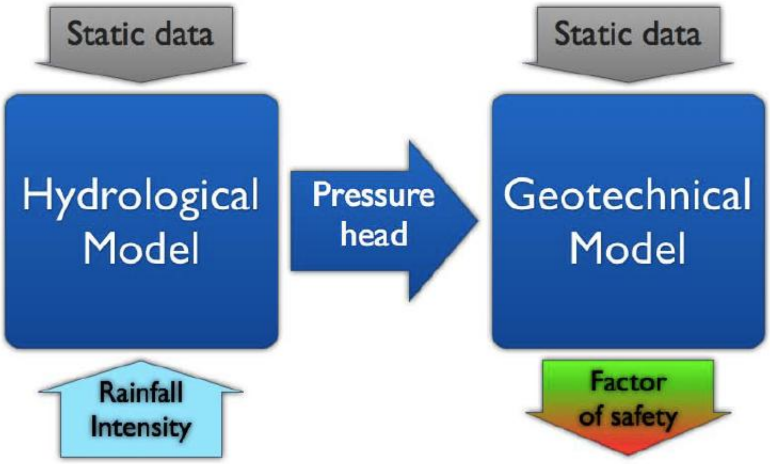


*Figure 8 - Block diagram of the deterministic stability model.*

The hydrological module calculates the values of interstitial pressure in the soil based on the intensity of atmospheric precipitation. The physical modeling of infiltration is based on the solution to Richards' equations, which describe the three-dimensional Darcy flow of a non-static fluid in a porous medium under conditions of varying saturation.

The geotechnical soil stability module is based on an infinite slope model (Skempton & Delory, 1957) and allows the calculation of the safety factor (FS) as the ratio of resisting forces to destabilizing forces. The soil stability module uses the interstitial pressure value, calculated by the hydrological module, as a dynamic input parameter.

The HIRESSS real-time structure is outlined in Figure 9. When making a predictive calculation, the software reads the initial soil saturation conditions. This information can be provided by third-party software or, if not available, can be reconstructed from previous rainfall data by running calculations with the hydrological model alone. This possibility reduces the input data requirements at the expense of greater uncertainty in the initial parameter. Static data and initial conditions are input into the processing cycle, at the end of which maps of instability probability for 24-hour periods with hourly resolution are produced.

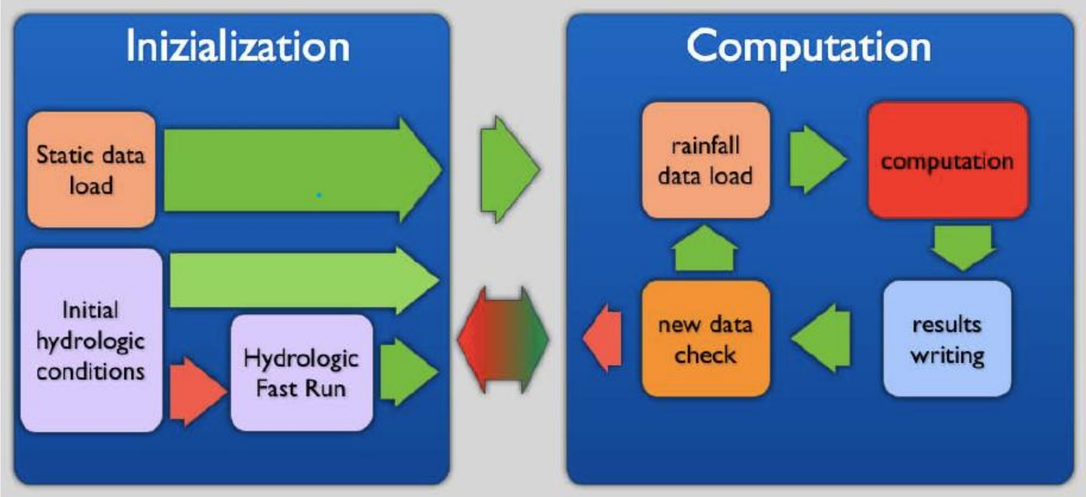


*Figure 9 - HIRESSS real-time functioning diagram.*

The HIRESSS model and the procedures adopted to improve the efficiency of its products are continuously updated with the central goal of maximizing the model's predictive capabilities for rainfall-induced superficial instabilities.

Recent developments have included: i) implementing the contribution of vegetation to slope stability in the model and conducting a thorough analysis of the effects of this development on the model; ii) aggregating the information related to the landslide trigger probability for each pixel in the maps resulting from simulations, in order to identify the best approaches for practically and accurately utilizing the model results.

The effects of vegetation on the mechanical and hydrological behavior of soils are widely recognized in academic and technological fields. However, difficulties remain in considering these effects in distributed models due to their broad spatial (and temporal) variability. To address the main mechanical effect of vegetation—its contribution to soil cohesion through root systems—the HIRESSS model has been modified, and a procedure has been established to estimate the distribution of root cohesion in large areas. Analyses conducted to verify the impact of this development on the model have shown an improvement in HIRESSS's predictive capabilities, particularly through a reduction in false alarms. These verifications also highlighted the possibility of enhancing the modeling approach used to describe the behavior of root cohesion as the soil water content varies.

The spatial and temporal aggregation of the model's outputs is a crucial aspect for efficiently and accurately utilizing HIRESSS results to meet civil protection needs, in order to predict expected risk scenarios according to the categories defined at the national level (green, yellow, orange, and red codes).

Recent applications of the model in various study areas have allowed tests on aggregating outputs through different procedures to identify the most efficient approach.

The most efficient aggregation procedure defined is as follows: i) dividing the area into territorial units considering the morphology of the surface (sub-watersheds) and the typical dimensions of instabilities in the area; ii) simulating an event over several days in which numerous landslide movements occurred; iii) classifying sub-watersheds according to the number of pixels with a trigger probability above a certain threshold within them; iv) spatial and temporal comparison of the identified unstable basins based on different combinations of pixel number/probability threshold and real landslide events, with the compilation of a contingency table (data related to the percentage of identified landslides, correct alarms, missed alarms, false alarms, correct non-alarms) for the various combinations; v) selecting the combination (based on the percentage of correct alarms/false alarms that best meet the needs) to be used in applying the model for risk scenario forecasting.

In Figure 10, an example of the aggregated output of the HIRESSS model at the sub-basin scale is shown.

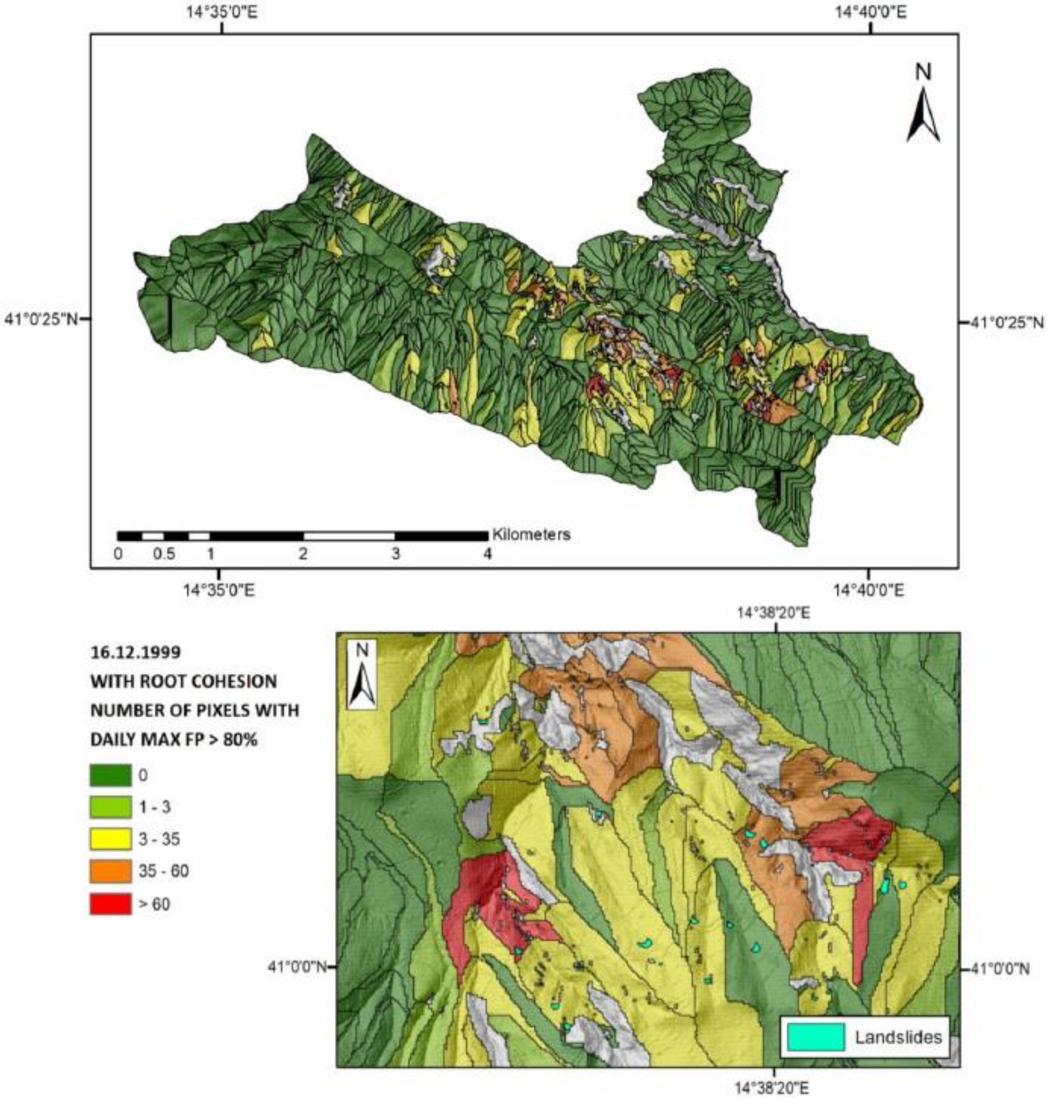


*Figure 10 - Example of model output aggregation by classifying territorial units according to the number of pixels above a certain probability threshold and the location of real landslide events.*

## 4.3 MACUMBA (MAssive CUMulative Brisk Analyzer)

MaCumBA (MAssive CUMulative Brisk Analyzer) is a software programme developed by the Department of Earth Sciences of the University of Florence (Segoni et al. 2014a, b) and tested in several case studies in Italy (Rosi et al. 2015, 2021; Segoni et al. 2014a, b) and in other countries (Rosi et al. 2016, 2019).

MaCumBA is programmed to automatically carry out the following tasks: (i) identification of the critical rainfall; (ii) definition of the critical parameters used to describe the rainfall event (I and D); (iii) selection of the most representative rainfall record for a given landslide; (iv) graphing of the appropriate I-D values, where each point represents the rainfall conditions associated to the triggering of a landslide; (v) definition of rainfall I-D thresholds using a set of standard statistical procedures. With this software, the automated procedure of rainfall analysis for threshold definition is standardized and can be consistently replicated in early warning systems.

One of the peculiarities of MaCumBA is the definition of an additional parameter to characterize the thresholds, called No-Rain-Gap (NRG). It expresses the number of consecutive hours without rain that is required to consider a rainfall event ended. This parameter plays a key role, ensuring the replicability of the analysis and facilitating the implementation of thresholds in an operational warning system (Segoni et al. 2014a, b).

Another parameter that can be implemented to refine the thresholds is the “minimum rainfall intensity”, which expresses which amount of rain is considered inessential (e.g., values below 0.2 mm, that generally indicate the presence of dew, fog, or condensation on the rain gauge).

The MaCumBA procedure can be summarized into three main phases:

1) Identification of rainfall events and definition of I and D parameters for each rainfall event for each rain gauge.

2) Selection of the most appropriate rain gauge for the characterization of each landslide, choosing the rain gauge, within a certain search radius from the landslides, with the most complete time series related to each event.

3) Choice of the most representative I-D threshold using a 95% confidence interval (Ensuring a statistically low number of Missed Alarms (MA)) and plotting it in a log–log graph.

The identified threshold is used to separate the ordinary level, which represents the absence of criticality, from the low criticality level. Then, it is translated upward to calibrate two higher thresholds representing the limits of the moderate and high criticality warning levels. These two additional criticality levels are calibrated based on the number of Correct Alarms (CA) and False Alarms (FA), according to the needs of the case study.

An example of a rainfall threshold system with increasing criticality, developed for a single Alert Zone in the Liguria region (Italy - Nocentini et al., 2024), is illustrated in Figure 11.

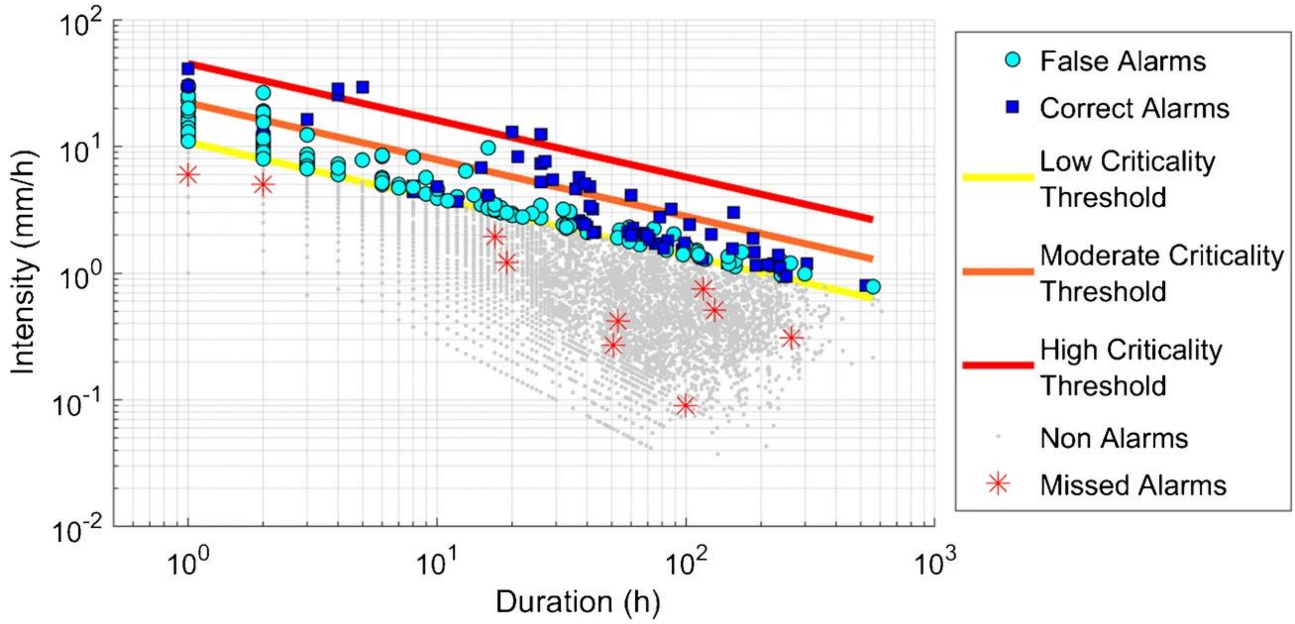


*Figure 11 - Example of rainfall thresholds system for a single alert zone.*

## 5. TEST SITE

Finally, as part of activity 7.6, the implementation of a test site was planned; the latter should be identified within the pilot sites defined in the project proposal. In this framework, the employment and installation of some of the acquired instruments as well as the visualization and processing of the data through the Monitoring and Early Warning Platform was scheduled.

On July 23-24 2024, a field survey was held with the staff of OGS and the Civil Protection of the Friuli Venezia Giulia Region to select the test site where part of the acquired surveying and monitoring instruments would have been deployed, and the visualization, monitoring, and early warning platform tested. The choice fell on one of the landslides affecting the old stretch of the SS 52 "Carnica" between the villages of Ampezzo and Forni di Sopra; the area is called “Passo della Morte”.

This area is geologically significant due to its susceptibility to mass movements, particularly deep-seated gravitational slope deformations (DGPV). The region has been affected by major landslides, including the well-documented Sacrovint landslide, which have shaped the landscape and pose ongoing risks to infrastructure.

In particular, the western part of the slope, where the old Passo della Morte tunnel and the new San Lorenzo tunnel of the SS 52 road pass through, is of great concern. The underlying geology, characterized by vertical stratification, weak intercalated materials, and numerous discontinuities (fractures and small faults), makes this area prone to block collapses and sliding. The risk is amplified by the proximity of the Tagliamento River at the base of the slope.

Recent studies, including geophysical investigations such as georadar and active seismic surveys, aim to monitor and understand the behavior of the slope, especially in the most unstable sections. Techniques such as microsismic monitoring, georadar scans, and site effect analysis have been employed to better characterize the rock mass and its movements.

The potential scenarios for this slope involve either the collapse or sliding of small blocks (around 1 m³), or the breakage of a larger section of the calcareous mass, which could involve up to

500,000 m³ of rock. This ongoing monitoring effort is crucial to mitigate risks to both the population and critical infrastructure, including transportation routes.

*Figure 12 – Location and front view of the test site*

After being selected as a test site for the ATLaS-ITINERIS measurement campaign, on November 25-27 2024 several monitoring instruments have been installed at the Passo della Morte tunnel. The instruments used in this site test are as follows:
2 tiltmeters;
2 bar extensometers;
2 GNSS nodes;
1 GBInSAR.

During the installation days, two LIDAR surveys were also conducted: one static survey using a terrestrial laser scanner (TLS) and the other using a mobile laser scanner (MLS). The instruments used are as follows:
RIEGL VZ-2000i;
GeoSLAM ZEB-HORIZON RT.

Currently, two georeferenced point clouds of the test area are available, along with the continuous data flow from the in-situ monitoring instruments (GBInSAR, extensometers, tiltmeters and GNSS nodes).

Figure 13 summarizes the analysis performed on the point cloud obtained from the MLS survey. The primary output of a LiDAR survey is a raw point cloud referenced in a local coordinate system, which can only be globally georeferenced if known ground control points are acquired using a GNSS system. After georeferencing, the next step is the point cloud classification, primarily distinguishing between noise and relevant features for the study. In Figure 13a, the point cloud was classified into tunnel (Figure 13b) and non-tunnel elements (e.g., vegetation, ground, people and other irrelevant objects). Within the tunnel dataset, the most representative rock mass outcrops were selected (Figure 13c) for geometrical analysis (Figure 13d).

Following the geometric characterization of the rock slope, which primarily allowed the development of susceptibility maps but did not include monitoring data, tiltmeters and extensometers were installed (Figure 14) to provide continuous monitoring of deformations and assess the stability of the tunnel slope over time. Thanks to remote connectivity via a modem, these instruments continuously transmit data to our laboratory, ensuring real-time monitoring of these specific measurement points.

To complement this localized instrumentation, a Ground-Based Interferometric Synthetic Aperture Radar (GBInSAR) was installed at the tunnel entrance Figure 15. This system provides a broader spatial coverage, enabling the continuous monitoring of potential millimetric displacement on the entire rock mass where the tunnel begins (Figure 4b). The integration of GBInSAR with the punctual instruments enhances the reliability of the monitoring framework, allowing for the detection of both

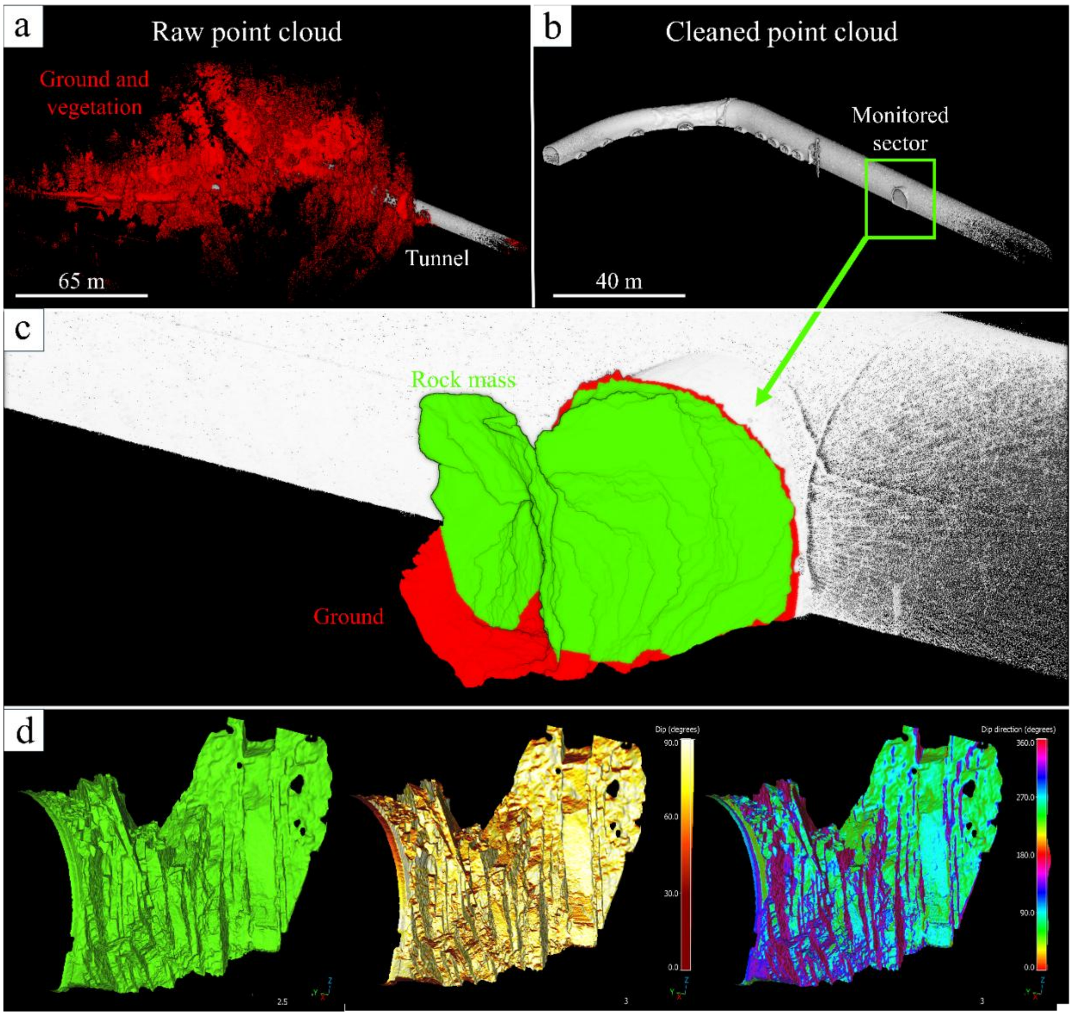


*Figure 13 – MLS point cloud analysis: a) georeferenced and classified point cloud; b) isolated tunnel point cloud; c) highlighted rock mass outcrop selected for analysis (in green); d) geometric analysis for kinematic assessment, shown from left to right: mesh generated from the point cloud, dip angle computation and dip direction computation.*

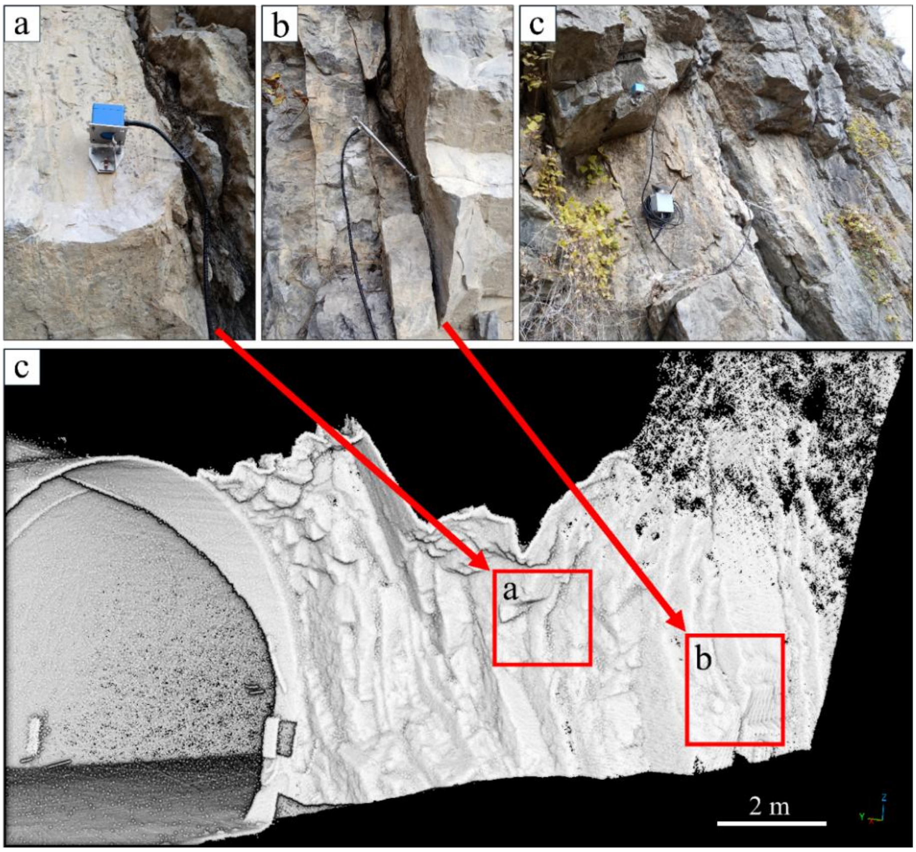


*Figure 14 – Monitoring instruments installed at the Passo della Morte Tunnel: a), b), and c) show the tiltmeter, extensometer, and data transmission hardware, respectively; d) tiltmeters and extensometers were installed on the selected rock mass outcrops along the most critical subvertical discontinuities and strata.*

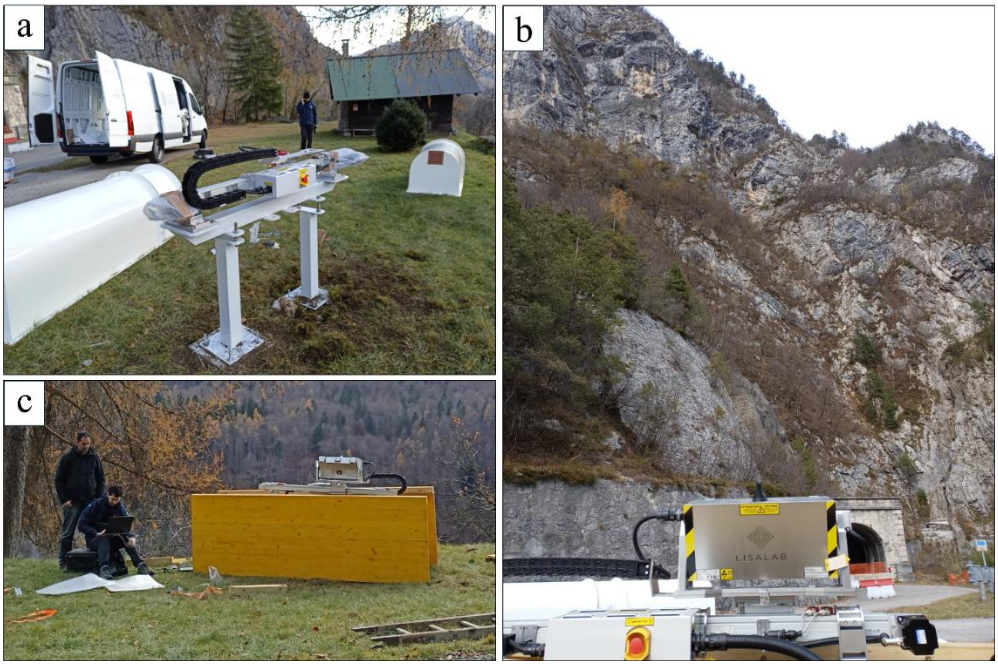


*Figure 15 – GBInSAR installation at the entrance of the Passo della Morte tunnel: a) logistics behind the installation; b) system activation check; c) rock mass within the radar's field of view.*

# 6. REFERENCES

Fukuzono, T. (1985). A new method for predicting the failure time of slope. 145–150.

Nocentini, N., Medici, C., Barbadori, F., Gatto, A., Franceschini, R., del Soldato, M., Rosi, A., Segoni, S., 2024a. Optimization of rainfall thresholds for landslide early warning through false alarm reduction and a multi-source validation. Landslides 21, 557–571. https://doi.org/10.1007/s10346-023-02176-7

Rosi A, Canavesi V, Segoni S, Dias Nery T, Catani F, Casagli N (2019) Landslides in the mountain region of Rio de Janeiro: a proposal for the semi-automated definition of multiple rainfall thresholds. Geosciences (Switzerland) 9. https://doi.org/10.3390/geosciences9050203

Rosi A, Lagomarsino D, Rossi G, Segoni S, Battistini A, Casagli N (2015) Updating EWS rainfall thresholds for the triggering of landslides. Nat Hazards 78:297–308. https://doi.org/10.1007/s11069-015-1717-7

Rosi A, Peternel T, Jemec-Auflič M, Komac M, Segoni S, Casagli N (2016) Rainfall thresholds for rainfall-induced landslides in Slovenia. Landslides 13. https://doi.org/10.1007/s10346-016-0733-3

Rosi A, Segoni S, Canavesi V, Monni A, Gallucci A, Casagli N (2021) Definition of 3D rainfall thresholds to increase operative landslide early warning system performances. Landslides 18:1045–1057. https://doi.org/10.1007/s10346-020-01523-2

Rossi, G., Catani, F., Leoni, L., Segoni, S., & Tofani, V. (2013). HIRESSS: a physically based slope stability simulator for HPC applications. Natural Hazards and Earth System Sciences, 13(1), 151.

Saito, M. (1969). Forecasting time of slope failure by tertiary creep. 2, 677–683.

Segoni S, Rosi A, Catani F, Casagli N, Segoni S, Rosi A, Rossi G, Catani F, Casagli N (2014a) Analysing the relationship between rainfalls and landslides to define a mosaic of triggering thresholds for regional scale warning systems. Nat Hazards Earth Syst Sci 14:2637–2648. https://doi.org/10.5194/nhessd-2-2185-2014

Segoni S, Rossi G, Rosi A, Catani F (2014b) Landslides triggered by rainfall: a semi-automated procedure to define consistent intensity-duration thresholds. Comput Geosci 63:123–131. https://doi.org/10.1016/j.cageo.2013.10.009

Wilkinson MD, Dumontier M, Aalbersberg IJ, et al (2016) The FAIR Guiding Principles for scientific data management and stewardship. Sci Data 3:160018. https://doi.org/10.1038/sdata.2016.18