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1. ABSTRACT

This Deliverable, part of Milestone 2.6 of Spoke 2 in the Extended Partnership RETURN Project, focuses on the theme “Application of outcomes from ground instability scenarios to structural vulnerability” as outlined in the Executive Work Plan – Milestone 2.6. It summarizes the scientific research activities conducted up to November 2025 by Task 2.5.1 (“Mitigation solutions with respect to ground instabilities”) of Work Package 2.5 (“Outcomes for mitigation strategies”). This task is a component of the vertical spoke VS2, “Ground Instabilities.

The focus of WP5 is on mitigation strategies, in a broad sense, examined in the present study.

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3. Classification and description of remedial measures

3.1 Introduction

The present deliverable deals with the scientific research activities carried out in the **Task 2.5.1 (Mitigation solutions with respect to ground instabilities)** of the **Work Package 2.5 (Outcomes for mitigation strategies)** within the framework of vertical spoke **VS2** “Ground Instabilities” of the Extended Partnership **RETURN** “multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate”.

RETURN is designed with the objective of strengthening key competences, encouraging technological and knowledge transfer, and reinforcing the activity of disaster risk management, by promoting the advancement of fundamental knowledge and technological applications.

A deeper understanding process will enhance predictive capabilities and support the effective use of planning and forecasting tools, ultimately leading to the development of an integrated framework. This framework will combine data from monitoring networks addressing a wide range of environmental, natural and anthropogenic hazards, and will rely on both conventional and advanced technologies.

The primary objects of the Spoke **VS2** are permanent ground instabilities causing deformations at ground level (e.g. slope failures, sinkholes, subsidence/uplift due to soil consolidation, and liquefaction).

This document reports some of the activities of the **WP5**, organized in 4 tasks, related to mitigation and remediation strategies.

Task 2.5.1 specifically addresses strategies for the mitigation of natural hazards (*Approaches for the definition of standard mitigation protocols and interventions (surficial and indeep reinforcements, drainages, etc.) for different types of ground instabilities and geological frameworks (namely, earthflows in fine-grained soils, debris-flow, liquefaction of loose sands, rock slope instabilities and sinkholes) will be implemented. To this end, numerical applications integrated with information from structural monitoring systems will be used*), with a focus on the identification, evaluation, and implementation of effective measures to reduce risks associated with the different instabilities mechanism.

The **deliverable 2.5.1** (*Application of outcomes from ground instability scenarios to structural vulnerability*) has been interpreted within the framework of the entire Spoke work process and designed as follows.

First, a classification of instability phenomena is reported, followed by a detailed analysis of mitigation strategies, traditionally distinguished between active (preventive) and passive (protective) measures. Subsequently, a concise review of the natural laboratories developed within the RETURN project is provided. For these cases, a classification is proposed in terms of instability mechanism, type of material involved, spatial scale of influence, and environmental setting. Furthermore, the mitigation strategies adopted for each case have been analyzed and described.

The partners involved in the WP5 are:

- University of Napoli Federico II (UNINA);
- University of Padova (UNIPD);
- University of Roma Sapienza (UNIROMA1);
- University of Bari Aldo Moro (UNIBA);
- Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS);
- Università degli studi di Palermo (UNIPA);
- Politecnico di Torino (POLITO);
- Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile (ENEA).

3.2 Reference framework of ground instabilities

The issue of Ground Instabilities classification has been addressed since the beginning of the RETURN project.

An initial classification among ground instabilities has been made distinguishing:

- landslides;
- sinkholes;
- subsidence;
- liquefaction.

Then, a more detailed differentiation is reported in **Table 1**, considering the kinematics of the phenomena as the primary discriminating element. Slow and fast typologies of ground instability are distinguished for subaerial landslides and sinkholes.

GENERAL CLASSIFICATION			
Ground Instabilities	Subaerial Landslides	Subaerial Slow Landslides Typologies	<i>Slow Flows (Earthflows)</i>
			<i>Slow Slides (Rotational and planar Slides, Soil slips)</i>
			<i>Slow Spread & Slow Slope Deformations (Spread (except Liquefaction), Rock/Soil Slope Deformations, Creep, DsGSD)</i>
		Subaerial Rapid Landslides Typologies	<i>Rapid Flows (Debris flows, Mudflows)</i>
			<i>Rapid Slides (Rock Slides, Rock Avalanches)</i>
			<i>Falls & Topples (Rock Falls, Rock Topples)</i>
	Submarine landslides	Submarine Landslides Typologies	<i>Canyon head Landslides</i>
			<i>Inner shelf/Insular shelf Landslides</i>
	Sinkholes	Slow Sinkholes Typologies	<i>Slow Sinkholes (All Types)</i>
		Rapid Sinkholes Typologies	<i>Rapid Sinkholes (All types)</i>
	Subsidence	Subsidence Typologies	<i>Subsidence (All types)</i>
	Liquefaction	Liquefaction Typologies	<i>Liquefaction (All types)</i>

Table 1 Typologies of Ground Instabilities.

3.3 Classification adopted for remedial measures

Risk is commonly considered a function of three fundamental components: Hazard, Vulnerability, and Exposure.

According to *Versace et al.*, (2023):

- Hazard refers to the probability of occurrence, within a specified geographic area and over a defined time period, of a potentially damaging event of natural or anthropogenic origin, characterized by a given intensity;

- Vulnerability expresses the susceptibility to damage of an exposed element, depending on the intensity of the hazardous event and the intrinsic characteristics of the element itself (e.g., a physical asset, community, system, or environmental component). It represents the relationship between the intensity of the adverse event and the resulting damage, i.e., the response of the system to the applied stress;

- Exposure denotes the quantity, quality and spatial distribution of elements at risk—such as people, buildings, infrastructure, movable assets, economic activities, and environmental resources—within the area under analysis.

The design of mitigation measures can follow approaches aimed at reducing hazard, exposure or vulnerability.

For the case of ground instabilities, mitigation actions aimed at reducing hazard include both active (preventive) measures and passive (protective) measures (**Figure 1**).

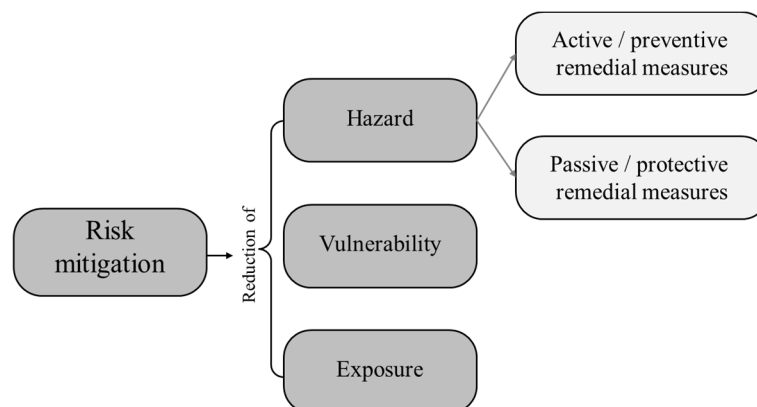


Figure 1 Methodological framework

The first category includes interventions aimed at reducing the probability of triggering a given instability phenomenon (by increasing stabilizing actions and reducing instabilizing ones); the second category, instead, comprises strategies designed to reduce the impact of the propagation of an instability phenomenon once it has been triggered.

The following sub-sections (par. **3.3.1 General description of active/preventive remedial measures** and **3.3.3 General description of passive/protective measures**) describe and summarize the prevention and protection measures in short descriptions of the operating principle, feature and specific execution technique associated with each intervention.

Table 2 and **Table 3** provide a more detailed classification of:

- the geomaterials involved, distinguishing by color between:
 - soils;
 - **rocks**.
- the features, distinguishing between:
 - structural invasive (**SI**)
 - structural non-invasive (**SN**)

- non-structural (NS) measures.

It worth to be underlined that, basing on the common meaning of the term, *structural invasive* measures refer to interventions that involve the construction of structures, whereas *structural non-invasive* measures do not necessarily involve the construction of an engineered structure but rather entail a modification of the configuration of the affected site, finally *non-structural* measures do not require the development of physical infrastructure, limiting exposure by means of alert system used to reduce the vulnerability of buildings and infrastructures.

3.3.1 General description of active/preventive remedial measures

Preventive measures (or active defense measures) are interventions aimed at reducing the likelihood of triggering a certain instability phenomenon by either enhancing the effect of stabilizing forces or decreasing instabilizing forces (Evangelista, 1995, Barile et al., 2004). Based on a detailed review of relevant literature and documents (Barile et al., 2004, Cascini et al., 2022, ISSMGE, 2001), the types of preventive interventions have been summarized in **Table 2**.

Principle	Method	Execution	Soils Rocks
Increase in stabilizing forces	Increase in normal stress	Backfilling and toe protection works	SN Landslides
	Increase in shear strength	Thermal stabilization	SN Liquefaction
		Injections	SN Sinkhole
		Increase in density	SN SI = Structural Invasive
		Adjustement of grain size distribution (replacement or mixing)	SN SN = Structural Non-invasive
		Reinforced soils (soli+ net/strips ecc)	SI
	Reduction in positive pore water pressure (increase in suction)	Drainage	SI NS = Non-Structural
		Electro-osmosis	SN
		Induced Partial Saturation (IPS)	SN
Decrease in instabilizing forces	Reduction in shear forces along the slip surface	Unloading excavation at the crest of the slope	SN
		Slope reshaping	SN
	Shear load transfer to structural elements or stable formations	Retaining and diaphragm walls	SI
		Soil nails	SI
		Anchors	SI
		Piles	SI

Table 2 Active / preventive remedial measures

The two physical principles underlying the considered intervention types are:

1. Increase of stabilizing forces;
2. Reduction of destabilizing forces.

It is possible to increase stabilizing forces through various approaches, which include, on one hand, increasing acting normal stress and shear strength of the material, and on the other hand, reducing pore pressures (which means an increase in suction).

To reduce destabilizing forces, the most widely spread approaches focus on decreasing the shear forces acting along the slip surface or redirecting the shear stresses responsible for the instability to stable formations or specifically designed structural elements.

It can be noted that, regarding the execution methods of each intervention, **Table 2** groups the interventions based on the same type of soil instability (landslide, liquefaction, and sinkhole) using colour coding.

Interventions aimed at increasing stabilizing forces are mostly associated with liquefaction-related instabilities, with the exception of backfilling and toe protection works, which primarily address landslide phenomena, and drainage and injection techniques, which are applicable across all three types of instability.

Measures targeting the reduction of destabilizing forces are generally more effective in relation to landslide processes.

Each intervention method is described in detail in sec. **3.3.2** Inventory of active/preventive remedial measures.

3.3.2 Inventory of active/preventive remedial measures

This section provides a description of each intervention method, with reference to the classification presented in **Table 2**

3.3.2.1 Intervention aimed at enhancing stabilizing forces by increasing normal stress

- Toe protection works

This execution technique determines an increase in normal stresses along the sliding surface. It is typically most effective for rotational-type landslides (*USGS, 2008*) since it increases the stabilizing moment.

To enhance slope stability, it may be beneficial to apply a load at the toe (*Gedney & Weber, 1978*) (**Figure 2**) using materials with appropriate mechanical properties (*Barile et al., 2004*). In addition, the backfill material should possess high drainage capacity to avoid adversely affecting the pore water pressure distribution acting within the slope.

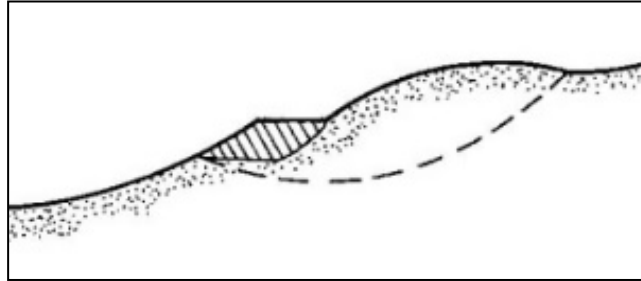


Figure 2 Simplified representation of "toe protection works"

3.3.2.2 Interventions aimed at enhancing stabilizing forces by increasing shear strength

- Thermal stabilization

This execution technique leads to an improvement in the shear strength of the soil, primarily as a consequence of physical alterations in the material structure. This type of treatment is typically applicable to clayey soils, using temperatures ranging between 600 and 1000 °C, which induce permanent changes in the properties of the treated soil, such as reduced compressibility and a significant increase in strength (*Barile et al., 2004*).

Various implementation technologies fall within this category, as reported by *Alsabhan & Hamid (2025)*, as thermal stabilization using a furnace, industrial microwave oven, muffle furnace ecc. Among the different treatment methods, **Figure 3** illustrates the forced-draught system, which involves injecting pre-heated air under pressure into a borehole, or initiating combustion under pressure within the borehole, and the natural-draught system, which entails allowing combustion products to pass through one or more interconnected boreholes and discharge into the atmosphere.

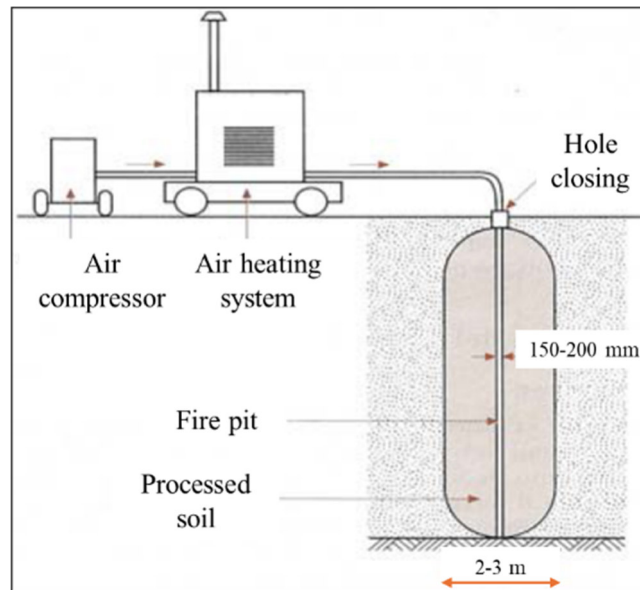


Figure 3 Simplified representation of "thermal stabilization" (after Barile *et al.*, 2004)

- Injections

This type of treatment is typically applied to ground instability phenomena such as liquefaction and sinkholes, and it is only rarely used for landslides. It produces an increase in the shear strength of the material, associated with both physical and chemical modifications of the soil (Barile *et al.*, 2004). For this purpose, the stabilizing element is injected into the natural soil deposit (ISSMGE, 2001) to fill ground voids, with the aim of increasing cohesion and friction (Moseley and Kirsch, 2004).

The stabilizing elements consist of mixtures whose composition varies significantly according to the permeability of the soil. More specifically, in soils with low permeability, chemical mixtures (either organic or inorganic) that rapidly harden even in the presence of water are preferred, whereas in soils with higher permeability cementitious mixtures (grouting) are adopted.

The types of grouting most commonly used for engineering purposes are (Figure 4) (CIRIA, 2000):

- hydrofracture grouting;
- compaction grouting;
- permeation grouting;
- jet grouting;
- rock grouting.

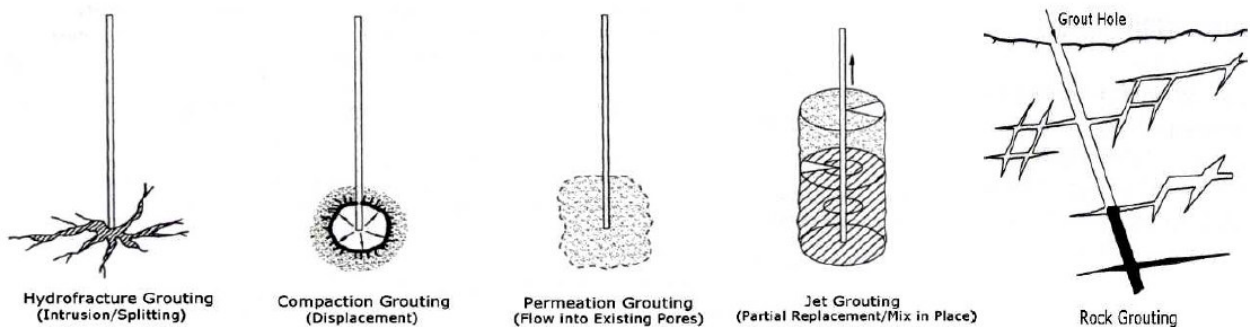


Figure 4 Types of engineering grouting (CIRIA 2000)

One of the most widespread interventions is the jet grouting technique. The peculiarity of this treatment lies in its ability to disaggregate the soil while simultaneously mixing it with a stabilizing cementitious fluid, thereby forming a column of material with improved mechanical properties compared to the untreated soil. As a result, columns of consolidated ground are created, which provide a significant increase in shear strength.

There are three main jet-grouting techniques (Colombo and Colleselli, 1996), which differ in the way soil disaggregation is achieved by using one of the three fluids for the injection (**Figure 5**).

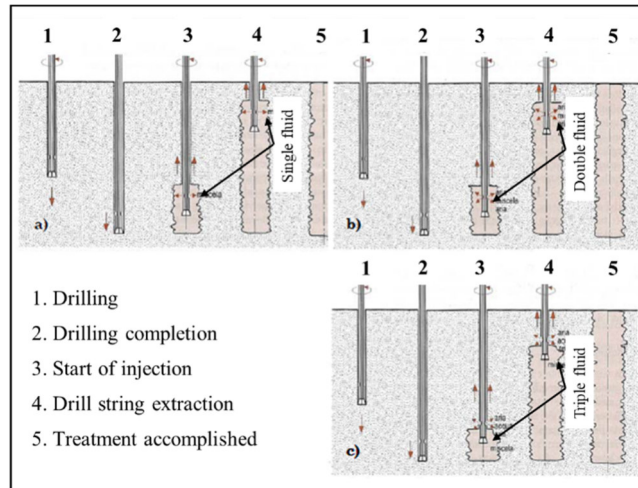


Figure 5 Jet grouting techniques: (a) single-fluid system (only stabilizing cementitious fluid); (b) double-fluid system (stabilizing cementitious fluid and air); (c) triple-fluid system (stabilizing cementitious fluid, water and air) (Colombo and Colleselli, 1996)

- *Densification*

This execution technique is particularly suitable for liquefaction phenomena affecting loose, saturated sandy deposits (Hamada, 2014). The technical literature indicates that density, together with other factors (e.g. OCR, degree of saturation, fine content and soil plasticity), represents one of the key parameters controlling liquefaction susceptibility (Seed and Lee, 1966; Ishihara, 1985; Mele et al., 2019c). Consequently, several liquefaction mitigation strategies are aimed at increasing soil density. This objective can be achieved through various approaches (ISSMGE, 2001, Huang et al., 2014), including:

- sand compaction pile;
- vibro-rod method;
- vibro-flotation;
- dynamic consolidation;
- vibratory tamper method;
- compaction by roller;
- compaction by explosion;
- group pile method.

A schematic representation of dynamic consolidation is reported in **Figure 6**.

In the dynamic compaction method, soil densification is achieved by applying a series of impacts (N) on the ground surface, generated by repeatedly dropping a heavy mass (W) from a considerable height (H) onto impact points arranged in a triangular or rectangular grid, as a result the maximum potent compaction energy delivered is $N \times W \times H$.

This technique is applicable to shallow layers (Sharma et al., 2021) and may have a great impact on nearby structures (Mele et al., 2024).

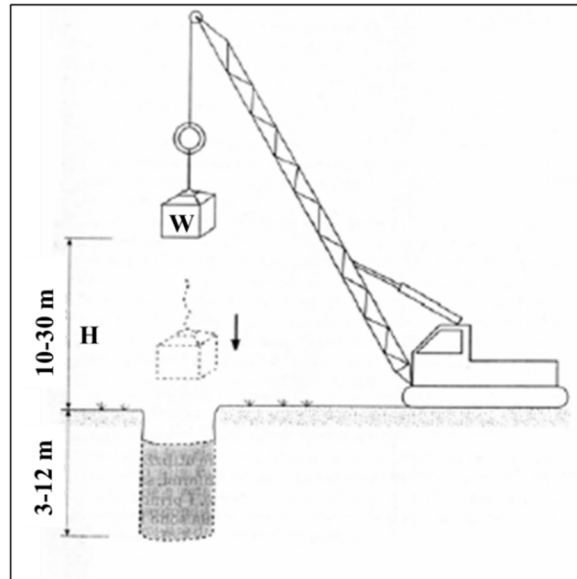


Figure 6 Dynamic consolidation (Colombo and Colleselli, 1996)

- Adjustment of grain size distribution (replacement or mixing)

This execution technique is also particularly suitable for liquefaction phenomena. Regulatory references (*NTC 2018*) have identified grain size ranges corresponding to potentially liquefiable soils, distinguishing between materials with a uniformity coefficient $U_c > 3.5$ and those with $U_c < 3.5$ (Figure 7). This objective can be pursued, where feasible, either by replacing the soil with non-liquefiable material or by modifying the existing grain size distribution through mixing with other materials.

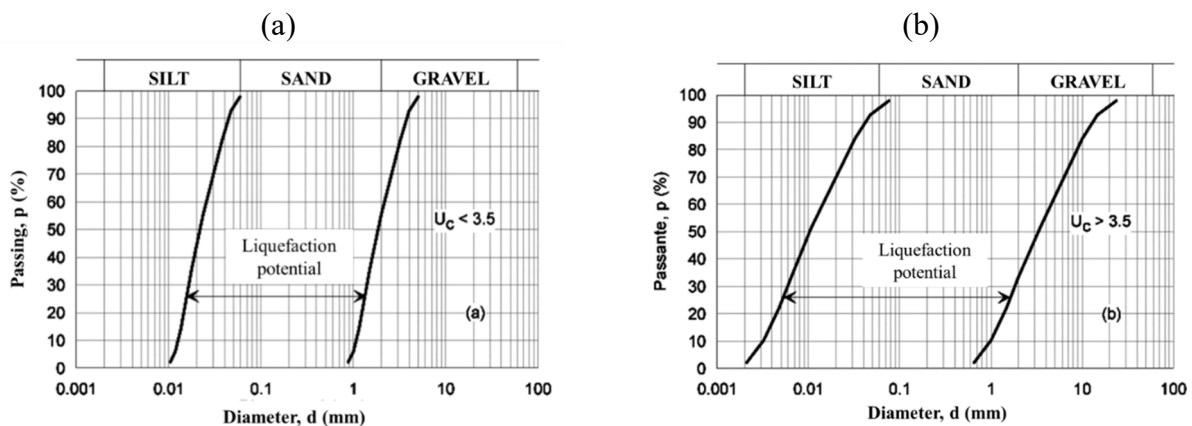


Figure 7 Grain size range within liquefaction may occur: a) $U_c < 3.5$; b) $U_c > 3.5$ (MIT, 2018)

A schematic representation of the soil replacement procedure is shown in Figure 8. In any case, such a procedure is not well-suited for large-scale sites, partly due to excessively high transportation costs of the material.

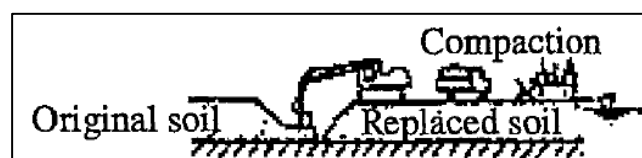


Figure 8 Adjustment of grain size distribution (replacement) (ISSMGE, 2001)

- Reinforced soils

This execution technique consists of the creation of a composite material (soil+reinforcement) that combines different types of strength with the aim of improving the overall performance of the system (*Barile et al., 2004*). Specifically, when coarse grained soil, which inherently provides frictional resistance is combined with elements offering tensile strength in the form of sheets, strips, net, or plastic fibres (*Saran, 2017*) a material made artificially cohesive (*Vidal, 1978*) is produced. The fields of application of reinforced soils are numerous (*Jones, 2013*) and are summarized in **Figure 9**.

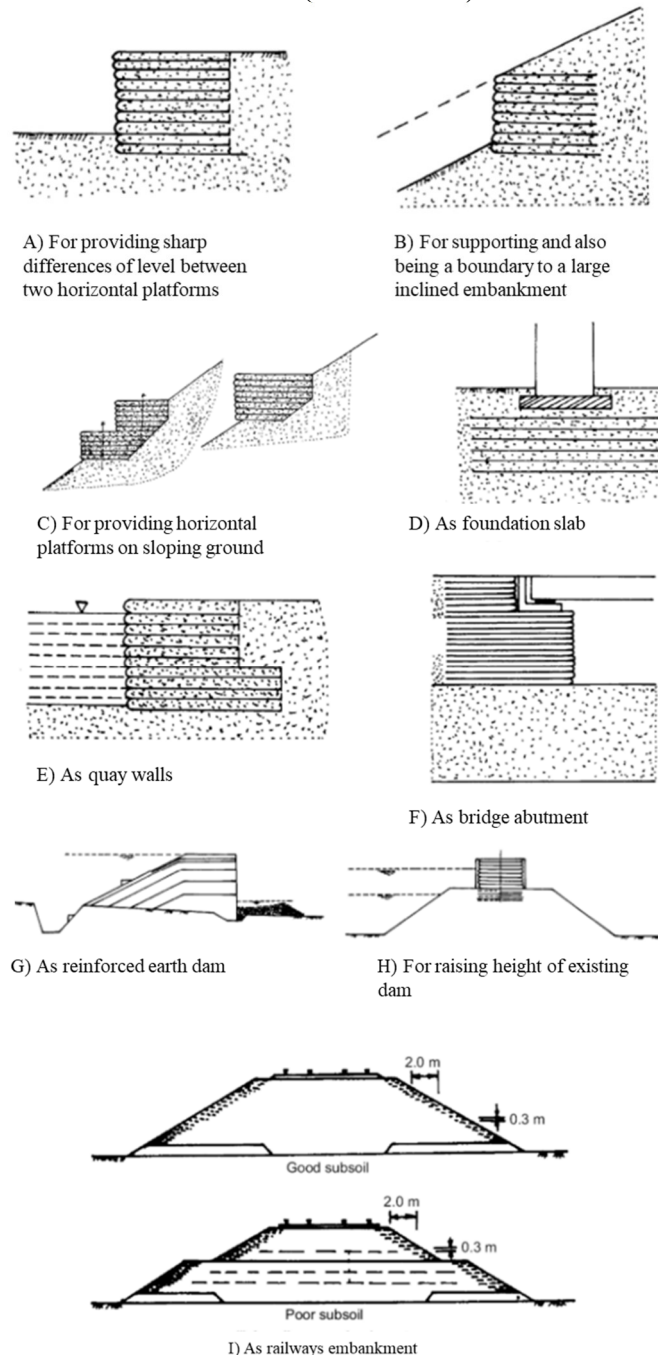


Figure 9 Use of reinforced earth for new-made constructions (*Jones 2013*)

Reinforced soils are frequently adopted to stabilize otherwise unstable slopes. The increase in stability provided by reinforcements makes possible to construct steepened slopes on firm foundations for new

highways, serving as alternatives to flatter, unreinforced terraced slopes or to conventional retaining walls. Roadways can also be widened over existing flatter slopes. In slope failure repair, the reconstructed slope will not only be safer but reusing the slide debris instead of importing higher-quality backfill can also yield substantial cost savings (*Elias et al., 2001*). Some of these applications are shown in **Figure 10**.

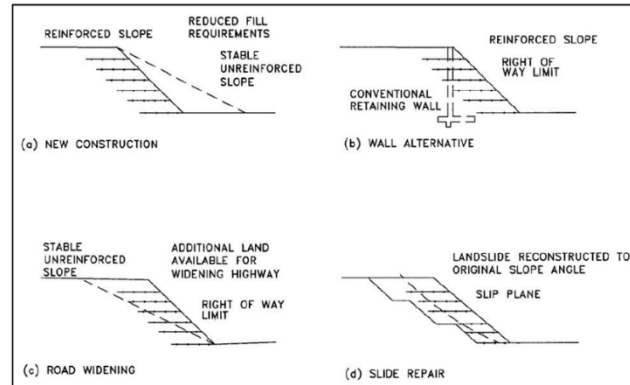


Figure 10 Application of reinforced soil for slope stabilization (*Kim et al., 2019*)

3.3.2.3 Interventions aimed at enhancing stabilizing forces by decreasing positive pore water pressure

- Drainage

Drainage interventions are aimed at preventing the increase of pore water pressures; for this reason, they represent an execution technique applicable to all types of instability considered. In the following, attention is focused on the use of drainage systems for landslide phenomena. Drainage modifies the in-situ pore pressure regime (*Desideri et al., 1998*), producing a dual beneficial effect: reducing the weight of the moving mass and increasing the shear strength of the soils involved in the landslide process. Among the various stabilization solutions, drainage systems are the most widely employed, as extensive experience has demonstrated their effectiveness and reliability in ensuring optimal results.

Drainage works can be classified into superficial and deep systems (*Barile et al., 2004*).

The former category includes:

- surface channels,
- interceptor ditches,
- catch drains.

The latter category comprises:

- drainage trenches and cut-off walls,
- sub-horizontal drains,
- drainage wells,
- drainage tunnels and galleries.

For the sake of brevity, only surface channels and drainage trenches are described in the following. Surface channels are constructed both inside and outside the unstable area, with the purpose of collecting and diverting surface water derived from rainfall, groundwater outflows, or stagnation within depressions. Depending on construction methods and materials used, different types of channels can be distinguished and are reported in *ANPA (2002)* (

Figure 11). Channels may be placed longitudinally or transversally to the slope; transverse channels must be connected to longitudinal drainage systems to ensure proper discharge of collected water

away from the landslide body. Drainage trenches (**Figure 12**), are adopted to stabilize shallow, predominantly translational landslides. The maximum achievable depth depends on excavation equipment. Trenches must be aligned longitudinally along the slope, following the maximum slope direction, and not transversally. They are typically arranged in Y- or T-shaped configurations with multiple levels, in order to intercept groundwater and discharge it downslope through collection pipes installed at the trench base. Trenches must be constructed starting from the lowest point of the area to be stabilized; this ensures that the drained water can be removed without additional works on the slope, and that the drainage function becomes effective immediately, even during the construction phase.

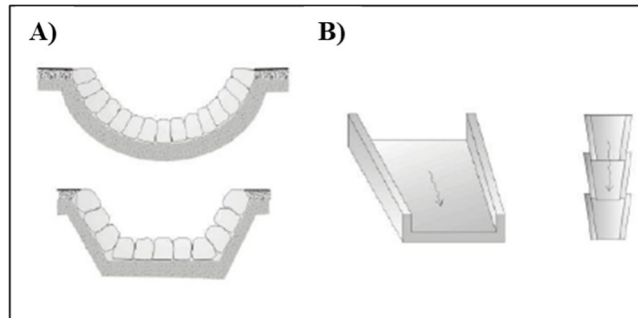


Figure 11 Surface channels: a) rough-hewn stone lining; b) pre-cast concrete elements (after *ANPA, 2002*)

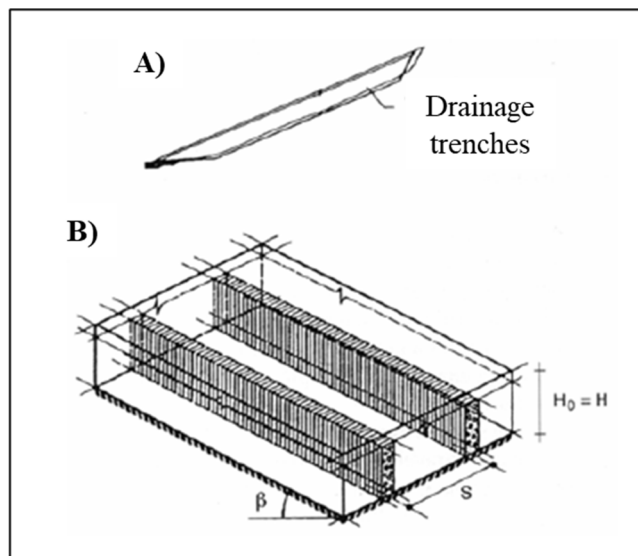


Figure 12 Drainage trenches: (a) longitudinal cross-section; (b) schematic installation of a trench ($H_0 = H$) within an infinite slope (*Desideri et al., 1998*).

- *Electro-osmosis*

The term electro-osmosis refers to a seepage flow induced by the application of an electric field in the absence of hydraulic gradients. Over the years, this technique has found several applications, including the consolidation of clayey soils (*Casagrande, 1949, Tamagnini et al., 1991*) and the stabilization of landslides (*Chappel and Burton, 1975*). Essentially, the electro-osmotic treatment—applicable exclusively to clayey soils—consists of generating within the soil a continuous electric field, applied through pairs of electrodes, which induces the migration of ionic charges present in the clay matrix (**Figure 13**).

The primary effect of this process is the reduction of water content in low-permeability soils (Gargano *et al.*, 2019; Flora *et al.*, 2017). Additionally, by selecting an appropriate anodic electrode material, a structural transformation of the clay can be achieved.

Electro-osmosis, together with other electrically-based ground improvement methods, is generally costly, requires a constant supply of electrical energy, and entails significant maintenance of the electrodes (Ente Forestale della Sardegna, 2013).

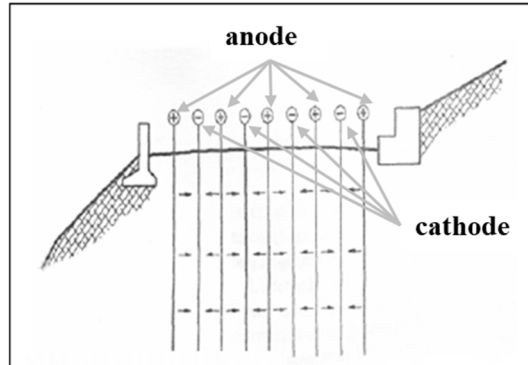


Figure 13 Slope undergoing electro-osmotic stabilization (after Barile *et al.*, 2004)

- Induced Partial Saturation (IPS)

Induced Partial Saturation (IPS) involves the introduction of gas or air bubbles into the pore water of saturated sandy soils in order to decrease their degree of saturation, thus enhancing liquefaction resistance (Hamada, 2014). This technique is considered economical, environmentally sustainable, and particularly suitable for urbanized areas, where mitigating the risk of liquefaction must be achieved while preserving the integrity of existing structures (Mele *et al.*, 2024). Research activity on this topic is currently extensive, encompassing numerical simulations, laboratory investigations (Seyedi-Viand and Eseller-Bayat, 2022), and in situ experimental campaigns, whose several applications have recently been explored (Astuto, 2021). Different methods have been proposed to induce partial saturation in sands to mitigate liquefaction hazard (Ciardi, 2017). These techniques, which rely on physical, chemical, or bio-chemical mechanisms, include:

- drainage-recharge (Yegian *et al.*, 2007);
- air injection (Chu, 2016) (**Figure 14**);
- water electrolysis (Acar and Alshawabkeh, 1993);
- use of chemical additives (Eseller-Bayat *et al.*, 2013);
- use of biogas (Astuto, 2021).

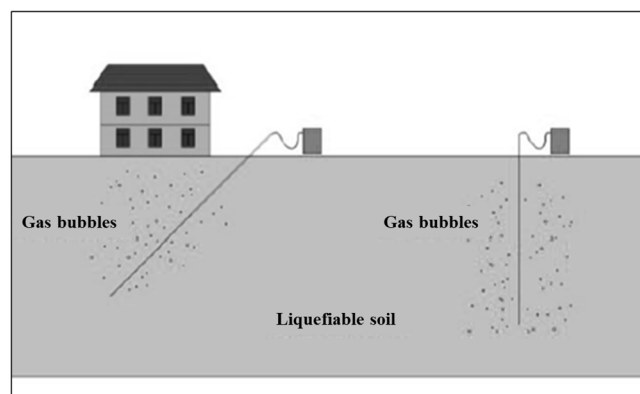


Figure 14 Example of air injection (after Chu, 2016)

3.3.2.4 Interventions aimed at decreasing instabilizing forces by reducing shear forces along the slip surface

- Unloading excavation at the crest of the slope

Unloading excavation at the crest interventions are commonly adopted to reduce the driving forces acting on the upper portion of a slope by removing part of the overburden mass, thus mitigating instability phenomena (**Figure 15**). This approach is particularly effective in cases where excessive surcharge at the crest contributes significantly to the triggering of failure mechanisms.

Whenever possible, crest unloading measures are combined with toe protection works (see **Figure 2**), typically realized with the material obtained from the excavation (*Ente Forestale della Sardegna, 2013*). Such a combined strategy provides a dual benefit: the reduction of instabilizing stresses in the upper slope sector, and the simultaneous increase of resisting forces at the toe. From a design perspective, crest unloading offers several advantages, including the use of local materials, cost-effectiveness, and relative simplicity of execution. However, it also entails potential drawbacks, such as modifications to the geomorphological setting, the need for careful management of excavated volumes, and possible environmental or landscape impacts. Generally, such a kind of interventions is implemented in the case of large-scale landslides involving deep-seated sliding surfaces.

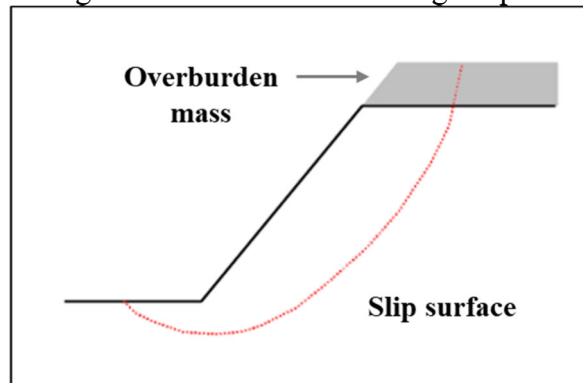


Figure 15 Example of unloading excavation at the crest of the slope (*Ente Forestale della Sardegna, 2013*)

- Slope reshaping

Slope reshaping interventions are primarily aimed at reducing slope steepness and are often implemented through the construction of a series of terraced benches (**Figure 16**). Although a slope subjected to this type of intervention may still be prone to shallow instability phenomena, the presence of benches allows the extent of such movements to be controlled, while simultaneously providing a general improvement in overall stability conditions.

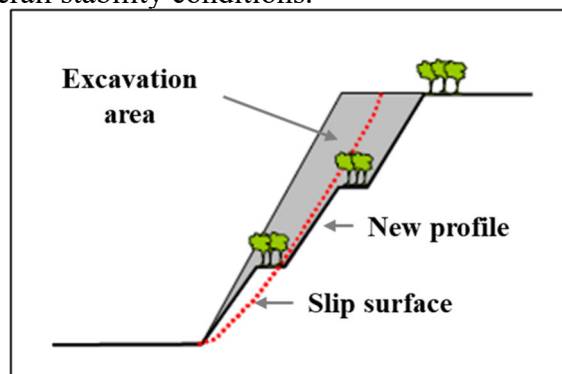


Figure 16 Example of slope reshaping (*Ente Forestale della Sardegna, 2013*)

3.3.2.5 Interventions aimed at decreasing instabilizing forces by transferring tangential stresses to structural elements or stable formations.

- Retaining walls

Retaining walls are interventions designed to counteract the thrust exerted by an unstable soil mass. They can be distinguished into rigid structures and flexible structures (**Figure 17**). Walls belonging to the first category do not adapt to soil deformations, unlike flexible structures. Furthermore, for rigid structures stability relies on the weight of the wall itself, whereas for flexible structures stability is ensured by soil strength and by other restraints, if present (e.g. anchors)

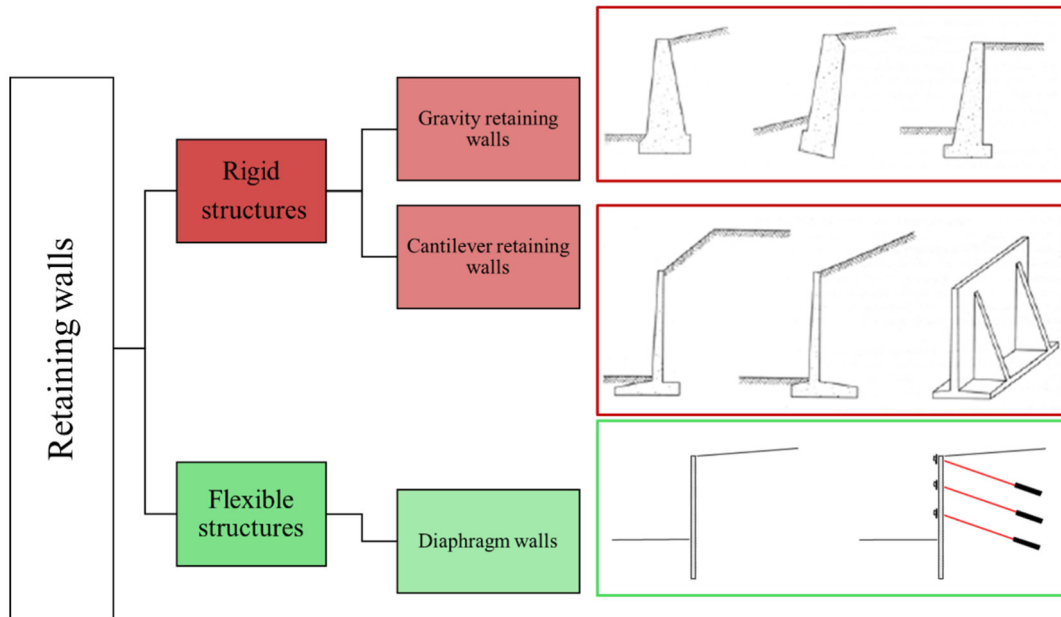


Figure 17 Retaining walls typologies

- Soil nails

Soil nailing consists of introducing, within a soil mass to be stabilized (natural slopes and/or artificial excavation faces (*Budania et al., 2016*)), a series of circular-section steel bars (with diameters typically ranging between 20–30 mm), placed in sub-horizontal boreholes (**Figure 18**). The primary objective is to absorb tensile stresses that the native soil, due to its nature, would not be able to withstand (*Ente Forestale della Sardegna, 2013*).

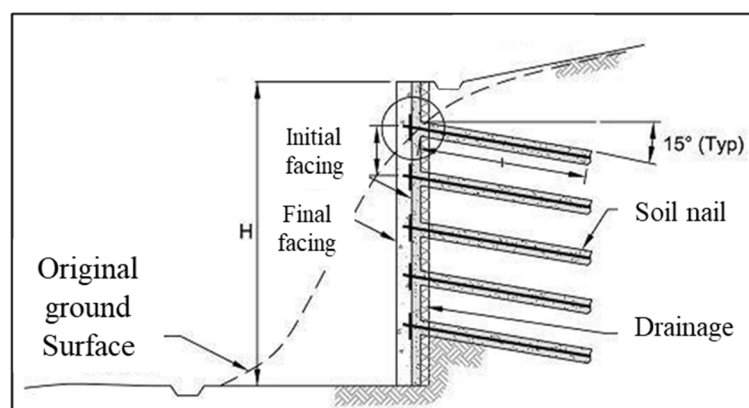


Figure 18 Example of soil nailing (*Byrne et al., 1996*)

The stabilization measure is generally completed by applying external facing systems (e.g., concrete with steel mesh, reinforced concrete, etc.), which serve both to protect the steel bars from corrosion and to effectively transfer stresses to the nearest stable zones (*Palmeira et al., 2008*).

The soil nailing mechanism relies on soil–nail interaction, which is mobilized upon the onset of soil deformations. The major contribution to resistance derives from the development of axial forces. Conventionally, shear and bending are assumed to provide only a minor contribution to the overall resisting mechanism (*Dey, 2015*).

- Anchors

Anchors consist of metallic structural elements (bars or cables) inserted into drilled boreholes, which, crossing the potential sliding surface, are fixed into the underlying stable mass (**Figure 19**). Anchors can be classified into two main categories:

1. Passive anchors (soil nails)
2. Active anchors (rock bolts and tiebacks)

For anchors of the first category, the tensile force required to support the potentially unstable soil mass is mobilized only through the displacements of the soil itself. In contrast, for those of the second category, the structural element is pre-tensioned and becomes effective immediately upon installation.

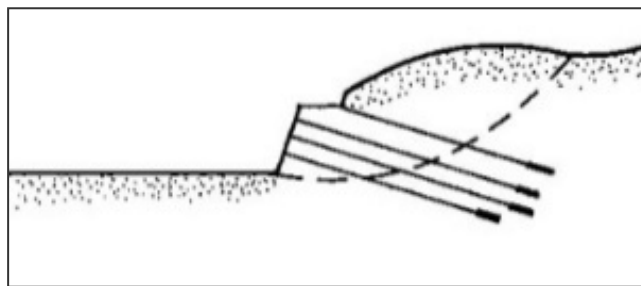


Figure 19 Example of anchors

- Piles

This type of intervention consists of the creation of a network of micropiles (installed either vertically or inclined) with the objective of forming a reinforcement system for the soil mass (**Figure 20**). For such a purpose, the piles must act together to create a stable block of reinforced ground.

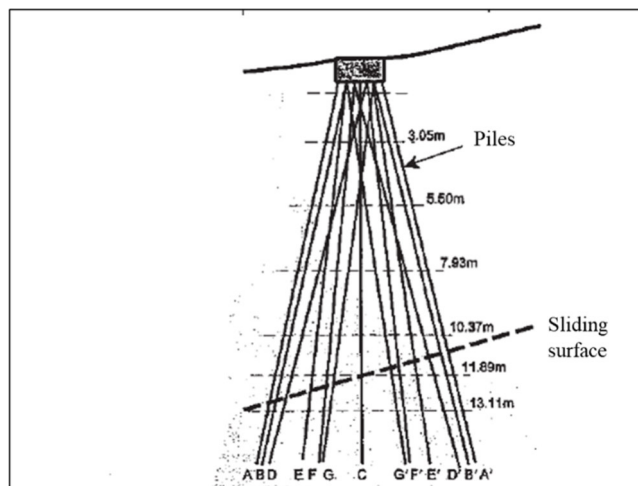


Figure 20 Example of piles (*Barry et al., 2006*)

According to some authors (*Pearlman et al., 2000; Palmerton, 1984*), groups of inclined micropiles provide greater effectiveness in connecting the unstable soil mass to the stable one. All piles terminate at the top in a rigid beam, from which anchors may eventually be developed.

- Anchored wiremesh and near-surface reinforcements

The purpose of these types of intervention (**Figure 21**) is to enhance the mechanical connection between the near-surface weathered layer and the intact material at depth. These systems may be installed in a simple configuration—anchored only at the top and toe—or strengthened by the addition of a wire-rope reinforcement grid and an adequate number of anchors (*Borselli 2020*).

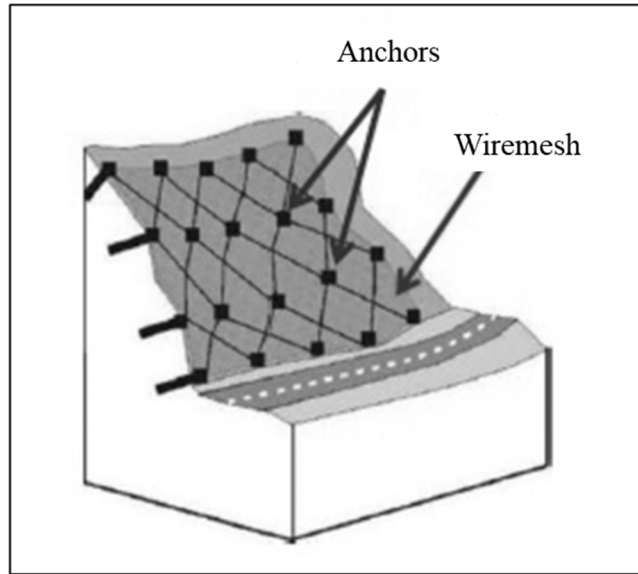


Figure 21 Example of anchored wiremesh and near surface reinforcements

3.3.3 General description of passive/protective measures

Protective measures (or passive defense measures) are generally focused on the propagation of potentially unstable volumes and are adopted to protect infrastructures and buildings located within areas of potential propagation (*Urciuoli, 2012*). As summarized in **Table 3**, this objective can be achieved by modifying the propagation kinematics or by intercepting and diverting the moving mass. Each intervention method is described in detail in the following.

Principle	Method	Execution		
Protection of exposed areas	Accumulation of the unstable mass volume	Collection basins	SI	Soils Rocks SI = Structural Invasive Landslides
	Slowing down and stoppage of propagation	Barriers/protective net	SI	Liquefaction
	Reduction of the kinetic energy of the unstable mass	Check dams	SI	Sinkhole

Table 3 Passive / protective remedial measures

3.3.4 Inventory of passive/protective remedial measures

This section provides a description of each intervention method, with reference to the classification presented in **Table 3**.

3.3.4.1 Interventions focused on the accumulation of the slowing down and stoppage of the propagation

- Collection basins

Generally, collection basins for unstable masses are structural measures located at specific points of the territory to protect inhabited areas. They may be equipped with an inlet that facilitates the entry of the unstable mass into the basin and are typically designed to accommodate the local morphology, widening downslope (**Figure 22**). The entrance of the unstable mass into the basin thus results in a deceleration of the propagation motion (Urciuoli, 2012).



Figure 22 example of collection basins (Quindici, Avellino, Campania Region) (Urciuoli, 2012)

3.3.4.2 Interventions focused on the accumulation of the unstable mass volume

- Barriers and protection net

The barriers are designed to alter the path of unstable masses. Different types of barriers can be identified based on their position relative to the potential propagation direction of the unstable mass (**Figure 23**), as outlined below:

- i) Lateral barriers: these consist of walls or steps constructed to limit the lateral movement of a debris flow, forcing it to follow a generally rectilinear path and thereby protecting areas located along the sides of the channel. Such barriers may also be formed by vegetation that is either naturally grown or planted on purpose along both sides of the channel.
- ii) Deflecting barriers: these structures are designed to divert a debris flow and prevent it from impacting buildings or infrastructures at risk. They are typically built in reinforced concrete or reinforced soil.
- iii) Frontal barriers: these are structures positioned normally to the debris flow path with the purpose of obstructing the movement and inducing sediment deposition. They are built with the same techniques as the previous ones and they are usually located in the distal portion of the deposition zone (hence referred to as terminal barriers).

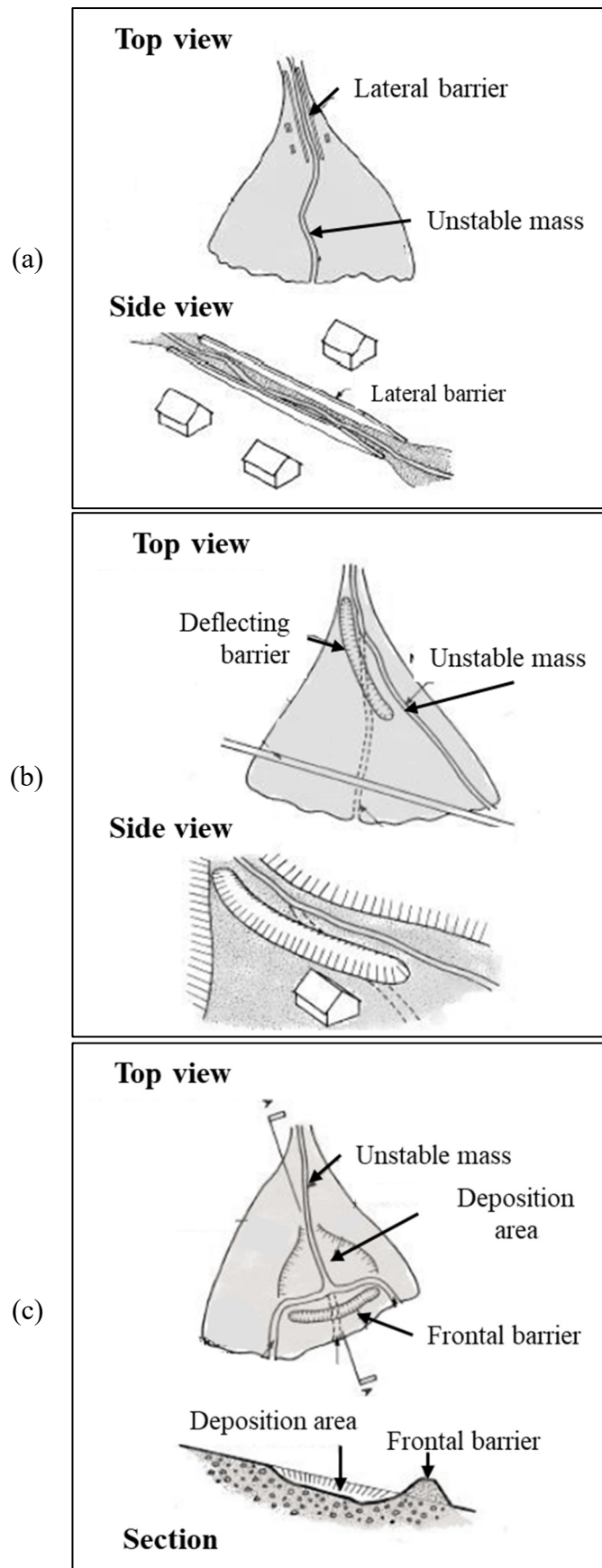


Figure 23 Examples of barrier: a) lateral, b) deflecting, c) frontal. (modified after *Ente Forestale della Sardegna*, 2013)

The rockfall protection nets are elastic systems usually deployed along and/or at the toe of rock slopes, designed to contain small-sized blocks (<60–100 cm). In addition to preventing the detachment of rock blocks from the slope, they guide falling rocks toward designated collection trenches, reducing the risk of hazardous rebounds.

These nets are typically made of galvanized steel or zinc–aluminum alloy wires, arranged to form a double-twisted hexagonal mesh. They can also be reinforced with steel cables placed vertically and/or obliquely to enhance structural resistance (**Figure 24**).



Figure 24 Example of protective net (Urciuoli, 2012)

3.3.4.3 Interventions focused on the reduction of kinetic energy of the unstable mass volume

- Check dams

A series of this type of intervention acts as a hydraulic control system designed to create a series of terraced steps that regulate the velocity of unstable mass of fluid or pseudo-fluid movements and enhance the erosion resistance of the channel bed (**Figure 25**).

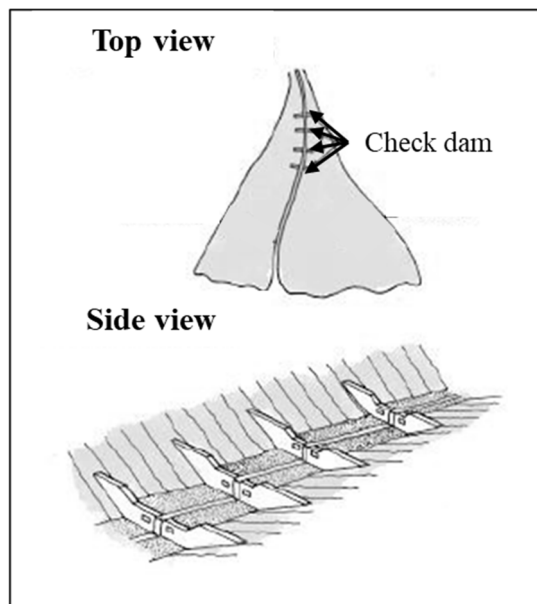


Figure 25 Example of check dam used for re-grading of the channel longitudinal profile (modified after *Ente Forestale della Sardegna, 2013*)

Check dams can be constructed from various materials, including wood, masonry, or reinforced concrete, depending on site conditions and design requirements.

Two main categories of check dams can be identified:

- i) stabilization check dams, which stabilize the streambed and reinforce the channel banks;
- ii) selective check dams, which are specifically intended to trap and retain solid material transported by the flow.

3.3.5 Monitoring for remedial measures efficiency assessment or non-structural mitigation

This section reviews the tools most commonly used for monitoring relevant physical variables. Such monitoring systems can serve several purposes, including:

- i) assessing the effectiveness of implemented remedial measures, by comparing pre- and post-intervention monitoring data;
- ii) reducing exposure in cases where active or passive interventions may be unsuitable for mitigating specific ground instabilities, by enabling the calibration of appropriate early-warning systems.

The physical variables most commonly monitored are listed in the **Table 4**.

Principle	Method	Execution	
Monitoring of suitable physical variables	Monitoring of kinematics variables	Displacement	NS
	Monitoring of hydrological variables	Pore water pressure	NS
		Volumetric water content	NS
	Monitoring of meteorological variables	Weather station	NS

Soils

Rocks

NS = Non-Structural

Landslides

Liquefaction

Sinkhole

Table 4 Tools for remedial measures efficiency assessment

3.3.5.1 Interventions focused on the monitoring of kinematic variables

- Displacements

The observation of deep ground movements is achieved through the installation of inclinometers placed inside boreholes (**Figure 26**). Such monitoring systems allow for:

- i) tracking slope movements over time, even after the implementation of stabilization remedial interventions;
- ii) identifying buried slip surfaces, indicated by a significant displacement gradient along the vertical profile.

For each inclinometer installation, the stratigraphic profile and the distribution of displacements with depth may be provided.

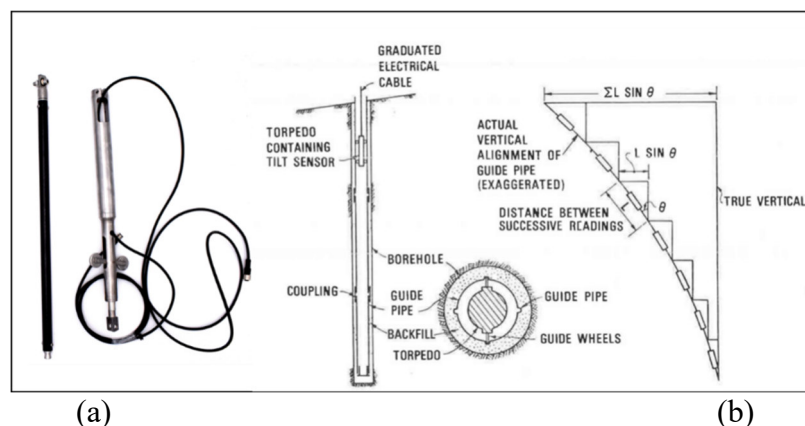


Figure 26 Example of inclinometer probe (a) and principle of inclinometer operation (Dunnicliff, 1993)

Regarding superficial displacements, the most common procedure involves topographic methods (i.e. laser scanner, GPS) (**Figure 27**). This approach requires the installation of monitoring benchmarks (mobile points) strategically positioned across the landslide body and reference stations (fixed points) located outside the affected area. Accurate and periodic measurements of their displacements enable the detection and assessment of any ongoing slope movements over time.

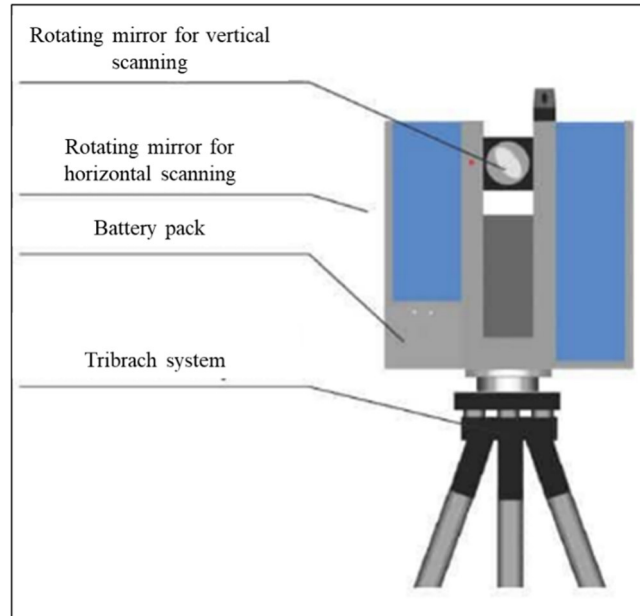


Figure 27 Example of laser scanner

3.3.5.2 Interventions focused on the monitoring of hydrological variables

- Pore water pressure

The monitoring of pore water pressure provides essential information on the hydraulic regime in the subsoil. Such monitoring systems can be adopted to identify the presence and depth of the groundwater table. Although the available types of measuring instruments may appear quite different, they are all based on a few common operating principles.

In general, the measurement technique consists of:

- i) a rigid porous element,
- ii) a measuring chamber,
- iii) a measuring device.

The porous element is saturated and contains water at the same pressure as the pore water in the surrounding soil. Its role is to transmit the stresses acting in the liquid phase to the measuring chamber, which is also saturated. This configuration enables the sensing device to measure the pressure of the liquid phase within the chamber.

Several types of instruments are available for monitoring pore water pressures, including piezometers and piezometric cells. An example of a Casagrande piezometer is shown in **Figure 28**, an example of vibrating wire piezometer is reported in **Figure 29**.

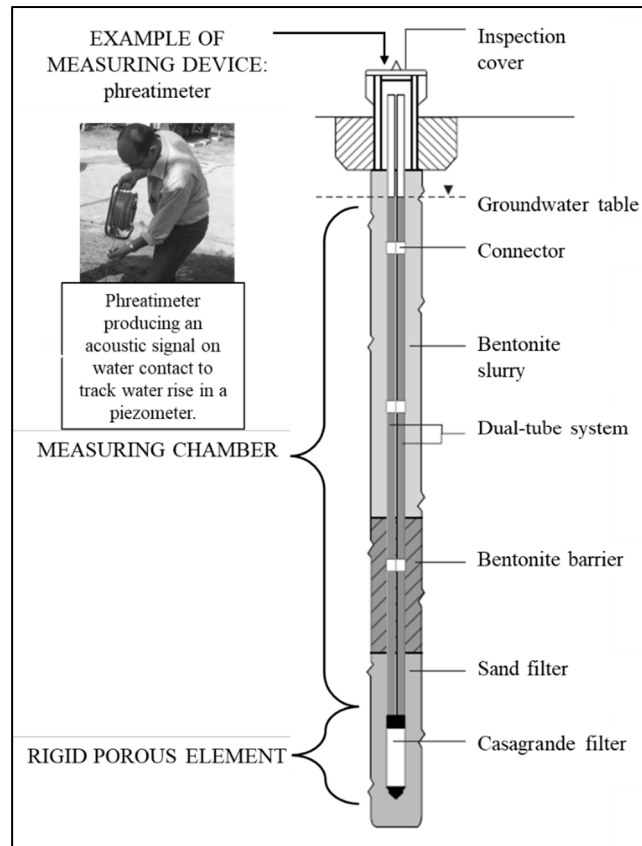


Figure 28 Example of Casagrande piezometer

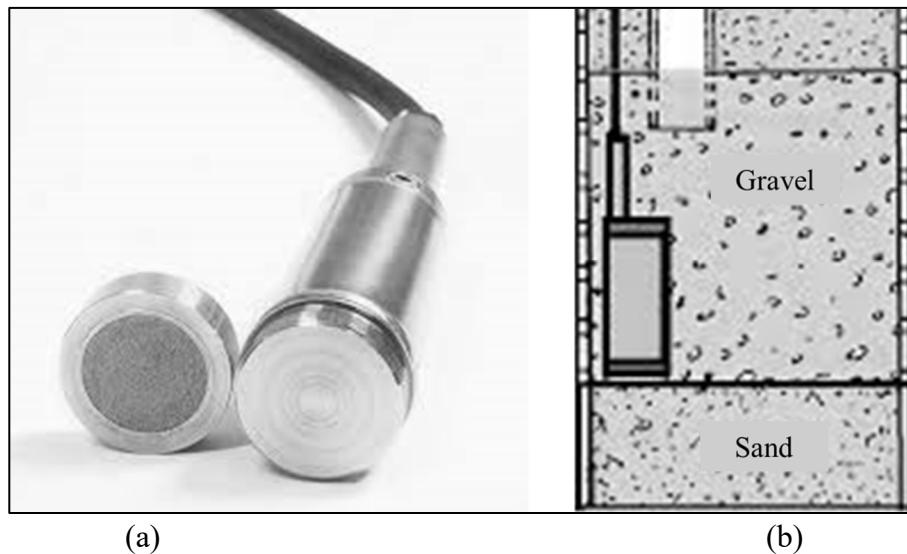


Figure 29 Example of vibrating wire piezometer (a) and its placement in the ground

It is also possible that liquid phase pressure may be negative. This can be assessed either with tensiometers, like piezometers for positive pressures, or by measuring soil water content and deriving the corresponding negative pore pressures.

Volumetric water content sensors (described later) effectively address the desaturation problem of the porous stone, a common limitation of tensiometers, thereby enabling the measurement of higher negative pore-water pressures ($u_w < -80$ kPa).

- Volumetric water content

Various instruments are available for measuring soil volumetric water content, based on different operating principles (Noborio, 2001). As an example, the Time Domain Reflectometry (TDR) technique is described here. TDR enables the determination of the soil dielectric constant, which is directly correlated with the volumetric water content. Several empirical relationships between these physical variables have been proposed (e.g., Topp *et al.*, 1980; Regalado, 2003). In practice, TDR probes usually require site-specific calibration to account for soil type and conditions (e.g. porosity). A typical TDR probe consists of an epoxy resin head with two or three metallic rods (**Figure 30**). The probe is connected to an oscilloscope and subjected to a voltage pulse. Reflections occur at discontinuities caused by transmission line geometry, dielectric properties, or probe termination. The oscilloscope records the reflected waveform, and the pulse travel time is used to derive the soil dielectric constant indirectly.

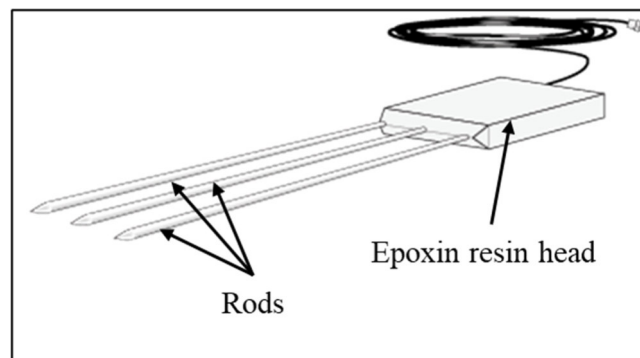


Figure 30 Example of TDR probe (TRD datasheet)

3.3.5.3 Intervention focused on the monitoring of meteorological variables

- Weather station

The monitoring of meteorological variables can be highly effective for estimating soil–atmosphere interaction processes that significantly influence the temporal evolution of pore-water pressures. In particular, an increase in pore water pressure is typically associated with a rainfall infiltration process, whereas a decrease is linked to evaporative phenomena.

A complete meteorological station (**Figure 31**) generally should include instruments for measuring:

- i) rainfall intensity (pluviometer);
- ii) air temperature (thermistor);
- iii) atmospheric pressure (barometer);
- iv) relative humidity (hygrometer);
- v) solar radiation (pyranometer);
- vi) wind speed, direction and inclination (anemometer).

In general, rainfall intensity measurements can be directly correlated with infiltration processes, while the remaining variables are typically used to numerically estimate the magnitude of evaporative losses.

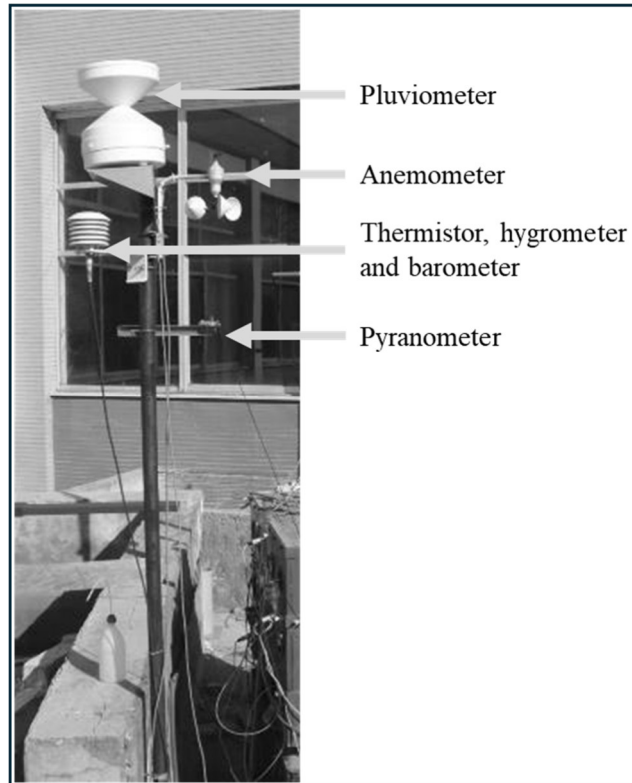


Figure 31 Example of weather station

4. Inventory of RETURN Natural Field Laboratories addressed to the study of remedial measures

4.1 Types of remedial measures adopted for Natural Field Laboratories (NFL)

4.1.1 Brief inventory of proposed natural field laboratories

Within the RETURN project, 12 Natural Field Laboratories (hereinafter, NFLs) were established by the various partners contributing to spoke VS2.

The proposed NFLs correspond to specific types of ground instabilities considered within the RETURN framework.

Differences can be identified among the various Natural Field Laboratories:

- i) some NFLs were also presented as Learning Examples (hereafter LEs) (DV. 2.2.1);
- ii) other sites were subsequently selected for investigation, even though they were not included among the LEs;
- iii) others were established specifically for the installation of innovative devices and/or advanced monitoring networks (DV. 2.3.2).

Specifically, the proposed NFLs are shown in **Figure 32**. They are almost evenly distributed between the northern (**Figure 33a**) and the southern regions (**Figure 33b**).

The NFLs proposed by the different partners (**Figure 34a**) fall within the categories of “subaerial landslides” (11 NFLs) and “liquefaction” (1 NFL) (**Figure 34b**). No Natural Field Laboratories were proposed for submarine landslides, sinkholes or subsidence.

The category of subaerial landslides can be further specified (**Figure 34c**) by distinguishing among:

- i) slow flows (1 NFL);
- ii) slow slides (5 NFLs);
- iii) rapid flows (2 NFLs);
- iv) falls (3 NFLs).

The purpose of each NFL and the correspondence between the types of ground instabilities and their associated Natural Field Laboratories are reported in

GENERAL CLASSIFICATION			PROPOSED NATURAL FIELD LABORATORIES (#12)					
			LEARNING EXAMPLE (DELIVERABLE 2.2.1, Fanti et al.)					
			FURTHER INSIGHT INTO THE PHENOMENON					
			INNOVATIVE SENSOR/INFRASTRUCTURE (DELIVERABLE 2.3.2, Colombero et al.)					
GROUND INSTABILITIES	Subaerial Landslides	Subaerial Slow Landslides Typologies	Slow Flows (Earthflows)	Pietrapertosa (UNINA)				
			Slow Slides (Rotational and planar Slides, Soil slips)	Fantoni (UNIPD)	Perarolo (UNIPD)	Val Paradisi (UNIPD)	Fossa Bradanica (UNIBA)	Cerda (UNIPA)
			Slow Spread & Slow Slope Deformations (Spread (except Liquefaction), Rock/Soil Slope Deformations, Creep, DsGSD)					
		Subaerial Rapid Landslides Typologies	Rapid Flows (Debris flows, Mudflows)	Messina (ENEA)	Ischia (UNINA)			
			Rapid Slides (Rock Slides, Rock Avalanches)					
			Falls & Topples (Rock Falls, Rock Topples)	Acuto (UNIROMA1)	Poggio Baldi (UNIROMA1)	Cuma (UNINA)		
	Submarine landslides	Submarine Landslides Typologies	Canyon head Landslides					
			Inner shelf/ Insular shelf Landslides					
	Sinkholes	Slow Sinkholes Typologies	Slow Sinkholes (All Types)					
		Rapid Sinkholes Typologies	Rapid Sinkholes (All types)					
	Subsidence	Subsidence Typologies	Subsidence (All types)					
	Liquefaction	Liquefaction Typologies	Liquefaction (All types)	Pieve di Cento (UNINA)				

Table 5.

The description of each natural field laboratory was provided by the proposing partners through the completion of simplified forms (**Appendix A**) as well as detailed forms (**Appendix B**).

The main characteristics of each Natural Field Laboratory are presented in the following sections.

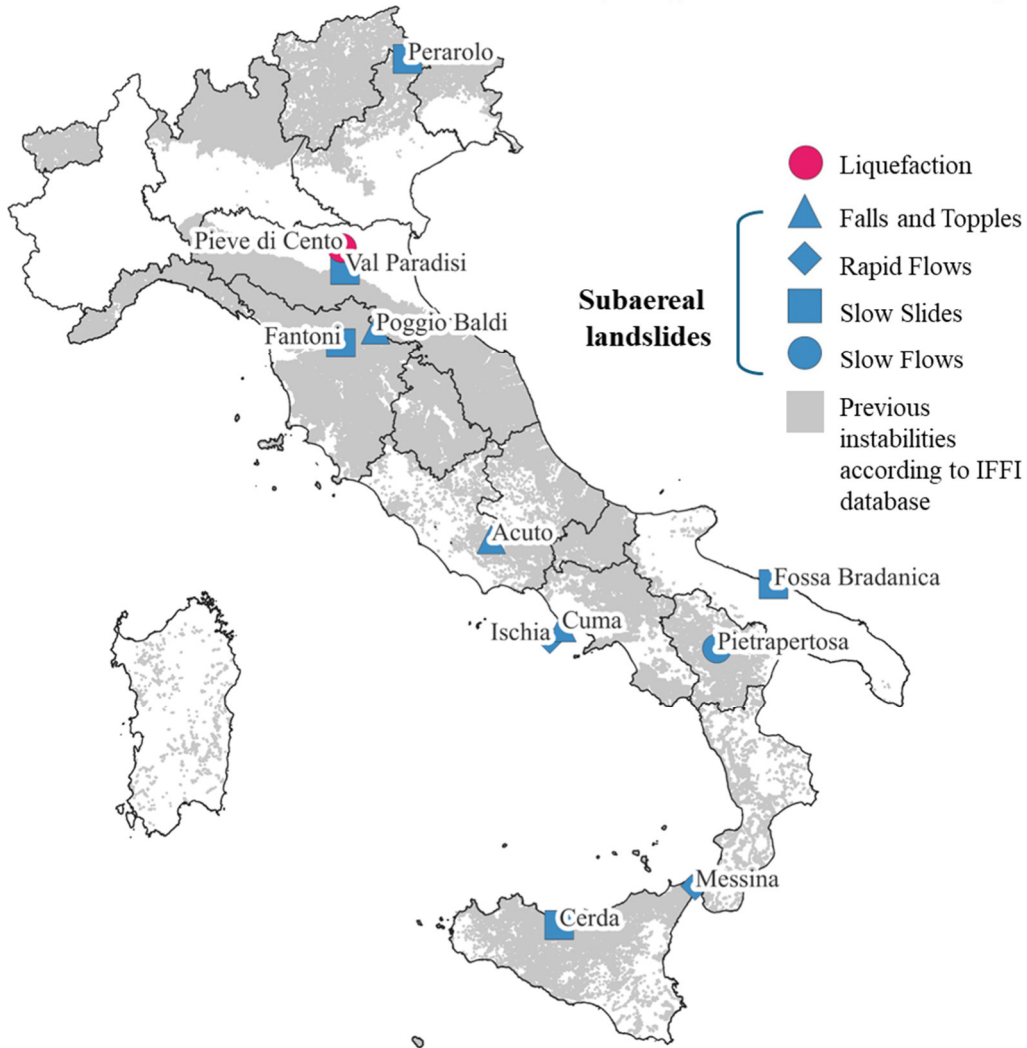


Figure 32 Spatial distribution of Natural Field Laboratories at the National Scale

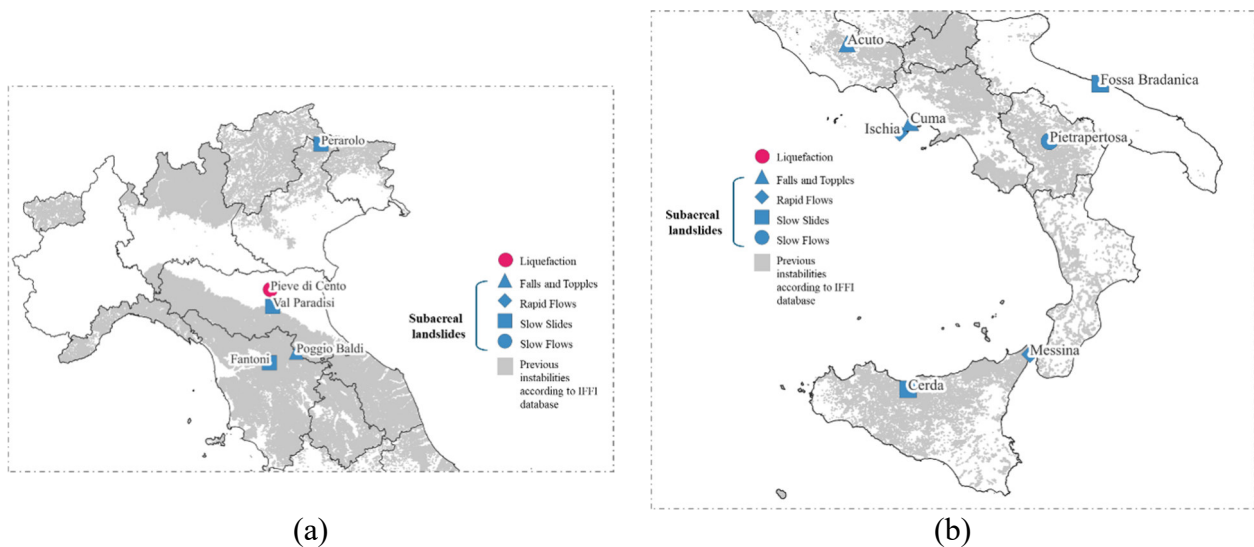


Figure 33 Identification of the proposed Natural Field Laboratories a) northern regions; b) southern regions

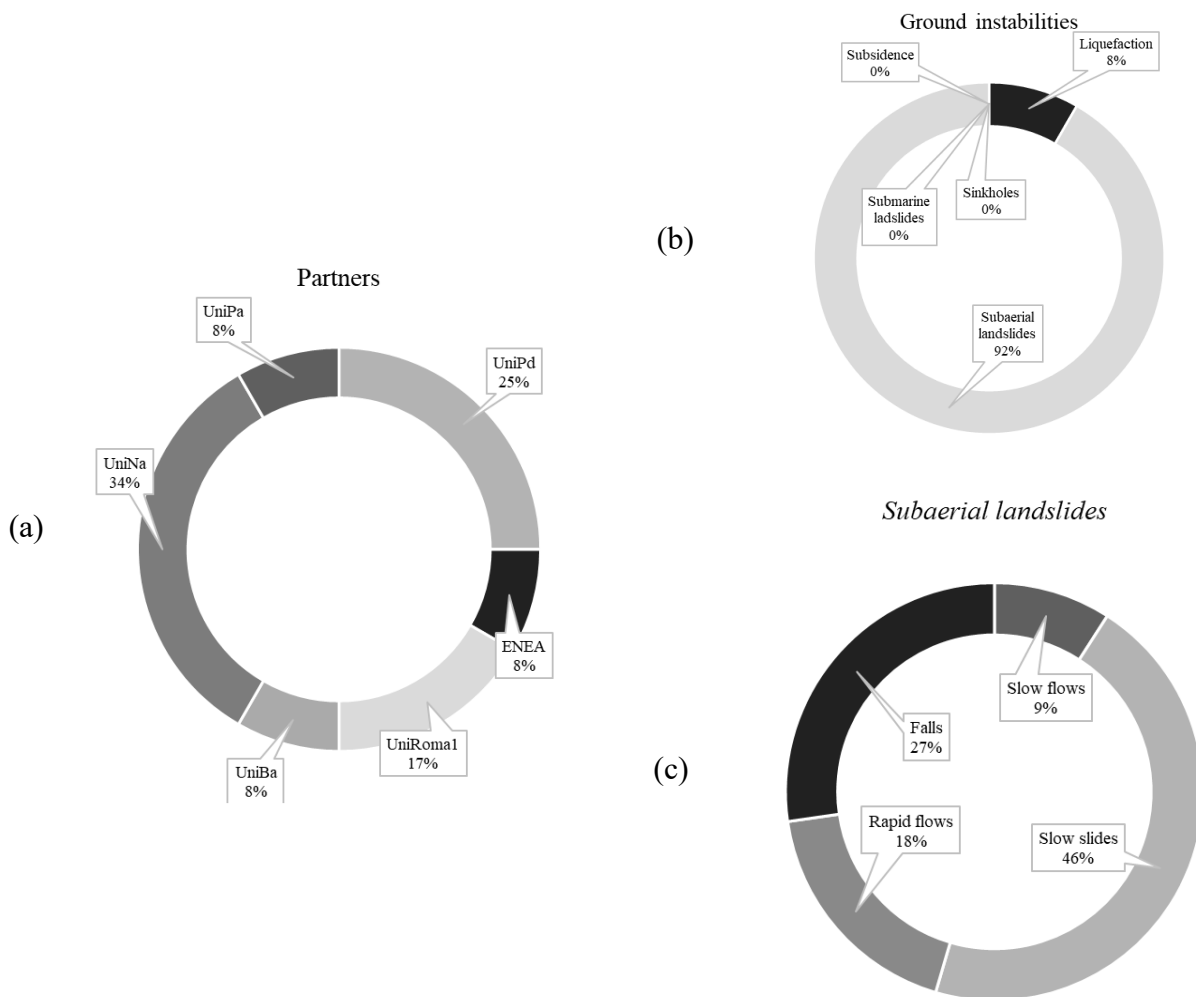


Figure 34 a) List of partners proposing a Natural Field Laboratory; b) typologies of ground instabilities focused; c) typologies of subaerial landslides focused

GENERAL CLASSIFICATION			PROPOSED NATURAL FIELD LABORATORIES (#12)					
			LEARNING EXAMPLE (DELIVERABLE 2.2.1, Fanti et al.)					
			FURTHER INSIGHT INTO THE PHENOMENON					
			INNOVATIVE SENSOR/INFRASTRUCTURE (DELIVERABLE 2.3.2, Colombero et al.)					
GROUND INSTABILITIES	Subaerial Landslides	Subaerial Slow Landslides Typologies	Slow Flows (Earthflows)	Pietrapertosa (UNINA)				
			Slow Slides (Rotational and planar Slides, Soil slips)	Fantoni (UNIPD)	Perarolo (UNIPD)	Val Paradisi (UNIPD)	Fossa Bradanica (UNIBA)	Cerda (UNIPA)
			Slow Spread & Slow Slope Deformations (Spread (except Liquefaction), Rock/Soil Slope Deformations, Creep, DsGSD)					
		Subaerial Rapid Landslides Typologies	Rapid Flows (Debris flows, Mudflows)	Messina (ENEA)	Ischia (UNINA)			
			Rapid Slides (Rock Slides, Rock Avalanches)					
			Falls & Topples (Rock Falls, Rock Topples)	Acuto (UNIROMA1)	Poggio Baldi (UNIROMA1)	Cuma (UNINA)		
	Submarine landslides	Submarine Landslides Typologies	Canyon head Landslides					
			Inner shelf/ Insular shelf Landslides					
	Sinkholes	Slow Sinkholes Typologies	Slow Sinkholes (All Types)					
		Rapid Sinkholes Typologies	Rapid Sinkholes (All types)					
	Subsidence	Subsidence Typologies	Subsidence (All types)					
	Liquefaction	Liquefaction Typologies	Liquefaction (All types)	Pieve di Cento (UNINA)				

Table 5 Typologies of Ground Instabilities and corresponding Natural Field Laboratories



4.1.2 Examples of slow/rapid subaerial landslides: description and adopted remedial measures

The following tables summarize the information provided by the partners who proposed each NFL. Regarding slow landslides (**Table 6**), the NFLs are primarily located in mountainous or hilly settings, and the relevant instability scale is generally local or intermediate between local and regional.

<i>SLOW SUBAEREAL LANDSLIDES</i>								
	Material	Context M – mountain, H – hill, P – plain, C – coast	Scale L – local, I – intermediate, R – regional	Existing remedial measures				
				Structural	Non structural	Laboratory	Field	Other (numerical applications)
<i>Pietrapertosa (earthflow)</i>	Clay	H	I	Row of concrete piles	Piezo-meters and inclinometers	-	Tensio-meters and inclinometers	-
<i>Fantoni (slowslide)</i>	Debris	M	L	Wells, drainage trench and anchored piles	Piezo-meters, extenso-meters and inclinometers			Stability analysis with Limit Equilibrium Method
<i>Perarolo (slowslide)</i>	Debris	M	L	Anchored micropiles and Jet-grouting columns	Inclino-meters			Stability analysis (3D-FEM) and propagation analysis (SPH)
<i>Val Paradisi (slowslide)</i>	Debris	M	L	Drainage trenches	Inclino-meters			Stability analysis with Limit Equilibrium Method
<i>Fossa Bradanica (slowslide)</i>	Silty clay	H	I		Topographic investigation			Erosion rate assessment through differences among DEM
<i>Cerda (slowslide)</i>	Clay	H	L		Weather station, piezo-meters and inclinometers			Numerical correlation among 5-months cumulated rainfall and pore water pressure

Table 6 Summary table of the main characteristics of the NFLs related to slow subaerial landslides

All proposed NFLs were already equipped with non-structural remedial measures prior to the RETURN project. These measures are mostly aimed at monitoring variables related to soil moisture conditions and displacements (both shallow and deep), and—in a few cases (e.g., Cerda)—also meteorological parameters. Only a subset of the proposed NFLs (Pietrapertosa, Fantoni, Perarolo,

Val Paradisi) featured structural and, generally, active remedial measures (e.g., piles, anchors and drainage systems), installed before the RETURN project. Within the RETURN project, only the Pietrapertosa NFL was upgraded through the installation of tensiometers and inclinometers (the devices installed have been well described within the framework of the DV 2.3.2).

The NFLs presented were examined with the aim of improving the understanding of the mechanisms governing the associated instabilities.

For the category of rapid landslides (**Table 7**), the proposed NFLs are generally located in hilly or mountainous settings. The relevant scale of the investigated instability is predominantly local; however, intermediate and regional scales were considered for the Ischia and Messina NFLs, respectively.

RAPID SUBAEREAL LANDSLIDE								
	Material	Context M – mountain, H – hill, P – plain, C – coast	Scale L – local, I – intermediate R – regional	Existing remedial measures		Upgrade with RETURN resources		
				Structural	Non structural	Laboratory	Field	Other (numerical applications)
<i>Messina (debris flow)</i>	Sand	M-H	R	-	-	-	Piezometers, tensiometer, pluviometers and thermistors	-
<i>Ischia (debris flow)</i>	Silty sand	M	I	-	Weather station and probes for soil humidity	-	First installation of the monitoring system	-
<i>Acuto (rock collapse)</i>	Jointed Micritic Lime- stones	H	L	-	Weather station, thermistors, displacement, acoustic emissions and strain probes	-	Prototype uniaxial compression and shear apparatus for soil and rock	Thermo- mechanical numerical modelling to frame effects of near surface temperature fluctuations.
<i>Poggio Baldi (rock collapse)</i>	Flysch	H - M	I	-	Weather station, displacement, acoustic emissions probes	-	Probes for soil humidity and surface displacements	-
<i>Cuma (rock collapse)</i>	-	P	L	-	Probes for deformation monitoring	-	-	Back analysis (FLAC 2D)

Table 7 Summary table of the main characteristics of the NFLs related to rapid subaerial landslides

As in the previous category, most NFLs were already equipped with non-structural remedial measures, primarily consisting of monitoring systems for physical variables related to soil moisture,

surface displacements, and atmospheric conditions. Within the RETURN project, some monitoring systems were enhanced by increasing the number of measurement points, whereas for other NFLs efforts focused on improving the mechanical characterization of the materials involved in the instability.

The primary purpose of the NFLs associated with rapid landslides is to improve understanding of the mechanisms that govern the evolution of these instabilities. In the case of Messina, the adopted approach may contribute to the calibration of slope failure thresholds.

4.1.3 Examples of liquefaction: description and adopted remedial measures

For instability phenomena related to liquefaction, the Pieve di Cento site was proposed (**Table 8**). This case study, extensively documented in the literature, has been addressed using active mitigation measures (IPS, see §00). It was included within the RETURN framework with the aim of providing insights into the applicability and effectiveness of active mitigation techniques.

LIQUEFACTION TYPOLOGIES								
Material	Context M – mountain, H – hill, P – plain, C – coast	Scale L – local, I – intermediate, R – regional	Existing remedial measures		Upgrade in Return			
			Structural	Non structural	Laboratory	Field	Other (numerical applications)	
<i>Pieve di Cento (liquefaction)</i>	Sand	P	I - R	-	IPS	Upgrade of triaxial apparatus	-	-

Table 8 Summary table of the main characteristics of the NFL related to liquefaction instabilities

5. Inventory of auxiliary equipment for further insights into ground instabilities

Within the framework of the Return Project, a set of auxiliary instruments has been procured with the purpose of complementing the monitoring activities previously delineated and of improving the hydraulic and mechanical characterization of soils affected by the identified ground instabilities.

Table 9 provides a concise summary of the partner responsible for the acquisition, a description of each instrument, its specific applications within the Return Project, and the corresponding Work Packages in which it will be deployed.

Monitoring activity				Soil characterization			
Partner	Equipment description	Application within Return	Involved WP	Partner	Equipment description	Application within Return	Involved WP
UniBo	Interferometric radar	expected use at multiple sites	WP2	UniGe	Triaxial apparatus	Laboratory mechanical characterization of the soil	WP2
PoliTo	Seismic sensor nodes	Monitoring of landslides (temporary NFL of Madonna del Sasso)	WP3-WP4	UniNa	Triaxial apparatus	Laboratory mechanical characterization of the soil	WP5
UniPd	Drone	drone-based surveys at multiple sites	WP2-WP4	UniPa	Triaxial apparatus	Laboratory mechanical characterization of the soil	WP5
UniPa	Laser scanner	expected use at multiple sites	WP2-WP3-WP4	Sapienza	Prototype device for uniaxial compression and shear tests	Laboratory mechanical characterization of the soil	WP3-WP4
Sapienza	Prototype device for GNSS monitoring	expected use at near shore sites	WP3-WP4	UniPd	Permeameter	Field hydraulic characterization of the soil	WP2
UniFi	Radar	expected use at multiple sites	WP2-WP3-WP4				
UniNa	Radar, weather station, laser scanner, seismic sensors, pressure transducers and strain gauge	Devices are to be installed at the Pennadomo site	WP2-WP4-WP5				

Table 9 Summary table of auxiliary equipment

It is noteworthy that the majority of the acquisitions were directed toward equipment that complements the monitoring activities previously documented in Appendices A and B. A single case

pertains to the implementation of instrumentation for the monitoring of atmospheric and hydrological variables, as well as radar sensors, at the Pennadomo site.

Conversely, several partners procured instruments specifically intended for the characterization of soils, addressing both mechanical and hydraulic properties. Equipment designated for mechanical characterization is predominantly suited for laboratory-based investigations, whereas instruments for hydraulic characterization are generally applicable to in situ testing. Furthermore, the table highlights that the acquired instruments are utilized across nearly all Work Packages within the VS2 spoke, underscoring their broad applicability within the project framework.

Further details regarding the auxiliary equipment are given in the **Appendix C**.

6. Conclusions

This document presents the activities conducted within Task 1 of Work Package 5, Spoke 2 “Ground Instabilities”. The work focuses on mitigation solutions for ground-instability phenomena.

An initial classification of the relevant types of instability is provided, followed by an in-depth analysis of mitigation strategies, conventionally categorized into active (preventive) and passive (protective) measures.

A concise review of the natural laboratories (NFLs) developed within the RETURN project is then presented. For each case, a classification is proposed based on the instability mechanism, the type of material involved, the spatial scale of influence, and the environmental setting. The mitigation strategies adopted at each site have been examined and described.

It emerged that most of the natural laboratories—regardless of the specific type of ground instability—were equipped with non-structural mitigation measures, primarily consisting of monitoring systems. Only a limited number of laboratories included structural interventions.

Within RETURN, several monitoring systems were upgraded, while for other NFLs the mechanical characterization of the materials involved in the instability processes was further investigated through laboratory testing. Auxiliary equipment purchased for the same aim was collected as well.

Finally, it is noted that most of the natural laboratories were proposed with the primary aim of improving the understanding of the underlying mechanisms of instability. Only a few cases include monitoring activities explicitly intended for the calibration of early-warning systems.

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Appendix A

This appendix presents the collection of summary sheets prepared for each Natural Field Laboratory
(

GENERAL CLASSIFICATION				PROPOSED NATURAL FIELD LABORATORIES (#12)				
				LEARNING EXAMPLE (DELIVERABLE 2.2.1, Fanti et al.)				
				FURTHER INSIGHT INTO THE PHENOMENON				
				INNOVATIVE SENSOR/INFRASTRUCTURE (DELIVERABLE 2.3.2, Colombero et al.)				
GROUND INSTABILITIES	Subaerial Landslides	Subaerial Slow Landslides Typologies	Slow Flows (Earthflows)	Pietrapertosa (UNINA)				
			Slow Slides (Rotational and planar Slides, Soil slips)	Fantoni (UNIPD)	Perarolo (UNIPD)	Val Paradisi (UNIPD)	Fossa Bradanica (UNIBA)	Cerda (UNIPA)
			Slow Spread & Slow Slope Deformations (Spread (except Liquefaction), Rock/Soil Slope Deformations, Creep, DsGSD)					
		Subaerial Rapid Landslides Typologies	Rapid Flows (Debris flows, Mudflows)	Messina (ENEA)	Ischia (UNINA)			
			Rapid Slides (Rock Slides, Rock Avalanches)					
			Falls & Topples (Rock Falls, Rock Topples)	Acuto (UNIROMA1)	Poggio Baldi (UNIROMA1)	Cuma (UNINA)		
	Submarine landslides	Submarine Landslides Typologies	Canyon head Landslides					
			Inner shelf/ Insular shelf Landslides					
	Sinkholes	Slow Sinkholes Typologies	Slow Sinkholes (All Types)					
		Rapid Sinkholes Typologies	Rapid Sinkholes (All types)					
	Subsidence	Subsidence Typologies	Subsidence (All types)					
	Liquefaction	Liquefaction Typologies	Liquefaction (All types)	Pieve di Cento (UNINA)				

Table 5), compiled by the respective proposing partner.

Each sheet also lists the members involved in the RETURN project, with core members indicated in bold and aggregated members in italics.

***RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Insights from learning examples

<u>Partner</u>	University or Organization
	University of Naples
<u>Authors and bibliography</u>	Authors involved and papers published on the topic (<i>indicate involvement in RETURN</i>) Coppola L., Silvestri F., Pagano L. Coppola L., Pagano L., Urciuoli G., Silvestri F. (2024) – Monitoraggio della suzione e dei movimenti superficiali di una colata in argilla: primi risultati Incontro annuale dei Ricercatori di Geotecnica (4-5-6/09/2024 Gaeta) ISBN: 9 788897 517191 Coppola L., Picarelli L., Urciuoli G., Pagano L. (2023) – Earthflow movement styles. An experience from southern Italy. 2nd Mediterranean Symposium on Landslides Coppola, L., Reder, A., Tarantino, A., Mannara, G., & Pagano, L. (2022). Pre-failure suction-induced deformation to inform early warning of shallow landslides: Proof of concept at slope model scale. <i>Engineering Geology</i>, 309, 106834.
<u>Localization of Learning Example</u>	Name of area
	Pietrapertosa (PZ)
<u>Context</u>	M – mountain, H – hill, P – plain, C – coast
	H
<u>Scale</u>	L – local, I – intermediate, R – regional
	L
<u>Mechanism</u>	Slow landslides, Debris flows, Rock collapses, Sinkholes (specify if urban/extra-urban areas and anthropic/natural instability factors), Liquefaction, etc.
	Slow landslide, previously quiescent and reactivated in 2019. It is severely damaging the SP13 provincial road that connects the village of Pietrapertosa to the Basentana national road.
<u>Involved material</u>	Report soil classification and main geotechnical characteristics (if available)
	Highly fissured stiff clays
<u>Existing remedial measures against ground instabilities</u>	Increase in shear strength, decrease in acting forces, improvement of physical properties and/or state conditions, monitoring of suitable physical properties



	Decrease in acting forces: bulkhead Monitoring of suitable physical properties: piezometers, inclinometers
<u>Upgrade of remedial measures against ground instabilities</u>	Main deficit of remedial measures and suggested additional solutions
	Measurement points have to be increased in number, with the aim of monitoring several depths. A weather station may be installed in order to monitoring even meteorological forcing.
<u>Monitoring systems</u>	Hydro-mechanical and meteorological variables recorded (specify if pre- and/or post- remediation)
	Pore water pressure and shallows displacements were monitored using the tensio-inclinometer
<u>Numerical applications carried out</u>	Aim of the numerical work, adopted code, preliminary results
	-
Notes	Specify any resources supported by RETURN
	The monitoring site was upgraded with tension-inclinometers (Coppola e al., 2022), purchased using RETURN funds

**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Insights from learning examples

<u>Partner</u>	University or Organization
	University of Padova – 1 st test site
<u>Authors and bibliography</u>	Authors involved and papers published on the topic (<i>indicate involvement in RETURN</i>) Cola S., Brezzi L. <i>Brezzi L., Fabbian N., Schenato L., Scala A., Cola S. (2024). Distributed Optical Fiber-Based Monitoring of Smart Passive Anchors for Soil Stabilization. SMAR 2024 – 7th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures. Salerno. https://doi.org/10.1016/j.prostr.2024.09.413</i> <i>Brezzi L., Tedesco G., Bisson A., Palmieri L., Cola S., Schenato L. (2022). Smart soil composite anchors for landslide remediation and monitoring. Optics InfoBase Conference Papers, https://dx.doi.org/10.1364/OFS.2022.W4.13</i> <i>Brezzi L. et al. (2022). Strain development measured with DFOS in experimental passive anchors used for landslide stabilization. 11th IS on Field Monitoring in Geomechanics, Ed. A.M. Ridley. London (UK). https://www.issmge.org/publications/publication/strain-development-measured-with-dfos-in-experimental-passive-anchors-used-for-landslide-stabilization</i> <i>Brezzi, L. et al. (2020). Digital Terrestrial Stereo-Photogrammetry for Monitoring Landslide Displacements: A Case Study in Recoaro Terme (VI). In: Calvetti, F., Cotecchia, F., Galli, A., Jommi, C. (eds) Geotechnical Research for Land Protection and Development. CNRIG 2019. Lecture Notes in Civil Engineering, vol 40. Springer, Cham. https://doi.org/10.1007/978-3-030-21359-6_17</i>
<u>Localization of Learning Example</u>	Name of area
	Fantoni Landslide (Recoaro Terme, Vicenza)
<u>Context</u>	M – mountain, H – hill, P – plain, C – coast
	M
<u>Scale</u>	L – local, I – intermediate, R – regional
	L
<u>Mechanism</u>	Slow landslides, Debris flows, Rock collapses, Sinkholes (specify if urban/extra-urban areas and anthropic/natural instability factors), Liquefaction, etc.

	Slow landslide formed by a rotational slide in the upper part and a creeping traslation in the lower part. Te Authors considered the Recoaro Terme municipality (North-East of Italy), known as Fantoni landslide. The observed slope movements are primarily driven by water infiltration and circulation and lithological weakness of the superficial materials relative to the bedrock.
<u>Involved material</u>	Report soil classification and main geotechnical characteristics (if available) Colluvium on a bedrock composed by Limestone and Porphyritis
<u>Existing remedial measures against ground instabilities</u>	Increase in shear strength, decrease in acting forces, improvement of physical properties and/or state conditions, monitoring of suitable physical properties 2009: One structural well in the upper zone and drainage trench in the lower zone; 2015: Three structural wells and anchored piles in the upper zone; 2020: Test site constituted by 6 Composite anchors equipped with Distributed optical fiber sensors (DFOSs) in the lower zone
<u>Upgrade of remedial measures against ground instabilities</u>	Main deficit of remedial measures and suggested additional solutions Even if the wells and the anchored piles improved the stability in the upper zone, the landslide is not completely stabilized, as a matter of fact, the intervention in the lower portion moves at 40 cm/year. The composite anchors are a pilot test performed for research. In the next future a real intervention with composite anchors is going to be realized.
<u>Monitoring systems</u>	Hydro-mechanical and meteorological variables recorded (specify if pre- and/or post- remediation) Monitoring has been carried out in some periods but with different systems in time: - topographic survey in 2009-2018; - few piezometers and extensometers in 2015-2018 and since 2024 to date; - digital photogrammetry and some laser scanner acquisitions in 2019-2021; - DFOS inside the composite anchors 2020-2024; - one fixed inclinometer in 2020-2024; - removable inclinometers in 2020 and from 2024.
<u>Numerical applications carried out</u>	Aim of the numerical work, adopted code, preliminary results None, only Stability analysis with LEM
<u>Notes</u>	Specify any resources supported by RETURN None

**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Insights from learning examples

<u>Partner</u>	University or Organization
	University of Padova – 2 nd test site
<u>Authors and bibliography</u>	Authors involved and papers published on the topic (<i>indicate involvement in RETURN</i>)
	Cola S., Brezzi L. Liu Y., Brezzi L., Liang Z., Gabrieli F., Zhou Z., Cola S. (2024), Image analysis and LSTM methods for forecasting surficial displacements of a landslide triggered by snowfall and rainfall. Landslides doi: 10.1007/s10346-024-02328-3. Brezzi, L.; Gabrieli, F.; Vallisari, D.; Carraro, E.; Pol, A.; Galgaro, A.; Cola, S. (2024). DIPHORM: An Innovative DIGital PHOtogrammetRIC Monitoring Technique for Detecting Surficial Displacements of Landslides. Remote Sens., 16, 3199. https://doi.org/10.3390/rs16173199. Brezzi L. et al. (2021). Post-collapse evolution of a rapid landslide from a sequential analysis with a FE and a SPH-based models. Geosciences, 11, 364. https://doi.org/10.3390/geosciences11090364. Teza, G. et al. (2022). Wadenow: a matlab toolbox for early forecasting of the velocity trend of a rainfall-triggered landslide by means of continuous wavelet transform and deep learning. Geosciences, 12, 205. https://doi.org/10.3390/geosciences12050205.
<u>Localization of Learning Example</u>	Name of area
	Perarolo Landslide (Perarolo, Belluno)
<u>Context</u>	M – mountain, H – hill, P – plain, C – coast
	M
<u>Scale</u>	L – local, I – intermediate, R – regional
	L
<u>Mechanism</u>	Slow landslides, Debris flows, Rock collapses, Sinkholes (specify if urban/extra-urban areas and anthropic/natural instability factors), Liquefaction, etc.
	Slow landslide formed by a rotational slide. Activation in 1986.
<u>Involved material</u>	Report soil classification and main geotechnical characteristics (if available)
	Detrital colluvium on a bedrock composed by Limestone with Gypsum layers (Travenanzes Unit) and Dolomite



<u>Existing remedial measures against ground instabilities</u>	Increase in shear strength, decrease in acting forces, improvement of physical properties and/or state conditions, monitoring of suitable physical properties
	Old intervention: Anchored micropiles and groups of micropiles and Jet-grouting columns
<u>Upgrade of remedial measures against ground instabilities</u>	Main deficit of remedial measures and suggested additional solutions
	The intervention carried out in the past are completely destroyed by the the slope movements caused by gypsum dissolution
<u>Monitoring systems</u>	Hydro-mechanical and meteorological variables recorded (specify if pre- and/or post- remediation)
	- Extensometers, a GPS receiver, and two inclinometers installed in 2000 (inclinometers damaged quite immediately); - Automatic topographic survey from 2014; - Digital Photogrammetry in 2021-2022, Gb-SAR in 2021-2023.
<u>Numerical applications carried out</u>	Aim of the numerical work, adopted code, preliminary results
	Stability analysis with 3D-FEM (MIDAS) and propagation analysis with SPH (Geo-Madrid) to evaluate the area interested by a possible total collapse.
Notes	Specify any resources supported by RETURN
	None

**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Insights from learning examples

<u>Partner</u>	University or Organization
	University of Padova – 3 rd test site
<u>Authors and bibliography</u>	Authors involved and papers published on the topic (<i>indicate involvement in RETURN</i>)
	Cola S., Brezzi L. <i>Brezzi L., Fabbian N., Schenato L., Scala A., Cola S. (2024). Distributed Optical Fiber-Based Monitoring of Smart Passive Anchors for Soil Stabilization. SMAR 2024 – 7th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures. Salerno. https://doi.org/10.1016/j.prostr.2024.09.413</i> <i>Brezzi L., Tedesco G., Bisson A., Palmieri L., Cola S., Schenato L. (2022). Smart soil composite anchors for landslide remediation and monitoring. Optics InfoBase Conference Papers, https://dx.doi.org/10.1364/OFS.2022.W4.13</i> <i>Brezzi L. et al. (2022). Strain development measured with DFOS in experimental passive anchors used for landslide stabilization. 11th IS on Field Monitoring in Geomechanics, Ed. A.M. Ridley. London (UK). https://www.issmge.org/publications/publication/strain-development-measured-with-dfos-in-experimental-passive-anchors-used-for-landslide-stabilization</i>
<u>Localization of Learning Example</u>	Name of area
	Val Paradisi Landslide (Ponte delle Alpi, Belluno)
<u>Context</u>	M – mountain, H – hill, P – plain, C – coast
	M
<u>Scale</u>	L – local, I – intermediate, R – regional
	L
<u>Mechanism</u>	Slow landslide, Debris flows, Rock collapses, Sinkholes (specify if urban/extra-urban areas and anthropic/natural instability factors), Liquefaction, etc.
	Slow landslides formed by a roto-translational slide in extra urban area. Activation in 2014, due to poor geotechnical properties, high water content at the moraine-Flysch interface, steep gradients and intense precipitation
<u>Involved material</u>	Report soil classification and main geotechnical characteristics (if available)



	Detrital colluvium on a bedrock composed by Flysch
<u>Existing remedial measures against ground instabilities</u>	Increase in shear strength, decrease in acting forces, improvement of physical properties and/or state conditions, monitoring of suitable physical properties 2023: Longitudinal and upper drainage trenches; 2024: 42 Composite anchors distributed on the landslide, 3 of them equipped with DFOS; 2024: removable inclinometers
<u>Upgrade of remedial measures against ground instabilities</u>	Main deficit of remedial measures and suggested additional solutions No deficit at the moment.
<u>Monitoring systems</u>	Hydro-mechanical and meteorological variables recorded (specify if pre- and/or post- remediation) Fixed inclinometers from 2023.
<u>Numerical applications carried out</u>	Aim of the numerical work, adopted code, preliminary results None, only Stability analysis with LEM
<u>Notes</u>	Specify any resources supported by RETURN None

**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Insights from learning examples

<u>Partner</u>	University or Organization
	University of Bari
<u>Authors and bibliography</u>	Authors involved and papers published on the topic (<i>indicate involvement in RETURN</i>)
	Capolongo, D., Marsico, A. Marsico, A., De Santis, V., Capolongo, D. (2021). Erosion Rate of the Aliano Biancana Badlands Based on a 3D Multi-Temporal High-Resolution Survey and Implications for Wind-Driven Rain. Land. 10. 828. 10.3390/land10080828. Refice A., Partipilo, L., Bovenga, F., Lovergine F.P., Nutricato, R., Nitti, D.O., Capolongo, D. (2022). Remotely Sensed Detection of Badland Erosion Using Multitemporal InSAR," IGARSS 2022 - 2022 IEEE International Geoscience and Remote Sensing Symposium, Kuala Lumpur, Malaysia, 2022, pp. 5989-5992, doi: 10.1109/IGARSS46834.2022.9883555. Gallicchio S., Colacicco R., Capolongo D., Girone A., Maiorano P., Marino M. & Ciaranfi N., 2023. Geological features of the Special Nature Reserve of Montalbano Jonico Badlands (Basilicata, Southern Italy), Journal of Maps, DOI: 10.1080/17445647.2023.2179435 Lazzari M., Piccarreta M. & Capolongo D., 2013, Landslide Triggering and Local Rainfall Thresholds in Bradanic Foredeep, Basilicata Region (Southern Italy). In: Margottini, C., Canuti, P., Sassa, K. (eds) Landslide Science and Practice. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-31445-2_88
<u>Localization of Learning Example</u>	Name of area
	Fossa Bradanica (bradanic foredeep)
<u>Context</u>	M – mountain, H – hill, P – plain, C – coast
	H
<u>Scale</u>	L – local, I – intermediate, R – regional
	I – L
<u>Mechanism</u>	Slow landslides, Debris flows, Rock collapses, Sinkholes (specify if urban/extra-urban areas and anthropic/natural instability factors), Liquefaction, etc.
	Slow landslide, extra urban area, natural instability factors



<u>Involved material</u>	Report soil classification and main geotechnical characteristics (if available)
	Silty clay, consolidated deposit
<u>Existing remedial measures against ground instabilities</u>	Increase in shear strength, decrease in acting forces, improvement of physical properties and/or state conditions, monitoring of suitable physical properties
	Topographic surveys by the use of TLS (Terrestrial Laser Scanner) since 2006 and UAV (Unmanned Aerial Vehicle) since 2019
<u>Upgrade of remedial measures against ground instabilities</u>	Main deficit of remedial measures and suggested additional solutions
	No upgrade made with further remedial measures but the monitoring thought TLS and UAV is still ongoing
<u>Monitoring systems</u>	Hydro-mechanical and meteorological variables recorded (specify if pre- and/or post- remediation)
	Erosion rate and topographic surveys
<u>Numerical applications carried out</u>	Aim of the numerical work, adopted code, preliminary results
	DEM of difference for topographical change detection
Notes	Specify any resources supported by RETURN
	TLS and SCENE software for point cloud processing

**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Insights from learning examples

<u>Partner</u>	University or Organization
	University of Palermo
<u>Authors and bibliography</u>	Authors involved and papers published on the topic (<i>indicate involvement in RETURN</i>)
	<i>Rosone M., Ziccarelli M., Ferrari A.</i> <i>Rosone, M., Ziccarelli, M., Ferrari, A., & Farulla, C. A. (2018). On the reactivation of a large landslide induced by rainfall in highly fissured clays. Engineering Geology, 235, 20-38</i>
<u>Localization of Learning Example</u>	Name of area
	Cerda (Palermo)
<u>Context</u>	M – mountain, H – hill, P – plain, C – coast
	H
<u>Scale</u>	L – local, I – intermediate, R – regional
	L
<u>Mechanism</u>	Slow landslides, Debris flows, Rock collapses, Sinkholes (specify if urban/extra-urban areas and anthropic/natural instability factors), Liquefaction, etc.
	Slow landslide in extra urban area, triggered by rain-induced increase in pore water pressure
<u>Involved material</u>	Report soil classification and main geotechnical characteristics (if available)
	<u>Varicoloured Clay formation</u> <u>Geotechnical characteristics</u> At the meso-fabric scale the stiff and highly fissured clays include gravel, made of scales and calcilutite fragments, having dimensions equal to or lower than 1 cm. Natural water content w_n , liquid limit w_l and plasticity index PI range as follow: $w_n = 10\text{--}22\%$; $w_l = 44\text{--}93\%$; $PI = 26\text{--}68\%$. Generally, the clays have high plasticity and, with reference to their activity, are normal or active ($IA = 0.75\text{--}1.5$). Mean peak shearing resistance parameters: $c'_p = 5\text{--}50$ kPa; $\phi'_p = 22\text{--}23^\circ$ Residual shear strength parameters: $c'_r = 0$; $\phi'_r = 12\text{--}14^\circ$ In situ hydraulic conductivity is about 10^{-7} cm/s;
<u>Existing remedial measures against ground instabilities</u>	Increase in shear strength, decrease in acting forces, improvement of physical properties and/or state conditions, monitoring of suitable physical properties
	No structural measures were implemented



<u>Upgrade of remedial measures against ground instabilities</u>	Main deficit of remedial measures and suggested additional solutions
	None
<u>Monitoring systems</u>	Hydro-mechanical and meteorological variables recorded (specify if pre- and/or post- remediation)
	Monitoring system to record rainfall, pore water pressures, and deep and surficial displacements was carried out for a period of three years.
<u>Numerical applications carried out</u>	Aim of the numerical work, adopted code, preliminary results
	An analysis of the monitoring data collected made it possible to establish a quantitative correlation between cumulative rainfall, pore water pressures, and the activity of the landslides in this complex soil formation. Site-specific equations were calibrated to relate the 5-month cumulated rainfall to the pore water pressure variations and the displacement rate of the landslide. The following relationship, valid for the proposed tool named CA PA_5_WP3, where provided: $\Delta u_w = a \cdot CR^b + c$ $\dot{d} = e \cdot CR^f + g$ where: Δu_w (kPa) variation of pore water pressure measured near the sliding surface of the landslide body; CR (mm) cumulative rainfall in the preceding five months on the landslide body; $\dot{d}$ (mm/day) displacement velocity of the landslide body; $a, b, c, e, f,$ and g are fitting parameters.
Notes	Specify any resources supported by RETURN
	High-pressure triaxial compression cell for testing (up to 30 MPa) on clayey soils, with automatic control of strain (axial and radial) and applied stresses (cell pressure, back-pressure, and axial stress). The device is currently under calibration.

**RETURN Project | VS2 – Ground Instabilities |
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Insights from learning examples

<u>Partner</u>	University or Organization
	ENEA
<u>Authors and bibliography</u>	Authors involved and papers published on the topic (<i>indicate involvement in RETURN</i>)
	<i>Falconi L.M., Puglisi C., Screpanti A.</i> Napoli R., Crovato C., Falconi L. Gioè C. (2015). Soil water content and triggering of debris flows in the Messina area (Italy): preliminary remarks. Engineering Geology for Society and Territory – Volume 2, Landslide Processes. Springer International Publishing Switzerland, ISBN: 978-3-319-09057-3, pp. 2113-2117. https://link.springer.com/chapter/10.1007/978-3-319-09057-3_378
<u>Localization of Learning Example</u>	Name of area
	Messina
<u>Context</u>	M – mountain, H – hill, P – plain, C – coast
	H
<u>Scale</u>	L – local, I – intermediate, R – regional
	I
<u>Mechanism</u>	Slow landslides, Debris flows, Rock collapses, Sinkholes (specify if urban/extra-urban areas and anthropic/natural instability factors), Liquefaction, etc.
	Debris flows
<u>Involved material</u>	Report soil classification and main geotechnical characteristics (if available)
	Loam and sandy loam (according to United States Department of Agriculture soil taxonomy, USDA)
<u>Existing remedial measures against ground instabilities</u>	Increase in shear strength, decrease in acting forces, improvement of physical properties and/or state conditions, monitoring of suitable physical properties
	The area already hosted five existing geo-hydrological field laboratories, installed by ENEA under a previous program agreement. The previous installed field laboratories were equipped with rain gauge and FDR probes.
<u>Upgrade of remedial measures against ground instabilities</u>	Main deficit of remedial measures and suggested additional solutions
<u>Monitoring systems</u>	Hydro-mechanical and meteorological variables recorded (specify if pre- and/or post- remediation)



	Geo-hydrological field laboratory with: air thermometer, rain gauge, Casagrande piezometer, direct and undirect tensiometer, FDR probes
<u>Numerical applications carried out</u>	Aim of the numerical work, adopted code, preliminary results
	-
<u>Notes</u>	Specify any resources supported by RETURN
	All the devices were purchased using RETURN funds

**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Insights from learning examples

<u>Partner</u>	University or Organization
	University of Naples Federico II
<u>Authors and bibliography</u>	Authors involved and papers published on the topic (<i>indicate involvement in RETURN</i>)
	Coppola L., Pagano L., Pirone M., Silvestri F.
<u>Localization of Learning Example</u>	Name of area
	Ischia (Monte Vezzi)
<u>Context</u>	M – mountain, H – hill, P – plain, C – coast
	M
<u>Scale</u>	L – local, I – intermediate, R – regional
	I
<u>Mechanism</u>	Slow landslides, Debris flows, Rock collapses, Sinkholes (specify if urban/extra-urban areas and anthropic/natural instability factors), Liquefaction, etc.
	Rainfall-induced debris flows in extra-urban areas
<u>Involved material</u>	Report soil classification and main geotechnical characteristics (if available)
	Pyroclastic soils
<u>Existing remedial measures against ground instabilities</u>	Increase in shear strength, decrease in acting forces, improvement of physical properties and/or state conditions, monitoring of suitable physical properties
	-
<u>Upgrade of remedial measures against ground instabilities</u>	Main deficit of remedial measures and suggested additional solutions
<u>Monitoring systems</u>	Hydro-mechanical and meteorological variables recorded (specify if pre- and/or post- remediation)
	Monitoring of hydrological and meteorological variables
<u>Numerical applications carried out</u>	Aim of the numerical work, adopted code, preliminary results
	-
<u>Notes</u>	Specify any resources supported by RETURN
	The whole monitoring system (cloud service for the data transmission included) has been purchased within the Return project

**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Insights from learning examples

<u>Partner</u>	University or Organization
	University of Rome
<u>Authors and bibliography</u>	Authors involved and papers published on the topic (<i>indicate involvement in RETURN</i>) Martino S., Bozzano, F., Mazzanti, P. Fantini, A., Fiorucci, M., & Martino, S. (2017). Rock falls impacting railway tracks: detection analysis through an artificial intelligence camera prototype. <i>Wireless Communications and Mobile Computing</i>, 2017(1), 9386928. Fiorucci, M., Marmoni, G. M., Martino, S., & <i>Mazzanti, P.</i> (2018). Thermal response of jointed rock masses inferred from infrared thermographic surveying (Acuto test-site, Italy). <i>Sensors</i>, 18(7), 2221. Fiorucci, M., Martino, S., Bozzano, F., & Prestininzi, A. (2020). Comparison of approaches for data analysis of multi-parametric monitoring systems: insights from the Acuto test-site (Central Italy). <i>Applied Sciences</i>, 10(21), 7658. Grechi, G., Fiorucci, M., Marmoni, G. M., & Martino, S. (2021). 3D thermal monitoring of jointed rock masses through infrared thermography and photogrammetry. <i>Remote Sensing</i>, 13(5), 957. Marmoni, G. M., Fiorucci, M., Grechi, G., & Martino, S. (2020). Modelling of thermo-mechanical effects in a rock quarry wall induced by near-surface temperature fluctuations. <i>International Journal of Rock Mechanics and Mining Sciences</i>, 134, 104440. Qian, Y., Fiorucci, M., Marmoni, G. M., Li, Q., Hussain, Y., Grechi, G., & Martino, S. (2025). Impact of environmental stressors on jointed rock cliffs by acoustic emission sensing: Preliminary findings from the Acuto field laboratory (central Italy). <i>Rock Mechanics and Rock Engineering</i>, 58(2), 1549-1568.
<u>Localization of Learning Example</u>	Name of area
	Acuto test-site, Acuto (FR), Italy
<u>Context</u>	M – mountain, H – hill, P – plain, C – coast
	H
<u>Scale</u>	L – local, I – intermediate, R – regional
	L
<u>Mechanism</u>	Slow landslides, Debris flows, Rock collapses, Sinkholes (specify if urban/extra-urban areas and anthropic/natural instability factors), Liquefaction, etc.

	Rockfalls, topples, rock slides
<u>Involved material</u>	Report soil classification and main geotechnical characteristics (if available)
	Jointed micritic limestones
<u>Existing remedial measures against ground instabilities</u>	Increase in shear strength, decrease in acting forces, improvement of physical properties and/or state conditions, monitoring of suitable physical properties
	Monitoring suitable physical properties: -meteorological variables. -rock temperature -fracture water flow -heat flux -displacements. -strain. -acoustic emissions -seismic signals
<u>Upgrade of remedial measures against ground instabilities</u>	Main deficit of remedial measures and suggested additional solutions
	High-resolution seismic monitoring devices and dataloggers. Acquisition of 8-channel dynamic datalogger with internal amplifier and adapters (Firewire 1-KAB272-W-0-2, 1-CON-P1025, Quantumx 1-CX22B-W, QuantumX amplifier univ. (8), license CATMAN Easy). Acquisition of 16-channel dynamic datalogger with internal amplifier (MX1601B) and adapters, QuantumX: CX22B-W + catmanAP. Prototype uniaxial compression and shear apparatus for soil and rock under controlled thermal and humidity cyclic conditions to link natural-laboratories and in-house laboratories.
<u>Monitoring systems</u>	Hydro-mechanical and meteorological variables recorded (specify if pre- and/or post- remediation)
	Rainfall, humidity, wind speed and direction, air temperature
<u>Numerical applications carried out</u>	Aim of the numerical work, adopted code, preliminary results
	Thermomechanical numerical modelling to evaluate effects of near surface temperature fluctuations.
<u>Notes</u>	Specify any resources supported by RETURN
	New instrumental acquisition as listed in Remedial Measurements

**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Insights from learning examples

<u>Partner</u>	University or Organization
	Sapienza University of Rome
<u>Authors and bibliography</u>	Authors involved and papers published on the topic (<i>indicate involvement in RETURN</i>)
	Bozzano F., Della Seta M., Esposito C., Mazzanti P. Mastrantoni, G., Santicchia, G., Cosentino, A., Molinari, A., Marmoni, G. M., & Mazzanti, P. (2024). Automatic photomonitoring analysis for spatiotemporal evaluation of rockfall failure hazard. <i>Engineering Geology</i>, 339, 107662. Robiati, C., Mastrantoni, G., Francioni, M., Eyre, M., Coggan, J., & Mazzanti, P. (2023). Contribution of high-resolution virtual outcrop models for the definition of rockfall activity and associated hazard modelling. <i>Land</i>, 12(1), 191. Esposito, C., Di Luzio, E., Baleani, M., Troiani, F., Della Seta, M., Bozzano, F., & Mazzanti, P. (2021). Fold architecture predisposing deep-seated gravitational slope deformations within a flysch sequence in the Northern Apennines (Italy). <i>Geomorphology</i>, 380, 107629. Mazzanti, P., Caporossi, P., Brunetti, A., Mohammadi, F. I., & Bozzano, F. (2021). Short-term geomorphological evolution of the Poggio Baldi landslide upper scarp via 3D change detection. <i>Landslides</i>, 18(7), 2367-2381. Romeo, S., Cosentino, A., Giani, F., Mastrantoni, G., & Mazzanti, P. (2021). Combining ground based remote sensing tools for rockfalls assessment and monitoring: The Poggio Baldi Landslide Natural Laboratory. <i>Sensors</i>, 21(8), 2632.
<u>Localization of Learning Example</u>	Name of area
	Poggio Baldi (locality), Santa Sofia (FC), Northern Apennine, Italy
<u>Context</u>	M – mountain, H – hill, P – plain, C – coast
	H - M
<u>Scale</u>	L – local, I – intermediate, R – regional
	I
<u>Mechanism</u>	Slow landslides, Debris flows, Rock collapses, Sinkholes (specify if urban/extra-urban areas and anthropic/natural instability factors), Liquefaction, etc.
	Rock wedge failure, earth flow, rockfalls
<u>Involved material</u>	Report on soil classification and main geotechnical characteristics (if available)



	Flysch
<u>Existing remedial measures against ground instabilities</u>	Increase in shear strength, decrease in acting forces, improvement of physical properties and/or state conditions, monitoring of suitable physical properties
	Monitoring suitable physical properties: -metereological variables -displacements -seismo-acoustic signals -morphological changes
<u>Upgrade of remedial measures against ground instabilities</u>	Main deficit of remedial measures and suggested additional solutions
	• Ground based multiparametric monitoring system including strain gages, air thermo-hygrometers ATMOS-14, one TEROS21, Hydraulic Head and Matric suction, 5 soil moisture sensors Sensor, TEROS11. 4 Datalogger mod.ZL6 Zentra Cloud for earth slope failures. • Implementation of a lab-scale tilting flume-test apparatus with integrated mini-tensiometers and moisture sensors to link natural-laboratories and in-house laboratories. • New prototypal monitoring system consisting of High-resolution Multi-Channel interferometric ground radar system with Multiple-Input-Multiple-Output (MIMO) architecture with real-time digital beamforming (DBF) imaging capabilities, combined with an integrated optical camera • Technological prototype system consisting of two high-performance 4K cameras, integrated with a laser distance meter measurement system and remote control • Prototype system for a drone-based synthetic aperture radar interferometry system, with GNSS antenna
<u>Monitoring systems</u>	Hydro-mechanical and meteorological variables recorded (specify if pre- and/or post- remediation)
	Meteorological monitoring.
<u>Numerical applications carried out</u>	Aim of the numerical work, adopted code, preliminary results
Notes	Specify any resources supported by RETURN
	New instrumental acquisition as listed in Remedial Measurements

**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Insights from learning examples

<u>Partner</u>	University or Organization
	University of Naples Federico II
<u>Authors and bibliography</u>	Authors involved and papers published on the topic (<i>indicate involvement in RETURN</i>)
	Di Martire D., Calcaterra D., Coda S., Tufano R.
<u>Localization of Learning Example</u>	Name of area
	Cuma Archeological site
<u>Context</u>	M – mountain, H – hill, P – plain, C – coast
	P
<u>Scale</u>	L – local, I – intermediate, R – regional
	L
<u>Mechanism</u>	Slow landslides, Debris flows, Rock collapses, Sinkholes (specify if urban/extra-urban areas and anthropic/natural instability factors), Liquefaction, etc.
	Rock collapses (extra-urban areas and anthropic/natural instability factors),
<u>Involved material</u>	Report soil classification and main geotechnical characteristics (if available)
	Neapolitan Yellow Tuff formation (NYT)
<u>Existing remedial measures against ground instabilities</u>	Increase in shear strength, decrease in acting forces, improvement of physical properties and/or state conditions, monitoring of suitable physical properties
	Monitoring of deformations
<u>Upgrade of remedial measures against ground instabilities</u>	Main deficit of remedial measures and suggested additional solutions
<u>Monitoring systems</u>	Hydro-mechanical and meteorological variables recorded (specify if pre- and/or post- remediation)
	Monitoring of deformations
<u>Numerical applications carried out</u>	Aim of the numerical work, adopted code, preliminary results
	Plaxis, preliminary results of stability analysis of the tunnel
<u>Notes</u>	Specify any resources supported by RETURN

	Z+F IMAGER 5016A model, purchased within the framework of the RETURN Project on August 1st, 2024 (University of Naples Federico II payment order no. 89465/2024).
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**RETURN Project | VS2 – Ground Instabilities |
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Insights from learning examples

<u>Partner</u>	University or Organization
	University of Naples
<u>Authors and bibliography</u>	Authors involved and papers published on the topic (<i>indicate involvement in RETURN</i>)
	<i>Flora A., Mele L., Silvestri F.</i>
	<i>Flora, A., Chiaradonna, A., Bilotta, E., Fasano, G., Mele, L., Lirer, S., Pingue L. & Fanti, F. (2019). Field tests to assess the effectiveness of ground improvement for liquefaction mitigation. In Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions (pp. 740-752). CRC Press.</i>
	<i>Flora, A., Bilotta, E., Chiaradonna, A., Lirer, S., Mele, L., & Pingue, L. (2021). A field trial to test the efficiency of induced partial saturation and horizontal drains to mitigate the susceptibility of soils to liquefaction. Bulletin of Earthquake Engineering, 19, 3835-3864.</i>
<u>Localization of Learning Example</u>	Name of area
	Pieve di Cento
<u>Context</u>	M – mountain, H – hill, P – plain, C – coast
	P
<u>Scale</u>	L – local, I – intermediate, R – regional
	L-I
<u>Mechanism</u>	Slow landslides, Debris flows, Rock collapses, Sinkholes (specify if urban/extra-urban areas and anthropic/natural instability factors), Liquefaction, etc.
	Liquefaction
<u>Involved material</u>	Report soil classification and main geotechnical characteristics (if available)
	Sand
<u>Existing remedial measures against ground instabilities</u>	Increase in shear strength, decrease in acting forces, improvement of physical properties and/or state conditions, monitoring of suitable physical properties

	-
<u>Upgrade of remedial measures against ground instabilities</u>	Main deficit of remedial measures and suggested additional solutions
	-
<u>Monitoring systems</u>	Hydro-mechanical and meteorological variables recorded (specify if pre- and/or post- remediation)
	-
<u>Numerical applications carried out</u>	Aim of the numerical work, adopted code, preliminary results
	-
Notes	Specify any resources supported by RETURN
	Within the framework of the RETURN project, financial support was allocated for the upgrade of a triaxial testing apparatus for the characterization of soils under partially saturated conditions. The upgrade comprised the replacement of the top cap and load cell, and the check of the proper functioning of the electrical and pneumatic circuits.

Appendix B

This appendix presents the collection of detailed sheets prepared for each Natural Field Laboratory (



GENERAL CLASSIFICATION			PROPOSED NATURAL FIELD LABORATORIES (#12)					
			LEARNING EXAMPLE (DELIVERABLE 2.2.1, Fanti et al.)					
			FURTHER INSIGHT INTO THE PHENOMENON					
			INNOVATIVE SENSOR/INFRASTRUCTURE (DELIVERABLE 2.3.2, Colombero et al.)					
GROUND INSTABILITIES	Subaerial Landslides	Subaerial Slow Landslides Typologies	Slow Flows (Earthflows)	Pietrapertosa (UNINA)				
			Slow Slides (Rotational and planar Slides, Soil slips)	Fantoni (UNIPD)	Perarolo (UNIPD)	Val Paradisi (UNIPD)	Fossa Bradanica (UNIBA)	Cerda (UNIPA)
			Slow Spread & Slow Slope Deformations (Spread (except Liquefaction), Rock/Soil Slope Deformations, Creep, DsGSD)					
		Subaerial Rapid Landslides Typologies	Rapid Flows (Debris flows, Mudflows)	Messina (ENEA)	Ischia (UNINA)			
			Rapid Slides (Rock Slides, Rock Avalanches)					
			Falls & Topples (Rock Falls, Rock Topples)	Acuto (UNIROMA1)	Poggio Baldi (UNIROMA1)	Cuma (UNINA)		
	Submarine landslides	Submarine Landslides Typologies	Canyon head Landslides					
			Inner shelf/ Insular shelf Landslides					
	Sinkholes	Slow Sinkholes Typologies	Slow Sinkholes (All Types)					
		Rapid Sinkholes Typologies	Rapid Sinkholes (All types)					
Subsidence	Subsidence Typologies	Subsidence (All types)						
Liquefaction	Liquefaction Typologies	Liquefaction (All types)	Pieve di Cento (UNINA)					

Table 5), compiled by the respective proposing partner.

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WP5 “Outcomes for mitigation strategies”**

Aim of Natural Field Laboratory: INNOVATIVE SENSOR/INFRASTRUCTURE
(DELIVERABLE 2.3.2, Colombero et al.)

Partner:

University of Naples Federico II
Department of Civil, Building and Environmental Engineering (DICEA)

Test site:

Pietrapertosa (Basilicata region)

Brief description of ground instability, involved material, existing remedial measures against ground instabilities and aim of the new (or updated) measures

The Pietrapertosa landslide, on the way between the towns of Pietrapertosa and Castelmezzano (Figure 1a), was reactivated in December 2019, making several key road sections in the Basento river area almost inaccessible. For this reason, considerable efforts have been devoted to characterize its evolution and mechanical behaviour (Di Maio, 2025). From a geological perspective, the instability affects a stratigraphic sequence composed of Varicolored Clays resting on the Miocene Gorgoglione Flysch. The most recent event involved a landslide body approximately 350 m long and about 50 m wide on average, covering nearly 20,000 m² and exhibiting a mean slope gradient of roughly 15° (Fig. 1b). The landslide area extends across zones situated at different elevations, separated by Provincial Road 13. The presence of a row of concrete piles makes the two sections independent from one another.

It should be specified that the row of concrete piles proved ineffective in containing the displacements of the landslide mass.

To capture the landslide hydro-mechanical evolution, tensio-inclinometers were installed within the active sector (red curve in Figure 1b), enabling the combined measurement of pore-water pressure fluctuations and shallow ground displacements.

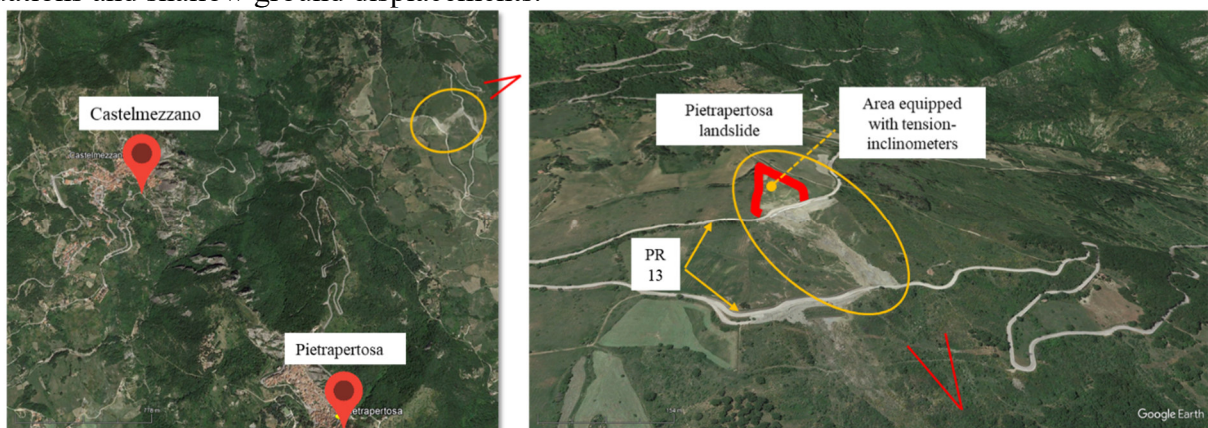


Figure 1: a) geographical setting of the landslide at the regional scale; b) landslide identification and monitoring system location

Design and construction details

The monitoring system integrates a conventional tensiometer—capable of measuring both negative and positive values of pore water pressure—with an accelerometer mounted at the top of the shaft to record its inclination (Coppola et al., 2022). The tensio-inclinometer (Figure 2) operates entirely wirelessly: power is supplied by an internal battery, and data are transmitted via a Wi-Fi connection. Since February 2025, three clusters of tensio-inclinometers have been installed along the longitudinal

axis of the landslide (Figure 3). Each cluster includes sensors positioned at depths of 15, 60, and 90 cm, all deployed through pressure insertion. Because no rain gauge is available directly at the landslide site, rainfall information was obtained from the Potenza meteorological station.

During the February–May monitoring period, the pore-water pressure response to rainfall proved to be remarkably rapid—contrary to what would normally be expected for a clayey deposit. This behaviour indicates a hydraulic conductivity significantly higher than typical clay values, likely attributable to shallow desiccation cracks visible at the ground surface, generated by pronounced reductions in near-surface pore-water pressures. Fluctuations associated with rainfall were most evident in the shallow instruments (15 cm), which recorded increasingly negative pore-water pressure values during dry periods (down to -60 kPa), followed by abrupt increases during rainfall events. Sensors installed at depths of 60 and 90 cm were less influenced by atmospheric changes, generally exhibiting values between -10 and 10 kPa. The tensiometers provide reliable pore-water pressure measurements down to approximately -70 kPa; beyond this threshold, re-saturation is required. As expected, this condition is reached first in the shallow sensors and later in those placed at greater depths. With respect to inclination measurements, no significant rotational variations associated with rainfall events were detected.

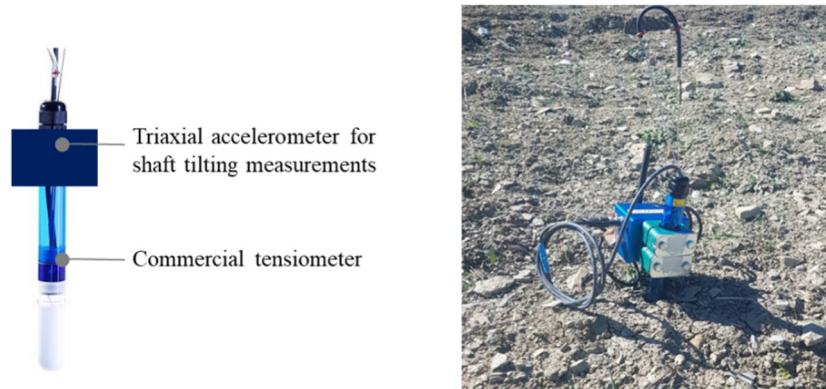


Figure 2: a) schematic layout of the tensio-inclinometer; b) installed tensio-inclinometer

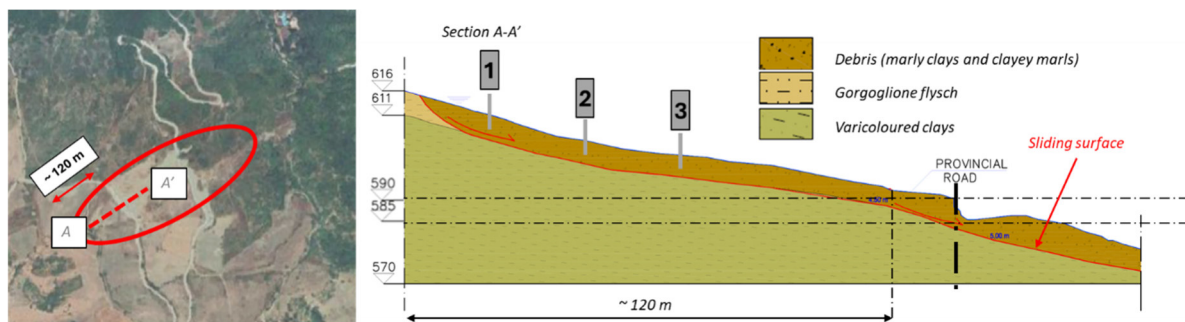


Figure 3: a) main section of the landslide body; b) geological section and tensio-inclinometers location

Numerical modelling

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Define the purpose of the natural laboratory: to gain insight into the phenomenon development or to assess the effectiveness of mitigation strategies

The Pietrapertosa natural laboratory was established with the aim of improving the understanding of the development mechanisms of earthflow-type phenomena. Given that this is a slow-moving landslide, the passive (non-structural) mitigation system implemented at the site enables the identification of potential correlations between atmospheric variables (rainfall) and the physical quantities monitored (pore-water pressure and near-surface kinematics).

Notes

Di Maio, C. (2025). Comportamento dei terreni argillosi e stabilità dei versanti in formazioni strutturalmente complesse. *Rivista Italiana di Geotecnica*: LIX, 1, 2025, 5-49.

Coppola, L., Reder, A., Tarantino, A., Mannara, G., & *Pagano, L.* (2022). Pre-failure suction-induced deformation to inform early warning of shallow landslides: proof of concept at slope model scale. *Engineering Geology*, 309, 106834.

RETURN Project | VS2 – Ground Instabilities | WP5 “Outcomes for mitigation strategies”

Aim of Natural Field Laboratory: FURTHER INSIGHT INTO THE PHENOMENON

Partner:

University of Padova
Department of Civil, Environmental and Architectural Engineering

Test site:

Fantoni landslide in Recoaro Terme municipality (Vicenza, North-East of Italy)

Brief description of ground instability, involved material, existing remedial measures against ground instabilities and aim of the new (or updated) measures

Fantoni landslide is active from 1975 and interesting colluvium material (mixture of gravel-sand and silty fraction) moving on a plastic layer of clayey soil, originated by the weathering of lower volcanic bedrock in an area rich of thermal groundwater. The area affected by movements encompasses a stretched surface of 57,000 m², divided into two sections by a provincial road (Figure 1) leading to a small village and a skiing area. The upstream section is characterized by a roto-traslational movement with a sliding surface approximately 40-45 m deep. The downstream section has a maximum width of about 90 m and extends in a west-east direction for approximately 350 m. This portion consists of a medium-slow translational soil mass moving over a stable bedrock situated at variable depth up to 8-12 m.

Between 2009 and 2015, four structural wells were built for stabilizing the upstream zone and a diaphragm wall, composed of bored piles anchored at the head, were partially constructed along the downstream sides of the road. Additionally, a longitudinal drainage trench, composed by polystyrene mats installed up to 1-2 m of depth, was realized along the downstream portion. The drainage trench proved insufficient to halt the movements in the downstream section, which continued to exhibit displacements of approximately 40-80 cm per year, depending on rainfall patterns.

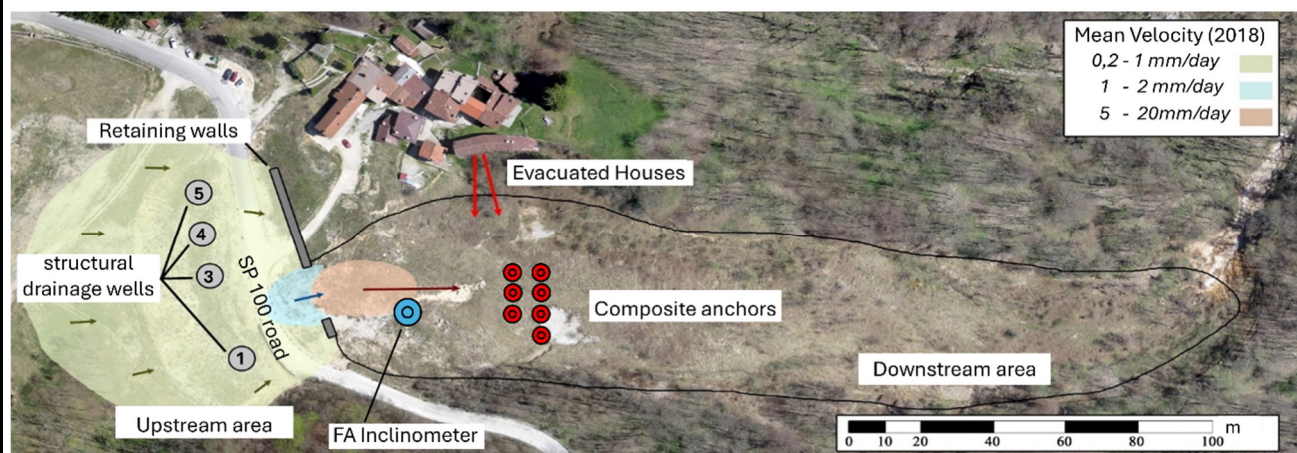


Figure 1. Landslide orthophoto with indication of the main structural and monitoring elements.

Design and construction details

In November 2020, the downstream section was selected as a suitable site for a test site in which seven experimental composite anchors were installed with the aim of studying their performance over time under ultimate limit state conditions. Sirive® Composite anchors (European Patent EP 2634313 B1) are self-drilling passive sub-horizontal reinforcements composed of 6 m long hollow carbon steel threaded rods, introduced in the soil with the self-drilling technique and connected one to each other with coupling nuts up to reach the desired installation depth (Bisson & Cola, 2014; Cola et al., 2019;

Brezzi et al., 2024). After the anchor installation, some tendons are introduced and cemented in the inner cavity to increase the overall traction resistance of the anchor. If the Composite anchor has to be used like a Smart anchor, (i.e. the anchor becomes a monitoring tool), a Distributed Optical Fiber Sensors (DOFS) for recording axial strain is introduced in the cavity together with the tendons.

In Figure 2, the respective lengths of the experimental anchors and their inclination angles with respect to the horizon are indicated. The lengths were adapted during perforation in order to penetrate at least for 8 m in the strong bedrock. The anchors are formed by a hollow bar of 76 mm with 4 tendons cemented inside. Six anchors (A.1 - A.6) were instrumented with a unique armoured corrugated optical fiber cable for strain measurement (BruSens® V9, Solifos), approximately 500 m long, introduced in the cavity together with the tendons.

The installation and grouting of the strands and DFOS in the cavity were completed on 1 December 2020. The reference measurement for all optical fibers was acquired on 2 December 2020. As of September 2025, 15 measurement campaigns have been carried out on anchors A.1–A.6 with the Brillouin Optical Frequency Domain Analyzer (BOFDA). Anchor A.0, also equipped with DFOS, was subjected to a pull-out test on 4 March 2021, after only three measurements were conducted on it. Thanks to the pull-out test on A.0 anchor and the strain measurements carried out in 5 years, the behaviour of these reinforcements could be well analysed. Moreover, the slope displacements are monitored with a fix inclinometer, installed just upstream the anchors, and with a photogrammetric system, properly developed for studying the evolution of slope characterized by medium-slow moving rate.

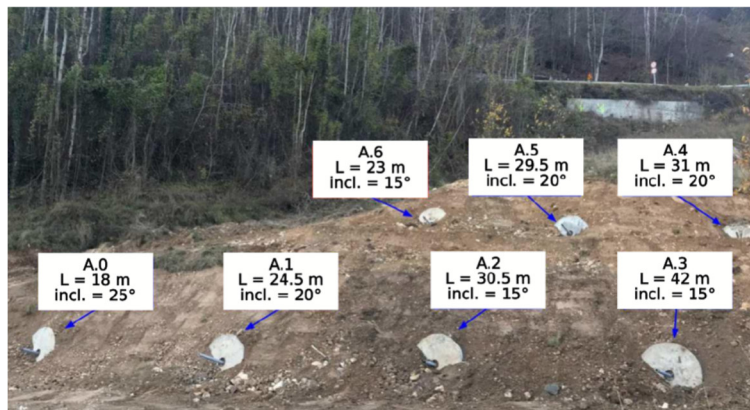


Figure 2: Smart soil anchors installed at Fantoni landslide

Numerical modelling

Some Limit Equilibrium Analyses were carried out for evaluating the possibility to stabilize the downstream portion of the slope. The axial strain data acquired on the experimental anchors permitted to calibrate the unitary pull-out resistance of the anchors.

Limit Equilibrium Analysis indicated that these experimental anchors would not be sufficient to stabilize the slope, and continued displacements were expected to eventually lead the anchors to failure.

Define the purpose of the natural laboratory: to gain insight into the phenomenon development or to assess the effectiveness of mitigation strategies

The main aim of this natural laboratory was to collect data about the interaction of these anchors with the ground when applied for the stabilization of moving slopes. The anchors installed in this site are under designed on purpose in order to evaluate the behaviour up to their failure.

The use of optical fiber sensors permitted to analyse the evolution of axial strain along the anchors with time in order to assess the effectiveness of the coupling of tendons with bar, and the capability of composite anchors in stabilizing the slope.

During 2025, the anchors gradually reached the traction failure and the slope returned to the previous moving rate.

This laboratory site started before the Return activity, but it continued during the project, giving important information about the long-term behaviour of passive anchors used in landslide stabilization.

Notes

Brezzi L., Fabbian N., Schenato L., Scala A., **Cola S.** (2024). Distributed Optical Fiber-Based Monitoring of Smart Passive Anchors for Soil Stabilization. SMAR 2024 – 7th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures. Salerno. <https://doi.org/10.1016/j.prostr.2024.09.413>

Brezzi L., Tedesco G., Bisson A., Palmieri L., **Cola S.**, Schenato L. (2022). Smart soil composite anchors for landslide remediation and monitoring. Optics InfoBase Conference Papers, <https://dx.doi.org/10.1364/OFS.2022.W4.13>

Brezzi L. et al. (2022). Strain development measured with DFOS in experimental passive anchors used for landslide stabilization. 11th IS on Field Monitoring in Geomechanics, Ed. A.M. Ridley. London (UK). <https://www.issmge.org/publications/publication/strain-development-measured-with-dfos-in-experimental-passive-anchors-used-for-landslide-stabilization>

Brezzi, L. et al. (2020). Digital Terrestrial Stereo-Photogrammetry for Monitoring Landslide Displacements: A Case Study in Recoaro Terme (VI). In: Calvetti, F., Cotecchia, F., Galli, A., Jommi, C. (eds) Geotechnical Research for Land Protection and Development. CNRIG 2019. Lecture Notes in Civil Engineering, vol 40. Springer, Cham. https://doi.org/10.1007/978-3-030-21359-6_17

**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Aim of Natural Field Laboratory: FURTHER INSIGHT INTO THE PHENOMENON

Partner:

University of Padova
Department of Civil, Environmental and Architectural Engineering

Test site:

Perarolo di Cadore village (Belluno)

Brief description of ground instability, involved material, existing remedial measures against ground instabilities and aim of the new (or updated) measures

The Sant'Andrea landslide (Figure 1), located in the municipality of Perarolo di Cadore (Belluno Province, northeastern Italian Alps), affects the left flank of the Boite River and represents a major hydrogeological hazard for the downstream village. The unstable sector forms part of a wider ancient slope deformation involving the southern flank of Mt. Zucco. Although instability signs have been documented since the late 20th century, landslide activity has intensified in recent years, with progressive acceleration and enlargement of the actively deforming area. Stabilization works carried out in the 1980s and 1990s proved only temporarily effective, as movements gradually resumed. Two smaller frontal portions, totaling about 3000 m³, were artificially collapsed using explosives.

In 2021, the landslide underwent a prolonged acceleration phase, mainly affecting the central sector. Following a wet spring, a rapid collapse of approximately 8000 m³ occurred in early June.

Geotechnical and geophysical investigations performed between 1997 and 2019 revealed that the landslide involves a ~30 m thick layer of calcareous debris overlying an evaporite-rich bedrock. The debris consists of a chaotic mixture of rock fragments within a silt-clay matrix and exhibits strong grain-size heterogeneity. The underlying bedrock corresponds to the Travenanzes Formation, a marly limestone sequence containing highly stratified, deformable anhydrite-gypsum levels disrupted by Alpine tectonics. The fractured upper bedrock exerts significant control on landslide kinematics, although the slip surface is not clearly restricted to a specific stratigraphic contact.

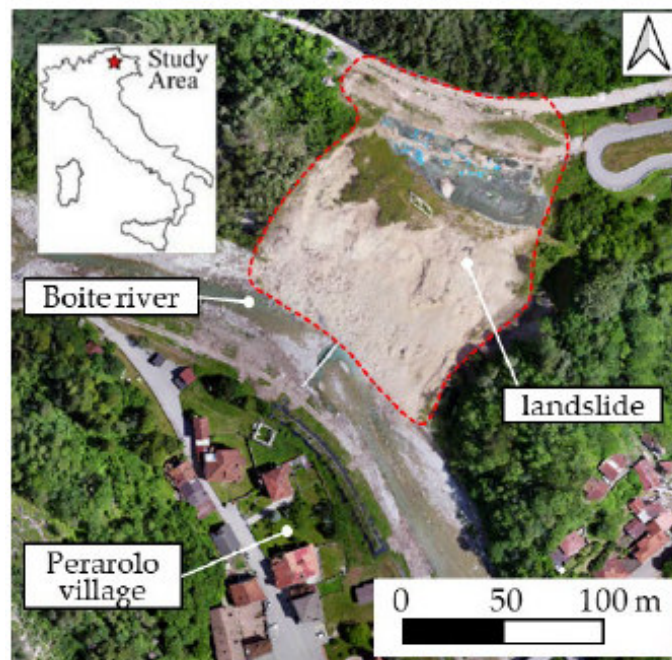


Figure 1: Aerial view of the Sant'Andrea landslide site and Perarolo di Cadore village (NE Italy)

Design and construction details

Although the earliest signs of movement date back to 1986, systematic monitoring of the landslide began only in the early 2000s, following the installation of several extensometers, a GPS receiver, and two inclinometers. The inclinometers subsequently became inoperative due to excessive deformation, and no replacements were installed thereafter. Since 2013, surface displacements have been tracked using a dedicated topographic monitoring system.

In 2021, a new photogrammetric monitoring system was implemented. The cameras were installed on the opposite side of the Boite Valley, directly facing the unstable slope sector, at an approximate distance of 350 m, as illustrated in Figure 2.



Figure 2: (a) Aerial view of the landslide with camera locations; (b,c) view of one of the monitoring systems; GPS surveys of (d) a corner and (e) a reference sphere, both located on the big scarp edge of the slope; and (f) laser scanning survey of the landslide.

Numerical modelling

Stability analysis with 3D-FEM (MIDAS) and propagation analysis with SPH (Geo-Madrid) to evaluate the area interested by a possible total collapse.

Define the purpose of the natural laboratory: to gain insight into the phenomenon development or to assess the effectiveness of mitigation strategies

The primary objective of this case study is to increase insight into this kind of phenomenon in particular into strengths and weaknesses of the photogrammetric system relative to the other conventional topographic methods.

Notes

Further details can be found in:

Brezzi, L., Gabrieli, F., Vallisari, D., Carraro, E., Pol, A., Galgaro, A., & Cola, S. (2024). DIPHORM: An Innovative DIGital PHOTogrammetRIC Monitoring Technique for Detecting Surficial Displacements of Landslides. *Remote Sensing*, 16(17), 3199.

**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Aim of Natural Field Laboratory: FURTHER INSIGHT INTO THE PHENOMENON

Partner:

University of Padova
Department of Civil, Environmental and Architectural Engineering

Test site:

Paradisi landslide in Ponte nelle Alpi municipality (Belluno)

Brief description of ground instability, involved material, existing remedial measures against ground instabilities and aim of the new (or updated) measures

This landslide, activated in 2014 on a quiescent movement (Figure 1), exhibits a complex mechanism: at the upper section, the movement is predominantly rotational; conversely, at the lower section, the phenomenon is characterized by the detachment of lobes that extend halfway down the slope. The landslide has an average width of approximately 115 m, a length of 200 m along the maximum slope gradient, and an estimated thickness ranging from 6 to 8 m. The estimated volume is about 200,000 m³ and is constituted by a soil, with a very high percentage of medium plasticity clay, generated by the Flysch alteration. Before its stabilization, the slope exhibited a movement rate of few cm per day, which led to the development of a distinct, visible fracture line upstream. This movement continued consistently until the initial phase of intervention conducted in the summer of 2022: it included a geometric profiling with a displacement of about 22,000 m³ and the installation of longitudinal drainage trenches up to 1.5-2 m deep. These measures resulted in a reduction in the rate of movement. To refine the geotechnical model and facilitate the application of the Observational Method, traditional instruments such as inclinometers and piezometers were newly installed in 2022. This enabled the reconstruction of a geotechnical model of the slope for the design of a second phase of interventions carried out in summer 2023. The second intervention focuses on the application of structural reinforcements to effectively contrast horizontal forces. In this context, passive anchors have been identified as one of the few viable solutions and the most economical one.



Figure 1: evolution of Paradisi landslide

Design and construction details

42 anchors were installed in 2023. As Figure 2 shows, the anchors are organized in five rows with an inter-anchor spacing of 8 m. The anchors were designed inclined at an angle of 15°-20° relatively to the horizontal plane, with a length of 30 m, ensuring a minimum embedment depth of 8 m into the stable bedrock. Equal to the Fantoni case, each anchor is composed by a Sirive® R76 Special bar containing four cemented tendons (Composite anchor). Three anchors (A1, A2, and A3) were instrumented with DFOS for strain measurement, employing a methodology analogous to that utilized in Fantoni landslide, while A1 was additionally equipped with DTS (optical cable sensor devoted to record temperature). To optimize operational efficiency, DTS and DFOS exiting from the anchors are prolonged with

transmission-only optical fibers, forming a closed-loop measurement system which can be interrogated from a position close to A1 along the road at the slope toe (Figure 2). The composite anchors were monitored using a Brillouin Optical Frequency Domain Analyzer (BOFDA), identical to the system adopted at the Fantoni landslide site. The boreholes S2, S4, and S5 are equipped with some fixed inclinometer installed at different elevations in the hole.

Displacement recorded from 2023 to date are limited to some millimetres, suggesting an overall slope stability. Only an accumulated movement of 10–15 mm was observed in the upper inclinometer at S5 at about 3m depth, but this displacement seems due to a small accumulation of material observed close S5, which led to the partial burial of the upper row of anchors.

The recorded strain at A1-A3 anchors are very low (Figure 3). Unlike the Fantoni landslide, where strain peaks of 3000–4000 $\mu\epsilon$ were measured within the first month due to the purpose limited number of anchors installed, the present dataset does not exceed 400–600 $\mu\epsilon$ over two years. As the elastic range of the bars is below 2300 $\mu\epsilon$, currently the reinforcement system is within the serviceability range and far from full mobilization. This quite negligible stress condition of the anchors is in agreement with the near-stable condition of the slope and to the fact that the first phase of remedial works has already stabilized the slope. In fact, for their activation passive anchors require some slope deformation, and this process has not yet occurred in a widespread or evident manner. These results, although collected over a quite extended period, should still be considered preliminary and not fully representative of the overall anchor behaviour.

The observed strains in the 3 monitored anchors show some differences mainly reflecting the progressive stabilization of the slope following the completion of mitigation interventions, although a slight increase in deformation, and therefore in load, is developing near A3. At present, however, no additional stabilization measures are required.

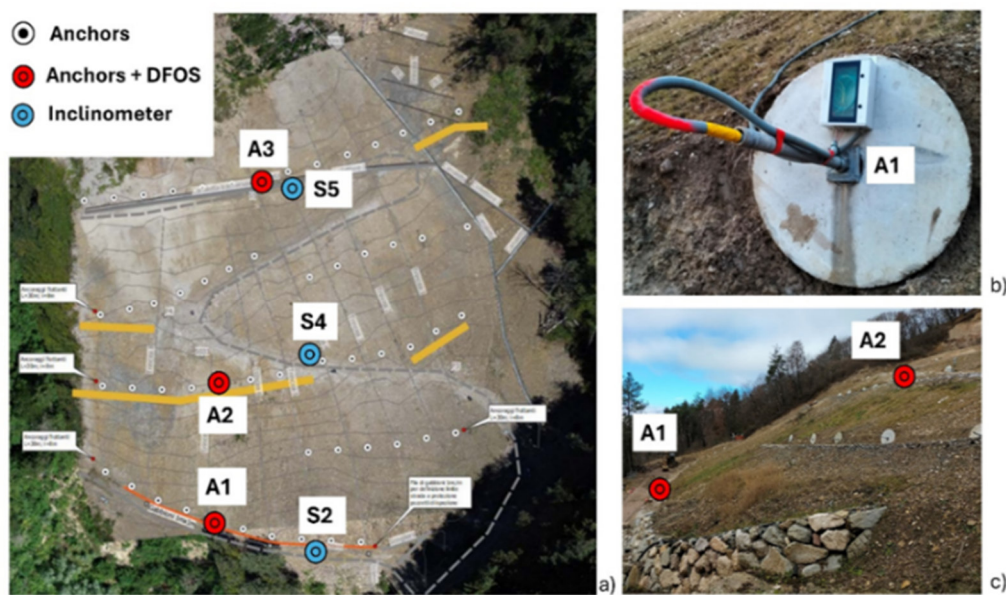


Figure 2: Composite Anchors: a) project configuration; b) Anchors n.1 (A1) monitored with DFOS after installation; c) Side overview at the end of second phase (Brezzi et al., 2024).

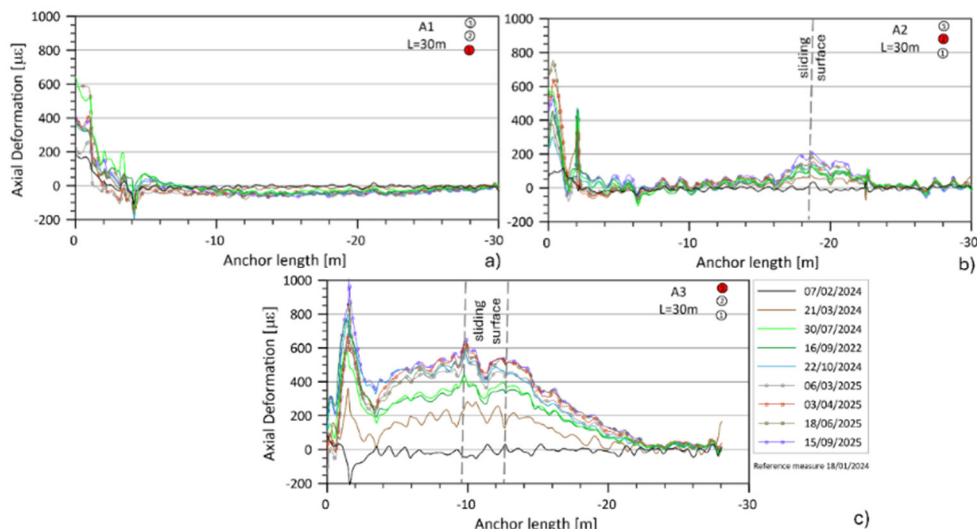


Figure 3: Strain measured in time [dd.mm.yyyy] in the instrumented anchors at Paradisi Landslide.

Numerical modelling

Limit Equilibrium and Finite Element Method analyses were carried out to design the mitigation measures. The axial strain data acquired during the monitoring activities will allow the unit pull-out resistance of the anchors to be calibrated in future analyses.

Define the purpose of the natural laboratory: to gain insight into the phenomenon development or to assess the effectiveness of mitigation strategies

The primary objective of this case study is to understand how an efficiently designed reinforcement system works. In this framework, optical fiber sensors were used to monitor the evolution of axial strain along the anchors and to estimate the actual load mobilized over time. According to the observational method, these measurements made it possible to assess whether additional anchors are required in the future to ensure adequate stability.

The data collected during the two years following installation showed that the implemented measures were sufficient to stabilize the landslide. No additional anchors were needed, which ultimately allowed the overall intervention costs to be optimized.

For improved background understanding, it is recommended to consult the WP5 report on Fantoni landslide in the Recoaro Terme municipality (North-East Italy).

Notes

Brezzi L., Fabbian N., Schenato L., Scala A., Cola S. (2024). Distributed Optical Fiber-Based Monitoring of Smart Passive Anchors for Soil Stabilization. SMAR 2024 – 7th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures. Salerno. <https://doi.org/10.1016/j.prostr.2024.09.413>

Brezzi L., Tedesco G., Bisson A., Palmieri L., Cola S., Schenato L. (2022). Smart soil composite anchors for landslide remediation and monitoring. Optics InfoBase Conference Papers, <https://dx.doi.org/10.1364/OFS.2022.W4.13>

Brezzi L. et al. (2022). Strain development measured with DFOS in experimental passive anchors used for landslide stabilization. 11th IS on Field Monitoring in Geomechanics, Ed. A.M. Ridley. London (UK). <https://www.issmge.org/publications/publication/strain-development-measured-with-dfos-in-experimental-passive-anchors-used-for-landslide-stabilization>

**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Aim of Natural Field Laboratory: LEARNING EXAMPLE (DELIVERABLE 2.2.1, Fanti et al.)

Partner:

University of Bari
Department of Earth and Environmental Sciences

Test site:

Fossa Bradanica (Bradanic Foredeep)

Brief description of ground instability, involved material, existing remedial measures against ground instabilities and aim of the new (or updated) measures

The test sites are located near the Aliano and Montalbano towns (Basilicata Region, Southern Italy) in a Badlands area where “calanchi” and “biancane” are the main geomorphic features. These sites are considered as highly unstable landscapes characterized by soft sedimentary rocks (silty clay, poorly consolidated deposit), sparse vegetation, and steep slopes.

Their fine-grained soils have low cohesion and permeability, making them extremely susceptible to water erosion during intense rainfall. Common ground instabilities include gully formation, rilling, small landslides, slumps, and piping, often triggered by intense rainfall. These processes lead to rapid surface deformation and continuous reshaping of the terrain.

We are monitoring slow landslides in extra urban area (Figure 1) occurring under natural instability factors. Particularly, we are surveying topographic changes and their relationship with meteorological variables such as rain, temperature and wind.

Periodically, we carry out monitoring tests by the use of Terrestrial Laser Scanner (TLS) and Unmanned Aerial Vehicle (UAV) to obtain high-detailed 3D model of the slopes and detect topographic changes that testify gradual mass movement and/or long-term terrain deformation.

Nowadays, no remedial measures against ground instabilities exists since surveys are still carrying. However, preliminary results show irregular slope changes depending on lithology, slope gradient, vegetation cover, and human activities at the slopes foot.



Figure 1: Badlands area near Aliano town (Basilicata, southern Italy) characterized by dome shaped Biancane

Design and construction details

The sites were surveyed by the use of UAV and TLS to integrate the UAV PCs with high-detailed TLS PCs. All datasets were collected at the same time.

The UAV acquisitions were performed with a DJI Mavic 3M, equipped with a 20 MP RGB camera and it was used to conduct flight missions at angles of 90° (ortho collection) and 45° (oblique collection); the flight height is 50 m in a E-W direction and 80% forward overlap.

DJI Terra and Agisoft Metashape were used for both RGB and LiDAR data processing: image post-processing followed the principles of Structure-from-Motion techniques (Figure 2). TLS data were collected with a FARO Laser Scanner Focus 3D that was positioned in several sites in and around each test site in order to cover the shadow areas. First dataset processing was done in FARO SCENE software while PCs registration, georeferencing, and dataset comparison were done using the Cloud Compare free software.



Figure 2: 3D model of study area derived from SfM

Numerical modelling

Post-processing of UAV images produced high detailed DEMs at 2.5 cm cell size. We compared multitemporal DSM derived from SfM processing of the test sites to obtain DEMs of Difference (DoD) by using the Geomorphic Change Detection (GCD) software. DoDs show pixels where deposition and erosion occur along slopes taking into account data processing errors. Data processing is affected by both systematic and random uncertainties such as georeferencing, reprojection and registration errors (varying from 1.5 to 7 cm) and we obtained the reduction of the total root mean square (RMS) error of the post-processing at about 2-3 cm.

The TLS dataset was processed to produce single slopes PCs and compare them in a multitemporal analysis. Point of Difference (PoD) allowed to investigate small topographic changes as result of low intensities rain events or wet/dry cycles.

Define the purpose of the natural laboratory: to gain insight into the phenomenon development or to assess the effectiveness of mitigation strategies

The purpose of this natural laboratory is to gain insights into the phenomenon development to assess the role of different parameters acting on the slope movements. Short-time monitoring of topographic changes can provide useful data for the detection of geomorphic processes involved in the erosion and sediment accumulation dynamics. The detected changes are in the validation phase thanks to further and more accurate surveys that can help to correlate them with weather events and better understand soil loss dynamics and sediment connectivity within the catchment.

Notes

Marsico, A., De Santis, V., **Capolongo, D.** (2021). Erosion Rate of the Aliano Biancana Badlands Based on a 3D Multi-Temporal High-Resolution Survey and Implications for Wind-Driven Rain. Land. 10. 828. 10.3390/land10080828.

Refice A., Partipilo, L., Bovenga, F., Lovergine F.P., Nutricato, R., Nitti, D.O., **Capolongo, D.** (2022). Remotely Sensed Detection of Badland Erosion Using Multitemporal InSAR," IGARSS 2022 - 2022 IEEE International Geoscience and Remote Sensing Symposium, Kuala Lumpur, Malaysia, 2022, pp. 5989-5992, doi: 10.1109/IGARSS46834.2022.9883555.



Gallicchio S., **Colacicco R.**, **Capolongo D.**, Girone A., Maiorano P., Marino M. & Ciaranfi N., 2023. Geological features of the Special Nature Reserve of Montalbano Jonico Badlands (Basilicata, Southern Italy), Journal of Maps, DOI: 10.1080/17445647.2023.2179435

Lazzari M., Piccarreta M. & **Capolongo D.**, 2013, Landslide Triggering and Local Rainfall Thresholds in Bradanic Foredeep, Basilicata Region (Southern Italy). In: Margottini, C., Canuti, P., Sassa, K. (eds) Landslide Science and Practice. Springer, Berlin, Heidelberg.
https://doi.org/10.1007/978-3-642-31445-2_88

**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Aim of Natural Field Laboratory: LEARNING EXAMPLE (DELIVERABLE 2.2.1, Fanti et al.)

Partner:

University of Palermo
Department of Civil, Environmental, Aerospace, Materials Engineering

Test site:

Cerda landslide (Palermo)

Brief description of ground instability, involved material, existing remedial measures against ground instabilities and aim of the new (or updated) measures

The Cerda landslide is located within a hilly landscape and affects an area of approximately 1.5 km² on the left slope of the Northern Imera River, in the municipality of Cerda (PA) (Figure 1). The main reactivation event occurred on September 6, 2002, following an earthquake with a magnitude of 5.6 on the Richter scale. This seismic event triggered a translational landslide characterized by slow movement with sliding surface located to a depth between 60 and 100 m (Agnesi et al, 2005). The landslide phenomenon affected two strategic water supply conduits, the old and the new Scillato aqueducts (one of the main drinking water Palermo city pipelines), and emerges near the Palermo-Catania highway. Following the seismic event, the area underwent periodic reactivations primarily linked to increases in pore water pressure induced by rainfall. The earthquake served as an exceptional triggering event that mobilized the entire landslide body, whereas subsequent reactivations were confined to specific sectors of the main landslide, exhibiting variations in both displacement rates and movement directions. The materials involved consist predominantly of highly fissured clays belonging to the Varicoloured Clay Formation (Figure 2), a lithological unit characterized by pronounced heterogeneity and a high susceptibility to slope instability. The alternation of clay layers with interbedded rock fragments and sandy inclusions gives rise to complex hydraulic and mechanical behaviours, manifested in the irregular distribution of pore water pressures and the intricate geometry of the sliding surface.

The landslide was investigated through an extensive field investigation campaign, complemented by a three-year monitoring program. To reconstruct the stratigraphic profiles of the landslide area and to identify the actual position of the landslide surface, 28 continuous-core boreholes were drilled to a maximum depth of 30 m, along with 30 exploratory trenches up to 5 m deep and approximately 10 seismic profiles.

For monitoring purposes, the following instruments were installed: 24 pairs of piezometers, 12 inclinometer tubes, 6 tensiometers, about 100 topographic benchmarks for surface displacement measurements using GPS technology, and one automatic rain gauge. Numerous soil samples were collected for geotechnical characterization. The landslide materials were tested through multiple direct shear and ring shear tests to determine peak and residual shear strength parameters, respectively. In situ permeability tests were also performed using the installed piezometers.

A detailed analysis was carried out to investigate the relationships between cumulative rainfall, variations in pore-water pressure caused by rainfall, and the resulting displacement rates within the landslide body, from which several correlations were derived.

The Cerda landslide was selected as a reference site, and previous investigations—together with the study of quantitative methods based on empirical relationships—were used to develop an analytical tool.

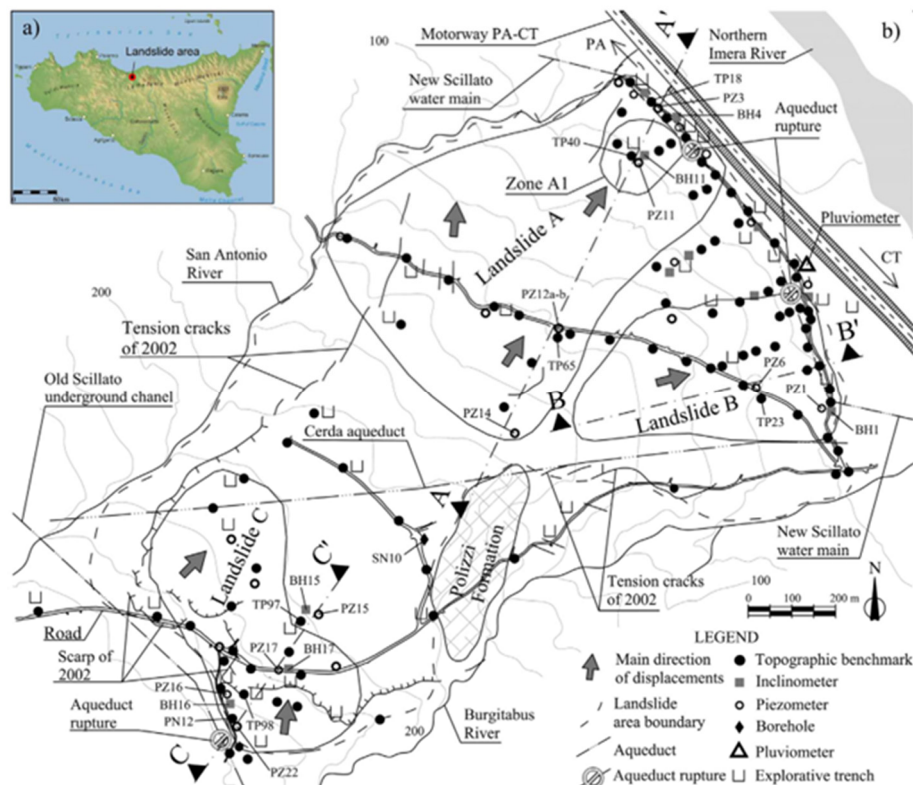


Figure 1. Sketch map of the landslide area. a) Location; (b) limits of the landslide area triggered by the September 6th, 2002 earthquake (within which landslides A, B and C reactivated by rainfall in the period 2008–2011 are drawn. Inside the landslide A has been detected a second shallow landslide indicated in the figure as zone A1). The figure shows the main “infrastructures” affected by the landslide, the monitoring system implemented in autumn 2008- late spring 2009 and the main geotechnical investigations performed (Rosone et al., 2018).

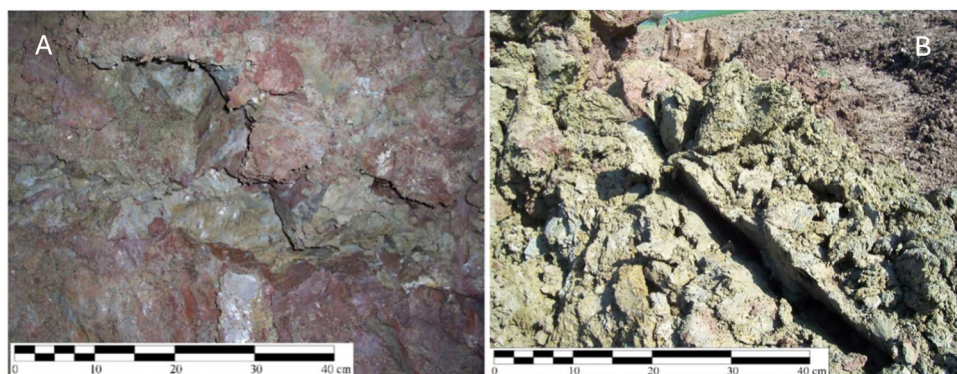


Figure 2. Varicoloured clay formation. a) remoulded clays, b) clay block through a sliding surface.

Design and construction details

The only intervention carried out concerned the repair of the Scillato water pipeline.

Numerical modelling

The case study involves numerical modelling through integrated back-analysis, using data collected from geotechnical investigations and samples taken along the landslide body. The geotechnical characterization of the materials was performed using direct shear tests, aimed at determining the shear strength parameters. The back-analysis was carried out applying the Spencer limit equilibrium method, assuming the piezometric line based on the measured piezometric head, the absence of seismic actions, and considering zero cohesion intercept. The results confirmed that these are

reactivated landslides, as the mean mobilized shear strength angle obtained from the back-analysis is very close to the residual shear strength angle measured by direct shear tests.

The relationships between cumulative rainfall, variations in pore water pressures due to rainfall, and variations in displacement rates caused by rainfall are site-specific, and the parameters were calibrated following the period of field monitoring. This method can be used to predict future process development scenarios from data calibrated over a monitoring period. In particular site-specific equations are available to relate the 5-month cumulated rainfall to the pore water pressure variations and the displacement rate of the landslide.

The following relationships were provided:

$$\Delta u_w = a \cdot CR^b + c \quad (1)$$

$$\dot{d} = e \cdot CR^f + g \quad (2)$$

where: Δu_w (kPa) is the variation of pore water pressures measured near the sliding surface of the landslide body; CR (mm) is the cumulative rainfall in the preceding five months on the landslide body; $\dot{d}$ (mm/day) is the displacement velocity of the landslide body; a , b , c , e , f , and g are fitting parameters.

Define the purpose of the natural laboratory: to gain insight into the phenomenon development or to assess the effectiveness of mitigation strategies

Funds of Return projects were allocated for the acquisition of a high-pressure triaxial which allows testing over a wide range of confinement pressures (maximum cell pressure equal to 30 MPa). The purpose of the high-pressure triaxial tests is to replicate the stress conditions of such a deep-seated landslide, enabling a reliable determination of shear strength parameters and the role of pore-water pressure. Samples from the original investigation campaign conducted on the Cerda landslide were tested using the new apparatus. Figures illustrating the experimental setup and details of the recently conducted laboratory activities are shown below (Figure 3).

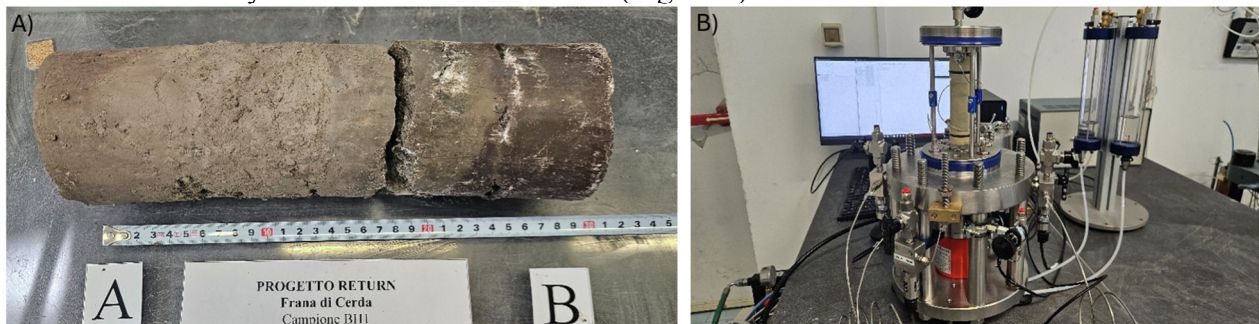


Figure 3. The new high-pressure triaxial apparatus installed in the Geotechnical Laboratory of UniPa. (a) a sample recovered from the Cerda landslide body prior to testing, while (b) shows the specimen positioned inside the triaxial cell.

Notes

Agnesi, V., Camarda, M., Conoscenti, C., Di Maggio, C., Diliberto, I. S., Madonia, P., & Rotigliano, E. (2005). A multidisciplinary approach to the evaluation of the mechanism that triggered the Cerda landslide (Sicily, Italy). *Geomorphology*, 65(1-2), 101-116.

Rosone, M., Ziccarelli, M., Ferrari, A., & Farulla, C. A. (2018). On the reactivation of a large landslide induced by rainfall in highly fissured clays. *Engineering Geology*, 235, 20-38.

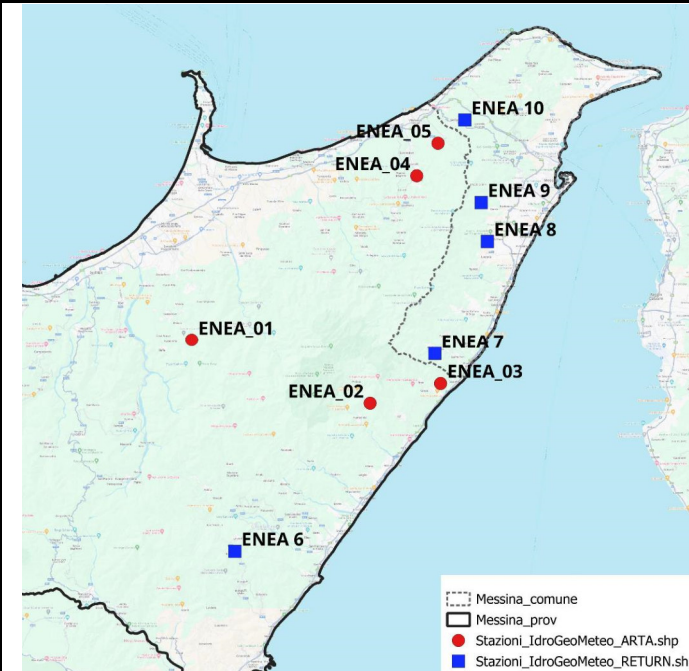
**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Aim of Natural Field Laboratory: LEARNING EXAMPLE (DELIVERABLE 2.2.1, Fanti et al.)

Partner:

ENEA (Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile)

Test site: Messina province



Code	Location	Z
ENEA_01	Castroreale	664
ENEA_02	Fiumedinisi	516
ENEA_03	Scaletta Zanclea	256
ENEA_04	Saponara	230
ENEA_05	Villafranca	134
ENEA_06	Roccafiorita	634
ENEA_07	Altolia	387
ENEA_08	Zafferia	322
ENEA_09	Cumia	482
ENEA_10	Gesso	231
CRS	EPSG:32632 - WGS 84 / UTM zone 32N	

Figure 1 - Location of the ENEA test sites pertaining to the Messina province NFL

Brief description of ground instability, involved material, existing remedial measures against ground instabilities and aim of the new (or updated) measures

The area where the geo-hydrological stations were located is interested by fast moving shallow landslides as debris flows, mud flows and debris avalanches involving the non-cohesive, uniform shallow material lying upon the bedrock, triggered by rainfall infiltration when the soil becomes saturated. They start on neoformation rupture surfaces as small roto-translational slides in the soil over the bedrock and then become a surging flows containing a variety of materials from fine particles to large boulders and tree branches. These phenomena frequently occur within the same catchment but often originate from slope areas not previously affected, as the removal of the cover material during an event prevents reactivation in the same location.

The involved materials are loams and sandy loams (USDA classification), generally sandy in shallow levels and finer in the deepen horizons, with low clay content (from 3 to 15 %, with a mean value of 10 %). The bedrock is primarily composed of a metamorphic crystalline basement formed by gneiss, schist, and phyllite and a sequences of younger, unmetamorphosed sedimentary rocks, including Mesozoic limestones and Tertiary flysch deposits, which record later marine transgressions.

This area already hosts five existing geo-hydrological field laboratories, installed by ENEA under a previous program agreement with the Department of Land and Environment of the Sicily Region. The five new stations established in 2025 under the RETURN project will expand this network and enhance its spatial density with more advanced instrumentation.

Design and construction details

The stations were distributed to ensure homogeneous coverage across Messina's province, following a balance between geomorphological suitability, logistical accessibility, and landowner availability. The previous

installed field laboratories were equipped with rain gauge and FDR probes. The new five field laboratories are equipped with

- air thermometer,
- barometer (Piezoresistive),
- rain gauge (MTX 200cm²),
- Casagrande piezometer (PIZZI, electric),
- direct tensiometer (IRROMETER SR),
- undirect tensiometer (IRROMETER - 200SS WATERMARK),
- FDR probes (Capacitive - PCTUM012).

All the new geo-hydrological station are equipped with a low-power, NB-IoT datalogger and powered by a 20W solar panel and a 12V AGM battery. The system features Bluetooth for proximity setup and NB-IoT for remote data transmission. All components are housed in a rugged polyester/fiberglass enclosure. Using a truck-transported, tracked mini-excavator equipped with a bucket, excavations were dug down to the bedrock at depths of 1 to 2 meters. All instruments were placed in alignment on the excavation's upslope wall (Figure 2).



Figure 2. Installation of the monitoring instruments

Numerical modelling

The long-term, high-frequency dataset serves as a critical ground-truth for calibrating and validating physically-based slope stability models (e.g., TRIGRS, SHALSTAB) as well as GIS-based model (e.g. SPRIn-SL), significantly enhancing their predictive reliability for landslide susceptibility and hazard mapping.

Define the purpose of the natural laboratory: to gain insight into the phenomenon development or to assess the effectiveness of mitigation strategies

The integrated geo-hydrological monitoring stations of the Messina Province net are engineered for the continuous, high-resolution measurement of critical parameters controlling the initiation mechanisms of shallow landslides. Its core function is to establish quantitative, field-validated thresholds for slope failure. The stations provide real-time data on rainfall intensity and soil matric suction, enabling the detection of precipitation patterns that lead to soil saturation. This allows for the issuance of alerts based on pre-defined hydro-meteorological thresholds, prior to slope failure. By correlating rainfall data with the dynamic response of soil moisture, the system provide information about two distinguished process:

- Preparatory process: progressive rise in soil moisture content during prolonged rainfall, leading to a decrease in soil suction and an increase in pore-water pressure, thereby reducing shear strength;
- Triggering process: short-duration, high-intensity rainfall events where infiltration capacity is exceeded, leading to superficial erosion and lateral flow.

The station's architecture ensures operational resilience in remote, high-risk terrain. The low-power datalogger, coupled with a 20W solar panel and a 12V AGM battery, guarantees uninterrupted functionality. NB-IoT connectivity enables reliable, low-power data transmission from inaccessible sites, facilitating a dense monitoring network for comprehensive basin-scale analysis. This geo-hydrological monitoring stations net aim to contribute moving landslide hazard assessment from a qualitative to data-driven approach, providing essential parameters for understanding precursor conditions, forecasting failure events, and implementing effective early warning protocols.

Notes

**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Aim of Natural Field Laboratory: INNOVATIVE SENSOR/INFRASTRUCTURE
(DELIVERABLE 2.3.2, Colombo et al.)

Partner:

University of Naples Federico II
Department of Civil, Building and Environmental Engineering (DICEA)
(with the contribution of Department of Earth Sciences, Environment and Resources, DISTAR)

Test site:

Mount Vezzi (Ischia)

**Brief description of ground instability, involved material, existing remedial measures
against ground instabilities and aim of the new (or updated) measures**

On 30 April 2006, five shallow landslides were triggered on the northern slope of Mount Vezzi, subsequently evolving downslope into rapid debris flows. One of these landslides impacted a residential building, causing its complete destruction and resulting in the loss of four human lives. From the earliest investigations, the landslides were classified as shallow, as they involved unconsolidated pyroclastic deposits overlying a rocky bedrock. The instability is clearly attributable to the prolonged rainfall event recorded by the nearby Forio d'Ischia rain gauge, as documented by Mazzarella and De Luise (2007). The general characteristics of the event allow the landslides at Mount Vezzi to be associated with those typically affecting the peri-Vesuvian area (De Vita et al., 2007). Detailed investigations (De Vita et al., 2007) led to the delineation of the areas affected by the five landslides, as shown in Figure 1.

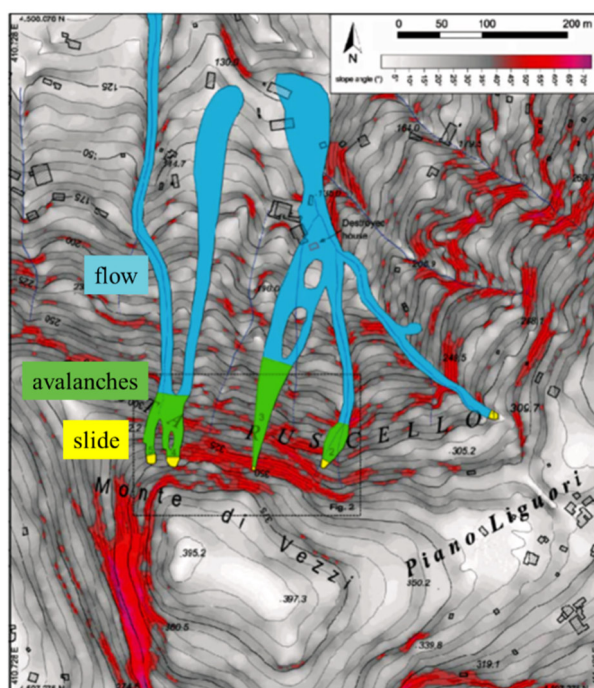


Figure 1. Perimeters and numeration of the landslide, mapped on the redraw of the 1982's regional technical cartography (the shading indicates the slope angle)

For the site under consideration, within the framework of the “Commissario straordinario per gli interventi di riparazione, di ricostruzione, di assistenza alla popolazione e di ripresa economica nei

territori dell'isola di Ischia" project, areas of potential initiation of similar instability phenomena were delineated. For this reason, dedicated instrumentation was acquired, and several field surveys were conducted in order to identify the most suitable locations for instrument deployment (Figure 2).

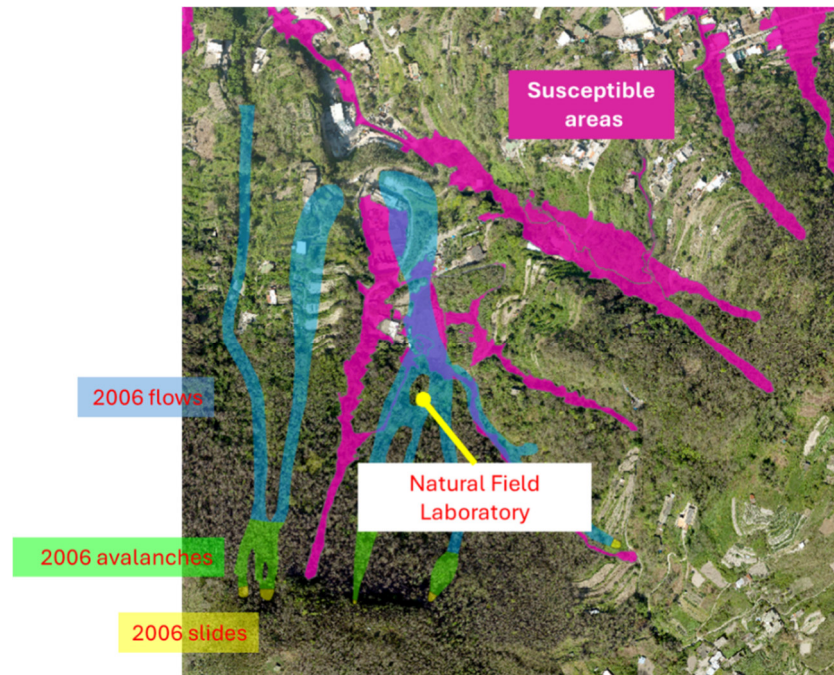


Figure 2. Perimeters of the potential susceptible areas and installation of NFL

Design and construction details

The monitoring system implemented is designed primarily to observe the hydrological variables of the slope, in conjunction with atmospheric parameters. Accordingly, the system includes the installation of the following components:

- probes for the measurement of soil water content;
- probes for the measurement of soil water potential;
- probes for the measurement of soil moisture and temperature;
- tensiometers for the measurement of pore water pressure;
- a meteorological station.

All the aforementioned sensors are connected to two data loggers equipped with remote data transmission capabilities via a cloud-based service (Figure 3).

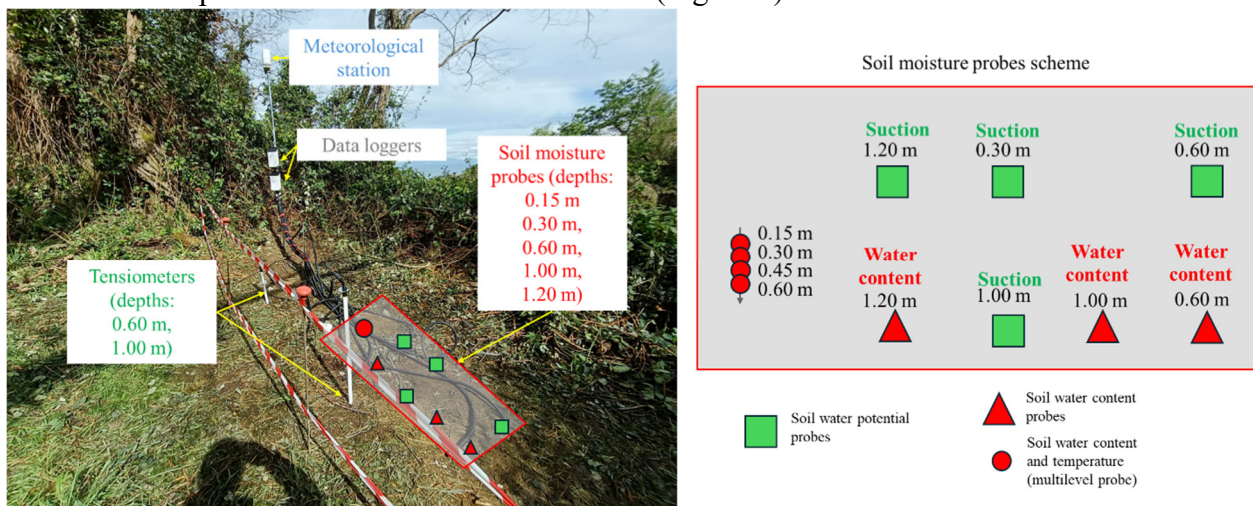


Figure 3. Picture and scheme of the Natural Field Laboratory of Monte Vezzi, installed on 26/03/2026

Numerical modelling

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Define the purpose of the natural laboratory: to gain insight into the phenomenon development or to assess the effectiveness of mitigation strategies

The primary objective of this case study is to increase insight into this kind of phenomenon.

Notes

De Vita, P., Di Clemente, E., Rolandi, M., & Celico, P. (2007). Engineering geological models of the initial landslides occurred on the April 30th, 2006, at the Mount di Vezzi (Ischia Island, Italy). Italian Journal of Engineering Geology and Environment, 2:119-141.
Mazzarella, A., & De Luise, E. (2007). L'evento meteorico del 30 Aprile 2006 a Ischia. (The meteoric event of 30th April 2006, at Ischia island, Italy). Italian Journal of Engineering Geology and Environment, 2:1-8.

**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Aim of Natural Field Laboratory: LEARNING EXAMPLE (DELIVERABLE 2.2.1, Fanti et al.)

Partner:

University of Roma Sapienza
Department of Earth Sciences

Test site:

Acuto Field Lab (FR)

Brief description of ground instability, involved material, existing remedial measures against ground instabilities and aim of the new (or updated) measures

Ground instability processes active in the site mainly consist of rock block failure mechanisms, including falls, planar and wedge slides and topples. In the Acuto quarry a 50m high cliff made of micritic limestone outcrops.

The new measures include high-resolution seismic monitoring devices and multi-channel dynamic dataloggers that allow the continuous recording of microseismic events, for early detection of precursory signals of instability.

To delve into the rock failure preparation process, mainly attributable to mechanical fatigue, the on-site natural condition monitored are linked and reproduced in the in-house laboratories, where a new Prototype for uniaxial compression and shear apparatus for rock mechanics allows long-term testing under controlled thermal and humidity cyclic condition, constituting a scaled analogue example of the full-scale process.

Design and construction details

The monitoring system is constituted by a network of geotechnical and environmental sensors capable of monitoring:

- i) meteorological variables.
- ii) rock temperature;
- iii) fracture water flow,
- iv) heat flux,
- v) fracture displacements,
- vi) rock matrix strain;
- vii) acoustic emissions and seismic signals.

Data are continuously recorded and transmitted to a remote Cloud IaaS (Infrastructure as a Service) server of the Earth Sciences Department of Sapienza University of Rome to allow researchers for their remote analysis and management.

Numerical modelling

Numerical results output the role of periodic daily, annual and compound thermal input in inducing irreversible deformation along joints under different rock mass through connection configuration, as a function of the intrinsic period of thermal input and joint attitude. Temperature distribution across joints was also analysed as a possible constraining effect for time and space distribution of yielding. A sensitivity analysis of heat propagation conditions was performed to infer the role of joint sets on induced thermo-mechanical strains at the rock block scale. A non-negligible influence on surficial as well as deeper portions of the rock mass was observed, highlighting how near-surface temperature fluctuations can drive the long-term evolution of rock block conditions towards failure. Results are summarised in Marmoni et al. (2020).

Define the purpose of the natural laboratory: to gain insight into the phenomenon development or to assess the effectiveness of mitigation strategies

The field laboratory named Acuto Field Lab is located inside the Cava Prenestina, Acuto (FR), and it aims at studying the role of environmental factors, such as temperatures and meteorological conditions, in preparing rock blocks toward ultimate failure (rockfall, slides or toppling). Furthermore, the laboratory also focuses on the study of triggering factors of rock block instabilities, such as rainfalls, strong winds and earthquakes. The mitigation strategies adopted in the laboratory consists of a multisensor and multiparametric monitoring system installed on three sectors of the quarry rock wall that are dedicated to:

- 1) study of the interactions between preparatory and triggering factors of instability at a small rock block scale (few meters);
- 2) study of the interactions between environmental stress and the stress-strain response of a stable sector of the rock mass with technological R&D of Fiber Bragg grating sensors;
- 3) study of the interactions between preparatory and triggering factors of instability at a medium rock block scale (tens of meters).

Notes

Fantini, A., Fiorucci, M., & **Martino, S.** (2017). Rock falls impacting railway tracks: detection analysis through an artificial intelligence camera prototype. *Wireless Communications and Mobile Computing*, 2017(1), 9386928.

Fiorucci, M., Marmoni, G. M., **Martino, S.**, & *Mazzanti, P.* (2018). Thermal response of jointed rock masses inferred from infrared thermographic surveying (Acuto test-site, Italy). *Sensors*, 18(7), 2221.

Fiorucci, M., **Martino, S.**, **Bozzano, F.**, & Prestininzi, A. (2020). Comparison of approaches for data analysis of multi-parametric monitoring systems: insights from the Acuto test-site (Central Italy). *Applied Sciences*, 10(21), 7658.

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Qian, Y., Fiorucci, M., Marmoni, G. M., Li, Q., Hussain, Y., Grechi, G., & **Martino, S.** (2025). Impact of environmental stressors on jointed rock cliffs by acoustic emission sensing: Preliminary findings from the Acuto field laboratory (central Italy). *Rock Mechanics and Rock Engineering*, 58(2), 1549-1568.

**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Aim of Natural Field Laboratory: FURTHER INSIGHT INTO THE PHENOMENON

Partner:

University of Roma Sapienza
Department of Earth Sciences

Test site:

Poggio Baldi Landslide.

Brief description of ground instability, involved material, existing remedial measures against ground instabilities and aim of the new (or updated) measures

Ground instability process active in the site mainly consist of rockfall activity from the steep cliff, (sub-vertical rock scarp about 100 m high and 250 m wide) which cause a persistent retrogressive activity of the detachment area by recurrent falls of block of various sizes ranging from a few cubic centimetres to tens of cubic meters. The volumetric and image change detection analyses enabled us to estimate volume changes in terms of fallen and accumulated debris and materials. The general loss of volume is estimated to be in the range of 2.0 to $2.8 \times 10^3 \text{ m}^3$ per year.

Over the landslide, featured by a complex mechanism resulting from a successive activation of major rock fall and mobilisation of the slope debris, a short-term geological/geomorphological evolutionary model composed of two stages, can be figured out:

- slope instabilities are primarily represented by rockfalls and toppling. Predisposing factors are geological, geomorphological and geo-structural. The detached debris and blocks, following their trajectories, find deposition surfaces over the cantilever arenaceous strata;
- over time, the volume of fallen material increases on the bulging arenaceous strata surfaces. At the same time, continuous volume loss causes a constant retrogressive activity of the above vertical rock cliff in some specific sectors. These events, repeated over time, affect the main scarp until the accumulated debris on the bulging strata surfaces, reaching non-equilibrium and collapse conditions, hence causing small debris avalanches.

This almost constantly increasing loading could act as one of the main predisposing factors for the long-term reactivation of the Poggio Baldi main landslide. If the above phenomenon were combined with an increase of pore water pressure induced by rainfall events and/or rapid snow melting (as occurred in 2010), it could cause the reactivation of the Poggio Baldi landslide.

The recent activation of March 2025 testifies the strict interlink between earth slide and flow mechanisms and the activity of the rocky cliff.

To delve and fully characterise the response of the debris talus and landslide deposits to rainfall input, new remedial measures focused on the monitoring have been adopted, namely:

- ground based multiparametric monitoring system including strain gages,
- air thermos-hygrometers ATMOS-14,
- one TERSO21,
- hydraulic head and matric suction, 5 soil moisture sensors TERSO11.
- 4 Datalogger mod.ZL6 Zentra Cloud, devoted to follow up the evolution of the water infiltration process before earth slope failures.

This system integrates with the remote sensing devices focused on the rockfall inventorying and monitoring. Such data are continuously linked to the in-house laboratory, where a flume test apparatus allow the scaled-experiments of shallow landslide triggering and earth failure mechanism. For the study in hands, new prototypal monitoring solutions have been developed, consisting of high-resolution multi-channel interferometric ground radar system with Multiple-Input-Multiple-Output (MIMO) architecture with real-time digital beamforming (DBF) imaging capabilities, combined with

an integrated optical camera. This prototype will allow the active monitoring of the debris movement in a multi-spectral band (radar and optical).

In addition, a new Prototype system for a drone-based synthetic aperture radar interferometry system, equipped with GNSS antenna, will enhance the monitoring capability by improving the radar monitoring revisit time and resolution with respect to the more established satellite-based interferometry.

For what concerns rockfall activity, a new technological prototype system consisting of two high-performance 4K cameras with a multi-focal lens, integrated with a laser distance meter measurement system and remote controller, will boost the monitoring potential of rockfall effects, by obtaining depth images through stereoscopic reconstruction.

Design and construction details

The monitoring system is constituted by a set of apparatus for the remote sensing on active gravitational processes. The ordinary continuous and periodic surveys include:

- Multi-temporal and multi-station surveys with Terrestrial Laser Scanner (TLS)
- Surveys with the Global Navigation Satellite System (GNSS)
- Photogrammetric surveys with a Remotely Piloted Aircraft System (RPAS) platform
- Gigapixel surveys with a robotic camera head
- Photomonitoring with 4G cameras.
- Monitoring using Terrestrial SAR interferometry (TInSAR).

With the creation of the permanent monitoring site, the laboratory is now completely autonomous in terms of power supply and data acquisition. Today, the laboratory continuously provides meteorological data, acoustic measurements, optical and thermal images every ten minutes. Periodic Doppler radar data and TLS acquisitions are seasonally recorded.

Numerical modelling

Numerical modelling encompasses the rockfall trajectories analysis. The rockfall model was implemented using Rockyfor3D. The software uses a three-dimensional rigid-body impact model that allows the calculation of the trajectories of single individually falling rocks with discrete geometry, allowing also pre-remediation of mitigation works (e.g. barriers).

Define the purpose of the natural laboratory: to gain insight into the phenomenon development or to assess the effectiveness of mitigation strategies

The laboratory purpose aim to go deeper in the analysis of rockfall precursor events in an early warning and risk mitigation perspective. The combination of active and passive remote sensing techniques in a multispectral band allow to gain knowledge on the rockfall activity and on landslide body response to meteorological triggers. Apart from the structural measures adopted in the past to stabilise the landslide, this approach represents the unique opportunity to detect early signals of instability.

Notes

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Mazzanti, P., Caporossi, P., Brunetti, A., Mohammadi, F. I., & **Bozzano, F.** (2021). Short-term geomorphological evolution of the Poggio Baldi landslide upper scarp via 3D change detection. *Landslides*, 18(7), 2367-2381.

Romeo, S., Cosentino, A., Giani, F., Mastrantonì, G., & **Mazzanti, P.** (2021). Combining ground based remote sensing tools for rockfalls assessment and monitoring: The Poggio Baldi Landslide Natural Laboratory. *Sensors*, 21(8), 2632.

**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Aim of Natural Field Laboratory: FURTHER INSIGHT INTO THE PHENOMENON

Partner:

University of Naples Federico II
Department of Earth Sciences, Environment and Resources (DISTAR)
(with the contribution of Department of Civil, Building and Environmental Engineering, DICEA)

Test site:

The Roman Crypt and the Sybil's cave in Cumae archaeological site (Phlegraean Fields, Naples)

Brief description of ground instability, involved material, existing remedial measures against ground instabilities and aim of the new (or updated) measures

The Roman Crypt was a military tunnel built in the 1st century BC. It extends for more than 200 meters along an east–west axis beneath the Cumae Acropolis, connecting the ancient port of Cumae with the centre of the city (Figure 1a). After the Roman period, historical evidence reported the partial collapse of the vault in correspondence of the western side of the tunnel. At present, it is part of the Archaeological Park of Cuma and remains closed to the public pending an assessment of its safety conditions. The Crypt was entirely excavated in a typical pyroclastic deposit formed during an explosive volcanic eruption about 15,000 years ago: the Neapolitan Yellow Tuff formation (NYT). Specifically, at the eastern entrance of the Roman Crypt, the yellow lithoid facies of NYT predominates, where fragments of Green Tuff, lithic materials, and pumice can be observed. The lithoid facies modifies into a less coherent facies as evident at the western exit of the Roman Crypt. The site is instrumented with one velocimeter and eleven strain gauges for deformation monitoring (Figure 1b). No structural interventions are present.

The second case study is the cave of the Greek prophet Sybil, that is the most famous monument in the Archaeological Park of Cuma. Archaeological research interprets the monument as a military tunnel dug into the Neapolitan Yellow Tuff parallel to the coast for a length of about 180 m between the end of the IV and the beginning of the III century BC. The initial trapezoidal shape was modified by Romans who lowered the ground level. On the wall oriented towards the coast, there are nine smaller tunnels, six of which are open to the front side. On the opposite wall, there is a rectangular room with three additional smaller rooms. At the end of the tunnel there is the main room, where it is said that the Sibyl prophesied.

In order to carry out, for the first time, stability analyses of both case studies, an investigation campaign was conducted to: a) perform a topographic survey using a 3D laser scanner (Figure 1c and d; see notes for details*); b) identify the main discontinuity systems on a specific cross-section (height: 9 m, width: 12 m; Figure 1d) located near the western entrance of the tunnel alignment for the crypta and in the main room for the Sybil cave; and c) collect existing measurements of the mechanical properties of the rock mass where available or several tuff blocks from site for laboratory testing. Based on the results of the investigation, the stability analysis was carried out with an increased level of complexity, through an empirical geomechanical assessment (not shown in this sheet), the use of stability charts from the literature (not shown in this sheet), and numerical modelling describing the stress–strain behaviour of the system.

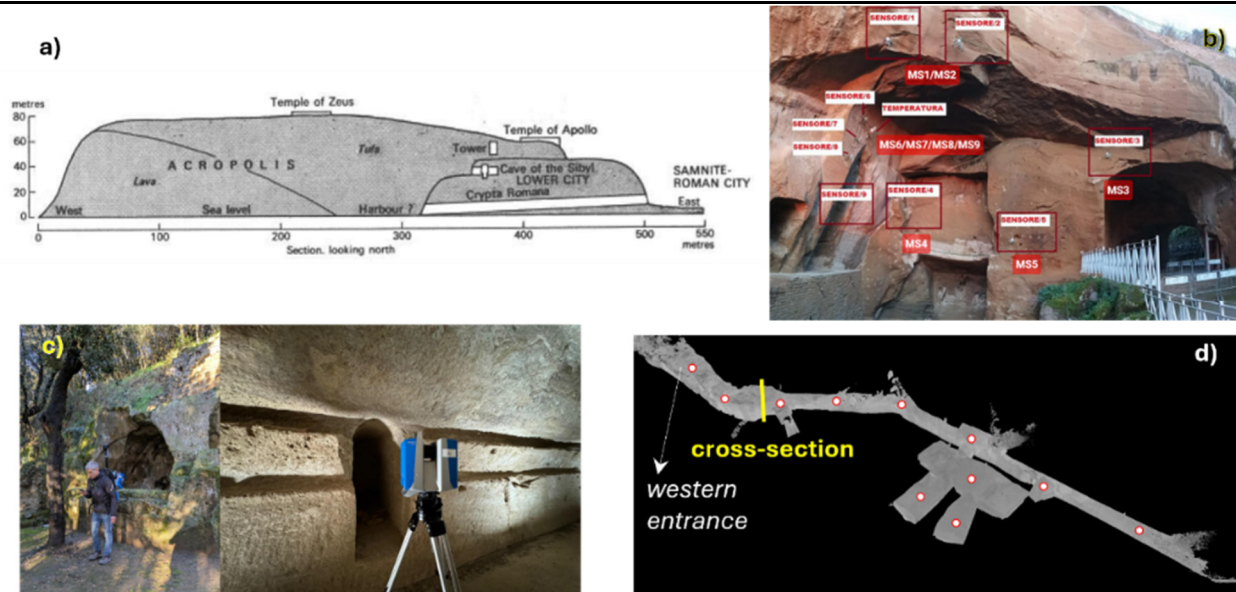


Figure 1. a) Sections with relative positions of Roman Crypt (Varenia, 2011); b) western entrance of the Roman Crypt and pre-existing instrumentation; c) 3D Laser Scanner Z+F; d) perspective view of the crypt from the topographic survey with measurement stations and cross-section location.

Design and construction details

To integrate the active monitoring system described in the previous section, a three-dimensional survey of the tunnel was carried out using laser scanner technology. Given the morphological and planimetric complexity of the cavity, 11 measurement stations were positioned along the tunnel alignment. The use of specific targets enabled precise georeferencing of the scans and the generation of an accurate 3D metric model representing the actual geometry of the structure. The survey was further integrated with a topographic campaign conducted using a total station, aimed at controlling and validating the metric accuracy of the 3D model. The parameters of discontinuities and intact rock were determined in the field using a Barton comb and a Schmidt hammer, while laboratory tests included the determination of physical properties such as apparent density and total porosity by Helium Pycnometry (HP). In addition, Point Load Tests (PLT) were performed to estimate the uniaxial compressive strength (σ_c).

Numerical modelling

Roman crypta

2D numerical analyses were carried out under plane strain and static conditions using the finite difference method implemented in FLAC. The simplified computational domain, shown in Figure 2, was discretized with 4-node elements of 25 cm. Fixed boundary conditions were assigned at the base, while the lateral sides were constrained only in the horizontal direction. Water was not included in the model, as field observations confirmed that the cavity is in dry conditions. The rock mass was treated as a continuous medium, represented by an elastic–perfectly plastic constitutive model following the equivalent Mohr–Coulomb failure criterion. The friction angle (ϕ) was kept constant, whereas cohesion (c) was varied by inverting the relation $\sigma_c = (2c \cos \phi) / (1 - \sin \phi)$. The model was first solved under lithostatic conditions and subsequently used to estimate the stress redistribution induced by the presence of the cavity. Parametric analyses were performed to evaluate roof stability by varying: (a) the uniaxial compressive strength (σ_c) from 1 MPa to 5 MPa, consistent with laboratory results; (b) the tensile cut-off (σ_t) between 5 % and 10 % of σ_c ; and (c) the unit weight (γ) between 16 and 18 kN/m³. The main outcomes are summarized in Figure 2, which illustrates the distribution of plastic zones for Tests 1, 4, 7, and 10. Plasticity develops mainly in the roof, where tensile failure dominates at low σ_c values (≈ 1 MPa). The thickness of the plastic band increases from

about 0.75 m to 1.5 m as σ_t decreases from $0.1 \sigma_c$ to $0.05 \sigma_c$, while the influence of the unit weight is negligible, as shown by the nearly identical plastic patterns between Tests 1–7 and 4–10.

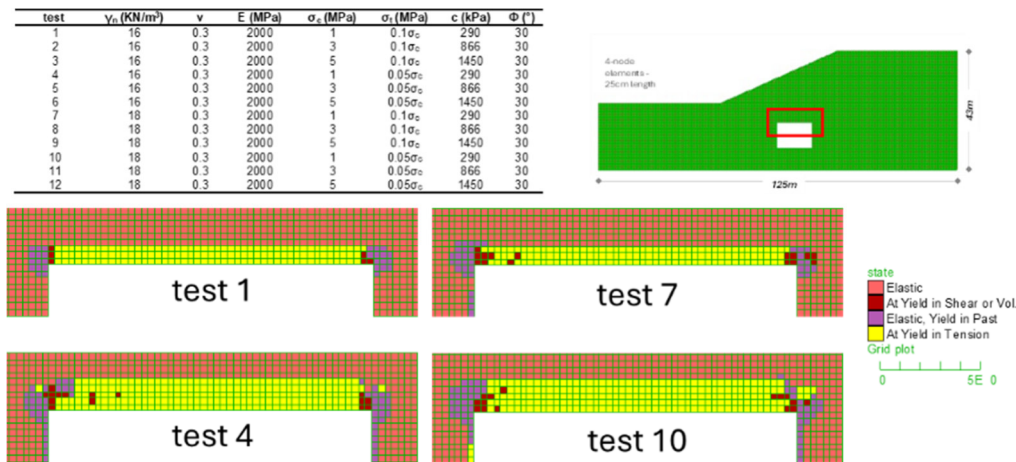


Figure 2. Scheme of the parametric analyses performed, model domain with 25 cm-long 4-node mesh elements, and resulting plastic points from tests 1, 4, 7, and 10.

Sybil's cave

The laser scanner survey of the cave and of the topographic surface were imported into FLAC3D to generate the numerical model of the portion closer to the main room, shown in Figure 3 a. The survey and the outcrop of the tuff roof on the lateral side have shown that the thickness of the tuff vault is very small at the end of the gallery, exactly where the main room is located.

Uniaxial compression tests performed on specimens obtained from tuff blocks found in the central area of the cave led to σ_c about 5 MPa on dry specimens and 4.3 MPa on saturated specimens, but the presence of numerous discontinuities detected on site reduces the strength of the rock mass. This was estimated to be 750 kPa by Diletto (2021), calibrating the Hoek and Brown (1980) criterion for a geological strength index $GSI=74$, resulting from the discontinuity analysis. Figure 3 a shows the parameters adopted in the numerical model considering the Mohr-Coulomb resistance criterion equivalent to that of Hoek and Brown in the range of $10 \text{ kPa} < \sigma'_3 < 150 \text{ kPa}$. Finally, a layer of degraded material with a thickness of 1 m was modelled, to consider the reduced cementation of the tuff roof.

The model was analyzed by firstly executing the lithostatic equilibrium of the hill and then by simulating the excavation through removal of the tuff rock elements.

Figure 3 b shows the plastic points in tension of the cavity roof at the end of the analysis. The cave resulted stable, except for some detachment of block expected to occur due to the local attainment of the tensile strength. The latter results in correspondence of section N for the Sybil's cave. This is in accordance with the prediction of stability charts accounting for the presence of joints and the strength variability (de Silva et al., 2026).

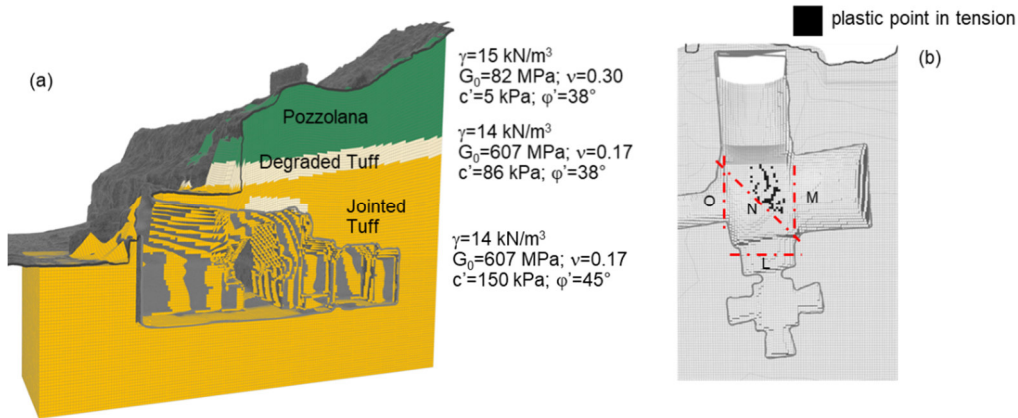


Figure 3. 3D numerical model (a) and plastic points in tension (b) of Sybil's cave.

Define the purpose of the natural laboratory: to gain insight into the phenomenon development or to assess the effectiveness of mitigation strategies

The survey of the plan-altimetric configuration of the site and the subsequent geomechanical characterization made it possible to gain insight into the development of the phenomenon and served as a preliminary step for the stability analysis. The case of the Sybil cave revealed the utility of additional destructive surveys, as drillings in the vault to measure the thickness of the NYT, that are difficult to execute in heritage sites.

Both the empirical geo-mechanical analysis and the stability charts analysis (whose application and results are not detailed in this sheet) consistently indicate a satisfactory overall stability of both the analysed cavities, while highlighting localized criticalities in the roof area, where rock quality and discontinuities reduce structural safety. The complementary numerical analyses were performed under 2D conditions for the crypta (Figure 2), assuming an elasto-plastic behaviour for the NYT. The parametric study, varying tensile strength and unit weight, showed that failure is mainly governed by tensile strength: when it falls below 0.1 MPa, plastic zones develop in the roof. Similarly, the parametric analyses executed on the 3D model of the main room of the Sybil cave revealed that the vault is safe with local critical attainments of the tensile strength depending on the thickness of the NYT in the roof. Overall, the results confirm that the roof of both caves remains stable under the evaluated conditions. In summary, although the analyses indicate that the roof is stable under the current conditions, the higher sensitivity to tensile failure for the crypta and to the unknown thickness of the NYT in the vault of the Sybil cave suggests that more comprehensive stabilization measures may be advisable compared to the sidewalls. Possible reinforcement solutions include rock bolting to anchor isolated unstable blocks, localized shotcrete application, installation of steel mesh, and regular in-situ monitoring to evaluate system performance and detect any time-dependent deformations.

Notes

- Diletto, M. (2021). Analisi delle condizioni di stabilità dell'area archeologica di Cuma (NA). MS Thesis in Civil Engineering, *Alma Mater Studiorum* University of Bologna.
- Hoek, E. and Brown, E.T. (1980). Empirical strength criterion for rock masses. *J. Geotech. Engng Div.*, ASCE 106 (GT9), pp. 1013-1035.
- de Silva F., Flora A., Nuzzo M., **Silvestri F.** (2026). Influence of uncertainties on the stability of rock cavities under gravity and seismic loads. 4th International Symposium on Geotechnical Engineering for the Preservation of Monuments and Historic Sites, Athens, September 16-18 2026.

**RETURN Project | VS2 – Ground Instabilities |
WP5 “Outcomes for mitigation strategies”**

Aim of Natural Field Laboratory: LEARNING EXAMPLE (DELIVERABLE 2.2.1, Fanti et al.)

Partner:

University of Naples Federico II
Department of Civil, Building and Environmental Engineering (DICEA)

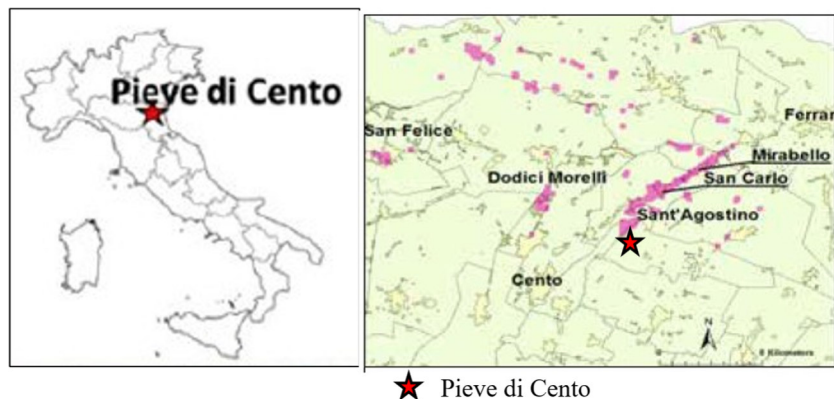
Test site:

Pieve di Cento, Bologna (Emilia Romagna region)

Brief description of ground instability, involved material, existing remedial measures against ground instabilities and aim of the new (or updated) measures

Due to the seismic event that hit the Emilia–Romagna region in 2012, several municipalities experienced liquefaction phenomena (Figure 1), including Mirabello, Cento, Pieve di Cento, the San Carlo district in Sant’Agostino, and Mirabello (Spacagna et al., 2018). Among these cases, the Pieve di Cento site was proposed as a natural laboratory within the RETURN framework. The soil involved in the phenomenon (loose and saturated sandy deposits) has been extensively characterized (Flora et al., 2021; Mele et al., 2022), and among the various liquefaction-mitigation techniques, induced partial saturation (hereafter IPS) was considered for this case study (Flora et al., 2026), due to the applicability of such interventions, particularly in densely urbanized settings.

It can generally be achieved either by sparging air into the saturated soil (Figure 2a) or by injecting a liquid mixture containing bacteria capable of generating gas through denitrification processes (bio-IPS, Figure 2b). For the Pieve di Cento case study, the former technique was adopted in research projects carried out prior to RETURN.



★ Pieve di Cento

Figure 1: Map of liquefaction phenomena observed in Emilia-Romagna following the seismic events of 20 and 29 May 2012.

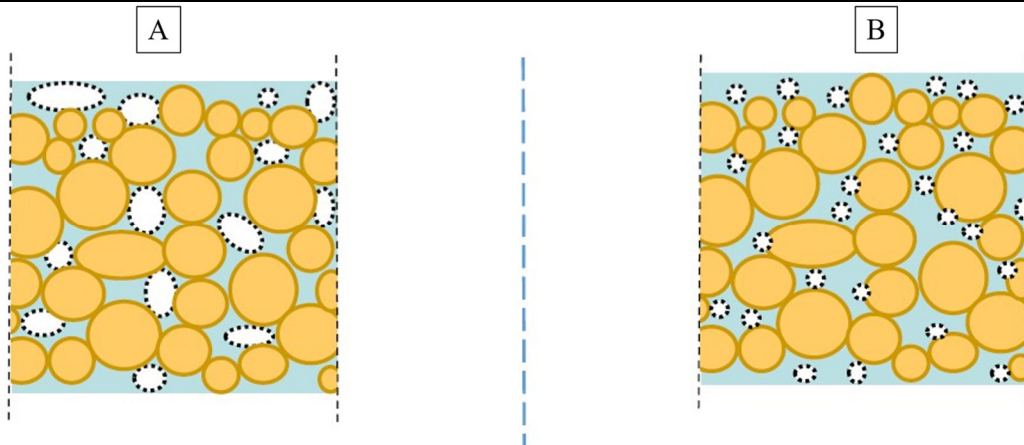


Figure 2: a) air sparging, b) bio-IPS

Design and construction details

Within the framework of the RETURN project, financial support was allocated for the upgrade of a triaxial testing apparatus for the characterization of soils under partially saturated conditions. The upgrade comprised the replacement of the top cap and load cell, and the check of the proper functioning of the electrical and pneumatic circuits.

Furthermore, the desktop replacement and software upgrade have been completed. The upgraded software allows real-time monitoring of the evolution of the main physical variables governing the triaxial test.

Numerical modelling

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Define the purpose of the natural laboratory: to gain insight into the phenomenon development or to assess the effectiveness of mitigation strategies

The Pieve di Cento natural laboratory was proposed within the RETURN project with the aim of providing insights regarding the implementation of active mitigation techniques.

Notes

Spacagna, R. L., Paoletta, L., Rasulo, A., & Modoni, G. (2018, June). Spatial variability of CPT data for liquefaction assessment. In *Proceedings of the 16th European conference on earthquake engineering, Thessaloniki* (pp. 18-21).

Flora, A., Bilotta, E., Chiaradonna, A., Lirer, S., Mele, L., & Pingue, L. (2021). A field trial to test the efficiency of induced partial saturation and horizontal drains to mitigate the susceptibility of soils to liquefaction. *Bulletin of Earthquake Engineering*, 19(10), 3835-3864.

Mele, L., Lirer, S., & Flora, A. (2022). An energetic interpretation of liquefaction laboratory tests on partially saturated soils. *Journal of Geotechnical and Geoenvironmental Engineering*, 148(10), 04022082.

Flora A., Lirer S., Mele L., **Silvestri F.** (2026). Field evidence of IPS durability at Pieve di Cento (Italy) test site. Submitted to *V International Conference on Performance-Based Design in Earthquake Geotechnical Engineering*, Puerto Varas (Chile).

Appendix C

This appendix presents the collection of details about auxiliary equipment purchased within the RETURN project.

The following inventory table reports the results of an inquiry among the research units which were involved in the characterization, analysis and monitoring of the different test sites listed in **Table 5** and described synthetically in **Tables 6-7-8**.

The rows in the inventory table which lack of information regarding either the use of on-purpose RETURN funding or the specific test sites are shaded in dark or light grey, respectively; the other rows, instead, can be considered as referring to official NFL of the VS2 Spoke, since the test site is well documented and instrumented through RETURN funding, as described in detail in the fact sheets collected in Appendices A-B.

Institution	Total budget	Equipment	Responsible	Objective	Status			Notes
					Installed (fully/partially) with site indication	To be installed with site indication	Used in-house with purpose indication	
UniBa								Fossa Bradanica test site fact sheet but no data on the use of RETURN budget
UniBo	139 k€	Hydra-G Terrestrial Interferometric Radar	Matteo Berti	To be used during the paroxysmal phase of landslides		Moved from site to site when needed		
PoliTo	68 k€	Wireless seismic sensors (1- or 3-components)	Chiara Colombero	Characterization and/or monitoring of potentially unstable sites	Temporarily installed (for testing) at the Madonna del Sasso (VB) NFL (see WP3) in May 2025		Available in laboratory for VS2, VS3, TS2 characterization and monitoring activities	Also used for VS3 and TS2 activities
UniFi	286 k€	ArcSAR HydraG Radar, Optical Pumping Gradiometer, FARO Focus Laser Scanner	Riccardo Fanti		Surveys and measurements at different sites (Fiesole - FI; Gonfienti PO; Valtourmanche - AO; Vollein - AO)			
UniGe	170 k€	3 triaxial cells for hydro-mechanical tests on partially saturated (2 cells) and fully saturated (1 cell) soil samples	Domenico Gallipoli	Characterization of mechanical behaviour of saturated and unsaturated soils			Installed at the UniGe geotechnical laboratory (2 partially saturated cells under calibration)	
ENEA (# NFL x 5 sites)	22 k€	Hydro-meteorological stations for soil moisture, VWC and suction measurement	Claudio Puglisi	Monitoring of rapid flows	Installed in 5 sites in the Messina Province (see NFL sheet)			Periodic maintenance and continuous data acquisition are performed
UniNa - DISTAR (#2 NFLs)	216 k€	Radar Doppler; Weather station; Laser Scanner ZF; Seismic sensors, pore pressure transducers; Extensometers	Domenico Calcaterra	Monitoring of landslides and sinkholes	Partially installed at Pennadomo (CH)	Surveys at Cuma site (NA)		
UniNa - DICEA (#3 NFLs)	82 k€	Acquisition units for tensiometers	Francesco Silvestri	Monitoring of suction in slow earthflows	Installed at Pietrapertosa (PZ)			
		Weather station		Monitoring of atmospheric variables on slope surface		To be installed at Pietrapertosa (PZ)		
		Soil moisture probes and associated dataloggers		Monitoring of VWC in rapid flows	Installed at Mount Vezzi (Ischia, NA)			Previously addressed to Pagani (SA)
		Upgrade of triaxial cell for controlled stress-path tests on partially saturated soils		Characterization of static and cyclic mechanical behaviour of saturated and unsaturated soils			Installed at the UniNa DICEA geotechnical laboratory (cyclic resistance of Pieve di Cento sands subjected to IPS)	Field CH and ERT tomographies funded by ReLUIS
UniPa (#1 NFL)	226 k€	Laser Scanner RIEGLE 3D VZ-2000i (with accessories)	Edoardo Rotigliano	Surveys and measurements at different sites		Moved from site to site when needed		
		High-pressure stress-path controlled triaxial cell	Alessio Ferrari	Characterization of mechanical behaviour of stiff clays			Available in laboratory for Cerda NFL	
UniPd (#3 NFLs)	101 k€	BOFDR optical fiber interrogation software for FTB 5020	Giorgio Cassiani	Monitoring of slope displacements		Moved from site to site when needed		
		DJI Matrice 350 RTK Drone with accessories	Filippo Catani	Optical and high-resolution Lidar surveys		Assigned to the Photography and Photogeology Laboratory, moved from site to site when needed		
		K-SAT permeameter and JET tensiometer		Permeability and soil moisture measurements		Available to the Geosciences Department, moved from site to site when needed		
		Direct shear test instrumentation in BST borehole		Measurement of surface soil shear strength		Available to the Geosciences Department, moved from site to site when needed		
		Workstation		Processing of drone LIDAR data			Available in laboratory for all NFLs	
		HP Elitebook 860	Simonetta Cola	Available as a field laptop for instrument data collection.		Moved from site to site when needed		

Institution	Total budget	Equipment	Responsible	Objective	Status			Notes
					Installed (fully/partially) with site indication	To be installed with site indication	Used in-house with purpose indication	
UniRoma1 (#2 NFLs)	953 k€	Drone Lidar with batteries, charging support and integrated software	Salvatore Martino			At the service of Acuto and Poggio Baldi NFLs		
		Uniaxial compression and shear prototype apparatus for soils and rocks under controlled thermal conditions		Characterization of mechanical properties of rocks			Installed at the Sapienza Earth Sciences Department to integrate observations at Acuto NFL	
		Advanced technological prototype system based on high-precision GNSS technology, identified as COMPADEV device, developed from LZERO MOB and LZERO NET kits		Topographic surveys of rock slopes/cliffs		At the service of near-shore experimental sites		
		Analog modeling apparatus for superficial landslides (FLUMTEST) with mini-tensiometers and humidity sensors		Model tests on rapid flows			Installed at the Sapienza Earth Sciences Department to integrate observations at Poggio Baldi NFL	
		8-channel signal acquisition for dynamic sensors and 16-channel acquisition for seismometric sensors			Installed at Acuto NFL			
		Supply, configuration, and programming of soil-air monitoring station		Management of analog modeling of soil instability processes	Installed at Poggio Baldi NFL			
		Data storage unit (NAS) for acquisition systems via contact sensors for rock slopes			Installed at Acuto NFL			
		Advanced technological prototype system with two high-performance 4K cameras, integrated with a laser distance measurement system and remote control			Installed at Poggio Baldi NFL			
		High-resolution multichannel terrestrial radar interferometry system with multiple-input-multiple-output (MIMO) architecture				At the service of Poggio Baldi NFL		
		Prototype system (Drone RADAR) including Synthetic Aperture Radar (SAR) interferometry				At the service of Poggio Baldi NFL		
		Ground based multiparametric monitoring system including raingages, air thermohygrometers ATMOS-14, one TERSO21 hydraulic head and matric suction sensor, 5 soil moisture TERSO11 sensors, 4 Dataloggers mod.ZL6 Zentra Cloud		Monitoring of meteorological and hydrological variables to characterize slope failure	Installed at Poggio Baldi NFL			