multi-Risk sciEnce for resilienT commUnities undeR a changiNgclimate

Codice progetto MUR: **PE00000005** – CUP LEAD PARTNER H93C22000610002

Deliverable title: Rationale for the quantification of parameters measuring the proneness to ground instabilities in offshore and onshore areas

Deliverable ID: DV 2.2.3

Due date: November 30, 2023

Submission date: November 30, 2023

AUTHORS

Mario Parise (UNIBA); Matteo Berti (UNIBO); Giuseppe Ciccarese (UNIBO); Riccardo Fanti (UNIFI); Isabella Lapietra (UNIBA); Isabella Serena Liso (UNIBA); Carlo Tacconi Stefanelli (UNIFI)

7) Technical references

Project Acronym	RETURN
Project Title	multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate
Project Coordinator	Domenico Calcaterra UNIVERSITA DEGLI STUDI DI NAPOLI FEDERICO II domcalca@unina.it
Project Duration	December 2022 – November 2025 (36 months)

Deliverable No.	DV2.2.5
Dissemination level*	PU
Work Package	WP2 - State of the art and knowledge base to define impact-oriented hazard indicators
Task	T2.2.3 - Spatial analysis of proneness to ground instabilities: statistical and deterministic approaches
Lead beneficiary	UNIBA
Contributing beneficiary/ies	UNIFI, UNIBO.

* PU = Public

PP = Restricted to other programme participants (including the Commission Services)

RE = Restricted to a group specified by the consortium (including the Commission Services)

CO = Confidential, only for members of the consortium (including the Commission Services)

Document history

Version	Date	Lead contributor	Description
0.1	22.11.2023	Mario Parise (UNIBA) Matteo Berti (UNIBO) Riccardo Fanti (UNIFI)	First draft
0.2	23.11.2023	Isabella S. Liso (UNIBA) Isabella Lapietra (UNIBA)	Draft of Chapter 5 Critical review and proofreading
0.3	24.11.2023	Mario Parise (UNIBA)	Chapters 1-3, Review and Proofreading of Chapters 4 and 5, Chapter 6
0.4	27.11.2023	Salvatore Martino, Francesca Bozzano (UniRoma1); Domenico Calcaterra, Diego Di Martire (UniNA), Ricardo Fanti (UniFI)	Edits for approval
1.0	28.11.2023	Participants to TK2.2.3	Final version

8) ABSTRACT

This Deliverable, part of Milestone 2.2 of Spoke 2 in the Extended Partnership RETURN Project, deals with the theme “Identification of impact-oriented indicators” as outlined in the Executive Work Plan – Milestone 2.1. It summarizes the scientific research activities conducted from January to November 2023 by Task 2.2.2 (“Quantitative analysis of predisposition to ground instabilities”) of Work Package 2.2 (“State of the art and knowledge base to define impact-oriented hazard indicators”). This task is a component of the vertical spoke VS2, “Ground Instabilities”, and involves 57 researchers from various institutions.

The focus of WP2 is on detecting and analysing predisposing factors to ground instabilities, while WP3 and WP4 concentrate on preparatory factors, and triggering and multiple geohazards cascading scenarios (MULTI-HAZARD), respectively. These work packages collectively aim to quantify ground instabilities’ effects on territories, buildings, and communities, and to develop an IT platform for the spatial and temporal analysis of these instabilities.

A significant phase within Task 2.2.2 involved defining Ground Instability categories, which were categorized initially into landslides, subsidence, liquefaction, and sinkholes. A more detailed differentiation was later made, particularly distinguishing between slow and fast types of ground instability in subaerial phenomena. These categories are detailed in Table 4.1 and have been fundamental in guiding the project’s direction.

The quantification of the parameters that play a role in determining the susceptibility of ground instabilities is a quite complicate issue that has been the object of many attempts in categorizing them as a function of the capability to express them, generally in terms of qualitative vs. quantitative assessments. Actually, the topic has many variables, that change depending, in first instance, upon the typology of ground instability taken into account, and upon the geological setting of the areas under study as well. Within the framework of the RETURN Project, all the difficulties in performing a full and comprehensive analysis of the available approaches guided us toward the decision to quantify the parameters identified to measure the proneness to ground instabilities on the basis of simple criteria, based upon the logs used to extract data from them. Therefore, in this document the predisposing factors were discriminated according to being described through a qualitative log, a semi-quantitative log, and a quantitative log.

3. Table of contents

4) Introduction

This Deliverable is drawn up as part of Milestone 2.2 of Spoke 2 having as its topic (from the Executive Work Pan – Milestone 2.1) "Identification of impact-oriented indicators". The Deliverables of Spoke 2 for this Milestone have therefore set themselves as an overall objective the identification of rationales, starting from specific learning examples of literature, for identifying both the ground instabilities through macro-categories of factors (predisposing, preparatory, triggers) and the construction of analytical tools which, arranged in a specific logical-executive order (tool-chain), should lead to the design of an IT platform for the restitution in the PoC of the spatial overlap (multiple-hazard) or the temporal succession (multi-hazard, i.e. chain effects) of ground instability processes. This will allow quantifying the ground instabilities effects on the territory with a view to their impact on buildings and communities also evaluating their suitability and reliability.

4.1 Project framework

This report summarizes the scientific research activities carried out in the period January 2023 - November 2023 by the **Task 2.2.2** *"Quantitative analysis of predisposition to ground instabilities through: (a) geological, geomorphological (including erosion, transport, deposition processes), and geotechnical parameters; (b) factors controlling coastal and seafloor environment, geomorphological setting, submarine mass wasting"* (hereinafter referred to as **TK2**) of the **Work Package 2.2** *"State of the art and knowledge base to define impact-oriented hazard indicators"* (hereinafter referred to as **WP2**) within the vertical spoke **VS2** "Ground Instabilities" of the Extended Partnership RETURN.

It should be noted that VS2 structured the work packages WP2, WP3 and WP4 by identifying the following areas of interest for each of them:

- WP2 focuses on the detection and analysis of **PREDISPOSING** factors to ground instabilities;
- WP3 targets **PREPARATORY** factors to ground instabilities;
- WP4 is centered on **TRIGGERING** and multiple geohazards cascading scenarios (**MULTI-HAZARD**).

In accordance with the definitions given within the VS2, the distinction between predisposing, preparatory and triggering factors/processes is made on a temporal basis: the predisposing factors are considered invariable on the observation scale, while the preparatory factors show changes or cyclical trends during the same period. As a consequence, a trigger is considered as a process that acts in a very short and well-defined time.

The partners involved in the **WP2** are ENEA, OGS, POLITO, UNIBA, UNIBO, UNIFI, UNIGE, UNINA, UNIPA, UNIPD and UNIROMA1. **WP2** leaders are Riccardo Fanti (UNIFI) and Mario Parise (UNIBA), **TK1** leader is Francesco Maria Chiocci (UNIROMA1), **TK2** leader is Mario Parise (UNIBA), **TK3** leader is Matteo Berti (UNIBO). 70 researchers participate in the activities of **WP2/TK2** (i.e., TK 2.2.3): 5 from ENEA, 4 from OGS, 5 from POLITO, 6 from UNIBA, 6 from UNIBO, 7 from UNIFI, 4 from UNIGE, 7 from UNINA, 12 from UNIPA, 6 from UNIPD and 8 from UNIROMA1.

The goal of **TK2** (*Quantitative analysis of predisposition to ground instabilities through: (a) geological, geomorphological (including erosion, transport, deposition processes), and geotechnical parameters; (b) factors controlling coastal and seafloor environment, geomorphological setting, submarine mass wasting*) and the issue of **DV 2.2.3** (*Rationale for the quantification of parameters measuring the proneness to ground instabilities in both offshore and onshore areas*) have been interpreted within the framework of the entire Spoke work process.

According with the main idea of the Project and of **VS2**, the learning phase had the objective of building a rationale for preparatory processes to be used as input to the Proof of Concept (PoC). This phase has been articulated in three stages:

i) Inventory of Learning Examples (LE).

ii) Individuation of the preparatory processes analyzed in each LE.

iii) Definition of a Rationale for each process based on the available LEs.

This **DV 2.2.3** represents the description of the transition from phase ii) above to phase iii).

In this sense, the work is a gradual transition from the exemplary level represented by the synthesis of the LE (i.e. recent experience of each partner, comprising leading-edge analyzes on the topic of characterization of predisposing factors and spatial and temporal quantification of susceptibility) to an exhaustive level consisting of a synthesis useful for the purposes of drafting a real Rationale.

To achieve this objective, we progressed through an "internal recall" phase, aimed at identifying, among the experiences of **TK2** participants, an additional set of LEs capable of integrating case studies of phenomena and approaches intended to better complete the emerging panorama during the initial phase (refer to DV 2.2.1 and DV 2.2.2). Subsequently, an additional phase of analyzing global case studies was added, too, involving a bibliographic review on the topic of **TK2**, to arrive at a final product (the present Rationale) that can serve as a valid and comprehensive support for the subsequent phases of the project.

Similar to **TK1** (see DV 2.2.1 and DV 2.2.2), during the implementation of **TK2** activities, the uniqueness of the theme of submerged environments was highlighted. For this reason, in **DV 2.2.3**, a specific analysis is dedicated to submarine phenomena, considered as a kind of "parallel" TK. This analysis has been coordinated by Francesco Maria Chiocci (UNIROMA1), serving as **TK1** leader and, more importantly, as an expert on the theme. Subsequently, the theme of the underwater environment is considered separately, while maintaining a conceptual framework as homogeneous as possible in comparison with the approach adopted for the subaerial environment. This is in accordance with the fact that **TK2** includes, at the same level, the two types of ground instability (*"Quantitative analysis of predisposition to ground instabilities through: (a) geological, geomorphological (including erosion, transport, deposition processes), and geotechnical parameters; (b) factors controlling coastal and seafloor environment, geomorphological setting, submarine mass wasting"*).

This document also includes sections dedicated to an update related to **WP3**. These are well-identified sections and chapters below that find space here as they are closer to the topic of this **WP2** than other documents within the same Milestone (M2).

Finally, it is considered important to preface this introduction with a significant operational phase carried out within **TK2**, fully shared by **TK1** and **TK3**. This phase involves the definition of Ground Instability categories, a topic to which the following paragraph is dedicated.

4.1.1 Ground Instability Typologies

The topic of defining the typologies of Ground Instability has evidently been addressed since the beginning of the Project (see the Executive Working Plan): as a preliminary step, a distinction was made between landslides, subsidence, liquefaction, and sinkholes. Based on this categorization, we proceeded with the identification of the LEs and their typological analysis, and all documents from the initial phase of the Project contain this distinction. Subsequently, **VS2** deemed it necessary to make a more detailed differentiation, considering the kinematics of the phenomena as the primary discriminating element, especially distinguishing between slow and fast typologies of ground instability in subaerial phenomena.

Following a series of collegial discussions at the level of the entire **WP2** (thus collaboratively involving **TK1**, **TK2**, and **TK3**), a subdivision of Ground Instability functional to this Project was established. It is crucial to note that this subdivision should not be interpreted as a proposal for a new classification of landslides, subsidence, sinkholes, and liquefaction. It is presented in Table 4.1 and serves as a reference for this document. Starting from the definition of this subdivision, different technical meetings have been organized, dedicated to each ground instabilities (respectively, Slow landslides, Fast landslides, Sinkholes/Subsidence/Liquefaction, and Marine Instabilities), aimed at sharing ideas and experiences before writing the Rationales. The meetings were attended by at least a reference person per each institution, with highly productive discussions among the attendees.

Ground Instabilities	Subaerial Landslides	Subaerial Slow Landslides Typologies	Slow Flows (Earthflows)
			Slow Slides (Rotational and Planar Slides, Soil slips)
			Slow Spread & Slow Slope Deformations (Spread (except Liquefaction), Rock/Soil Slope Deformations, Creep, DsGSD)
		Subaerial Rapid Landslides Typologies	Rapid Flows (Debris flows, Mudflows)
			Rapid Slides (Rock Slides, Rock Avalanches)
			Falls & Topples (Rock Falls, Rock Topples)
	Submarine Landslides	*Submarine Landslides Typologies*	Slow Submarine Landslides (Creep, DsGSD)
			Rapid Submarine Landslides (Flows, Avalanches, Slides)
	Sinkholes	Slow Sinkholes Typologies	Slow Sinkholes (Suffosion Sinkholes, Solution sinkholes)
		Rapid Sinkholes Typologies	Rapid Sinkholes (Collapse Sinkholes, Cover-collapse Sinkholes)
	Subsidence	Subsidence Typologies	Subsidence (All Types)
	Liquefaction	Liquefaction Typologies	Liquefaction (All Types)

Table 4.1 – Typologies of Ground Instabilities.

5. Predisposing Factors for ground instabilities

5.1 Methods

The process of identifying the Predisposing Factors for ground instabilities employed an expert-based approach (Figure 5.1). As outlined in the introductory chapter, our starting point was the findings from previous deliverables of Work Package 2 (WP2), namely DV2.2.1 and DV2.2.2, along with an analysis of learning examples provided by all partners involved in the project.

This wok was initially done by the WP and Task leaders and led to the formulation of a preliminary list of Predisposing Factors.

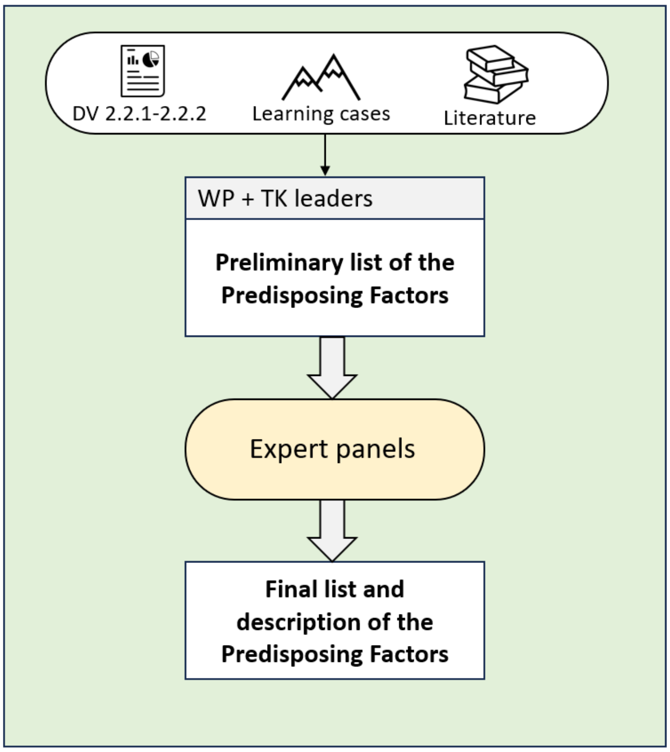

Figure 5.1: flowchart of the approach for identifying Predisposing Factors for Ground Instabilities

The preliminary list underwent refinement and expansion through discussions within dedicated expert panels. We established a specific expert panel for each category of ground instability: slow landslides, fast landslides, and sinkhole/subsidence/liquefaction. The makeup of these panels is detailed in Figure 5.2.

A separate panel focused exclusively on Submarine Ground Instabilities, given the unique nature of underwater landslide phenomena. Due to the distinct characteristics and complexities associated with submarine landslides, this panel operated independently. The understanding of underwater instabilities is not as advanced as that of subaerial ones, necessitating specialized discussions among experts in the field. The findings and insights from this panel's work on Submarine Instabilities is presented in this deliverable in SECTION B- OFFSHORE AREAS., which comprehensively addresses the specific challenges and knowledge gaps in this area.

Slow landslides	Fast landslides	Sinkholes / Subsidence / Liquefaction
Riccardo Fanti	Matteo Berti	Mario Parise
Giuliana Rossi	Gaia Righini	Matteo Del Soldato
Piernicola Lollino	Maria Rita Migliazza	Pierluigi Confuorto
Antonella Marsico	Monica Barbero	Vincenzo Allocca
Carlo Tacconi Stefanelli	Maria Lia Napoli	Rita Tufano
Giacomino Pepe	Isabella Lapietra	Benedetta Antonielli
Paola Salmona	Giuseppe Ciccarese	Mario Floris
Luigi Guerriero	Rossella Bovolenta	Alessandro Zuccarini
Chiara Di Muro	Paola Salmona	
Benedetta Antonielli	Antonio Santo	
Fabio Rollo	Marianna Pirone	
Chiara Martinello	Gian Marco Marmoni	
Simonetta Cola	Benedetta Antonielli	
Lorenzo Brezzi	Edoardo Rotigliano	
	Chiara Cappadonia	

Figure 5.2: composition of expert panels for the different types of ground instabilities. The color coding represents the kinematics of the ground instabilities: green for slow-moving processes, pink for fast-moving processes, and a combination of green/pink for processes involving both slow and fast movements.

In the expert panels, each of the partners contributed their insights and expertise to collectively determine the primary factors influencing each type of ground instability. As is characteristic of expert-based methods, the results of this approach carry a degree of subjectivity and potential bias reflective of personal experiences. To mitigate this, we endeavored to balance individual perspectives with established knowledge from the scientific literature. Our goal was to compile a list of predisposing factors that holds general validity and stands on a firm foundation of both empirical evidence and expert consensus.

For each identified factor, we provided a detailed description, highlighting its significance to a particular type of ground instability. These descriptions were designed to elucidate the impact of the factor (for example, Lithology) on the occurrence of specific instability processes (such as Earthflows), considering the unique characteristics of each process. Undertaking this task was demanding, yet it allowed to refine our understanding of the factors' relevance, and to achieve a more uniform perspective on the predisposing factors for ground instabilities.

The task of describing each factor was undertaken by the leaders of the respective expert panels (see Introduction for details). Once these descriptions were drafted, they were shared with the entire group of experts for further input. This collaborative process allowed for the incorporation of various suggestions and enhancements, ensuring that the descriptions were comprehensive and benefited from the collective expertise and insights of all panel members. This approach not only enriched the quality of the work but also fostered a more collaborative and inclusive assessment of the factors contributing to ground instabilities.

5.2 Results

The results of the work are presented in Table 5.1 and the subsequent pages. Table 5.1 organizes 35 predisposing factors for ground instability in rows, while various types of ground instabilities are listed across the columns. For each type of ground instability, the table highlights the significance of each factor, with each cell demonstrating the relevance of a specific factor to a particular ground instability.

It is important to highlight that the cells marked with an "X" indicate a factor's significant role in the occurrence of a specific ground instability, irrespective of the magnitude or frequency of the process. In this context, these factors are indicative of the susceptibility to ground instability, meaning they reflect the likelihood or tendency of an area to experience such issues, based on the existing local conditions.

Susceptibility assessments focus solely on inherent vulnerabilities without accounting for any external preparatory or triggering factors, such as rainfall or seismic events. Therefore, susceptibility essentially evaluates the natural vulnerability of an area to ground instabilities under its present conditions. The progression from understanding susceptibility to evaluating hazard, which involves considering preparatory and triggering factors, is addressed in Work Packages 3 and 4. These work packages specifically deal with the external factors that can prepare and initiate ground instabilities.

Following the table, detailed descriptions of each Predisposing Factor are provided. These descriptions are specifically tailored to the type of ground instability under consideration and serve as a reference for selecting factors to include in a susceptibility assessment.

Each description of the instability types concludes with a list of pertinent references for further reading and understanding of that specific process.

↓ Predisposing Factors ↓		Log			Slow Landslides Typologies				Rapid Landslides Typologies			Sinkholes Typologies		Subsidence Typologies	Liquefaction Typologies
Macro-category	Main Factors	qualitative	semi-quantitative	quantitative	Slow Flows *(Earthflows)*	Slow Slides *(Rotational and Planar Slides, Soil slips)*	Spreads *(except Liquefaction)*	Slow Slope Deformations *(Rock/Soil SD, Creep, DsGSD)*	Rapid Flows *(Debris flows, Mudflows)*	Rapid Slides *(Rock Slides, Rock Avalanches)*	Falls & Topples *(Rock Falls, Rock Topples)*	Slow Sinkholes	Rapid Sinkholes	Subsidence (All Types)	Liquefaction (All Types)
Geology	Lithology	x					X		X	X	X			X	X
	Structural features (large scale)	x	x				X	X		X		X	X	X	
	Stratigraphic features	x				X		X		X				X	X
	Karstification degree		x									X	X		
	Talus/Weathering		x		X	X		X	X		X	X	X		
Geomorphology	Slope morphology/Topography			x	X	X	X	X	X	X	X	X	X	X	X
	Upslope area			x	X				X						
	Undercutting	x				X					X				
	Erosion by running water	x			X	X			X				X		
	Glaciers and snowfields	x					X	X	X						
	Distance from coastline			x								X	X		
	Overburden thickness			x								X	X		
	Cave geometry and size			x								X	X		
	Presence of previous events	x	x			X			X	X	X	X	X		
Physical and mechanical properties	Rock mass structure		x	x			X	X		X	X	X	X		
	Grainsize distribution/Particle shape		x	x	X				X						X
	Porosity/Density			x	X				X			X	X	X	X
	Shear strength			x	X	X	X		X	X	X				
	Mineralogy and plasticity			x											X
	Hydraulic Properties		x	x	X	X		X	X			X	X	X	
Seismotectonics	Seismic activity		x	x						X	X				X
	Faulting System/Distance to faults	x		x						X	X	X	X	X	
	Site effects (amplification/resonance)			x						X	X				
Land Cover & Vegetation	Land Use/Land Cover		x		X	X			X		X	X	X	X	
	Soil Type/Soil Thickness		x	x	X	X			X			X	X	X	
	Vegetation	x	x		X	X		X	X		X	X	X		
Hydrogeology	Groundwater/Saturation		x	x		X	X	X				X	X	X	X
	Rising acid fluids	x													
	Water inflow/outflow during flood/seastorm	x	x									X	X		
Climate	Rainfall Regime			x	X	X	X	X				X	X	X	
	Temperature Regime			x			X	X							
Anthropogenic Factors	Structures/Infrastructures/Buildings			x		X							X	X	
	Groundwater/Gas/Oil exploitation			x										X	
	River banks/levees typology		x												X
	Slope/Drainage changes		x	x	X	X			X		X				

Table 5.1: correlation matrix of Predisposing Factors and Ground Instabilities. The cells indicate the relevance of a specific factor to each instability type.

Slow landslides

Slow Flows (Earthflows)

Description of the main predisposing factors	
Geology • Lithology	Earthflows commonly occur in areas with fine-grained materials, such as residual soils that form from the weathering of bedrock, colluvial soils which accumulate at the base of slopes, and clay-bearing rocks that are prone to weathering. These landslides also frequently happen in areas with deposits from previous earthflows, indicating a recurring susceptibility. Consequently, areas that exhibit these specific lithological characteristics are more prone to earthflows, with the fine-grained nature of the materials playing a pivotal role in their occurrence and behavior.
Geomorphology • Slope morphology/ Topography	Among the different terrain morphology parameters, the slope angle plays a fundamental role as predisposing factor for earthflows, particularly in their initiation zones. The source area of earthflows is often marked by steep slopes formed by previous events, featuring a complex topography of scarps, ridges, and channels. In these terrains, various triggers can cause minor landslides, potentially leading to further instabilities and the reactivation of larger earthflows. Given that the slope angle is a major factor in initiating these early slides, it holds a role in assessing the overall probability of earthflows.
Geomorphology • Upslope area • Erosion by running water	The presence of surface and subsurface water is particularly important in the initiation and propagation of earthflows. A well-developed drainage network can effectively regulate the water content in clay soils by facilitating the removal of excess water and reducing infiltration. On the other hand, in areas without adequate drainage or where the natural drainage network has been compromised, water tends to accumulate and seep into the soil. This accumulation and infiltration of water can substantially reduce the stability of slopes, increasing the likelihood of earthflows.
Geomorphology • Presence of previous events	The tendency of earthflows to occur multiple times in the same areas, often referred to as reactivation, is a critical aspect in understanding and evaluating susceptibility to such events. Regions with a history of earthflows are often characterized by specific geological and hydrological conditions that make them prone to repeated occurrences. Additionally, past earthflows often result in altered drainage patterns, disrupted vegetation, and the accumulation of material that has reached its residual strength, thereby affecting the stability of the slope. Thus, the history of earthflow events in a particular area is an integral factor in evaluating the potential for future occurrences.
Physical and mechanical characteristics • Grainsize distribution	Earthflows are commonly found in soils that have a distinct grain size distribution, predominantly composed of fine-grained materials. Soils prone to earthflows typically feature a substantial amount of clay and silt particles. However, they may also contain notable amounts of sand particles, coarse clay aggregates, or rock blocks dispersed in the matrix. The presence of these various grain sizes fundamentally influences the soil capacity to hold water, which is a key factor in triggering movement. Additionally, this composition governs the rheological properties of the soil, determining its fluid-like behavior and the overall mobility.

Physical and mechanical characteristics • Porosity	Soil porosity is an important characteristic for shallow earthflows. High porosity soils can absorb and hold significant water, becoming rapidly saturated during intense rainfall. When saturated, these soils might have reduced cohesion because of diminished soil water tension, causing the slope to fail. Additionally, in the event of failure, a highly porous and saturated soil can experience fluidization. The transition to a fluid-like behavior is often due to internal remolding that occurs during the propagation stage of the earthflow.
Physical and mechanical characteristics • Shear strength • Hydraulic properties	The onset of earthflows is intricately linked to the mechanical and hydraulic characteristics of the soil. Factors such as the soil strength (effective cohesion, effective friction angle, undrained cohesion), combined with the pore water pressure, directly control the potential for failure and remobilization of the existing landslide deposits. Mechanical discontinuities within the soil also play a crucial role. Typically, at the base of earthflows, there is a significantly deformed shear zone where the soil structure has been either drastically altered or completely transformed. The existence of mechanically weak layers within the slope is a major contributing factor to the formation of these sliding surfaces. Furthermore, the hydraulic properties of the soil govern aspects like the rate of water infiltration, subsurface drainage patterns, and changes in soil moisture during rainfall events. In slow-moving earthflows, it is often the interplay of these hydraulic properties with the soil geotechnical features that becomes the critical factor.
Land Cover & Vegetation • Land Use/Land Cover • Vegetation	The impact of different land cover types on earthflow susceptibility is complex and multi-faceted. In areas with forests or vegetation, plant and tree roots enhance soil stability by reinforcing the soil matrix and adding cohesion. Additionally, vegetation plays a role in managing soil moisture levels through transpiration. Yet, it is noteworthy that dense forest cover does not entirely prevent earthflow occurrence since sliding surfaces may develop well below the root depth. The decomposition of roots and organic matter, leading to larger soil pores, can increase water absorption into slopes, adding to the complexity of this relationship. Agricultural lands exhibit a more direct link to earthflow susceptibility. Common agricultural activities, such as soil tilling, can disturb the soil structure and promote increased water infiltration, thereby elevating the risk of earthflows. These practices may also interfere with natural drainage patterns. Coupled with inefficient irrigation methods, such agricultural interventions can considerably undermine the stability of shallow soil layers. Overall, while different types of land cover do influence earthflow susceptibility, the nature and extent of this influence can vary considerably, based on specific environmental conditions and land use practices.
Land Cover & Vegetation • Soil type/ Soil thickness	The soil type significantly contributes as a predisposing factor to the likelihood of earthflows. The presence of fine-grained shallow soil can be an indicator of underlying clay bedrock, which has significant implications for the potential occurrence of large earthflows. Clay soils can be readily identified on a large scale through their distinct spectral signature, infrared reflectance, texture, and color. Consequently, identifying shallow soil types yields valuable insights into the susceptibility to earthflows.

Climate • Rainfall Regime	The rainfall regime, encompassing factors like average rainfall, and the typical intensity and duration of rainstorms, serves as a significant predisposing factor for earthflows. In regions that experience prolonged rainstorms, there is typically a general increase in groundwater levels, which greatly heightens their susceptibility to earthflows. This contrasts with areas that receive either low-intensity rainfall over extended periods or areas that experience short-lived but intense thunderstorms. The differences in these rainfall patterns are critical in influencing the buildup of groundwater pressure in sloped areas. Yet, it is important to note that the connection between rainfall patterns and slope stability is complex. This complexity arises from how different types of rainfall interact with the unique geological and hydrological characteristics of each slope, making the relationship between rainfall and slope stability an intricate aspect of earthflow susceptibility.
Anthropogenic Factors • Slope/Drainage changes	Infrastructural development can markedly influence earthflows, as construction activities often modify the natural slope geometry and drainage patterns. These alterations can result in both localized and more widespread impacts on the stability of slopes. For instance, they can change the flow direction of both surface and subsurface water across different scales, thereby affecting the soil's saturation state at various depths. Even minor disruptions caused by local construction interventions can significantly impact the overall stability of earthflows. These changes, though sometimes subtle, can lead to a series of small failures that reactivate larger, more significant landslides. Therefore, the role of infrastructure development in altering the natural balance and stability of slopes is a critical consideration in both urban planning and environmental management.

References for Slow landslides (slow flows – Earthflows)

Calcaterra, D., & Parise, M. (2010). Weathering as a predisposing factor to slope movements: an introduction. Geological society, London, Engineering Geology Special Publications, 23(1), 1-4.

Cascini, L. (2008). Applicability of landslide susceptibility and hazard zoning at different scales. Engineering Geology, 102(3-4), 164-177.

Ciuffi, P., Bayer, B., Berti, M., Franceschini, S., & Simoni, A. (2021). Deformation detection in cyclic landslides prior to their reactivation using two-pass satellite interferometry. Applied Sciences, 11(7), 3156.

Conforti, M., & Ietto, F. (2021). Modeling shallow landslide susceptibility and assessment of the relative importance of predisposing factors, through a GIS-based statistical analysis. Geosciences, 11(8), 333.

Conforti, M., Mercuri, M., & Borrelli, L. (2020). Morphological changes detection of a large earthflow using archived images, LiDAR-derived DTM, and UAV-based remote sensing. Remote Sensing, 13(1), 120.

Conoscenti, C., Ciaccio, M., Caraballo-Arias, N. A., Gómez-Gutiérrez, Á., Rotigliano, E., & Agnesi, V. (2015). Assessment of susceptibility to earth-flow landslide using logistic regression and multivariate adaptive regression splines: a case of the Belice River basin (western Sicily, Italy). Geomorphology, 242, 49-64.

Corominas, J., & Moya, J. (2008). A review of assessing landslide frequency for hazard zoning purposes. Engineering geology, 102(3-4), 193-213.

Cotecchia, F., Vitone, C., Santaloia, F., Pedone, G., & Bottiglieri, O. (2015). Slope instability processes in intensely fissured clays: case histories in the Southern Apennines. Landslides, 12, 877-893.

Donnarumma, A., Revellino, P., Grelle, G., & Guadagno, F. M. (2013). Slope angle as indicator parameter of landslide susceptibility in a geologically complex area. Landslide Science and Practice: Volume 1: Landslide Inventory and Susceptibility and Hazard Zoning, 425-433.

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., & Savage, W. Z. (2008). Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. Engineering geology, 102(3-4), 85-98.

Glade, T., & Crozier, M. J. (2005). The nature of landslide hazard impact. Landslide hazard and risk, 41-74.

Guzzetti, F., Ardizzone, F., Cardinali, M., Galli, M., Reichenbach, P., & Rossi, M. (2008). Distribution of landslides in the Upper Tiber River basin, central Italy. Geomorphology, 96(1-2), 105-122.

Highland, L. M., & Bobrowsky, P. (2008). The landslide handbook-A guide to understanding landslides (No. 1325). US Geological Survey.

Hungr, O., Leroueil, S., & Picarelli, L. (2014). The Varnes classification of landslide types, an update. Landslides, 11, 167-194.

McColl, S. T. (2022). Landslide causes and triggers. In Landslide hazards, risks, and disasters (pp. 13-41). Elsevier.

Meisina, C. (2006). Characterisation of weathered clayey soils responsible for shallow landslides. Natural Hazards and Earth System Sciences, 6(5), 825-838.

Pellicani, R., Frattini, P., & Spilotro, G. (2014). Landslide susceptibility assessment in Apulian Southern Apennine: heuristic vs. statistical methods. Environmental earth sciences, 72, 1097-1108.

Pinto, F., Guerriero, L., Revellino, P., Grelle, G., Senatore, M. R., & Guadagno, F. M. (2016). Structural and lithostratigraphic controls of earth-flow evolution, Montaguto earth flow, Southern Italy. Journal of the Geological Society, 173(4), 649-665.

Schädler, W. (2011). Slope movements of the earthflow type-engineering-geological investigation, geotechnical assessment and modelling of the source areas on the basis of case studies from the Alps and Apennines. Logos Verlag Berlin GmbH.

Sidle, R. C. (1985). Factors influencing the stability of slopes. In Proceedings of the workshop on slope stability: problems and solutions in forest management. Gen. Tech. Rep. PNW-180. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station (pp. 17-25).

Spalluto, L., Fiore, A., Miccoli, M. N., & Parise, M. (2021). Activity maps of multi-source mudslides from the Daunia Apennines (Apulia, southern Italy). Natural Hazards, 106(1), 277-301.

Slow landslides

Slow Slides (Rotational and Planar Slides, Soil slips)

Description of the main predisposing factors	
Geology • Stratigraphic features	The presence of weak layers within the stratigraphic succession is an important predisposing factor for deep-seated slow slides. Such weak layers, common in many rock formations, arise from variations in depositional environments, sediment origins, or changes that occurred post-deposition over geological epochs. Layers rich in clay or encompassing clay-bearing rocks can be present. Furthermore, these clay-rich layers can obstruct water flow, resulting in increased pore water pressure either within or above the layer.
Geology • Talus/weathering	The presence of talus/weathering is important for shallow slides. Areas with abundant loose sediments, weakly consolidated rocks, or recently disturbed ground (due to activities like logging or forest fire) are particularly vulnerable to shallow failures. This susceptibility is attributed not only to the ease with which materials can be mobilized, but also to the potential magnification of event severity. The impact of shallow slides can range significantly, affecting areas as small as several square meters to as large as several hectares, regardless of the time frame. Consequently, the presence, extent and thickness of the talus become critical factors. This is particularly relevant in instances of soil slips, which can impact vast areas during a single rainfall event.
Geomorphology • Slope morphology/ Topography	In the realm of slope morphology, the slope angle stands out as a crucial predisposing factor for slow slides. As the slope becomes steeper, an imbalance is created, enhancing the shear stress (the driving forces) and reducing the normal stress (the resisting forces), thus increasing the risk of failure. The fundamental principle of balancing driving and resisting forces is relevant to all types of landslides. Its significance, however, is particularly evident in the case of slow slides. These types of landslides usually occur along a clearly defined slip surface, which closely aligns with the basic principles of limit equilibrium mechanics. In this framework, the angle of the slope is a key determinant of stability.
Geomorphology • Undercutting • Erosion by running water	Planar and rotational slides usually involve dip slopes that have been undercut by erosion or excavation. In some cases, the undercutting is not complete and a "toe breakout" mechanism involving failure of the intact material must develop. The undercutting can also expose planar sliding surfaces, thus acting as an important predisposing factor. Water erosion can also lead to the removal of protective vegetation cover, modify the shape and steepness of a slope, and result in increased soil saturation, particularly during periods of intense rainfall. The cumulative impact of these factors can significantly heighten the vulnerability of a slope to shallow slides, as the erosion processes both structurally weaken the slope and alter its hydrological conditions.

Geomorphology • Presence of previous events	Prior landslide occurrences can make an area more susceptible to future events, effectively serving as a predisposing factor. The likelihood of recurrence is shaped by various changes, such as alterations in the slope conditions, modifications in the drainage network, and variations in the vegetation cover. Additionally, the areas affected by previous landslides typically feature deposits with lower shear strength compared to undisturbed soil, further heightening the risk of future slides. Consequently, landslides in these regions tend to be subject to continuous reactivations, with the potential to recur over long durations, sometimes extending over many years or even centuries. This ongoing vulnerability underscores the importance of considering past landslide activity in assessing the susceptibility.
Physical and mechanical characteristics • Shear strength • Hydraulic properties	The shear strength and hydraulic properties of soil are crucial predisposing factors for slow slides, but their influence varies significantly based on the type of slide. Slow slides encompass a wide range of phenomena, from shallow to deep failures, and involve diverse materials, from soil to rock. This diversity underscores the complexity and variability inherent in slow slide phenomena, making it challenging to generalize how mechanical factors predispose to such slides. Generally, the effective friction angle is a key parameter for both shallow and deep slides. Effective cohesion is even more critical but exceedingly difficult to evaluate on a large scale due to variables like soil and rock heterogeneity, root presence, and the effects of matric suction. Consequently, cohesion is often estimated through calibration or sensitivity analysis when assessing susceptibility to slow slides. Hydraulic properties hold particular significance for shallow slides. Steep, forested slopes can maintain temporary stability through the stabilizing effects of matric suction (soil tension in unsaturated conditions) and the reinforcement provided by roots within the soil. However, during prolonged and intense rainfall, any reduction in matric suction or the development of positive pore water pressures can create conditions conducive to landslides. Moreover, the complex interplay between air, water, and soil particles in unsaturated conditions critically influences soil shear strength. The shear strength of unsaturated soils, which differs from that of saturated soils, depends on additional challenging-to-measure parameters like matric suction, the Soil-Water Characteristic Curve, and the impact of suction on apparent cohesion. This complexity highlights the importance of conducting thorough geological and geotechnical analyses to understand these elements better and assess landslide susceptibility accurately.
Land Cover & vegetation • Land Use/Land Cover • Soil type/Soil Thickness • Vegetation	Land cover significantly influences the environmental conditions on slopes and affects how water interacts with the subsurface systems. Areas with bare rock or sparse vegetation are more directly exposed to environmental factors such as rainfall, snowmelt, and temperature fluctuations. In contrast, densely forested areas may protect rock surfaces from direct exposure to these elements. However, the tree roots in these forests can aid water infiltration into the subsurface through fissures or macropores, acting as channels that facilitate water flow and potentially contribute to slope instability. Consequently, the role of land cover as a predisposing factor for slides varies considerably and should be assessed on a case-by-case basis, considering factors such as the type of landslide (shallow or deep) and the specific characteristics of the soil.
Hydrogeology • Groundwater/ saturation	The influence of groundwater on the likelihood of slow slides varies depending on the type of slide involved. For deep-seated failures, an increase in pore water pressure at depth, particularly in already saturated soils, is a common trigger. In such scenarios, the average groundwater level within the slope emerges as a predisposing factor to instability. Groundwater level results from the interaction of various elements,

	including the characteristics of the soil and rock, the topography, the vegetation presence, the proximity to rivers, and the human activities like water withdrawal or increased recharge from irrigation. Each of these elements affects how water is collected, distributed, and retained within the slope. In contrast, the occurrence of shallow slides is more closely tied to the saturation level of the soil, which is a more complex aspect to gauge. Typically, areas prone to water pooling or where water tends to accumulate maintain higher saturation levels, increasing the susceptibility of the slope to failure. This underscores the need for a nuanced understanding of both deep and shallow slides, as their mechanisms and influencing factors can differ substantially, especially in how groundwater impacts their stability.
Climate • Rainfall Regime	The predisposition of an area to slow slides is significantly influenced by the rainfall regime, including the duration and intensity of rainfall events. In regions where the rainfall regime is characterized by intense but brief events, the rapid accumulation of water can overwhelm the soil capacity to absorb moisture, leading to an immediate increase in surface runoff and the saturation of the shallow layers. This can trigger landslides, especially shallow slides on steep slopes. On the other hand, regions characterized by less intense but more prolonged rainfall, where dry periods are not as prominent, present a different scenario. In these areas, the soil can gradually absorb water over time. This slow, steady infiltration elevates the moisture content in the shallow layers and enables deeper water penetration during intense episodes, like thunderstorms. This process can heighten the risk of deep-seated landslides. However, it is important to note that the interplay between climatic conditions and the stability of deeper slopes remains a complex subject. The gradual changes in soil moisture over time and the varying responses of different soil types and slopes to prolonged moisture exposure contribute to this complexity, making the prediction and understanding of landslide susceptibility in these scenarios a challenging task.
Anthropogenic Factors • Structures/Infrastructures/ Buildings • Slope/Drainage changes	Presence of roads and infrastructures can impact the possibility of occurrence of slow slides. The vibrations related to heavy traffic, or to frequent passage of vehicles in urban areas may predispose the ground to further instabilities. Particularly in urban areas, the presence of sewer systems in the first meters below the ground, may have a strong influence on the occurrence of slow slides, both rotational and planar. Leakages from such systems may induce an increase in the degree of saturation of terrains or rock masses, bringing toward conditions favorable to failures. Constructing roads and infrastructures can significantly impact slow slides movements. Often, the creation of pathways or leveled terrains necessitates excavation or blasting. These activities can disrupt the rock mass's natural stability, producing or expanding discontinuities. Additionally, infrastructural development can modify natural drainage patterns, modifying local water drainage and causing water to pool in specific regions. This can have an effect both locally and at the slope scale, thus influencing the directions of surface and underground water flow at various scales and with it the state of saturation of the soil at various depths.

References for Slow landslides - ***Slow Slides (Rotational and Planar Slides, Soil slips)***

Bednarik, M., Magulová, B., Matys, M., & Marschalko, M. (2010). Landslide susceptibility assessment of the Kraľovany–Liptovský Mikuláš railway case study. Physics and Chemistry of the Earth, Parts A/B/C, 35(3-5), 162-171.

Calvello, M., Peduto, D., & Arena, L. (2017). Combined use of statistical and DInSAR data analyses to define the state of activity of slow-moving landslides. Landslides, 14, 473-489.

Cascini, L. (2008). Applicability of landslide susceptibility and hazard zoning at different scales. Engineering Geology, 102(3-

Catani, F., Casagli, N., Ermini, L., Righini, G., & Menduni, G. (2005). Landslide hazard and risk mapping at catchment scale in the Arno River basin. Landslides, 2, 329-342.

Corominas, J., & Moya, J. (2008). A review of assessing landslide frequency for hazard zoning purposes. Engineering geology, 102(3-4), 193-213.

Di Maio, R., De Paola, C., Forte, G., Piegari, E., Pirone, M., Santo, A., & Urciuoli, G. (2020). An integrated geological, geotechnical and geophysical approach to identify predisposing factors for flowslide occurrence. Engineering Geology, 267, 105473.

Du, J., Yin, K., Nadim, F., & Lacasse, S. (2013). Quantitative vulnerability estimation for individual landslides. In Proceedings of the 18th international conference on soil mechanics and geotechnical engineering, Paris (pp. 2181-2184).

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., & Savage, W. Z. (2008). Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. Engineering geology, 102(3-4), 85-98.

Glade, T., & Crozier, M. J. (2005). The nature of landslide hazard impact. Landslide hazard and risk, 41-74.

Guzzetti, F., Ardizzone, F., Cardinali, M., Galli, M., Reichenbach, P., & Rossi, M. (2008). Distribution of landslides in the Upper Tiber River basin, central Italy. Geomorphology, 96(1-2), 105-122.Hungr, O., Leroueil, S., & Picarelli, L. (2014). The Varnes classification of landslide types, an update. Landslides, 11, 167-194.

Highland, L. M., & Bobrowsky, P. (2008). The landslide handbook-A guide to understanding landslides (No. 1325). US Geological Survey.

Hungr, O., Leroueil, S., & Picarelli, L. (2014). The Varnes classification of landslide types, an update. Landslides, 11, 167-194.

Komac, M. (2006). A landslide susceptibility model using the analytical hierarchy process method and multivariate statistics in perialpine Slovenia. Geomorphology, 74(1-4), 17-28.

Lacroix, P., Handwerger, A. L., & Bièvre, G. (2020). Life and death of slow-moving landslides. Nature Reviews Earth & Environment, 1(8), 404-419.

Lu, P., Catani, F., Tofani, V., & Casagli, N. (2014). Quantitative hazard and risk assessment for slow-moving landslides from Persistent Scatterer Interferometry. Landslides, 11, 685-696.

Magliulo, P., Di Lisio, A., Russo, F., & Zelano, A. (2008). Geomorphology and landslide susceptibility assessment using GIS and bivariate statistics: a case study in southern Italy. Natural hazards, 47, 411-435.

Manzo, G., Tofani, V., Segoni, S., Battistini, A., & Catani, F. (2013). GIS techniques for regional-scale landslide susceptibility assessment: the Sicily (Italy) case study. International Journal of Geographical Information Science, 27(7), 1433-1452.

Martinello, C., Cappadonia, C., Conoscenti, C., Agnesi, V., & Rotigliano, E. (2021). Optimal slope units partitioning in landslide susceptibility mapping. Journal of Maps, 17(3), 152-162.

Martinello, C., Cappadonia, C., Conoscenti, C., & Rotigliano, E. (2022). Landform classification: a high-performing mapping unit partitioning tool for landslide susceptibility assessment—a test in the Imera River basin (northern Sicily, Italy). Landslides, 1-15.

Meusburger, K., & Alewell, C. (2009). On the influence of temporal change on the validity of landslide susceptibility maps. Natural Hazards and Earth System Sciences, 9(4), 1495-1507.

Montrasio, L. (2000). Stability analysis of soil-slip. WIT transactions on ecology and the environment, 45.

Ozturk, U., Pittore, M., Behling, R., Roessner, S., Andreani, L., & Korup, O. (2021). How robust are landslide susceptibility estimates?. Landslides, 18, 681-695.

Rosi, A., Tofani, V., Tanteri, L., Tacconi Stefanelli, C., Agostini, A., Catani, F., & Casagli, N. (2018). The new landslide inventory of Tuscany (Italy) updated with PS-InSAR: geomorphological features and landslide distribution. Landslides, 15, 5-19.

Ruff, M., & Czurda, K. (2008). Landslide susceptibility analysis with a heuristic approach in the Eastern Alps (Vorarlberg, Austria). Geomorphology, 94(3-4), 314-324.

Samia, J., Temme, A., Bregt, A., Wallinga, J., Guzzetti, F., Ardizzone, F., & Rossi, M. (2017). Characterization and quantification of path dependency in landslide susceptibility. Geomorphology, 292, 16-24.

Taalab, K., Cheng, T., & Zhang, Y. (2018). Mapping landslide susceptibility and types using Random Forest. Big Earth Data, 2(2), 159-178.

Terwilliger, V. J., & Waldron, L. J. (1991). Effects of root reinforcement on soil-slip patterns in the Transverse Ranges of southern California. Geological Society of America Bulletin, 103(6), 775-785.

Trigila, A., Frattini, P., Casagli, N., Catani, F., Crosta, G., Esposito, C., ... & Lari, S. (2013). Landslide susceptibility mapping at national scale: the Italian case study. Landslide Science and Practice: Volume 1: Landslide Inventory and Susceptibility and Hazard Zoning, 287-295.

Slow landslides

Slow Spread/DsGSD

Description of the main predisposing factors	
Geology • Lithology	Lateral spread and Deep-seated Gravitational Slope Deformation (DsGSD) are complex geological phenomena strongly controlled by the type and structure of the rock. Lithology is among the primary factors for occurrence of slow spreads, as this type of landslide typically requires the near-horizontal stretching of coherent rock masses. This stretching is a consequence of intense deformation of a weaker underlying material, or it may be due to multiple retrogressive slides governed by a fragile basal surface. A common manifestation of this phenomenon is rock slope spreading, where rigid blocks of more robust rocks undergo displacement and rotation. This happens due to the severe plastic deformation of a weaker rock layer underneath. Such spreading is particularly prevalent in areas with horizontally bedded, weak sedimentary sequences, where the contrast in rock strength between the layers sets the stage for this type of movement. Similarly, DsGSD are common in areas with notable contrasts in rock strength, although the lithological conditions can vary more widely. Areas with weak or fractured rock layers, weathered material, and significant lithological diversity are especially prone to DsGSD. In these cases, the variability in rock strength and structure plays a key role in the development and progression of the landslide.
Geology • Structural features (large scale) • Stratigraphic features	Large-scale structural features such as thrust planes, major bedding planes, or schistosity, are important predisposing factor for both slow spreads and DsGSD. The geological structures have the potential to serve as sliding surfaces, enabling a large volume of rock to detach and move. Moreover, these large-scale discontinuities can also influence groundwater flow, acting either as conduits or barriers. This can lead to changes in pore pressure along potential sliding surfaces, further affecting slope stability. Similarly, the presence of specific stratigraphic features, such as formations that are inherently weak, contain clay, or have layers of soft material, is equally significant. These features are key in determining where a deep-seated sliding surface might develop, potentially leading to large-scale landslide movements.
Geomorphology • Slope morphology/Topography	Slope angle is a crucial predisposing factor both for spreads and DsGSD. In lateral spreads, the slope is typically made of a stiff, rigid rock layer that overlies a weaker, more deformable material. The slope angle of this underlying weak layer plays a key role in how stresses are distributed and managed within the system. If the slope angle of the weak layer is relatively gentle, the overlying stiff rock may remain relatively stable, with only minor deformations occurring over time. However, as the slope angle of the weak material increases, the gravitational forces acting on the overlying stiff rock become more significant. This increased force can exceed the strength of the weaker material, leading to its deformation under the weight of the stiff rock. The steeper the slope, the greater the gravitational component acting parallel to the slope, which can facilitate sliding or spreading movements.

	Similarly, in DsGSD, the slope geometry and angle are influential as they dictate the strength of gravitational forces at play. Steeper slopes are more likely to reveal structural weaknesses or stratigraphic layers that could serve as potential sliding surfaces. This is particularly evident in high mountain areas, where DsGSD frequently occurs, demonstrating that the steepness of a slope is a critical determinant in its vulnerability to such landslides.
Geomorphology • Glaciers and snowfield	In high mountainous regions, glaciers play a vital role as structural supports for mountain slopes, especially those composed of weaker or fractured rocks. When these glaciers retreat, the support they provide is removed, significantly altering the stress and strain within the slope rock mass. This change in stress distribution can reveal and intensify existing weaknesses in the rock, such as fractures or faults, and can lead to the slope becoming predisposed to slow spread/DsGSD movements. Furthermore, as glaciers recede, they uncover new rock surfaces, exposing them to the atmosphere. This exposure leads to increased water infiltration into the rock, further influencing the slope's stability. The effects of glacial debuttressing on slope stability, however, may not be immediate. Often, there is a lag between the glacier retreat and the onset of slope movements. The processes that lead to the destabilization and weakening of the rock structure are gradual and take time to evolve. In this context, the processes associated with glacial retreat can be considered more as predisposing factors rather than immediate triggers for slope instability. They set the stage for future instability, creating conditions under which movements are more likely to occur over time
Physical and mechanical characteristics • Rock mass structure • Shear strength • Hydraulic properties	The role of rock mass structure, shear strength, and hydraulic properties in the movement of lateral spread/DsGSD is crucial. In lateral spreading, the movement is largely driven by the disparity in shear strength between the overlying stiff rock and the underlying soft soil. The stiff rock layer, typically having higher shear strength, remains more resistant to deformation and movement. In contrast, the underlying soft soil, characterized by lower shear strength, is more susceptible to deformation under stress. When subjected to actions such as gravitational load or increased water pressure, this softer layer can deform more easily. In these scenarios, the key factors that predispose the area to lateral spreading include the effective friction angle and the cohesion of the soft soil. These properties determine how much the soil layer can resist shearing forces before it starts deforming. Another crucial aspect is the presence of sub-vertical discontinuities in the stiff rock layer above. These discontinuities can create weak zones, allowing rock blocks to detach and spread, especially when the supporting soil layer starts to deform. DsGSD encompass a wide array of geological and geomorphological conditions, making it challenging to pinpoint specific shear strength factors that universally control their occurrence. This complexity arises from the fact that DsGSD can develop under a variety of scenarios, each influenced by a unique combination of geological characteristics and processes. Given this diversity, each instance of DsGSD is a unique interplay of numerous factors, necessitating a case-by-case approach to understanding the mechanical and hydrogeological predisposition to instability.

Hydrogeology • Groundwater/ Saturation	Both lateral spreads and DsGSD typically involve long-term and steady movements, which are usually not significantly influenced by regular rainfall. This gradual movement is indicative of the ongoing, albeit slow, deformation of the soil or rock mass and the corresponding adjustment in the internal stress field. The consistent and gradual nature of these movements is a key characteristic of spreads and DsGSD, setting them apart from the more sudden types of landslides. However, during severe rainfall events, the behavior of these landslides can shift significantly. Heavy and sustained rainfall can provoke localized failures, especially in areas around cliffs. In these instances, landslides can occur as secondary effects within the broader context of slow movements. In such cases, the average position of the groundwater within the slope is a crucial predisposing factor for instability.
Climate • Rainfall Regime • Temperature Regime	The behavior of both lateral spreading and DsGSD is profoundly affected by long-term rainfall and temperature regimes through a series of complex and interrelated processes. In areas frequently experiencing prolonged rainfall, the sustained and extensive periods of moisture contribute to the heightened saturation of soil and rock materials. This heightened saturation, over time, can promote deep-seated movements. Temperature also plays a pivotal role, especially in regions subject to freeze-thaw cycles. These cycles lead to the expansion and contraction of soil and rock, progressively weakening the material's structure and facilitating water infiltration. Additionally, the ongoing changes in global climate patterns are altering snowmelt and glacial dynamics, potentially leading to deeper instabilities in certain environments. Accurately quantifying these influences is however fraught with challenges. The dynamic and intricate nature of these factors, along with their inherent variability and dependence on scale, makes it difficult to measure and predict their impacts precisely. This complexity is compounded by the evolving nature of climate patterns and the diverse geological characteristics they interact with, presenting significant hurdles in the comprehensive assessment and quantification of these factors at a large scale.

References for Slow landslides - *Slow Spread/DsGSD*

Agliardi, F., Crosta, G., & Zanchi, A. (2001). Structural constraints on deep-seated slope deformation kinematics. Engineering Geology, 59(1-2), 83-102.

Agnesi, V., Rotigliano, E., Tammaro, U., Cappadonia, C., Conoscenti, C., Obrizzo, F., ... & Pingue, F. (2015). GPS monitoring of the Scopello (Sicily, Italy) DGSD phenomenon: Relationships between surficial and deep-seated morphodynamics. In Engineering Geology for Society and Territory-Volume 2: Landslide Processes (pp. 1321-1325). Springer International Publishing.

Bayer, B., Simoni, A., Mulas, M., Corsini, A., & Schmidt, D. (2018). Deformation responses of slow moving landslides to seasonal rainfall in the Northern Apennines, measured by InSAR. Geomorphology, 308, 293-306.

Bovis, M. J., & Evans, S. G. (1996). Extensive deformations of rock slopes in southern Coast Mountains, southwest British Columbia, Canada. Engineering Geology, 44(1-4), 163-182.

Capitani, M., Ribolini, A., & Bini, M. (2013). The slope aspect: A predisposing factor for landsliding?. Comptes Rendus Geoscience, 345(11-12), 427-438.

Crosta, G. B., Frattini, P., & Agliardi, F. (2013). Deep seated gravitational slope deformations in the European Alps. Tectonophysics, 605, 13-33.

De Vita, P., Carratù, M. T., La Barbera, G., & Santoro, S. (2013). Kinematics and geological constraints of the slow-moving Pisciotta rock slide (southern Italy). Geomorphology, 201, 415-429.

Di Martire, D., Novellino, A., Ramondini, M., & Calcaterra, D. (2016). A-differential synthetic aperture radar interferometry analysis of a deep seated gravitational slope deformation occurring at Bisaccia (Italy). Science of the Total Environment, 550, 556-573.

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). Geomorphology, 380, 107629.

Glastonbury, J., & Fell, R. (2008). Geotechnical characteristics of large slow, very slow, and extremely slow landslides. Canadian Geotechnical Journal, 45(7), 984-1005.

Highland, L. M., & Bobrowsky, P. (2008). The landslide handbook-A guide to understanding landslides (No. 1325). US Geological Survey.

Hungr, O., Leroueil, S., & Picarelli, L. (2014). The Varnes classification of landslide types, an update. Landslides, 11, 167-194.

Leroueil, S. (2001). Natural slopes and cuts: movement and failure mechanisms. Géotechnique, 51(3), 197-243.

Martinotti, G., Giordan, D., Giardino, M., & Ratto, S. (2011). Controlling factors for deep-seated gravitational slope deformation (DSGSD) in the Aosta Valley (NW Alps, Italy). Geological Society, London, Special Publications, 351(1), 113-131.

Morelli, S., Pazzi, V., Frodella, W., & Fanti, R. (2018). Kinematic reconstruction of a deep-seated gravitational slope deformation by geomorphic analyses. Geosciences, 8(1), 26.

Novellino, A., Cesarano, M., Cappelletti, P., Di Martire, D., Di Napoli, M., Ramondini, M., ... & Calcaterra, D. (2021). Slow-moving landslide risk assessment combining Machine Learning and InSAR techniques. Catena, 203, 105317.

Pánek, T., & Klimeš, J. (2016). Temporal behavior of deep-seated gravitational slope deformations: A review. Earth-Science Reviews, 156, 14-38.

Persichillo, M. G., Bordoni, M., Meisina, C., Bartelletti, C., Barsanti, M., Giannecchini, R., ... & Galve, J. P. (2017). Shallow landslides susceptibility assessment in different environments. Geomatics, Natural Hazards and Risk, 8(2), 748-771.

Piacentini, D., Devoto, S., Mantovani, M., Pasuto, A., Prampolini, M., & Soldati, M. (2015). Landslide susceptibility modeling assisted by Persistent Scatterers Interferometry (PSI): An example from the northwestern coast of Malta. Natural Hazards, 78, 681-697.

Richer, B., Saeidi, A., Boivin, M., & Rouleau, A. (2020). Overview of retrogressive landslide risk analysis in sensitive clay slope. Geosciences, 10(8), 279.

Tomás, R., Abellán, A., Cano, M., Riquelme, A., Tenza-Abril, A. J., Baeza-Brotons, F., ... & Jaboyedoff, M. (2018). A multidisciplinary approach for the investigation of a rock spreading on an urban slope. Landslides, 15, 199-217.

Fast landslides

Debris flows / Mud flows

Description of the main predisposing factors	
Geology • Lithology	Even though debris flows and mud flows primarily involve soil, the underlying bedrock lithology plays a significant role in their onset and nature. Different rocks break down at diverse rates, with the softer ones offering ample loose material for these landslides. Rocks rich in clay yield finer soils, making mudflows more likely, while harder rocks generate coarser soils, leading to debris flows. Moreover, bedrock lithology shapes the slope structure and its evolution, as well as the formation of drainage paths and erosion patterns, which directly influence the likelihood of debris and mud flows.
Geology • Talus/Weathering	Areas with abundant loose sediments, poorly consolidated rocks, pyroclastic soils or recently disturbed ground (due to activities like logging or forest fire) are more susceptible to debris flows and mud flows. This susceptibility is attributed not only to the ease with which materials can be mobilized, but also to the potential magnification of the event severity. Basins with a greater accumulation of loose material can produce larger, more destructive flows, especially if a large portion of the material becomes mobilized simultaneously (supply-unlimited condition). Conversely, basins dominated by exposed bedrock and sparse unconsolidated materials typically experience fewer and less frequent flows (supply-limited conditions). Proper understanding of the material availability and distribution within a basin is crucial for assessing the likelihood of debris flows and mud flows occurrences.
Geomorphology • Slope morphology/Topography	Among the different terrain morphology parameters, the slope angle stands out as a crucial predisposing factor for both debris flows and mud flows. When these flows are initiated by landslides, the slope angle primarily dictates the shear stress that mobilizes materials. For flows caused by channel runoff, a steeper slope increases the chance of turbulent flow, which is essential for erosion, and for picking up materials as well. Steep terrains, including mountain channels, often exhibit features like bedrock steps and slope breaks, which can become areas for material accumulation later available for landslides or erosional processes. The presence of small morpho-selection scarps is, in some cases, the most important predisposing factor for the triggering of these landslides, due to the locally high slope and the disturbance it can cause to the shallow subsurface flow.
Geomorphology • Upslope area	Another significant geomorphic factor is the contributing upslope area. Converging slopes are especially prone to debris flows and mud flows for several reasons. First, they naturally funnel and concentrate surface runoff from a wide area into a more localized channel or gully; this concentration increases the volume and velocity of water, enhancing its erosive power and its capacity to mobilize and transport sediment and debris. Second, convergent areas concentrate the subsurface water flow and can lead to localized zones of saturation of the soil cover. Third, convergent zones can act as natural traps for sediments and debris ready to be mobilized.

	However, it is worth noting that debris and mud flows can also occur on even, flat slopes with minimal upslope contribution. In such instances, surface or subsurface flows play a diminished role, with direct infiltration likely being the primary cause.
Geomorphology • Erosion by running water	Certain drainage patterns, like dendritic or trellis, can effectively channel and concentrate surface runoff into specific pathways or gullies. This concentration can increase the volume and velocity of water, enhancing its ability to erode and transport material, potentially leading to debris or mud flow occurrences. The drainage network also impacts subsurface water movement. Slopes with intricate drainage networks may have spots of soil saturation, elevating landslide risks, especially if local infillings are present. The degree of activity of the drainage network often correlates with visible erosional processes. While erosion helps to remove materials, it also induces slope instability and ensures a steady supply of sediment to channels.
Geomorphology • Glaciers and snowfield	The presence of a large amount of water is especially important in the initiation of mud flows, which inherently have a higher water content compared to debris flows. This water can originate from events such as glacial lake outbursts, rapid melting of snow on volcanic slopes, or dam collapses. In these scenarios, the sudden supply of a large amount of water rapidly saturates the soil and brings the material in a fluid state. This predisposing factor is less important for debris flows since the material is coarser and less water is needed to reach fluidity.
Geomorphology • Previous events	Past debris flow or mud flow events can predispose an area to future events. These landslides often reshape channel and drainage path morphologies, leading to deeper channels, new deposition areas, and steeper banks, all of which can favor subsequent flows. Additionally, by stripping areas of stabilizing vegetation, they increase the terrains vulnerability to erosion and to the subsequent debris mobilization. Furthermore, not all materials from prior events might be completely evacuated, leaving substantial residual debris along channels, ready to be mobilized in subsequent events.
Physical and mechanical characteristics • Grainsize distribution	Debris flows and mud flows are characterized by a mixed and non-uniform grain size distribution. The coarser components ensure the movement of the mass, while the finer particles help maintain elevated pore pressures, facilitating a fluid-like flow. The thick consistency, arising from its blend of water, clay, and silt, enables the transportation of larger fragments, such as cobbles and boulders, with the finer particles. This non-uniform grain size distribution enables the mobilization of the soil into a fluid and allow debris flows and mud flows to move over long distances incorporating other sediments along their path. Consequently, areas with poorly-sorted soils are crucial indicators when assessing susceptibility.
Physical and mechanical characteristics • Porosity	For debris flows and mud flows, soil porosity is another key aspect. High porosity soils can absorb and hold significant water, becoming rapidly saturated during intense rainfall. When saturated, these soils might have reduced cohesion because of diminished soil water tension, causing the slope to fail. Furthermore, a saturated soil with high porosity can undergo liquefaction upon failure due to the buildup of excess pore pressure stemming from structural collapse.

Physical and mechanical characteristics • Shear strength • Hydraulic properties	The onset of landslide-induced debris and mud flows is intricately linked to the soil mechanical and hydraulic properties. The interplay of these factors, especially during intense rainfall, determines the susceptibility of a slope to produce these types of landslides. Hydraulic properties control the infiltration rate, the subsurface drainage, and the transient variation of soil water content during a rainfall event. Often, steep forested slopes remain temporarily stable due to the combined stabilizing effects of matric suction (soil tension from unsaturated conditions) and the physical binding of roots within the soil structure. However, during intense rainfall, if there is a decline in this matric suction or if positive pore water pressures develop, it can set the stage for a landslide. Furthermore, the intricate relationship between air, water, and soil particles in unsaturated conditions is a key determinant of the soil shear strength. The shear strength of unsaturated soils is different from that of saturated soils and depends on additional parameters that are difficult to evaluate, such as the matric suction, the Soil-Water Characteristic Curve, and effect of suction on apparent cohesion. All these complexities underscore the need for thorough geological and geotechnical assessments in areas prone to these landslides.
Land use: • Land use/Land cove • Soil type • Vegetation	Land use significantly impacts the predisposition to debris flows and mud flows, with vegetation being a central factor. Vegetation, notably trees and dense shrubs with extensive root systems, strengthen and anchors the soil. This process amplifies soil cohesion, enhancing its resistance to erosion and decreasing the chances of mobilization. Vegetation canopy and undergrowth also shield the soil from direct rainfall, mitigating erosion. Additionally, plants serve as natural obstructions, decelerating surface runoff, thereby diminishing its capacity to erode, and can extract moisture from the soil, thereby minimizing saturation-driven slope instabilities. Conversely, the decay of roots and organic content can foster the formation of larger soil pores, augmenting infiltration and subsurface storm flows. Fallen trees, at times, form temporary barriers, accumulating sediment behind these natural dams which, under heavy rainfall, might unexpectedly fail. As such, whether vegetation can mitigate or enhance the likelihood of these landslides depends on the specific environmental context, and it is still a matter of discussion. Remote sensing capability to distinguish and categorize soil types greatly aids in broad-scale evaluations of debris and mud flow susceptibility. Specifically, unvegetated regions have notable spectral signatures, making them readily identifiable in satellite imagery due to their standout reflectance, especially against vegetated zones. Additionally, the health and variety of vegetation often hint at the soil underlying characteristics. Satellites can identify soils rich in clay and silt—typically more susceptible to mud flows—or detect shifts in land use, like areas of deforestation or those affected by fires.

Anthropogenic factors • Slope/Drainage changes	Human activities can significantly influence the occurrence of debris and mud flows, especially since these are shallow landslides. As such, they are highly sensitive to surface and near-surface changes often resulting from human interventions. Even slight changes in drainage patterns, brought on by infrastructure development, can profoundly alter surface runoff and shallow groundwater movement, heightening the likelihood of triggering in certain areas. This includes subtle alterations to natural waterways or adding impermeable surfaces that amplify or redirect surface runoff. Building activities can also modify the slope morphology, creating areas with steeper inclines more vulnerable to failure. Moreover, vegetation removal, whether from deforestation or land conversion for agriculture, strips the surface soil layers of protection from erosion and weakens the soil through loss of root binding, enhancing the likelihood of its mobilization.

References for Fast landslides - *Debris flows / Mud flows*

Bardou, E., Ancey, C., Bonnard, C., Vulliet, L. (2003). Classification of debris-flow deposits for hazard assessment in alpine areas. In: Rickenmann, D., Chen, C.-L. (Eds.), Debris- Flow Hazards Mitigation: Mechanics Prediction and Assessment. Millpress, Rotterdam, Davos (Switzerland), pp. 799–808.

Baum, R.L., Godt, J.W. (2010). Early warning of rainfall-induced shallow landslides and debris flows in the USA. Landslides 7 (3), 259–272.

Berenguer, M., Sempere-Torres, D., Hürlimann, M. (2015). Debris-flow forecasting at regional scale by combining susceptibility mapping and radar rainfall. Nat. Hazards Earth Syst. Sci. 15, 587–602.

Bertrand, M., Liébault, F., Piégay, H. (2013). Debris-flow susceptibility of upland catchments. Nat. Hazards 67, 497–511.

Coe, J.A., Kinner, D.A., Godt, J.W. (2008). Initiation conditions for debris flows generated by runoff at Chalk Cliffs, central Colorado. Geomorphology 96, 270–297.

Godt, J.W., Baum, R.L., Lu, N. (2009). Landsliding in partially saturated materials. Geophys. Res. Lett. 36, L02403. https://doi.org/10.1029/2008GL035996.

Hungr, O., Evans, S.G., Bovis, M.J., Hutchinson, J.N. (2001). A review of the classification of landslides of the flow type. Environ. Eng. Geosci. 7, 221–238.

Hungr, O., Leroueil, S., Picarelli, L. (2014). The Varnes classification of landslide types, an update. Landslides 11, 167–194.

Hürlimann, M., Rickenmann, D., Graf, C. (2003). Field and monitoring data of debris-flow events in the Swiss Alps. Can. Geotech. J. 40, 161–175.

Iverson, R.M. (1997). The physics of debris flows. Rev. Geophys. 35, 245–296.

Iverson, R.M., Reid, M.E., LaHusen, R.G. (1997). Debris-flow mobilization from landslides. Annu. Rev. Earth Planet. Sci. 25, 85–138.

Iverson, R.M., Logan, M., LaHusen, R.G., Berti, M. (2010). The perfect debris flow? Aggregated results from 28 large-scale experiments. J. Geophys. Res. 115. https:// doi.org/10.1029/2009JF001514.

Jakob, M., Hungr, O. (2005). Debris-flow Hazards and Related Phenomena. Springer, Berlin pp.739.

Kean, J.W., McCoy, S.W., Tucker, G.E., Staley, D.M., Coe, J.A. (2013). Runoff-generated debris flows: observations and modeling of surge initiation, magnitude, and frequency.

Rickenmann, D. (1999). Empirical relationships for debris flows. Nat. Hazards 19 (1), 47–77.

Savage, W.Z., Baum, R.L. (2005). Instability of steep slopes. In: Jakob, M., Hungr, O. (Eds.), Debris-Flow Hazards and Related Phenomena. Springer, pp. 53–79.

Takahashi, T. (2019). Debris Flow: Mechanics, Prediction and Countermeasures, 2nd edition. CRC Press, Balkema.

Tobler, D., Kull, I., Jacquemart, M., Haehlen, N. (2014). Hazard management in a debris flow affected area: case study from Spreitgraben, Switzerland. World Landslide Forum 3. pp. 25–30.

Vázquez, R., Capra, L., Coviello, V. (2016). Factors controlling erosion/deposition phenomena related to lahars at Volcán de Colima, Mexico. Nat. Hazards Earth Syst. Sci. 16, 1881–1895.

Wieczorek, G.F., Glade, T. (2005). Climatic factors influencing occurrence of debris flow. In: Jakob, M., Hungr, O. (Eds.), Debris-Flow Hazards and Related Phenomena. Springer, Berlin, pp. 325–362.

Wilford, D.J., Sakals, M.E., Innes, J.L., Sidle, R.C., Bergerud, W.A. (2004). Recognition of debris flow, debris flood and flood hazard through watershed morphometrics. Landslides 1, 61–66.

Fast landslides

Rock slides / Rock avalanches

Description of the main predisposing factors	
Geology • Structural features (large scale)	Large-scale geological features typically span lengths from hundreds of meters to several kilometers. Common examples are faults, folds, thrust planes, major bedding planes, schistosity. These features are the main predisposing factors for rock slides /rock avalanches since they can act as potential sliding surfaces, enabling a large volume of rock to detach and move. Large-scale discontinuities often lack of stabilizing rock bridges, common in smaller discontinuity, thus providing an uninterrupted plane of weakness within the rock mass. Further, large-scale discontinuities can also act as conduits (or barrier) for groundwater flow and increase the pore pressure along the potential sliding surface. These major features area often identified through regional geological mapping, aerial surveys, and satellite imagery but must be carefully evaluated at the slope scale.
Geology • Stratigraphic features	A significant precursor to rock slides is the presence of a weak layer embedded within a sound rock formation. Such weak layers, common in many rock formations, arise from variations in depositional environments, sediment origins, or changes that occurred post-deposition over geological epochs. Layers rich in clay or encompassing clay-bearing rocks present a low resistance to shear forces, often becoming prime candidates for developing slip planes. The synergy between the weak sliding surface and the fragile nature of the overlying rock mass plays a pivotal role in the swift intensification of rock slides. Furthermore, these clay-rich layers can obstruct water flow, resulting in increased pore water pressure either within or above the layer. Notably, some of the most devastating rock slides and avalanches have been influenced by the existence of these stratigraphic features.
Geomorphology • Slope morphology/Topography	Slope morphology is undeniably critical in the context of rock slide susceptibility. Specifically, the height of a slope directly affects the potential energy stored with the rock mass, that can be released during a rock slide increasing its velocity and destructiveness. Taller slopes can have deeper failure points, potentially leading to greater material breakdown and possibly resulting in a rock avalanche. Additionally, the higher the slope, the greater the chance it intersects with significant structural or stratigraphic features that could serve as slide surfaces. The slope curvature is equally important; an outward-bulging (convex) shape can create unfavorable stress conditions due to reduced side support from the surrounding rock.
Physical and mechanical characteristics • Rock mass structure	In large rock slides, small-scale rock mass structure is typically less important than the major discontinuities. Nonetheless, rock mass structure can still influence the initiation, progression, and final runout of the slide. For example, the presence of smaller-scale discontinuities can break up the sliding mass into smaller blocks, influence the fragmentation during movement, or alter the dynamics of the slide. In this regard, the spacing and persistence of discontinuities are the most important factors since they might dictate how the rock mass breaks apart after the initial movement.

Physical and mechanical characteristics • Shear strength	Rock slides commonly occur along major, persistent discontinuity planes within the rock mass. This underlines the need for an in-depth analysis of these elements during geological and geotechnical assessments. It is crucial to pinpoint weakened or modified materials, such as fault gouge, and to identify infillings that exceed the undulation wavelength. In such cases, in fact, the shear strength of the discontinuity might be notably diminished due to the absence of the roughness stabilizing influence.
Seismotectonis • Seismic activity • Distance to faults • Site effects	Much like rockfalls, rock slides are impacted by the area prolonged seismic activity. Here, the combined effects of numerous seismic events, along with other contributing factors like hydrogeological changes or human interventions, can substantially elevate the risk of rock slope failures. Additionally, factors such as heightened susceptibility to seismic amplification and the potential for resonance are established as notable predisposing factors for such failures.

References for Fast landslides – *Rock slides / Rock avalanches*

Aaron, J., Hungr, O. (2016). Dynamic analysis of an extraordinarily mobile rock avalanche in the Northwest Territories, Canada. Can. Geotech. J. 53, 899–908. doi: 10.1139/cgj-2015-0371

Aaron, J., McDougall, S. (2019). Rock avalanche mobility: the role of path material. Eng. Geol. 257:105126. doi: 10.1016/j.enggeo.2019.05.003.

Agliardi, F., Crosta, G., Zanchi, A. (2001). Structural constraints on deep-seated slope deformation kinematics. Eng. Geol. 59, 83–102. doi: 10.1016/S0013-7952(00)00066-1.

Bowman, E.T., Take, W.A., Rait, K.L., Hann, C. (2012). Physical models of rock avalanche spreading behaviour with dynamic fragmentation. Can. Geotech. J. 49, 460–476. doi: 10.1139/t2012-007.

Clayton, A., Stead, D., Kinakin, D., Wolter, A. (2017). Engineering geomorphological interpretation of the Mitchell Creek Landslide, British Columbia, Canada. Landslides 14, 1655–1675. doi: 10.1007/s10346-017-0811-1.

Coe, J.A., Baum, R.L., Allstadt, K.E., Kochevar, B.F., Schmitt, R.G., Morgan, M.L., et al. (2016). Rock-avalanche dynamics revealed by large-scale field mapping and seismic signals at a highly mobile avalanche in the West Salt Creek valley, western Colorado. Geosphere 12, 607–631. doi: 10.1130/GES01265.1.

Cruden, D., Krahn, J. (1978). Frank Rockslide, Alberta, Canada, ed. B. Voight (Amsterdam: Elsevier Scientific Publishing), 97–112.

Dufresne, A., Bösmeier, A., Prager, C. (2016). Sedimentology of rock avalanche deposits – Case study and review. Earth Sci. Rev. 163, 234–259. doi: 10.1016/j.earscirev.2016.10.002

Glade, T., Crozier, M. J. (2004). “The nature of landslide hazard impact,” in Landslide Hazard and Risk, eds T. Glade, M. Anderson, and M. J. Crozier (Hobken, NJ: John Wiley and Sons), 43–74.

Glueer, F., Loew, S., Manconi, A., Aaron, J. (2019). From toppling to sliding: progressive evolution of the Moosfluh Landslide, Switzerland. J. Geophys. Res. 124, 2899–2919. doi: 10.1029/2019JF005019

Grämiger, L.M., Moore, J.R., Vockenhuber, C., Aaron, J., Hajdas, I., Ivy-Ochs, S. (2016). Two early Holocene rock avalanches in the Bernese Alps (Rinderhorn. Switzerland). Geomorphology 268, 207–221. doi: 10.1016/j.geomorph.2016.06.008

Hungr, O., Evans, S.G. (2004). Entrainment of debris in rock avalanches: an analysis of a long run-out mechanism. Geol. Soc. Am. Bull. 116, 1240–1252. doi: 10.1130/B25362.1

Hungr, O., Leroueil, S., Picarelli, L. (2014). The Varnes classification of landslide types, an update. Landslides 11, 167–194. doi: 10.1007/s10346-013-0436-y

Nagelisen, J., Moore, J. R., Vockenhuber, C., Ivy-Ochs, S. (2015). Post-glacial rock avalanches in the Obersee Valley. Glarner Alps, Switzerland. Geomorphology 238, 94–111. doi: 10.1016/j.geomorph.2015.02.031

Volken, S. (2015). The Flims Rockslide: A New Perspective on Failure Mechanisms and Kinematics. MSc Thesis, ETH Zurich, Zurich.

Wolter, A., Gischig, V., Stead, D., Clague, J. J. (2016). Investigation of geomorphic and seismic effects on the 1959 Madison Canyon, Montana, landslide using an integrated field, engineering geomorphology mapping, and numerical modelling approach. Rock Mech. Rock Eng. 49, 2479–2501. doi: 10.1007/s00603-015-0889-5

Description of the main predisposing factors	
Geology • Talus/Weathering	Weathering can significantly influence the propensity for rockfalls in several ways. Chemical weathering (such as hydrolysis, oxidation, and carbonation) can break down primary minerals in rocks, leading to a reduction in the rock cohesive strength. This makes the rock mass more susceptible to detachment and failure. Mechanical or physical weathering processes, such as freeze-thaw cycles, can result in the disintegration of rocks. Water can then enter rock cracks, freeze, and expand, forcing the cracks to widen and causing rock to detach. The increased persistence and aperture of discontinuities due to weathering can change the stability conditions of rock blocks.
Geomorphology • Slope morphology/Topography	Slope morphology plays a critical role in rockfalls. Among the various factors, slope angle stands out as the most crucial. Rockfalls are primarily driven by gravitational forces and the movement of rock blocks is governed by rapid dynamics, often mirroring the characteristics of free-fall. As the slope becomes steeper, gravity exerts a more pronounced downward force on rock blocks, thus allowing rapid detachment and propagation. Steeper slopes also allow discontinuities to daylight, creating conditions for potential movements. For these reasons, very steep slopes are generally more prone to rockfalls. The aspect of the slope, in relation to the orientation of discontinuities, affects the probability of rockfalls, dictating potential modes of movement such as planar sliding, wedge sliding, or toppling. Furthermore, the orientation of a slope relative to the sun influences the temperature changes a rock face undergoes. This can lead to increased fracturing and a greater likelihood of rock blocks detachment. Slope curvature can influence the initial detachment or triggering of a rock block. Concave areas frequently serve as collection points for water, intensifying the weathering processes. Water accumulation in these areas can instigate freeze-thaw cycles and amplify rock degradation, potentially heightening the risk of detachment. Nonetheless, the significance of this factor is difficult to quantify and often depends on specific local conditions. In general, a morphologically complex slope with protruding sectors, overhangs, or isolated pinnacles may be more susceptible to collapse compared to a regular one because it offers more surface area exposed to weathering and it has more points of stress concentration that increase the potential for rockfall.
Geomorphology • Undercutting	Slopes that are undercut, either by erosion processes like river or wave action or by human activities, can become unstable. The most direct impact of undercutting is the removal of the foundational support for the rock layers above. This makes the overlying rock mass cantilevered or overhanging, with increased gravitational stress acting on it. Another effect is the shift in center of gravity: as the base of a slope or rockface is eroded away, the center of gravity of the overhanging mass might move outward, making the rock more prone to toppling or to outward rotation. Furthermore, undercutting can lead to an increase in tensile and shear stresses in the overlying rock,

	making it more susceptible to failure, or may expose weaker layers or unfavorable discontinuity planes, further compromising the stability of the slope. Undercutting is a major predisposing factor in rocks made of a stratigraphic alternation of strong and weak layers. As the weaker layers erode more rapidly, they may form recesses or undercuts beneath the more resistant layers, that can become unstable over time due to the loss of supporting material underneath. This process can lead to the cyclic renewal of the cliff face. Sea waves are particularly efficient in creating overhanging slopes due to the combined effect of abrasion, solution, and the hydraulic action of the water that crashing against a rock face compress air in cracks. Over time, the cumulative effect of these processes can lead to the retreat of cliff faces and significant landform changes along coastlines.
Geomorphology • Previous events	Previous rockfall events can significantly influence the initiation and propagation of subsequent rockfalls. The most important effect is the alteration of slope morphology: When a rockfall event occurs, it can change the overall geometry of the slope or rock face. Such changes might create new overhangs, reduce support for certain rock masses, or change the slope overall angle, making it more susceptible to further rockfalls. Moreover, the removal of a large rock mass during a rockfall can change the stress distribution within the remaining rock face. Areas that were previously compressed might now be under tension, increasing the risk of further rockfalls. Previous rockfalls can also expose fresh rock surfaces that might be more susceptible to weathering processes, further weakening them. In general, recognizing past rockfall deposits or evidence of prior rockfall occurrences (such as changes in vegetation along the slopes) is crucial for evaluating the likelihood of future rockfall events. The factors that instigated past rockfalls often signal potential risks for similar events in the future, provided that the geological, geomorphological, and climatic conditions remain consistent.
Physical and mechanical characteristics • Rock mass structure	The pattern and orientation of discontinuities (joints, fractures, bedding planes, schistosity) control the kinematic feasibility, potential size, and shape of rock blocks that may detach. Among all the factors, the length or persistence of a discontinuity is critical. Even if the discontinuity has an orientation that would allow for movement, if it is not persistent enough to allow the block to be entirely bounded by discontinuities, the block may not be released. Faults and bedding planes generally display strong persistence, and at the slope scale they can frequently be considered as having infinite length. Spacing is the second critical factor. Discontinuities that are closely spaced can weaken the rock mass, making it more susceptible to external triggers like rainfall, freeze-thaw cycles, or seismic activity. To the other hand, a rock mass with wider discontinuity spacing can be more stable against minor triggers but might still be susceptible to larger-scale destabilization events. Aperture is also of great importance. The width of the opening of a discontinuity can influence water infiltration, which in turn can impact rockfall due to freeze-thaw processes or increased hydrostatic pressure. In rocks like limestone, gypsum, or other soluble formations, dissolution processes play a prominent role in the enlargement and development of discontinuities. This dissolution, often referred to as chemical weathering or more specifically as karstification, can progressively widen and enlarge the discontinuity, increasing the susceptibility to rockfall.

	Other factors like roughness, infilled material, or strength of the discontinuity walls can be regarded as less important for rockfall predisposition.
Physical and mechanical characteristics • Shear strength	Discontinuity shear strength is one of the critical factors determining the stability of a rock block. Estimating the shear strength of rock discontinuities often involves a combination of direct measurements, empirical correlations, and modeling. Unfortunately, given the spatial and temporal variability of factors involved, there is inherent uncertainty in these estimates. When assessing rockfalls, the presence of rock bridges – intact segments of rock extending over a discontinuity – emerges as a paramount mechanical determinant. However, the characteristics and strength of these bridges can vary extensively, making them challenging to precisely quantify even after thorough inspection. This complexity has led to the adoption of statistical and probabilistic methodologies to better capture and estimate this crucial factor.
Seismotectonics • Seismic activity • Distance to faults • Site effects	The area seismic activity plays a crucial role in inducing rockfalls. Continuous exposure to even moderate seismic events can accumulate damage in rock slopes and fragment rock bridges along discontinuities. In rockfall research, it is vital to recognize and incorporate the area seismic predisposition. This predisposition can be deduced from the region seismic history, examining the frequency and magnitude of past earthquakes, and the proximity of active fault lines. Regions close to these fault lines are more likely to experience intense seismic disturbances, elevating their rockfall risk. Additionally, specific local conditions might enhance seismic effects on a slope, and there is a potential for matching frequencies between seismic waves and rock slopes or blocks, leading to resonance.
Land cover & Vegetation • Land use/ Land cover • Vegetation	Land cover directly affects the environmental conditions to which a rock mass is exposed, playing a role in the predisposition to rock block detachment. Generally, regions with bare rock or limited vegetation show a heightened vulnerability to rockfalls due to increased exposure to elements like direct rainfall, freeze-thaw effects, and varying temperatures. On the contrary, dense forests often shield rock surfaces from these elements. Vegetation, however, holds a complex role in influencing rockfall susceptibility, offering both stabilization and potential hazards. On one hand, the root systems of many plants, especially deep-rooted trees and shrubs, bind soil and rock particles together, making it more resistant to rockfall initiation. Conversely, as roots grow and expand, they can penetrate fractures and joints in the rock, exerting pressure and potentially widening these fractures. Furthermore, tall trees, especially those growing near the edge of cliffs or on steep slopes, can act as levers during strong winds. Consequently, the specific effect in any situation hinges on the nature and density of the vegetation, in conjunction with the prevailing geological and geomorphological conditions.
Climate • Temperature Regime	Long-term temperature variations significantly affect the triggering of rockfalls, a process that unfolds through several interconnected mechanisms. In regions where temperatures fluctuate considerably, especially those experiencing freeze-thaw cycles, the impact on rock stability can be profound. During freeze-thaw cycles, water that has seeped into cracks and fissures in the rock expands as it freezes, exerting pressure on the rock. In addition to freeze-thaw cycles, long-term warming trends, such as those associated with climate change, also play a role. Rising temperatures can lead to the melting of permafrost in high alpine regions. Permafrost acts as a stabilizing agent in these environments, and its loss can significantly reduce the structural integrity of rock faces, making them more susceptible to rockfalls.

Anthropogenic factors • Slope/drainage changes	Constructing roads and infrastructures in mountainous areas, along with human-driven alteration to slopes, can significantly impact rockfalls, particularly the initiation of rock block detachments. Often, the creation of pathways or leveled terrains necessitates excavation or blasting. These activities can disrupt the natural stability of rock masses, producing or expanding discontinuities that enhance the likelihood of rock block detachment. Additionally, infrastructural development can modify the natural drainage patterns, causing water to pool in specific regions. This, combined with the vibrations from heavy vehicular movement, can further compromise rock stability. Notably, if a high-resolution Digital Elevation Model (DEM) is available, some of the factors can be directly accounted as changes in slope morphology. In certain situations, traditional landscape management structures like dry-stone walls, which have been employed globally for centuries, might inadvertently contribute to rockfall. This risk emerges when the wall is inadequately constructed, when erosion affects the wall base, or when regular maintenance is neglected. Regular inspections and evaluations of these walls are crucial to avert unforeseen failures.

References for Fast landslides - *Rockfalls / Topples*

Akgun, A., Dag, S., Bulut, F. (2008). Landslide susceptibility mapping for a landslide-prone area (Findikli, NE of Turkey) by likelihood-frequency ratio and weighted linear combination models. Environ Geol 54, 1127–1143.

Alqadhi, S., Mallick, J., Talukdar, S., Bindajam, A.A., Van Hong, N., Saha, T.K. (2021). Selecting optimal conditioning parameters for landslide susceptibility: an experimental research on Aqabat Al-Sulbat, Saudi Arabia. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-15886-z.

Alvioli, M., Santangelo, M., Fiorucci, F., Cardinali, M., Marchesini, I., Reichenbach, P., Rossi, M., Guzzetti, F., Peruccacci, S. (2021). Rockfall susceptibility and network-ranked susceptibility along the Italian railway. Eng. Geol. 293, 106301. https://doi.org/10.1016/j.enggeo.2021.106301.

Ansari, M.K., Ahmad, M., Singh, R., Singh, T.N. (2014). Rockfall hazard assessment at Ajanta Cave Aurangabad, Maharashtra, India. Arabian J. Geosci. 7, 1773–1780.

Bajni, G., Camera, C.A.S., Brenning, A., Apuani, T. (2022). Assessing the utility of regionalized rock-mass geomechanical properties in rockfall susceptibility modelling in an Alpine environment. Geomorphology 415, 108401. https://doi.org/10.1016/j.geomorph.2022.108401.

Budetta, P. (2004). Assessment of rockfall risk along roads. Nat Hazards Earth Syst Sci. 4, 71–81.

Cevik, E., Topal, T. (2003). GIS-based landslide susceptibility mapping for a problematic segment of the natural gas pipeline, Hendek (Turkey). Environ. Geol. 44, 949–962.

Cignetti, M., Godone, D., Bertolo, D., Paganone, M., Thuegaz, P., Giordan, D. (2021). Rockfall susceptibility along the regional road network of Aosta Valley region (northwestern Italy). J. Maps 17 (3), 54–64. https://doi.org/10.1080/17445647.2020.1850534.

Copons, R., Vilaplana, J., Linares, R. (2009). Rockfall travel distance analysis by using empirical models (SolAd’Andorra la Vella, Central Pyrenees). Natural Hazards and Earth System Sciences 9 (6), 2107–2118.

Dorren, L.K.A., Berger, F., Putters, U.S. (2006). Real-size experiments and 3-D simulation of rockfall on forested and non-forested slopes. Natural Hazards and Earth System Sciences 6, 145–153.

Evans, S.G., Hungr, O. (1993). The assessment of rockfall hazard at the base of talus slopes. Can Geotech J 30 (4), 620–636.

Frattini, P., Crosta, G.B., Carrara, A., Agliardi, F. (2008). Assessment of rockfall susceptibility by integrating statistical and physically-based approaches. Geomorphology 94 (3–4), 419–437.

Hoek, E., Bray, J.W. (1981). Rock slope engineering. Institution of Mining and Metallurgy, London.

Michoud, C., Derron, M.-H., Horton, P., Jaboyedoff, M., Baillifard, F.-J., Loye, A., Nicolet, P., Pedrazzini, A., Queyrel, A. (2012). Rockfall hazard and risk assessments along roads at a regional scale: example in Swiss Alps. Natural Hazards and Earth System Science 12 (3), 615–629.

Topal, T., Akin, M., Ozden, A.U. (2007). Assessment of rockfall hazard around Afyon Castle. Environ Geol 53 (1), 191–200.

Wang, X.L., Zhang, L.Q., Wang, S.J., Agliardi, F., Frattini, P., Crosta, G.B., Yang, Z.F. (2012). Field investigation and rockfall hazard zonation at the Shjing Mountains Sutra caves cultural heritage (China). Environmental Earth Sciences 66, 1897–1908.

Wang, X.L., Frattini, P., Crosta, G.B., Zhang, L.Q., Agliardi, F., Lari, S., Yang, Z.F. (2014). Uncertainty assessment in quantitative rockfall risk assessment. Landslides 11 (4), 711–722.

Slow sinkholes

Suffosion and solution sinkholes

Description of the main predisposing factors	
Geology • Lithology	Lithology is among the primary factors for occurrence of slow sinkholes (solution sinkholes and suffosion sinkholes, according to the internationally accepted classification). The presence of soluble rocks (mainly, carbonates and evaporites) is in fact necessary, both at the surface (for solution sinkholes) than as bedrock below cover deposits (in the case of suffosion sinkholes) in order to start the process of karstification. In general, solution sinkholes therefore develop where geological features guarantee the presence of soluble rocks prone to karst development at the outcrop, whilst suffusion sinkholes interest areas with a cover consisting of non-soluble deposits above a carbonate bedrock.
Geology • Stratigraphic features	Stratigraphy may have a crucial role in sinkhole occurrence, due to possibility of differences in geological and sedimentological features in the overall succession, that may also correspond to variations in permeability of the deposits of the cover overlying the soluble bedrock. Depending upon changes in the stratigraphy (different layers, grainsize, porosity/density, etc.), these influence the flow of water and the erosional effects such flow may determine.
Geology • Karstification degree	The degree of karstification has a strong influence on the development of sinkholes because when a rock mass is interested by deep karstification, this results in a high presence of voids, conduits and caves within the rock mass, potentially sink areas for the downward movement and flow of the materials above. In mountain and hill areas, the karstification degree is the main factor controlling development and density of solution sinkholes, that may locally become the main landform characterizing the landscape.
Geology • Talus/Weathering	Weathering can significantly influence the proneness to solution and suffosion sinkholes in several ways. Chemical weathering (such as hydrolysis, oxidation, and carbonation) can break down primary minerals in rocks, leading to a reduction in the cohesive strength of the rock mass. Mechanical or physical weathering processes, such as those related to mechanical erosion by rapid inflow of water into underground voids, can result in degradation and disintegration of walls and vault, enhancing localized failures. The increase in persistence and aperture of discontinuities due to weathering can change the stability conditions of blocks of rock in the underground environment, and favor general failure.
Geomorphology • Slope Morphology / Topography	There exist different morphological and physical setting corresponding to variable possibilities of occurrence of slow sinkholes. Highplains, plateaus, and plains are typically more prone than slopes or mountain ridges to formation of these typologies of sinkholes. This has to be related to the combined action of the physical setting and the possibility of water stagnancy or runoff at the ground surface, with this latter directly influencing the possibility of water infiltration in the subsoil.

Geomorphology • Distance from coastline	The distance from the coastline is a factor controlling the occurrence of slow sinkholes, due to the mixing zone between freshwater and sea water, derived by marine intrusion in coastal aquifers. The deriving brackish solution strongly enhances the dissolution rate, potentially enlarging the size of karst caves and voids, and thus contributing to further predisposing the area to sinkholes. This is especially true along coastal plains, where the low topography allows higher advancement inland of the intrusion wedge (Ghyben Herzberg interface).
Geomorphology • Overburden thickness	Thickness of the overburden, that is the material between the cave vault, or the conduits, and the ground surface, is a critical factor for occurrence of slow sinkholes. It, combined with geotechnical properties of the materials (cohesive or not) and their grainsize, may control the downward movement of grains into the fissure networks of the bedrock, in order to start the sinkhole process. In case of caves or voids wider than a few decimeters, the overburden thickness is, together with cave geometry and size, a crucial factor for characterizing the underground voids in the predisposition of stability charts.
Geomorphology • Cave geometry and size	Geometry and size of underground voids influence their stability: given certain values of the geomechanical properties, the ratio between width and height of the cave/conduits/voids may be a preliminary approach to assess the overall stability, and the tendency of the void toward the general failure. Cave geometry and size are, together with thickness of the overburden, crucial factors for characterizing the underground voids in the predisposition of stability charts.
Geomorphology • Presence of previous events	Slow sinkholes may occur as isolated feature but also in clusters. Density of the sinkhole distribution, that can be evaluated through sinkhole inventory maps, or through multi-temporal activity maps of sinkholes, represents therefore an important factor to evaluate the proximity of each individual sinkhole to the others. Neighboring sinkholes are expected to interact in the future, through enlargement of their areas due to failures from the rims, eventually leading to coalescence and formation of compound sinkholes or uvala.
Physical and mechanical properties • Rock mass structure	The presence of discontinuities in the bedrock (cropping out at the surface for solution sinkholes, and below the cover for suffosion sinkholes) is an important factor that control the overall weakness of the rock mass, and, as a consequence, its capability in resisting to destabilizing forces. Discontinuities may be of primary origin (bedding planes), related to the modality of formation of the rock, or having a secondary origin (joints and fractures), formed by tectonic forces. Whatever their origin, the presence of discontinuities within a rock mass hosting caves and conduits influences the possibility of occurrence of slow sinkholes. The pattern and orientation of discontinuities control the kinematic feasibility, and the potential downward movement of materials within the fracture network. Among all involved factors, persistence and continuity of the discontinuity is critical. Spacing is the second critical factor: closely spaced discontinuities weaken the rock mass much more than those located at higher distances, and they can work to facilitate the downward flow of loose materials. Together with the above, aperture is also of great importance, since width of the opening of a discontinuity can influence water infiltration, and its flow within the subsoil.

Physical and mechanical properties • Grainsize distribution/Particle shape	As concerns soils making up the loose cover above soluble bedrock, shape of the particles, together with the grainsize distribution, are among the physical and mechanical properties that appear to control the movement of particles within the discontinuity systems, and therefore the onset of suffosion sinkholes. These properties also influence the cohesion of the deposits, and the facility of the materials to be removed and transported by water.
Physical and mechanical properties • Porosity/Density	Porosity, that is the ratio between volume of the voids and volume of the solid in a terrain or rock, is an important parameter to determine the capability of a material to allow movement of water within itself. In detail, effective porosity, meaning the connection among interconnecting pores, is the crucial parameter at this regard. In the case of karst voids, evaluating effective porosity is crucial in order to understand the likely effect of flowing water within the terrain or the rock mass.
Physical and mechanical properties • Hydraulic properties	Strictly related to effective porosity, discussed above, there are other hydraulic properties such as permeability and transmissivity. These hydraulic properties, overall, characterize the ability of a terrain or rock to transfer water, and, as a consequence, to assess the effects of its passage throughout the material, likely predisposing to deepening of solution sinkholes and to dropout of loose materials from the cover into fissures and cracks in the rock mass, eventually leading to formation of suffosion sinkholes.
Seismotectonics • Seismic activity	Seismicity of an area influences the proneness to suffosion sinkholes. Seismic shaking is generally regarded as a triggering factor for sinkhole occurrence, but actually it may also play a role in its predisposition, in the sense that a non-seismic area has definitely less possibility to develop a sinkhole than a seismic area. In this latter case, the frequency of seismic events might possibly favor the more or less continuous dropout of loose deposits. In seismic areas, shaking determines a likely reduction in the thickness of the overburden, due to occurrence of local failures at the cave/conduit vaults, or to drop out of the loose material from the cover. In addition, it acts in worsening the rock mass strength. To properly evaluate the proneness to suffosion sinkholes, it is therefore vital to recognize and incorporate the seismic predisposition of the area. This can be deduced from the region seismic history, examining the frequency and magnitude of past earthquakes, and the proximity to active fault lines (see below).
Seismotectonics • Faulting systems / Distance from faults	Faults represent a weakness zone in rock masses (fault damage zone), where water flow typically may concentrate, due to higher permeability. Fracturing in the fault damage zone, in fact, promotes fluid circulation and weathering of soluble rocks at depth. Location of underground voids near a fault may be indicative of poor quality of the rock mass, with higher fracturing density, and therefore of higher proneness to instability, or to dropping out of the cover materials into the bedrock.

Land cover & Vegetation • Land Use / Land Cover	Land cover directly affects the environmental conditions of the rock masses affected by solution sinkholes, playing a role in the possibility for water to enter the subterranean systems at certain locations. Generally, regions with bare rock or limited vegetation are directly exposed to elements like rainfall, snow thawing, and changes in temperature. On the other hand, dense forests often shield rock surfaces from these elements, but roots of trees play a role in facilitating the infiltration of water in fissures of the rock mass, serving as wedges that promote detachment. Land cover is shaped by several factors such as geology, climate, and topography. While land cover holds importance in specific contexts, each of these factors can be evaluated and addressed separately in susceptibility analyses of slow sinkholes.
Land cover & Vegetation • Soil Type / Soil Thickness	Presence of a soil, and its main characters, that essentially include type and thickness, may be relevant for impeding or favoring the infiltration of water underground, and, as a consequence, the loss in mechanical properties due to an increase in the degree of saturation. At this regard, permeability of the soil plays a crucial role, together with the gradient of the ground surface above the conduit/void: in sub-horizontal or low topography there is possibility of water stagnancy, and of slow infiltration of significant amount of water. On the other hand, in condition of higher slope the low permeability of a soil acts in favoring the surface runoff rather than the infiltration.
Hydrogeology • Groundwater/Saturation	The water content, expressed by the degree of saturation, is a crucial factor to evaluate the strength of soils or rock masses hosting underground voids. High water content cause significant reduction in the resistance of the materials, thus predisposing them toward more likely instability conditions. Increase in the degree of saturation may depend upon infiltration of rainfall, or of water from irrigation or leakages, but may also occasionally be related to flood events. Presence of the water table in proximity of underground voids may potentially increase the proneness to instability, as an effect of the water table dynamics, and of its related fluctuations. Rising of the water level, up to reach the depth where cave/conduits/voids are present, results in flooding the voids. This increases the degree of saturation, with remarkable reduction in the mechanical parameters and a significantly lower capability to counteract the destabilizing forces. Overall, the final effect is represented by a tendency toward downward movement of the loose deposits from the cover.
Climate • Rainfall regime	Rainfall regime, in terms of average rainfall, and typical intensity and duration of rainstorms, can be considered as a predisposing factor for the occurrence of slow sinkholes. Areas characterized by concentrated rainstorms, likely leading to rapid arrival of significant amount of water underground, are definitely more prone to these processes than areas with low intensity and prolonged rainfall. It is clear that rainfall can be considered also as preparatory and/or triggering factor for suffosion sinkholes, but in this report we focus on the rainfall regime as predisposing factor.
Anthropogenic factors • River banks/levees typology	Presence of artificial river banks or levees may be a predisposing factor for the occurrence of slow sinkholes: water movement in the proximity of the river, with particular regard to its fluctuations, may induce development of erosional features such as piping, with dropout of the materials and opening of suffosion sinkholes. In addition, leakages from pipelines for irrigation may favor increases in the degree of saturation of the terrains, again acting toward conditions favorable to erosion and movement of loose particles.

Anthropogenic factors • Slope/drainage changes	Modifications in the natural drainage patterns may cause water to infiltrate and/or to become stagnant in specific areas, compromising the overall terrain stability through decrease of the mechanical properties. Higher presence of water increases the possibility of development of erosional processes, able to move loose material, thus creating the formation of voids, until a suffosion sinkhole is originated.

References for Slow sinkholes - *Suffosion and solution sinkholes*

Al-Halbouni D., Holohan E.P., Taheri A., Watson R.A., Polom U., Schöpfer M.P.J., Emam S. & Dahm T. (2019). Distinct element geomechanical modelling of the formation of sinkhole clusters within large-scale karstic depressions. Solid Earth, 10, 1219-1241.

Bianchini S., Confuorto P., Intrieri E., Sbarra P., Di Martire D., Calcaterra D. & Fanti R. (2022). Machine learning for sinkhole risk mapping in Guidonia-Bagni di Tivoli plain (Rome), Italy. Geocarto International 37 (27), 16687-16715, doi: 10.1080/10106049.2022.2113455.

Choi J.H., Edwards P., Ko K. & Kim Y.S. (2016). Definition and classification of fault damage zones: A review and a new methodological approach. Earth Science Reviews, 152, 70-87.

Gutierrez F., Parise M., De Waele J. & Jourde H. (2014). A review on natural and human-induced geohazards and impacts in karst. Earth Science Reviews, vol. 138, p. 61-88, doi: 10.1016/j.earscirev.2014.08.002.

Liso I.S. & Parise M. (2023). Sinkhole development at the freshwater-saltwater interface in Apulia (southern Italy). In: Land L., Kromhout C. & Suter S. (Eds.), Proceedings of the 17th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Tampa (Florida, USA), 27-31 March 2023**,** NCKRI Symposium no. 9**,** p. 229-238.

Lollino P. & Parise M. (2023). Sinkhole hazard quantitative assessment: Insights from the application of numerical modelling techniques. In: Land L., Kromhout C. & Suter S. (Eds.), Proceedings of the 17th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Tampa (Florida, USA), 27-31 March 2023**,** NCKRI Symposium no. 9, p. 141-150.

Margiotta S., Marini G., Fay S., D'Onghia F.M., Liso I.S., Parise M. & Pinna M. (2021). Hydro-stratigraphic conditions and human activity leading to development of a sinkhole cluster in a Mediterranean water ecosystem. Hydrology, 8, 111. https://doi.org/10.3390/hydrology8030111.

McGrath A.G. & Davison I. (1995). Damage zone geometry around fault tips. J. Struct. Geol. 17, 1011–1024.

Parise M. (2019). Sinkholes. In: White W.B., Culver D.C. & Pipan T. (Eds.), Encyclopedia of Caves. Academic Press, Elsevier, 3rd edition, ISBN ISBN 978-0-12-814124-3, p. 934-942.

Parise M. (2022). Sinkholes, Subsidence and Related Mass Movements. In: Shroder J.J.F. (Ed.), Treatise on Geomorphology, vol. 5. Elsevier, Academic Press, pp. 200–220. https://dx.doi.org/10.1016/B978-0-12-818234- 5.00029-8. ISBN: 9780128182345.

Perrotti M., Lollino P., Fazio N.L., Pisano L., Vessia G., Parise M., Fiore A. & Luisi M. (2018). Finite Element–based stability charts for underground cavities in soft calcarenites. ASCE International Journal of Geomechanics, 18 (7), 04018071.

Perrotti M., Lollino P., Fazio N.L. & Parise M. (2019). Stability charts based on the finite element method for underground cavities in soft carbonate rocks: validation through case-study applications. Natural Hazards and Earth System Sciences, 19, 2079-2095.

Vennari C. & Parise M. (2022). A chronological database about natural and anthropogenic sinkholes in Italy. Geosciences, vol. 12, 200, https://doi.org/10.3390/geosciences12050200.

Rapid sinkholes

Collapse sinkholes, cover collapse sinkholes, caprock collapse sinkholes

Description of the main predisposing factors	
Geology • Lithology	Lithology is among the primary factors for occurrence of rapid (collapse) natural sinkholes, since it is necessary the presence of soluble rocks (mainly, carbonates and evaporites) in order to let start the process of karstification, and the consequent formation of underground voids and caverns. However, collapse sinkholes may also occur in areas characterized by different types of rock, such as volcanic materials; this typically happens in urban areas with presence of artificial cavities, excavated by man in different epochs and with different purposes. Cities as Rome, Naples and Palermo have been frequently affected by collapses of this type, as well as many other smaller Italian towns. In general, collapse sinkholes therefore develop where geological features guarantee the presence of soluble rocks prone to karst development, or of soft rocks easy to dig by man.
Geology • Stratigraphic features	Stratigraphy may have a crucial role in sinkhole occurrence, due to possibility of differences in geological and sedimentological features in the overall succession, that may also correspond to variations in permeability of the deposits above the karst cave or the artificial cavity. Depending upon changes in the stratigraphy, these influence the flow of water and the erosional effects such flow might determine.
Geology • Karstification degree	The degree of karstification has a strong influence on the development of sinkholes because when a rock mass is interested by deep karstification, this results in a high presence of voids and caves within the rock mass, potentially weakening its mechanical resistance, and favoring the tendence toward a progressive failure, eventually leading to collapse.
Geology • Talus/Weathering	Weathering can significantly influence the proneness to collapse sinkholes in several ways. Chemical weathering (such as hydrolysis, oxidation, and carbonation) can break down primary minerals in rocks, leading to a reduction in the cohesive strength of the rock mass, making it more susceptible to detachment and failure from both vault and walls of the cave. Mechanical or physical weathering processes, such as those related to mechanical erosion by rapid inflow of water into underground voids, can result in degradation and disintegration of walls and vault, enhancing localized, if not overall, failures. Water can then enter rock fissures and expand, forcing them to widen and causing further detachments. The increase in persistence and aperture of discontinuities due to weathering can change the stability conditions of blocks of rock in the underground environment, and favor general failure. Another type of weathering is represented by dissolution, with may be a significant factor for the enlargement of karst caves, and contribute to move the rock mass hosting the cave toward conditions of higher instability. Depending upon the rate of dissolution (in turn, a function of rock type, local climate, and microclimatic conditions in the underground void), conduits and voids in the cave system may widen, possibly leading to local failures and detachment of rock blocks of variable size.

Geomorphology • Slope Morphology / Topography	There exist different morphological and physical setting corresponding to variable possibilities of occurrence of collapse sinkholes. Highplains, plateaus, and plains are typically more prone than slopes or mountain ridges to sinkhole formation. This has to be related to the combined action of the physical setting and the possibility of water stagnancy or runoff at the ground surface. This latter directly influences the possibility of water infiltration in the subsoil. Nevertheless, even mountain areas can be interested by sinkhole collapse, due to progressive upward stoping in karst caves, typically with creation of vertical shafts.
Geomorphology • Erosion by running water	When water enters dramatically into a cave system, or an artificial cavity, in consequence of a flood event the main effects are represented by the turbulent action of the running water (including the solid materials transported) and its mechanical erosion on the vault and walls of the underground void. Further, water may fill, partially or totally, the cave, and a variable time (hours to days) is required to discharge such amount, which, on the other hand, increases the degree of saturation of the hosting rock or soil. The same effects can be observed during sea storms for caves located along the coast or in its immediate proximity, within the zone potentially involved by the arrival of sea waves. Along the coasts, in addition, the distance from the sea may act as an additional factor controlling the occurrence of collapse sinkholes, due to the mixing zone between freshwater and sea water, derived by marine intrusion in coastal aquifers. The deriving brackish solution strongly enhances the dissolution rate, potentially enlarging the size of karst caves and voids, and thus contributing to further predisposing the area toward the final collapse. This is especially true along coastal plains, where the low topography allows higher advancement inland of the intrusion wedge (Ghyben Herzberg interface).
Geomorphology • Overburden thickness	Thickness of the overburden, that is the material between the cave vault and the ground surface, is a critical factor for stability of underground voids, and therefore for occurrence of collapse sinkholes. Depending upon the materials involved, and their mechanical properties, a reduction in the overburden thickness (due to repeated detachments from the vault) may reach a threshold above which stability is not guaranteed anymore, and failure occurs. The overburden thickness is, together with cave geometry and size, a crucial factor for characterizing the underground voids in the predisposition of stability charts.
Geomorphology • Cave geometry and size	Geometry and size of underground voids influence their stability: given certain values of the geomechanical properties, the ratio between width and height of the cave may be a preliminary approach to assess the overall stability, and the tendency of the void toward the general failure. Another issue to consider is represented by proximity with other underground spaces: typically, in subterranean quarries/mines the system consists of several nearby galleries, so that collapses occurring in one passage may affect also the stability of the neighboring ones. As a matter of fact, this typology of artificial cavities is the most affected by collapse sinkholes. Cave geometry and size are, together with thickness of the overburden, crucial factors for characterizing the underground voids in the predisposition of stability charts.
Geomorphology • Presence of previous events	Collapse sinkholes may occur as isolated feature but also in clusters. Density of the sinkhole distribution, that can be evaluated through sinkhole inventory maps, or through multi-temporal activity maps of sinkholes, represents therefore an important factor to evaluate the proximity of each individual sinkhole to the others. Neighboring sinkholes are expected to interact in the future, through enlargement of their areas due to failures from the rims, eventually leading to coalescence and formation of compound sinkholes or uvala.

Physical and mechanical properties • Rock mass structure	The presence of discontinuities in the rock mass is an important factor that control the overall weakness of the rock, and, as a consequence, its capability in resisting to destabilizing forces. Discontinuities may be of primary origin (bedding planes), related to the modality of formation of the rock, or having a secondary origin (joints and fractures), formed by tectonic forces. Whatever their origin, the presence of discontinuities within a rock mass hosting karst caves or artificial cavities influences negatively the possibility of occurrence of collapse sinkholes, through progressive detachment of blocks from their vaults. In detail, the pattern and orientation of discontinuities (primary, as bedding planes, and secondary, as joints and fractures) control the kinematic feasibility, potential size, and shape of rock blocks that may detach in underground voids. Among all involved factors, persistence of a discontinuity is critical, since this parameter may control the detachment of the blocks from the vault of a cavern. Spacing is the second critical factor: closely spaced discontinuities weaken the rock mass much more than those located at higher distances. A close spacing, in detail, makes the rock mass more susceptible to external triggers like rainfall, freeze-thaw cycles, or seismic activity. Aperture is also of great importance, especially underground. The width of the opening of a discontinuity can influence water infiltration, and its flow within the subsoil; this, in turn, can impact rock failure due to increased hydrostatic pressure. Other factors like roughness, infilling material, or strength along the discontinuity walls can be regarded as less important for predisposition to rock failure in subterranean voids.
Physical and mechanical properties • Porosity/Density	Porosity, that is the ratio between volume of the voids and volume of the solid in a terrain or rock, is an important parameter to determine the capability of a material to allow movement of water within itself. In detail, effective porosity, meaning the connection among interconnecting pores, is the crucial parameter at this regard. In the case of karst voids, or artificial cavities excavated in soft rocks, evaluating effective porosity is crucial in order to understand the likely effect of flowing water within the terrain or the rock mass.
Physical and mechanical properties • Shear strength	Discontinuity shear strength is one of the critical factors determining the stability of rock blocks in underground settings. Its estimates, however, are often characterized by uncertainties. When assessing rock failures in caves and cavities, the presence of rock bridges – intact segments of rock extending over a discontinuity – emerges as a paramount mechanical determinant. However, the characteristics and strength of these bridges can vary extensively, making challenging their precise quantification. Such a complexity has led to the adoption of statistical and probabilistic methodologies to better capture and estimate this crucial factor. As a further element, chemical weathering (such as hydrolysis, oxidation, and carbonation) can break down primary minerals in rocks, leading to a reduction in the cohesive strength of the rock mass, making it more susceptible to detachment and failure from both vault and walls of the cave. As concerns soils, the geotechnical properties (in terms of shear strength) must be considered for cover collapse sinkholes, since poor values in these properties may result in significant reduction of the overburden thickness within the cover, thus favoring the occurrence of a catastrophic collapse.

Physical and mechanical properties • Hydraulic properties	Water infiltration, from the surface in consequence of rainfall, or in turbulent way on the occasion of flood events, may fill partially or totally the cave, and a variable time (hours to days) is required to discharge such amount, which, on the other hand, increases the degree of saturation of the hosting rock or soil. Strictly related to effective porosity, discussed above, there are also other hydraulic properties such as permeability and transmissivity. These hydraulic properties, overall, characterize the ability of a terrain or rock to transfer water, and, as a consequence, to assess the effects of its passage throughout the material, likely predisposing to failure in underground voids and to catastrophic collapse.
Seismotectonics • Seismic activity	Seismicity of an area influences the proneness to collapse sinkholes. Seismic shaking is generally regarded as a triggering factor for occurrence of the collapse, but actually it may also play a role in its predisposition, in the sense that a non-seismic area has definitely less possibility to develop a general failure in an underground void than a seismic area. In this latter case, the frequency of seismic events might possibly weaken the rock mass, thus predisposing it toward development of a rock failure. The seismic activity plays a crucial role in inducing rock failures within underground voids. Continuous exposure to even moderate seismic events can accumulate damage within the rock mass, and work in fragmenting the rock bridges along discontinuities. To properly evaluate the proneness to collapse sinkholes, it is therefore vital to recognize and incorporate the seismic predisposition of the area. This can be deduced from the region seismic history, examining the frequency and magnitude of past earthquakes, and the proximity to active fault lines.
Seismotectonics • Faulting Systems / Distance from faults	Faults represent a weakness zone in rock masses (fault damage zone), where water flow typically may concentrate, due to higher permeability. Fracturing in the fault damage zone, in fact, promotes fluid circulation and weathering of soluble rocks at depth. Location of underground voids near a fault may be indicative of poor quality of the rock, with higher fracturing density, and therefore of higher proneness to instability.
Land cover & Vegetation • Land Use / Land Cover	Land cover directly affects the environmental conditions of terrains above underground voids, playing a role in the possibility for water to enter the subterranean systems. Generally, regions with bare rock or limited vegetation are directly exposed to elements like rainfall, snow thawing, and changes in temperature. On the other hand, dense forests often shield rock surfaces from these elements, but roots of trees play a role in facilitating the infiltration of water in fissures of the rock mass, serving as wedges that promote detachment. Land cover is shaped by several factors such as geology, climate, and topography, but it also depends on anthropogenic activities. While land cover holds importance in specific contexts, each of these factors can be evaluated and addressed separately in susceptibility analyses of collapse sinkholes.
Land cover & Vegetation • Soil Type / Soil Thickness	Presence of a soil above natural caves or artificial cavities, and its main characters, that essentially include type and thickness, may be relevant for impeding or favoring the infiltration of water underground, and, as a consequence, the loss in mechanical properties due to an increase in the degree of saturation. At this regard, permeability of the soil plays a crucial role, together with the gradient of the ground surface above the void: in sub-horizontal or low topography there is possibility of water stagnancy, and of slow infiltration of significant amount of water. On the other hand, in condition of higher slope the low permeability of a soil acts in favoring the surface runoff rather than the infiltration, thus carrying away most of the water from the area above the cave.

Land cover & Vegetation • Vegetation Type	As pointed out for the factor "Land Use / Land Cover", the type of vegetation above underground voids may play an important role as concerns the possibility, and the modality as well, of water infiltration in the subsoil. Regions with limited vegetational cover are directly exposed to elements like rainfall, snow thawing, and changes in temperature, whilst dense forests often shield rock surfaces from these elements. Nevertheless, roots of trees play a role in facilitating the infiltration of water in fissures of the rock mass, serving as wedges that promote detachment. There are trees with very well-developed roots that are able to penetrate fissures and discontinuities in the rock mass, enlarge them and promote detachment of wedges or portions of the rock, at the same time favoring the water infiltration into the subsoil. This behavior, causes an overall weakening of the geotechnical properties, that has to be considered together with the load related to presence of the trees (and of their roots as well) over the cave. Depending upon the vegetation type, different effects may be observed, and this factor should be carefully evaluated, aimed at understanding its role in promoting or not events of instability within caves and cavities. For instance, fig trees are generally indicative of an underground space with high moisture (caves or conduits), and reeds characterize the areas with water stagnancy or where water is close to the ground surface.
Hydrogeology • Groundwater / Saturation	Presence of the water table in proximity of an underground void, both of natural and anthropogenic origin, may potentially increase the proneness to instability, as an effect of the water table dynamics, and of its related fluctuations. Rising of the water level, up to reach the depth of the cave, results in flooding the lower part, if not all, the void. This increases definitely the degree of saturation, with remarkable reduction in the mechanical parameters and a significantly lower capability to counteract the destabilizing forces. Overall, the final effect is represented by a tendency toward failure of the rock mass in the cave and general collapse leading to sinkhole formation. The water content, expressed by the degree of saturation, is in fact a crucial factor to evaluate the strength of soils or rock masses hosting underground voids. High water content cause significant reduction in the resistance of the materials, thus predisposing them toward more likely instability conditions. Increase in the degree of saturation may depend upon infiltration of rainfall, or of water from irrigation or leakages, but may also occasionally be related to flood events, with concentrated water inflow into the cave system.
Hydrogeology • Rising acid fluids	Rising acidic fluids, moving along faults or other secondary discontinuities from depths, predispose the rocks and terrains through which they move to possible enlargement of karst voids, and, in consequence of this, to progressive failure toward the surface, until a collapse sinkhole is formed. This may also occur as cover or caprock collapse sinkhole (according to the internationally accepted classification on sinkholes), depending upon the characters of the materials covering the bedrock affected by karst processes.
Hydrogeology • Water inflow/outflow during flood/seastorm	When water enters dramatically into a cave system, or an artificial cavity, in consequence of a flood event the main effects are represented by the turbulent action of the running water (including the solid materials transported) and its mechanical erosion on the vault and walls of the underground void. Further, water may fill, partially or totally, the cave, and a variable time (hours to days) is required to discharge such amount, which, on the other hand, increases the degree of saturation of the hosting rock or soil.

	The same effects can be observed during sea storms for caves located along the coast or in its immediate proximity, within the zone potentially involved by the arrival of sea waves.
Climate • Rainfall regime	Rainfall regime, in terms of average rainfall, and typical intensity and duration of rainstorms, can be considered as predisposing factor for the occurrence of collapse sinkholes. Areas characterized by concentrated rainstorms, likely leading to rapid arrival of significant amount of water underground, are definitely more prone to these processes than areas with low intensity and prolonged rainfall. It is clear that rainfall can be considered also as preparatory and/or triggering factor for collapse sinkholes, but in this report we focus on the rainfall regime as predisposing factor.
Anthropogenic factors • Structures / Infrastructures / Buildings	Particularly in urban areas, the presence of pipelines, sewer systems and infrastructures in the first meters below the ground, and above subterranean voids, may have a strong influence on the possibility of occurrence of sinkholes. In detail, leakages from such systems and modifications in the natural drainage patterns may cause water to infiltrate and/or to become stagnant in specific areas, compromising the overall rock stability through degradation of the mechanical properties. Further, leakages from pipelines may induce an increase in the degree of saturation of terrains or rock masses, again bringing toward conditions favorable to failures. Problems related to maintenance works of pipelines and other lifelines have also to be taken into account, as they may additionally contribute to underground instability. Presence of roads and infrastructures above underground voids can also significantly impact the possibility of occurrence of sinkholes: the vibrations related to heavy traffic, or to frequent passage of vehicles in urban areas, in addition to those deriving from opening of building and construction sites, may predispose the materials hosting the cavities to further instabilities, eventually leading to opening of a collapse sinkhole. These activities may expand the discontinuity apertures, or determine formation of new cracks, enhancing the likelihood of rock block detachment. In addition, infrastructural development can modify the natural drainage patterns, causing water to infiltrate and/or to become stagnant in specific areas, compromising the overall rock stability through degradation of the mechanical properties.

References for Rapid sinkholes - *Collapse sinkholes, cover collapse sinkholes, caprock collapse sinkholes*

Al-Halbouni D., Holohan E.P., Taheri A., Watson R.A., Polom U., Schöpfer M.P.J., Emam S. & Dahm T. (2019). Distinct element geomechanical modelling of the formation of sinkhole clusters within large-scale karstic depressions. Solid Earth, 10, 1219-1241.

Bianchini S., Confuorto P., Intrieri E., Sbarra P., Di Martire D., Calcaterra D. & Fanti R. (2022). Machine learning for sinkhole risk mapping in Guidonia-Bagni di Tivoli plain (Rome), Italy. Geocarto International 37 (27), 16687-16715, doi: 10.1080/10106049.2022.2113455.

Choi J.H., Edwards P., Ko K. & Kim Y.S. (2016). Definition and classification of fault damage zones: A review and a new methodological approach. Earth Science Reviews, 152, 70-87.

Esposito C., Belcecchi N., Bozzano F., Brunetti A., Marmoni G.M., Mazzanti P., Romeo S., Cammillozzi F., Cecchini G. & Spizzirri M. (2021). Integration of satellite-based A-DInSAR and geological modeling supporting the prevention from anthropogenic sinkholes: a case study in the urban area of Rome. Geomatics, Natural Hazards and Risk 12 (1), 2835-2864. 10.1080/19475705.2021.1978562.

Galeazzi C. (2013). The typological tree of artificial cavities: a contribution by the Commission of the Italian Speleological Society. Opera Ipogea, 1, 9-18.

Guarino P. M. & Nisio S. (2012). Anthropogenic sinkholes in the territory of the city of Naples (Southern Italy). Phys. Chem. Earth, parts A/B/C, 49, 92-102.

Guarino P. M., Santo A., Forte G., De Falco M. & Niceforo D. M. A. (2018). Analysis of a database for anthropogenic sinkhole triggering and zonation in the Naples hinterland (Southern Italy). Natural Hazards, 91, 173–192.

Gutierrez F., Parise M., De Waele J. & Jourde H. (2014). A review on natural and human-induced geohazards and impacts in karst. Earth Science Reviews, vol. 138, p. 61-88, doi: 10.1016/j.earscirev.2014.08.002.

Liso I.S. & Parise M. (2023). Sinkhole development at the freshwater-saltwater interface in Apulia (southern Italy). In: Land L., Kromhout C. & Suter S. (Eds.), Proceedings of the 17th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Tampa (Florida, USA), 27-31 March 2023, NCKRI Symposium no. 9, p. 229-238.

Lollino P. & Parise M. (2023). Sinkhole hazard quantitative assessment: Insights from the application of numerical modelling techniques. In: Land L., Kromhout C. & Suter S. (Eds.), Proceedings of the 17th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Tampa (Florida, USA), 27-31 March 2023, NCKRI Symposium no. 9, p. 141-150.

Margiotta S., Marini G., Fay S., D'Onghia F.M., Liso I.S., Parise M. & Pinna M. (2021). Hydro-stratigraphic conditions and human activity leading to development of a sinkhole cluster in a Mediterranean water ecosystem. Hydrology, 8, 111. https://doi.org/10.3390/hydrology8030111.

McGrath A.G. & Davison I. (1995). Damage zone geometry around fault tips. J. Struct. Geol. 17, 1011–1024.

Parise M. (2019). Sinkholes. In: White W.B., Culver D.C. & Pipan T. (Eds.), Encyclopedia of Caves. Academic Press, Elsevier, 3rd edition, ISBN ISBN 978-0-12-814124-3, p. 934-942.

Parise M. (2022). Sinkholes, Subsidence and Related Mass Movements. In: Shroder J.J.F. (Ed.), Treatise on Geomorphology, vol. 5. Elsevier, Academic Press, pp. 200–220. https://dx.doi.org/10.1016/B978-0-12-818234- 5.00029-8. ISBN: 9780128182345.

Parise M. & Vennari C. (2016) Distribution and features of natural and anthropogenic sinkholes in Apulia. In: Renard P. & Bertrand C. (Eds.) Eurokarst 2016, Neuchâtel. Advances in Karst Science, Springer, ISBN 978-3-319-45464-1, doi: 10.1007/978-3-319-45465-8_3.

Parise M., Galeazzi C., Bixio R., Dixon M. (2013). Classification of artificial cavities: a first contribution by the UIS Commission. In: Filippi M. & Bosak P. (Eds.), Proc. 16th Int. Congr. Speleology, Brno, 21-28 July 2013, 2, pp. 230-235.

Pepe P., Pentimone N., Garziano G., Martimucci V. & Parise M. (2013). Lessons learned from occurrence of sinkholes related to man-made cavities in a town of southern Italy. In: Land L., Doctor D.H. & Stephenson B. (Eds.), Proceedings of the 13th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Carlsbad (New Mexico, USA), 6-10 May 2013, National Cave and Karst Research Institute, p. 393-401.

Perrotti M., Lollino P., Fazio N.L., Pisano L., Vessia G., Parise M., Fiore A. & Luisi M. (2018). Finite Element–based stability charts for underground cavities in soft calcarenites. ASCE International Journal of Geomechanics, 18 (7), 04018071.

Perrotti M., Lollino P., Fazio N.L. & Parise M. (2019). Stability charts based on the finite element method for underground cavities in soft carbonate rocks: validation through case-study applications. Natural Hazards and Earth System Sciences, 19, 2079-2095.

Scotto di Santo A., Forte G. & Santo A. (2018). Analysis of sinkhole triggering mechanisms in the hinterland of Naples (southern Italy). Engineering Geology 237, 42-52. https://doi.org/10.1016/j.enggeo.2018.02.014.

Tufano R., Guerriero L., Corona M. A., Bausilio G., Di Martire D., Nisio S., Calcaterra D. (2022). Anthropogenic sinkholes of the city of Naples, Italy: an update. Natural Hazards, 1-32.

Vennari C. & Parise M. (2022). A chronological database about natural and anthropogenic sinkholes in Italy. Geosciences, vol. 12, 200, https://doi.org/10.3390/geosciences12050200.

Vennari C., Salvati P., Bianchi C., Casarano D., Parise M., Basso A. & Marchesini I. (2022). AReGeoDatHa: Apulian Regional GeoDatabase for geo-hydrological Hazards. Journal of Environmental Management 322, 116051. https://doi.org/10.1016/j.jenvman.2022.116051.

Vigliotti M. & Ruberti D. (2018). Campania Grey Tuff and Anthropogenic Tuff Cavities in the Southern Metropolitan Area of Caserta (Southern Italy). Alp. Mediterr. Quat., 31, 247–251.

Subsidence

Description of the main predisposing factors	
Geology ● Lithology	Fine-grained soils, notably clay and silt, are particularly prone to causing subsidence due to their capacity to shrink and swell based on moisture content and changes in pore water pressure. These soils exhibit significant volume changes in response to varying water levels, leading to ground subsidence. Conversely, non-cohesive soils like sand and gravel are less likely to shrink and swell, but they can still contribute to subsidence through processes like underground piping, where water flow erodes and removes soil particles. Subsidence is also notably pronounced in geological formations composed of highly compressible sediments, such as those found in pro-deltas, delta plains, and swamp muds. The thickness and compressibility of these sediments make them particularly susceptible to volume changes and settling. Additionally, in regions with soils rich in organic materials like peat, subsidence can occur as these materials decompose, leading to a reduction in volume. The rate of this decomposition, and thus the rate of subsidence, varies depending on the specific type of organic material and is influenced by environmental factors such as temperature and moisture.
Geology ● Stratigraphic features	Soil compaction primarily takes place in the initial stages of sedimentation, known as primary consolidation. In this context, older geological formations, having been subject to natural processes over extended periods, have typically undergone significant consolidation. In contrast, geologically younger formations are more susceptible to ongoing subsidence due to secondary compaction. This is particularly true for fine-grained soils that contain substantial amounts of peat and organic matter, as they are more prone to further compaction and subsidence. The subsurface stratigraphy of an area is also a key determinant of the aquifer system's structure. This stratigraphy governs the distribution and interplay of aquifer and aquitard layers, which in turn control the dynamics of groundwater movement. Consequently, these layers have a direct impact on the distribution of pore pressure, which is a critical factor in the soil consolidation process. The arrangement of these layers influences potential drainage paths, affecting how water moves through and exits the soil. Additionally, the thickness of compressible soil layers, which are typically fine-grained, plays a significant role in subsidence processes. The proportion of these layers and how they are interspersed with coarser-grained materials can influence the overall susceptibility of the area to subsidence. The vertical arrangement and variability of these different soil types within the stratigraphic sequence are crucial in determining how prone a region is to subsidence under various environmental and anthropogenic influences.
Geomorphology ● Slope Morphology / Topography	Subsidence phenomena are typically present in alluvial plains, coastal plains, wide depressed areas. These areas are generally composed of recent, loosely packed deposits and often suffer from inadequate drainage, leading to the accumulation and prolonged presence of water. Fluctuations in groundwater levels and changes in surface load in these environments are key contributors to ground subsidence. Additionally, the topography of these areas plays a significant role in dictating the movement of groundwater, which is a crucial factor in the development of subsidence. The way groundwater navigates through these landscapes can greatly influence the stability of the

	ground, underscoring the interconnectedness of topographical features and subsidence phenomena.
Geomorphology ● Presence of previous events	As for all other natural hazards, the presence of previous episodes of subsidence phenomena is indicative of the possibility of occurrence of such an hazard. Therefore, knowing the areas where subsidence has already occurred, or where it is occurring at present, is among the main elements to know in order to provide a preliminary indication of the areas most susceptible to subsidence.
Physical and mechanical properties ● Grainsize distribution/Particle shape ● Porosity / Density ● Mineralogy and plasticity ● Hydraulic properties	The physical and mechanical properties of soil are critical in determining the likelihood and severity of ground subsidence. Among these properties, soil compressibility stands out as particularly important. This property measures the degree to which soil volume decreases under pressure. The compressibility of fine-grained soils is often linked to their in situ condition, characterized by factors such as void ratio and over-consolidation ratio (OCR). Within the realm of soil compressibility, the oedometric or constrained modulus (Em) is a key parameter. In situations where detailed measurements of compressibility are not available, the tendency of soil to undergo volume changes can be estimated based on other properties. These include grain size distribution, porosity, and soil plasticity. Soils with a significant amount of fine particles, such as clay and silt, usually possess smaller pores, lower permeability, and higher plasticity, all contributing to greater compressibility. In such cases, Atterberg limits are often utilized for a preliminary assessment of the soil's compressibility potential. The presence and quantity of organic matter in the soil also significantly affect its mechanical properties. Organic-rich soils can exhibit extreme plasticity and very high compressibility.
Hydrogeology ● Groundwater / Saturation	The hydrogeological setting of the area has a profound impact on ground subsidence. The spatial arrangement of aquifers and aquitards affect how water is stored and moves underground, influencing the pressure distribution and the saturation levels with depth. Changes in these factors, whether due to natural conditions or human activities, can alter the stability of the ground. While aquifers are the source of water extraction, it is often the characteristics and response of the aquitards, with their fine-grained composition and susceptibility to volume changes, that play a pivotal role in the occurrence of ground subsidence. Understanding the hydrogeological profile of an area, including the distribution and characteristics of aquifers and aquitards, is essential for assessing subsidence susceptibility. Groundwater levels are also subject to seasonal variations, which are influenced by the amount of rain infiltrating the subsoil and by human actions such as groundwater withdrawal or recharge from irrigation. In areas where groundwater levels fluctuate, the sediments experience hydrodynamic compaction, leading to vertical displacement of the ground. This process, often occurring in conjunction with shallow groundwater level changes, can cause localized ground settlements, a phenomenon typically referred to as shrinkage.

Climate ● Rainfall regime ● Temperature regime	The role of the long-term rainfall regime in ground subsidence is significant, as it is a crucial component of the water cycle. This is especially important in the context of anthropogenic subsidence, which is often linked to activities like water pumping. The patterns of long-term rainfall play a key role in establishing groundwater levels, which in turn have a substantial impact on soil settlement. Maintaining stable groundwater levels is essential for preserving the pressure balance within the soil and helping to mitigate subsidence. However, this balance can be disrupted during prolonged periods of drought. Insufficient rainfall leads to reduced replenishment of groundwater reserves, a critical issue in maintaining soil stability. This situation is exacerbated when ongoing human activities continue to extract water, leading to further depletion of groundwater levels. As these levels drop, the risk of soil compaction and subsequent subsidence increases, posing a threat to ground stability. Climate change introduces additional challenges to this scenario. It alters global weather patterns, potentially leading to more extreme and less predictable climatic conditions. These changes can affect the frequency, intensity, and distribution of rainfall, impacting the natural water cycle and, consequently, groundwater replenishment. The effects of climate change could therefore amplify the impact of long-term rainfall patterns on ground subsidence, making the issue more complex and challenging.
Anthropogenic factors ● Structures/Infrastructures/Buildings	Land subsidence can be affected by the load exerted by buildings, infrastructures, as well as by specific human activities. Areas with a high concentration of buildings often experience increased subsidence due to the heavy load these structures impose. Moreover, the way land is utilized can result in distinct patterns of water usage. For instance, during irrigation periods for crops like wheat, which typically coincide with dry weather, extensive groundwater extraction to meet irrigation needs can cause land subsidence. This is especially true in regions where irrigated agriculture is widespread and coupled with rapid population growth, making groundwater withdrawal a predominant factor in subsidence. A variety of human-induced actions play a role in causing land subsidence. Among these, several are directly related to the presence of man-made structures and infrastructures. These include: • The consolidation of ground materials under the weight of buildings and other built-up structures. • The decomposition and compaction of organic-rich soils, often seen in areas where marshlands have been reclaimed for development. • Deformations caused by local or widespread structural failures, including the lack of support in underground cavities like abandoned mines or tunnels. These can lead to upward stoping, where voids gradually expand upwards, potentially affecting surface stability. Understanding the interplay between these anthropogenic factors and natural soil properties is essential for assessing predisposition to subsidence.
Anthropogenic factors ● Groundwater/Gas/Oil exploitation	The exploitation of natural resources is a primary cause of subsidence phenomena. Specifically, the extraction of groundwater, gas, or oil typically leads to a reduction in pore pressure within compressible soils. This can occur across extensive areas, resulting in noticeable vertical ground displacements. The rate of resource extraction plays a crucial role in the dynamics of subsidence; rapid extraction tends to cause abrupt changes in underground pressures, leading to immediate and more pronounced subsidence. On the other hand, a slower pace of extraction usually results in more gradual ground settlement. The management practices of resource extraction, such as the employed extraction techniques and the maintenance of groundwater pressures, are key factors that determine the severity and scope of subsidence. Poorly managed extraction, often a challenge in developing countries due to limited resources or regulatory oversight, can exacerbate the

	problem, leading to greater environmental and infrastructural impacts, including damage to infrastructure, alteration of watercourses, and increased risk of flooding.

References for Subsidence

Bell F., Stacey T. & Genske D. (2000). Mining subsidence and its effect on the environment: some differing examples. Environmental Geology, 40, 135–152. https://doi.org/10.1007/s002540000140

Bozzano F., Esposito C., Mazzanti P., Patti M. & Scancella S. (2018). Imaging Multi-Age Construction Settlement Behaviour by Advanced SAR Interferometry. Remote Sensing 10 (7), 1137. https://doi.org/10.3390/rs10071137.

Bozzano F., Esposito C., Franchi S., Mazzanti P., Perissin D., Rocca A. & Romano E. (2015). Understanding the subsidence process of a quaternary plain by combining geological and hydrogeological modelling with satellite InSAR data: The Acque Albule Plain case study. Remote Sensing of Environment 16, 219-238. https://doi.org/10.1016/j.rse.2015.07.010.

Buffardi C., Barbato R., Vigliotti M., Mandolini A. & Ruberti D. (2021). The Holocene Evolution of the Volturno Coastal Plain (Northern Campania, Southern Italy): Implications for the Understanding of Subsidence Patterns. Water, 13(19), 2692. https://doi.org/10.3390/w13192692

Fiaschi S., Fabris M., Floris M. & Achilli V. (2018). Estimation of land subsidence in deltaic areas through differential SAR interferometry: the Po River Delta case study (Northeast Italy). International Journal of Remote Sensing. 10.1080/01431161.2018.1490977.

Figueroa-Miranda S., Tuxpan-Vargas J., Ramos-Leal J.A., Hernández-Madrigal V.M. & Villaseñor-Reyes C.I. (2018). Land subsidence by groundwater over-exploitation from aquifers in tectonic valleys of Central Mexico: A review. Engineering Geology, 246, 91-106, ISSN 0013-7952, https://doi.org/10.1016/j.enggeo.2018.09.023.

Floris M., Fontana A., Tessari G. & Mulè M. (2019). Subsidence Zonation Through Satellite Interferometry in Coastal Plain Environments of NE Italy: A Possible Tool for Geological and Geomorphological Mapping in Urban Areas. Remote Sensing 11 (2), 165. https://doi.org/10.3390/rs11020165.

Grassi F., Mancini F., Bassoli E. & Vincenzi L. (2022). Contribution of anthropogenic consolidation processes to subsidence phenomena from multi-temporal DInSAR: a GIS-based approach. GIScience & Remote Sensing, 59 (1), 1901-1917. DOI: 10.1080/15481603.2022.2143683

Khakim M.Y.N., Tsuji T. & Matsuoka T. (2014). Lithology-controlled subsidence and seasonal aquifer response in the Bandung basin, Indonesia, observed by synthetic aperture radar interferometry. Int. J. Appl. Earth Obs. Geoinf., 32, 199-207. http://dx.doi.org/10.1016/j.jag.2014.04.012

Kazuhiro K, Pokhrel RM, Takashi K. & Kazuo K. (2015). Liquefaction-induced ground subsidence extracted from Digital Surface Models and its application to hazard map of Urayasu city, Japan. Japanese Geotechnical Society Special Publication, 2 (22), 829-834. https://doi.org/10.3208/jgssp.TC203-02

Jones C.E., An K., Blom R.G., Kent J.D., Ivins E.R. & Bekaert D. (2016). Anthropogenic and Geologic Influences on Subsidence in the Vicinity of New Orleans, Louisiana. J. Geophys. Res. Solid Earth, 121, 3867–3887.

Ma T., Du Y., Ma R. et al. (2018). Review: Water–rock interactions and related eco-environmental effects in typical land subsidence zones of China. Hydrogeology Journal, 26, 1339–1349. https://doi.org/10.1007/s10040-017-1708-8

Modoni G., Darini G., Spacagna R.L., Saroli M., Russo G. & Croce P. (2013). Spatial analysis of land subsidence induced by groundwater withdrawal. Engineering Geology 167, 59-71. https://doi.org/10.1016/j.enggeo.2013.10.014.

Ronchi L., Fontana A., Cohen K.M. & Stouthamer E. (2021). Late Quaternary landscape evolution of the buried incised valley of Concordia Sagittaria (Tagliamento River, NE Italy): A reconstruction of incision and transgression. Geomorphology 373, 107509. https://doi.org/10.1016/j.geomorph.2020.107509.

Rosi A., Tofani V., Agostini A., Tanteri L., Tacconi Stefanelli C., Catani F. & Casagli N. (2016). Subsidence mapping at regional scale using persistent scatters interferometry (PSI): the case of Tuscany region (Italy). International Journal of Applied Earth Observation and Geoinformation 52, 328-337. https://doi.org/10.1016/j.jag.2016.07.003.

Scardino G., Sabatier F., Scicchitano G., Piscitelli A., Milella M., Vecchio A., Anzidei M. & Mastronuzzi G. (2020). Sea-Level Rise and Shoreline Changes Along an Open Sandy Coast: Case Study of Gulf of Taranto, Italy. Water 12 (5), 1414. https://doi.org/10.3390/w12051414.

Scardino G., Anzidei M., Petio P., Serpelloni E., De Santis V., Rizzo A., Liso S.I., Zingaro M., Capolongo D., Vecchio A., et al. (2022). The Impact of Future Sea-Level Rise on Low-Lying Subsiding Coasts: a case study of Tavoliere delle Puglie (Southern Italy). Remote Sensing 14, 4936. https://doi.org/10.3390/rs14194936.

Sowers G.F. (1976). Mechanism of subsidence due to underground openings. In: Subsidence over mines and caverns, moisture and frost actions, and classification. National Academy of Sciences, Washington, D.C. (ed.). 612, pp 1-8. ISSN: 0361-1981.

Teatini P., L. Tosi & Strozzi T. (2011). Quantitative evidence that compaction of Holocene sediments drives thepresent land subsidence of the Po Delta, Italy. J. Geophys. Res. 116, B08407. doi:10.1029/2010JB008122.

Thongprapha T., Fuenkajorn K. & Daemen J.J.K. (2015). Study of surface subsidence above an underground opening using a trap door apparatus. Tunnelling and Underground Space Technology, 46, 94-103. https://doi.org/10.1016/j.tust.2014.11.007.

Zhou C., Gong H., Chen B., Gao M., Cao Q., Cao J., Duan L., Zuo J. & Shi M. (2020). Land Subsidence Response to Different Land Use Types and Water Resource Utilization in Beijing-Tianjin-Hebei, China. Remote Sensing, 12, 457. https://doi.org/10.3390/rs12030457.

Liquefaction

Description of the main predisposing factors	
Geology • Lithology	Lithology is one of the most important predisposing factors for occurrence of liquefaction. The process is triggered by strong-motion earthquakes in cohesionless soils, encompassing sandy silts to sandy gravels, provided that seismic shaking is faster than the capacity of the soil to dissipate the induced excess pore water pressure. As a consequence, the rapid loss of shear strength and stiffness of soils occurs with catastrophic effects.
Geology • Stratigraphic features	Liquefaction involves shallow saturated layers of sandy soils, generally placed in the first 20 m from the ground surface. When confined by fine-grained non-liquefiable soil layers characterized by low permeability, sandy soils result more susceptible to liquefaction, due to the reduction of the rate of dissipation of the excess pore water pressure.
Geomorphology • Slope Morphology / Topography	Liquefaction phenomena typically occur in topographically flat areas such as alluvial and coastal plains, as well as in lacustrine basins and marshlands. They can also affect abandoned meanders of rivers, in peculiar conditions. Therefore, the topography, combined with the lithological and stratigraphic characteristics of the site, can provide a preliminary indication of the areas most susceptible to liquefaction.
Geomorphology • Presence of previous events	As for all other natural hazards, the presence of previous episodes of liquefaction is indicative of the possibility of occurrence of such an hazard. Therefore, knowing the areas where liquefaction has already occurred, or where it is occurring at present, is among the main elements to know in order to provide a preliminary indication of the areas most susceptible to this hazard.
Physical and mechanical properties • Grainsize distribution/Particle shape	Soils with rounded particle shapes are known to densify more easily than soils with angular grains, implying that their liquefaction resistance is lower with respect to angular-grained soils.
Physical and mechanical properties • Porosity / Density	Relative density plays an important role in liquefaction. Loose sands (lower relative densities) are more prone to liquefaction than dense sands. In loose contractive soils, 'flow liquefaction' occurs when pore water pressure increasingly accumulates and effective stress approaches zero; denser soils with a tendency to dilate show alternate increase and reduction of pore pressure leading to a less catastrophic phenomenon know as 'cyclic mobility'.
Physical and mechanical properties • Mineralogy and plasticity	Experimental evidence shows that, besides grain size, plasticity also influences the liquefaction susceptibility of soils with a non-negligible fine content (i.e. higher than 5%). Some authors have shown that plasticity index is one of the most important parameters influencing liquefaction resistance. Sands containing high plastic fines generally exhibit a higher resistance to liquefaction than clean sands, even though the presence of fines is expected to decrease the hydraulic conductivity. Volcanic silty sands prove to be less

	liquefiable than alluvial soils with comparable grain size, even though the fine ash fraction is usually non-plastic.
Seismotectonics • Seismic activity	Seismic activity plays a fundamental role in the predisposition of a territory to liquefaction processes. This means that the first requirement for the occurrence of liquefaction, together with a suitable stratigraphy and the presence of a water table, is the seismicity of the area under study. In this sense, seismic activity is here considered as a predisposing factor. The rationale for the existence of a threshold in the seismic severity for the liquefaction phenomenon could be related to the undrained behaviour of soil specimens observed in laboratory tests. It has been found that, under cyclic loadings, there is a 'volumetric threshold' shear strain amplitude beyond which pore water pressure increases. This means that the pore water pressure buildup, and the eventual liquefaction, are necessarily associated with strong-motion earthquakes inducing peak accelerations high enough to mobilize strains higher than the above-defined threshold amplitude. It is conventionally assumed that sandy soils are prone to liquefaction when peak ground accelerations are higher than 0.1g. Below this acceleration level, liquefaction is assumed to be unlikely, whatever the duration of the ground motion.
Hydrogeology • Groundwater / Saturation	The presence of groundwater table is a crucial predisposing factor for the occurrence of liquefaction processes. Beside its presence, and the mean depth (discussed below as a separate predisposing factor) it has to be determined the typology of water table, since confined groundwater, in pressure, highly predispose the soil to liquefaction. The degree of saturation considerably affects the liquefaction resistance. When the degree of saturation decreases, the liquefaction resistance increases, due to a higher compressibility of the gassy fluid phase in partially saturated sands. Liquefaction mainly occurs in saturated sandy soils. It means that sands above the ground water table are generally less prone to liquefaction than those fully saturated. It is conventionally assumed that, when the ground water table is deeper than 15-20 m, liquefaction should not be expected even for strong-motion earthquakes.
Climate • Rainfall regime	The predisposing factor for liquefaction can be ascribed not only to the soil properties but also to the presence of water and the possible variation of hydraulic boundary conditions. The pore water pressure regime is strictly related to the seasonal and long-term variation of the groundwater table induced by rainfalls and evaporation. The rise of the water level reduces the initial effective stress and leads to an aggravation of the stability condition related to soil saturation. These effects are further exacerbated by ongoing climate change, with more frequent extreme rainfall events.

Anthropogenic Factors • River banks/levees typology	Liquefaction phenomena often affect earth structures such as levees, dykes and dams, especially when these have been built with the same natural soil constituting the alluvial deposits where rivers and channels flow. In these cases, the earthquake-induced damage consists of cracking, settlement, lateral spreading and slumping in the body of the embankment. Although evidences of soil liquefaction, such as sand boils, are not always observed in the embankment body, the longitudinal fissuring pattern detected along the crown can be compatible with a lateral spreading mechanism.

References for Liquefaction

Chiaradonna A. & Reder A. (2020). Influence of initial conditions on the liquefaction strength of an earth structure. Bulletin of Engineering Geology and the Environment, 79(2), 687-698.

Chiaradonna A., Tropeano G., d'Onofrio A. & Silvestri F. (2019). Interpreting the deformation phenomena of a levee damaged during the 2012 Emilia earthquake. Soil Dynamics and Earthquake Engineering, 124, 389-398.

Cubrinovski M. (2013). Liquefaction-induced damage in the 2010-2011 Christchurch (New Zealand) Earthquakes. 7th International Conference on Case Histories in Geotechnical Engineering, Chicago (USA), April-May 2013.

Del Prete S., Iovine G., Parise M. & Santo A. (2010). Origin and distribution of different types of sinkholes in the plain areas of Southern Italy. Geodinamica Acta, 23 (1/3), 113-127.

Evangelista L. & Santucci de Magistris F. (2011). Upgrading the simplifed assessment of the liquefaction susceptivity for the city of Naples, Italy. 5th International Conference on Earthquake Geotechnical Engineering, January 2011, 10-13 Santiago, Chile.

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.

Gargiulo F., d'Onofrio A. & Silvestri F. (2021). Approccio multi-livello per le verifiche a liquefazione: un'applicazione all'Isola di Ischia. Incontro Annuale dei Ricercatori di Geotecnica – IARG2021_online, 1-6.

Iovine G. & Parise M. (2008). I sinkholes in Calabria. Memorie Descrittive della Carta Geologica d'Italia, 85, 335-386.

Ishihara K. (1993). Liquefaction and flow failure during earthquakes. Geotechnique, 43(3), 351-451.

Ishihara K. & Koseki J. (1989). Cyclic shear strength of fines-containing sands. Proc. 12th International Conference Soil Mechanics, Rio de Janeiro, 101-106.

Koseki J., Wakamatsu K., Sawada S. & Matsushita K. (2015). Liquefaction-induced damage to houses and its countermeasures at Minami-Kurihashi in Kuki City during the 2011 Tohoku Earthquake, Japan. Soil Dynamics and Earthquake Engineering, 79, 391-400.

Kramer S. L. (1996). Geotechnical earthquake engineering. Prentice Hall, Upper Saddle River, NJ 07458.

Licata V., d'Onofrio A., Silvestri F. (2018). Microstructural factors affecting the static and the cyclic resistance of a pyroclastic silty sand. Géotechnique, 68(5):434–441 (Technical note) doi:10.1680/jgeot.16.P.319

Lirer S., Chiaradonna A. & Mele L. (2020). Soil liquefaction: from mechanisms to effects on the built environment. Rivista Italiana di Geotecnica, 3, 2020.

Mele L., Tian J. T., Lirer S., Flora A. & Koseki J. (2019). Liquefaction resistance of unsaturated sands: experimental evidence and theoretical interpretation. Géotechnique, 69(6), 541-553.

Mele L., Lirer S., & Flora A. (2020). The effect of densification on Pieve di Cento sands in cyclic simple shear tests. In Geotechnical Research for Land Protection and Development: Proceedings CNRIG 2019 7, Springer International Publishing, pp. 446-453.

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.

Santucci de Magistris F. (2005). Liquefaction. Geotechnical aspects of the design in seismic areas. Italian Geotechnical Association (AGI), Patron (Eds.), pp. 99–108 (in Italian).

Santucci de Magistris F. (2006). Liquefaction: a contribution to the Eurocode from the Italian Guideline, Geotechnical Aspects of the Design in Seismic Areas. ISSMGE ETC-12 workshop, NTUA Athens, Greece, 2006.

Santucci de Magistris F. (2011). Beyond EC8: the New Italian Seismic Code. Geofizika, 28, 65–82 (http://geofizika-journal.gfz.hr/vol_28/No1/28_1_santucci.pdf)

Santucci de Magistris F., Lanzano G., Forte G. & Fabbrocino G. (2013). A database for PGA threshold in liquefaction occurrence. Soil Dynamics and Earthquake Engineering 54, 17-19 https://doi.org/10.1016/j.soildyn.2013.07.011.

Santucci de Magistris F., Lanzano G., Forte G., & Fabbrocino G. (2014). A peak acceleration threshold for soil liquefaction: lessons learned from the 2012 Emilia earthquake (Italy). Natural Hazards, 74, 1069-1094.

Sasaki Y. (2009). River dike failures during the 1993 Kushiro-oki earthquake and the 2003 Tokachi-oki earthquake. In: Earthquake Geotechnical Case Histories for Performance-based Design, pp. 131–157.

Tonni L., Gottardi G., Amoroso S., Bardotti R., Bonzi L., Chiaradonna A., d'Onofrio A., Fioravante V., Ghinelli A., Giretti D., Lanzo G., Madiai C., Marchi M., Martelli L., Monaco P., Porcino D., Razzano R., Rosselli S., Severi P., Silvestri F., Simeoni L., Vannucchi G., Aversa S. (2015). Analisi dei fenomeni deformativi indotti dalla sequenza sismica emiliana del 2012 su un tratto di argine del Canale Diversivo di Burana (FE). Rivista Italiana di Geotecnica, 49, 28-58.

Vannucchi G., Crespellani T., Facciorusso J., Ghinelli A., Madiai C., Puliti A. & Renzi S. (2012). Soil liquefaction phenomena observed in recent seismic events in Emilia-Romagna Region, Italy. Ingegneria sismica, 2016 (3), 20-30.

Vucetic M. (1994). Cyclic threshold shear strains in soils. J Geotech. Geoenviron. Eng., ASCE, 120–12, 2208–2227.

6. Quantification of parameters measuring the proneness to ground instabilities

The quantification of the parameters that play a role in determining the susceptibility of ground instabilities is a quite complicate issue that has been the object of many attempts in categorizing them as a function of the capability to express them, generally in terms of qualitative vs. quantitative assessments. Actually, the topic has many variables, that change depending, in first instance, upon the typology of ground instability taken into account, and upon the geological setting of the areas under study as well.

Within the framework of the RETURN Project, starting from the first discussions during the phases of collection and analysis of the learning examples, it appeared very clear that there is a multitude of possible approaches and techniques. Some of these can be considered as robust and traditionally used, having been made available since a quite long time (from years to decades); on the other hand, more recent, technologically-advanced, approaches are less frequent but start to be widely used, and to rapidly improve their ability in dealing with natural and anthropogenic hazards. All these difficulties in performing a full and comprehensive analysis of the available approaches, at least at the level of susceptibility assessment, guided us toward the decision to quantify the parameters identified to measure the proneness to ground instabilities on the basis of simple criteria, based upon the logs used to extract data from them. Thus, we discriminating among a qualitative log, a semi-quantitative log, and a quantitative log. To provide an example, taking into account an analysis dealing with a sample of rock or water, a qualitative analysis is the detection or identification of the constituent elements in the sample, a semi-quantitative analysis is the estimation of their approximate concentrations, whilst a quantitative analysis is the accurate determination of their concentrations.

At a greater detail, qualitative analyses use subjective judgments, typically based on non-quantifiable data, that are evaluated without the use of statistics or numerical models. In this category, heuristic research is included: in such a framework, while making efforts to understand the physical nature of a phenomenon, the researcher gives great importance to her/his own expertise, and is confident on the comprehension of the phenomenon under study, that is directly based upon her/his previous experiences. Qualitative research is not less important and/or useful with respect to the other logs, since it can be based on rigorous methods and on factual evidence. Actually, in many types of research applications the results tend to be qualitative.

Semi-quantitative analyses typically refer to systematic procedures to ascertain, or to confirm, whether certain elements or features are present within a population, and in what amount or concentrations. Semi-quantitative analyses are similar to the qualitative ones, in the sense that they do not measure precise values, but rather provide a ranking, or establish indices or classes to discriminate among different percentages. Even though the semi-quantitative adjective seems to indicate not very accurate results, in many cases providing a ranking in different classes, or defining an index able to express the variation within a population of data, is an important step toward the better comprehension of the variables involved in a given phenomenon.

A quantitative approach, eventually, consists of the analysis of a phenomenon, a situation or event through a complex set of techniques that use mathematical and statistical modeling, measurement, and research to understand and reproduce a specific behavior. Different types of quantitative research, with variable degree of complexity, may be identified: they cover approaches that go from the descriptive, to the correlational, the causal-comparative, up to the experimental research.

Starting from the above statements, each one of the 35 main predisposing factors has been analyzed with the aim to indicate the most frequent logs by means of which they are dealt with. It appears obvious that, for many of them, more than a single log is possible, and this is also partly due to the variety of ground instability processes. Table 6.1 shows the distinction among the different logs, and will represent the starting point for further, more detailed analysis, according to the single processes of ground instability.

↓ Predisposing Factors ↓		Log		
Macro-category	Main Factors	qualitative	semi-quantitative	quantitative
Geology	Lithology	x		
	Structural features (large scale)	x	x	
	Stratigraphic features	x		
	Karstification degree		x	
	Talus/Weathering		x	
Geomorphology	Slope morphology/Topography			x
	Upslope area			x
	Undercutting	x		
	Erosion by running water	x		
	Glaciers and snowfields	x		
	Distance from coastline			x
	Overburden thickness			x
	Cave geometry and size			x
	Presence of previous events	x	x	
Physical and mechanical properties	Rock mass structure		x	x
	Grainsize distribution/Particle shape		x	x
	Porosity/Density			x
	Shear strength			x
	Mineralogy and plasticity			x
	Hydraulic Properties		x	x
Seismotectonics	Seismic activity		x	x
	Faulting System/Distance to faults	x		x
	Site effects (amplification/resonance)			x
Land Cover & Vegetation	Land Use/Land Cover		x	
	Soil Type/Soil Thickness		x	x
	Vegetation	x	x	
Hydrogeology	Groundwater/Saturation		x	x
	Rising acid fluids	x		
	Water inflow/outflow during flood/seastorm	x	x	
Climate	Rainfall Regime			x
	Temperature Regime			x
Anthropogenic Factors	Structures/Infrastructures/Buildings			x
	Groundwater/Gas/Oil exploitation			x
	River banks/levees typology		x	
	Slope/Drainage changes		x	x

Table 6.1: logs for Predisposing Factors of Ground Instabilities

7. References

This section was produced by merging of the single reference lists related to each typology of ground instabilities.

Aaron, J., and Hungr, O. (2016a). Dynamic analysis of an extraordinarily mobile rock avalanche in the Northwest Territories, Canada. Can. Geotech. J. 53, 899–908. doi: 10.1139/cgj-2015-0371

Aaron, J., and McDougall, S. (2019). Rock avalanche mobility: the role of path material. Eng. Geol. 257, 105126. doi: 10.1016/j.enggeo.2019.05.003

Agliardi, F., Crosta, G., & Zanchi, A. (2001). Structural constraints on deep-seated slope deformation kinematics. Engineering Geology, 59(1-2), 83-102.

Agnesi, V., Rotigliano, E., Tammaro, U., Cappadonia, C., Conoscenti, C., Obrizzo, F., ... & Pingue, F. (2015). GPS monitoring of the Scopello (Sicily, Italy) DGSD phenomenon: Relationships between surficial and deep-seated morphodynamics. In Engineering Geology for Society and Territory-Volume 2: Landslide Processes (pp. 1321-1325). Springer International Publishing.

Al-Halbouni D., Holohan E.P., Taheri A., Watson R.A., Polom U., Schöpfer M.P.J., Emam S. & Dahm T. (2019). Distinct element geomechanical modelling of the formation of sinkhole clusters within large-scale karstic depressions. Solid Earth, 10, 1219-1241.

Akgun, A., Dag, S., Bulut, F. (2008) Landslide susceptibility mapping for a landslide-prone area (Findikli, NE of Turkey) by likelihood-frequency ratio and weighted linear combination models. Environ. Geol. 54, 1127–1143.

Alqadhi, S., Mallick, J., Talukdar, S., Bindajam, A.A., Van Hong, N., Saha, T.K. (2021) Selecting optimal conditioning parameters for landslide susceptibility: an experimental research on Aqabat Al-Sulbat, Saudi Arabia. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-15886-z.

Alvioli, M., Santangelo, M., Fiorucci, F., Cardinali, M., Marchesini, I., Reichenbach, P., Rossi, M., Guzzetti, F., Peruccacci, S. (2021) Rockfall susceptibility and network-ranked susceptibility along the Italian railway. Eng. Geol. 293, 106301. https://doi.org/10.1016/j.enggeo.2021.106301.

Ansari, M.K., Ahmad, M., Singh, R., Singh, T.N. (2014) Rockfall hazard assessment at Ajanta Cave Aurangabad, Maharashtra, India. Arabian J. Geosci. 7, 1773–1780.

Bajni, G., Camera, C.A.S., Brenning, A., Apuani, T. (2022) Assessing the utility of regionalized rock-mass geomechanical properties in rockfall susceptibility modelling in an Alpine environment. Geomorphology 415, 108401. https://doi.org/10.1016/j.geomorph.2022.108401.

Bardou, E., Ancey, C., Bonnard, C., Vulliet, L., (2003). Classification of debris-flow deposits for hazard assessment in alpine areas. In: Rickenmann, D., Chen, C.-L. (Eds.), Debris- Flow Hazards Mitigation: Mechanics Prediction and Assessment. Millpress, Rotterdam, Davos (Switzerland), pp. 799–808.

Baum, R.L., Godt, J.W., (2010). Early warning of rainfall-induced shallow landslides and debris flows in the USA. Landslides 7 (3), 259–272.

Bayer, B., Simoni, A., Mulas, M., Corsini, A., & Schmidt, D. (2018). Deformation responses of slow moving landslides to seasonal rainfall in the Northern Apennines, measured by InSAR. Geomorphology, 308, 293-306.

Bednarik, M., Magulová, B., Matys, M., & Marschalko, M. (2010). Landslide susceptibility assessment of the Kraľovany–Liptovský Mikuláš railway case study. Physics and Chemistry of the Earth, Parts A/B/C, 35(3-5), 162-171.

Bell F., Stacey T. & Genske D. (2000). Mining subsidence and its effect on the environment: some differing examples. Environmental Geology, 40, 135–152. https://doi.org/10.1007/s002540000140

Berenguer, M., Sempere-Torres, D., Hürlimann, M., (2015). Debris-flow forecasting at regional scale by combining susceptibility mapping and radar rainfall. Nat. Hazards Earth Syst. Sci. 15, 587–602.

Bertrand, M., Liébault, F., Piégay, H., (2013). Debris-flow susceptibility of upland catchments. Nat. Hazards 67, 497–511.

Bianchini S., Confuorto P., Intrieri E., Sbarra P., Di Martire D., Calcaterra D. & Fanti R. (2022). Machine learning for sinkhole risk mapping in Guidonia-Bagni di Tivoli plain (Rome), Italy. Geocarto International 37 (27), 16687-16715, doi: 10.1080/10106049.2022.2113455.

Bovis, M. J., & Evans, S. G. (1996). Extensive deformations of rock slopes in southern Coast Mountains, southwest British Columbia, Canada. Engineering Geology, 44(1-4), 163-182.

Bowman, E.T., Take, W.A., Rait, K.L., Hann, C. (2012). Physical models of rock avalanche spreading behaviour with dynamic fragmentation. Can. Geotech. J. 49, 460–476. doi: 10.1139/t2012-007

Bozzano F., Esposito C., Mazzanti P., Patti M. & Scancella S. (2018). Imaging Multi-Age Construction Settlement Behaviour by Advanced SAR Interferometry. Remote Sensing 10 (7), 1137. https://doi.org/10.3390/rs10071137.

Bozzano F., Esposito C., Franchi S., Mazzanti P., Perissin D., Rocca A. & Romano E. (2015). Understanding the subsidence process of a quaternary plain by combining geological and hydrogeological modelling with satellite InSAR data: The Acque Albule Plain case study. Remote Sensing of Environment 16, 219-238. https://doi.org/10.1016/j.rse.2015.07.010.

Budetta, P. (2004) Assessment of rockfall risk along roads. Nat. Hazards Earth Syst. Sci. 4, 71–81.

Buffardi C., Barbato R., Vigliotti M., Mandolini A. & Ruberti D. (2021). The Holocene Evolution of the Volturno Coastal Plain (Northern Campania, Southern Italy): Implications for the Understanding of Subsidence Patterns. Water, 13(19), 2692. https://doi.org/10.3390/w13192692

Calcaterra, D., & Parise, M. (2010). Weathering as a predisposing factor to slope movements: an introduction. Geological society, London, Engineering Geology Special Publications, 23(1), 1-4.

Calvello, M., Peduto, D., & Arena, L. (2017). Combined use of statistical and DInSAR data analyses to define the state of activity of slow-moving landslides. Landslides, 14, 473-489.

Capitani, M., Ribolini, A., & Bini, M. (2013). The slope aspect: A predisposing factor for landsliding?. Comptes Rendus Geoscience, 345(11-12), 427-438.

Cascini, L. (2008). Applicability of landslide susceptibility and hazard zoning at different scales. Engineering Geology, 102(3-4), 164-177.

Catani, F., Casagli, N., Ermini, L., Righini, G., & Menduni, G. (2005). Landslide hazard and risk mapping at catchment scale in the Arno River basin. Landslides, 2, 329-342.

Cevik, E., Topal, T. (2003) GIS-based landslide susceptibility mapping for a problematic segment of the natural gas pipeline, Hendek (Turkey). Environ. Geol. 44, 949–962.

Chiaradonna A. & Reder A. (2020). Influence of initial conditions on the liquefaction strength of an earth structure. Bulletin of Engineering Geology and the Environment, 79(2), 687-698.

Chiaradonna A., Tropeano G., d'Onofrio A. & Silvestri F. (2019). Interpreting the deformation phenomena of a levee damaged during the 2012 Emilia earthquake. Soil Dynamics and Earthquake Engineering, 124, 389-398.

Choi J.H., Edwards P., Ko K. & Kim Y.S. (2016). Definition and classification of fault damage zones: A review and a new methodological approach. Earth Science Reviews, 152, 70-87.

Cignetti, M., Godone, D., Bertolo, D., Paganone, M., Thuegaz, P., Giordan, D. (2021) Rockfall susceptibility along the regional road network of Aosta Valley region (northwestern Italy). J. Maps 17 (3), 54–64. https://doi.org/10.1080/17445647.2020.1850534.

Ciuffi, P., Bayer, B., Berti, M., Franceschini, S., & Simoni, A. (2021). Deformation detection in cyclic landslides prior to their reactivation using two-pass satellite interferometry. Applied Sciences, 11(7), 3156.

Clayton, A., Stead, D., Kinakin, D., Wolter, A. (2017). Engineering geomorphological interpretation of the Mitchell Creek Landslide, British Columbia, Canada. Landslides 14, 1655–1675. doi: 10.1007/s10346-017-0811-1

Coe, J.A., Kinner, D.A., Godt, J.W. (2008). Initiation conditions for debris flows generated by runoff at Chalk Cliffs, central Colorado. Geomorphology 96, 270–297.

Coe, J.A., Baum, R.L., Allstadt, K.E., Kochevar, B.F., Schmitt, R.G., Morgan, M.L., et al. (2016). Rock-avalanche dynamics revealed by large-scale field mapping and seismic signals at a highly mobile avalanche in the West Salt Creek valley, western Colorado. Geosphere 12, 607–631. doi: 10.1130/GES01265.1.

Conforti, M., & Ietto, F. (2021). Modeling shallow landslide susceptibility and assessment of the relative importance of predisposing factors, through a GIS-based statistical analysis. Geosciences, 11(8), 333.

Conforti, M., Mercuri, M., & Borrelli, L. (2020). Morphological changes detection of a large earthflow using archived images, LiDAR-derived DTM, and UAV-based remote sensing. Remote Sensing, 13(1), 120.

Conoscenti, C., Ciaccio, M., Caraballo-Arias, N. A., Gómez-Gutiérrez, Á., Rotigliano, E., & Agnesi, V. (2015). Assessment of susceptibility to earth-flow landslide using logistic regression and multivariate adaptive regression splines: a case of the Belice River basin (western Sicily, Italy). Geomorphology, 242, 49-64.

Copons, R., Vilaplana, J., Linares, R. (2009) .Rockfall travel distance analysis by using empirical models (SolAd'Andorra la Vella, Central Pyrenees). Natural Hazards and Earth System Sciences 9 (6), 2107–2118.

Corominas, J., & Moya, J. (2008). A review of assessing landslide frequency for hazard zoning purposes. Engineering geology, 102(3-4), 193-213.

Cotecchia, F., Vitone, C., Santaloia, F., Pedone, G., & Bottiglieri, O. (2015). Slope instability processes in intensely fissured clays: case histories in the Southern Apennines. Landslides, 12, 877-893.

Crosta, G. B., Frattini, P., & Agliardi, F. (2013). Deep seated gravitational slope deformations in the European Alps. Tectonophysics, 605, 13-33.

Cruden, D., Krahn, J. (1978). Frank Rockslide, Alberta, Canada, ed. B. Voight (Amsterdam: Elsevier Scientific Publishing), 97–112.

Cubrinovski M. (2013). Liquefaction-induced damage in the 2010-2011 Christchurch (New Zealand) Earthquakes. 7th International Conference on Case Histories in Geotechnical Engineering, Chicago (USA), April-May 2013.

Del Prete S., Iovine G., Parise M. & Santo A. (2010). Origin and distribution of different types of sinkholes in the plain areas of Southern Italy. Geodinamica Acta, 23 (1/3), 113-127.

De Vita, P., Carratù, M. T., La Barbera, G., & Santoro, S. (2013). Kinematics and geological constraints of the slow-moving Pisciotta rock slide (southern Italy). Geomorphology, 201, 415-429.

Di Maio, R., De Paola, C., Forte, G., Piegari, E., Pirone, M., Santo, A., & Urciuoli, G. (2020). An integrated geological, geotechnical and geophysical approach to identify predisposing factors for flowslide occurrence. Engineering Geology, 267, 105473.

Di Martire, D., Novellino, A., Ramondini, M., & Calcaterra, D. (2016). A-differential synthetic aperture radar interferometry analysis of a deep seated gravitational slope deformation occurring at Bisaccia (Italy). Science of the Total Environment, 550, 556-573.

Donnarumma, A., Revellino, P., Grelle, G., & Guadagno, F. M. (2013). Slope angle as indicator parameter of landslide susceptibility in a geologically complex area. Landslide Science and Practice: Volume 1: Landslide Inventory and Susceptibility and Hazard Zoning, 425-433.

Dorren, L.K.A., Berger, F., Putters, U.S. (2006) Real-size experiments and 3-D simulation of rockfall on forested and non-forested slopes. Natural Hazards and Earth System Sciences 6, 145–153.

Du, J., Yin, K., Nadim, F., & Lacasse, S. (2013). Quantitative vulnerability estimation for individual landslides. In Proceedings of the 18th international conference on soil mechanics and geotechnical engineering, Paris (pp. 2181-2184).

Dufresne, A., Bösmeier, A., Prager, C. (2016). Sedimentology of rock avalanche deposits – Case study and review. Earth Sci. Rev. 163, 234–259. doi: 10.1016/j.earscirev.2016.10.002.

Esposito C., Belcecchi N., Bozzano F., Brunetti A., Marmoni G.M., Mazzanti P., Romeo S., Cammillozzi F., Cecchini G. & Spizzirri M. (2021). Integration of satellite-based A-DInSAR and geological modeling supporting the prevention from anthropogenic sinkholes: a case study in the urban area of Rome. Geomatics, Natural Hazards and Risk 12 (1), 2835-2864. 10.1080/19475705.2021.1978562.

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). Geomorphology, 380, 107629.

Evangelista L. & Santucci de Magistris F. (2011). Upgrading the simplifed assessment of the liquefaction susceptivity for the city of Naples, Italy. 5th International Conference on Earthquake Geotechnical Engineering, January 2011, 10-13 Santiago, Chile.

Evans, S.G., Hungr, O. (1993). The assessment of rockfall hazard at the base of talus slopes. Can. Geotech J. 30 (4), 620–636.

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., & Savage, W. Z. (2008). Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. Engineering geology, 102(3-4), 85-98.

Fiaschi S., Fabris M., Floris M. & Achilli V. (2018). Estimation of land subsidence in deltaic areas through differential SAR interferometry: the Po River Delta case study (Northeast Italy). International Journal of Remote Sensing. 10.1080/01431161.2018.1490977.

Figueroa-Miranda S., Tuxpan-Vargas J., Ramos-Leal J.A., Hernández-Madrigal V.M. & Villaseñor-Reyes C.I. (2018). Land subsidence by groundwater over-exploitation from aquifers in tectonic valleys of Central

Mexico: A review. Engineering Geology, 246, 91-106, ISSN 0013-7952, https://doi.org/10.1016/j.enggeo.2018.09.023.

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.

Floris M., Fontana A., Tessari G. & Mulè M. (2019). Subsidence Zonation Through Satellite Interferometry in Coastal Plain Environments of NE Italy: A Possible Tool for Geological and Geomorphological Mapping in Urban Areas. Remote Sensing 11 (2), 165. https://doi.org/10.3390/rs11020165.

Frattini, P, Crosta, G.B., Carrara, A., Agliardi, F. (2008). Assessment of rockfall susceptibility by integrating statistical and physically-based approaches. Geomorphology 94 (3–4), 419–437.

Galeazzi C. (2013). The typological tree of artificial cavities: a contribution by the Commission of the Italian Speleological Society. Opera Ipogea, 1, 9-18.

Gargiulo F., d'Onofrio A. & Silvestri F. (2021). Approccio multi-livello per le verifiche a liquefazione: un'applicazione all'Isola di Ischia. Incontro Annuale dei Ricercatori di Geotecnica – IARG2021_online, 1-6.

Glade, T., Crozier, M.J. (2004). The nature of landslide hazard impact, in Landslide Hazard and Risk, eds T. Glade, M. Anderson, and M. J. Crozier (Hobken, NJ: John Wiley and Sons), pp. 43–74.

Glade, T., & Crozier, M. J. (2005). The nature of landslide hazard impact. Landslide hazard and risk, 41-74.

Glastonbury, J., & Fell, R. (2008). Geotechnical characteristics of large slow, very slow, and extremely slow landslides. Canadian Geotechnical Journal, 45(7), 984-1005.

Glueer, F., Loew, S., Manconi, A., Aaron, J. (2019). From toppling to sliding: progressive evolution of the Moosfluh Landslide, Switzerland. J. Geophys. Res. 124, 2899–2919. doi: 10.1029/2019JF005019.

Godt, J.W., Baum, R.L., Lu, N., (2009). Landsliding in partially saturated materials. Geophys. Res. Lett. 36, L02403. https://doi.org/10.1029/2008GL035996.

Grämiger, L.M., Moore, J.R., Vockenhuber, C., Aaron, J., Hajdas, I., Ivy-Ochs, S. (2016). Two early Holocene rock avalanches in the Bernese Alps (Rinderhorn. Switzerland). Geomorphology 268, 207–221. doi: 10.1016/j.geomorph.2016.06.008.

Grassi F., Mancini F., Bassoli E. & Vincenzi L. (2022). Contribution of anthropogenic consolidation processes to subsidence phenomena from multi-temporal DInSAR: a GIS-based approach. GIScience & Remote Sensing, 59 (1), 1901-1917. DOI: 10.1080/15481603.2022.2143683

Guarino P. M. & Nisio S. (2012). Anthropogenic sinkholes in the territory of the city of Naples (Southern Italy). Phys. Chem. Earth, parts A/B/C, 49, 92-102.

Guarino P. M., Santo A., Forte G., De Falco M. & Niceforo D. M. A. (2018). Analysis of a database for anthropogenic sinkhole triggering and zonation in the Naples hinterland (Southern Italy). Natural Hazards, 91, 173–192.

Gutierrez F., Parise M., De Waele J. & Jourde H. (2014). A review on natural and human-induced geohazards and impacts in karst. Earth Science Reviews, vol. 138, p. 61-88, doi: 10.1016/j.earscirev.2014.08.002.

Guzzetti, F., Ardizzone, F., Cardinali, M., Galli, M., Reichenbach, P., & Rossi, M. (2008). Distribution of landslides in the Upper Tiber River basin, central Italy. Geomorphology, 96(1-2), 105-122.

Highland, L. M., & Bobrowsky, P. (2008). The landslide handbook-A guide to understanding landslides (No. 1325). US Geological Survey.

Hoek, E., Bray, J.W. (1981). Rock slope engineering. Institution of Mining and Metallurgy, London.

Hungr, O., Evans, S.G. (2004). Entrainment of debris in rock avalanches: an analysis of a long run-out mechanism. Geol. Soc. Am. Bull. 116, 1240–1252. doi: 10.1130/B25362.1.

Hungr, O., Leroueil, S., Picarelli, L. (2014). The Varnes classification of landslide types, an update. Landslides 11, 167–194. doi: 10.1007/s10346-013-0436-y.

Hungr, O., Evans, S.G., Bovis, M.J., Hutchinson, J.N. (2001). A review of the classification of landslides of the flow type. Environ. Eng. Geosci. 7, 221–238.

Hürlimann, M., Rickenmann, D., Graf, C. (2003). Field and monitoring data of debris-flow events in the Swiss Alps. Can. Geotech. J. 40, 161–175.

Iovine G. & Parise M. (2008). I sinkholes in Calabria. Memorie Descrittive della Carta Geologica d'Italia, 85, 335-386.

Ishihara K. (1993). Liquefaction and flow failure during earthquakes. Geotechnique, 43(3), 351-451.

Ishihara K. & Koseki J. (1989). Cyclic shear strength of fines-containing sands. Proc. 12th International Conference Soil Mechanics, Rio de Janeiro, 101-106.

Iverson, R.M. (1997). The physics of debris flows. Rev. Geophys. 35, 245–296.

Iverson, R.M., Reid, M.E., LaHusen, R.G. (1997). Debris-flow mobilization from landslides. Annu. Rev. Earth Planet. Sci. 25, 85–138.

Iverson, R.M., Logan, M., LaHusen, R.G., Berti, M. (2010). The perfect debris flow? Aggregated results from 28 large-scale experiments. J. Geophys. Res. 115. https:// doi.org/10.1029/2009JF001514.

Jakob, M., Hungr, O. (2005). Debris-flow Hazards and Related Phenomena. Springer, Berlin pp.739.

Jones C.E., An K., Blom R.G., Kent J.D., Ivins E.R. & Bekaert D. (2016). Anthropogenic and Geologic Influences on Subsidence in the Vicinity of New Orleans, Louisiana. J. Geophys. Res. Solid Earth, 121, 3867–3887.

Kazuhiro K, Pokhrel RM, Takashi K. & Kazuo K. (2015). Liquefaction-induced ground subsidence extracted from Digital Surface Models and its application to hazard map of Urayasu city, Japan. Japanese Geotechnical Society Special Publication, 2 (22), 829-834. https://doi.org/10.3208/jgssp.TC203-02

Kean, J.W., McCoy, S.W., Tucker, G.E., Staley, D.M., Coe, J.A. (2013). Runoff-generated debris flows: observations and modeling of surge initiation, magnitude, and frequency.

Khakim M.Y.N., Tsuji T. & Matsuoka T. (2014). Lithology-controlled subsidence and seasonal aquifer response in the Bandung basin, Indonesia, observed by synthetic aperture radar interferometry. Int. J. Appl. Earth Obs. Geoinf., 32, 199-207. http://dx.doi.org/10.1016/j.jag.2014.04.012

Komac, M. (2006). A landslide susceptibility model using the analytical hierarchy process method and multivariate statistics in perialpine Slovenia. Geomorphology, 74(1-4), 17-28.

Koseki J., Wakamatsu K., Sawada S. & Matsushita K. (2015). Liquefaction-induced damage to houses and its countermeasures at Minami-Kurihashi in Kuki City during the 2011 Tohoku Earthquake, Japan. Soil Dynamics and Earthquake Engineering, 79, 391-400.

Kramer S. L. (1996). Geotechnical earthquake engineering. Prentice Hall, Upper Saddle River, NJ 07458.

Lacroix, P., Handwerger, A. L., & Bièvre, G. (2020). Life and death of slow-moving landslides. Nature Reviews Earth & Environment, 1(8), 404-419.

Leroueil, S. (2001). Natural slopes and cuts: movement and failure mechanisms. Géotechnique, 51(3), 197-243.

Licata V., d'Onofrio A., Silvestri F. (2018). Microstructural factors affecting the static and the cyclic resistance of a pyroclastic silty sand. Géotechnique, 68(5):434–441 (Technical note) doi:10.1680/jgeot.16.P.319

Lirer S., Chiaradonna A. & Mele L. (2020). Soil liquefaction: from mechanisms to effects on the built environment. Rivista Italiana di Geotecnica, 3, 2020.

Liso I.S. & Parise M. (2023). Sinkhole development at the freshwater-saltwater interface in Apulia (southern Italy). In: Land L., Kromhout C. & Suter S. (Eds.), Proceedings of the 17th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Tampa (Florida, USA), 27-31 March 2023**,** NCKRI Symposium no. 9**,** p. 229-238.

Lollino P. & Parise M. (2023). Sinkhole hazard quantitative assessment: Insights from the application of numerical modelling techniques. In: Land L., Kromhout C. & Suter S. (Eds.), Proceedings of the 17th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Tampa (Florida, USA), 27-31 March 2023**,** NCKRI Symposium no. 9, p. 141-150.

Lu, P., Catani, F., Tofani, V., & Casagli, N. (2014). Quantitative hazard and risk assessment for slow-moving landslides from Persistent Scatterer Interferometry. Landslides, 11, 685-696.

Ma T., Du Y., Ma R. et al. (2018). Review: Water–rock interactions and related eco-environmental effects in typical land subsidence zones of China. Hydrogeology Journal, 26, 1339–1349. https://doi.org/10.1007/s10040-017-1708-8

Magliulo, P., Di Lisio, A., Russo, F., & Zelano, A. (2008). Geomorphology and landslide susceptibility assessment using GIS and bivariate statistics: a case study in southern Italy. Natural hazards, 47, 411-435.

Manzo, G., Tofani, V., Segoni, S., Battistini, A., & Catani, F. (2013). GIS techniques for regional-scale landslide susceptibility assessment: the Sicily (Italy) case study. International Journal of Geographical Information Science, 27(7), 1433-1452.

Margiotta S., Marini G., Fay S., D'Onghia F.M., Liso I.S., Parise M. & Pinna M. (2021). Hydro-stratigraphic conditions and human activity leading to development of a sinkhole cluster in a Mediterranean water ecosystem. Hydrology, 8, 111. https://doi.org/10.3390/hydrology8030111.

Martinello, C., Cappadonia, C., Conoscenti, C., Agnesi, V., & Rotigliano, E. (2021). Optimal slope units partitioning in landslide susceptibility mapping. Journal of Maps, 17(3), 152-162.

Martinello, C., Cappadonia, C., Conoscenti, C., & Rotigliano, E. (2022). Landform classification: a high-performing mapping unit partitioning tool for landslide susceptibility assessment—a test in the Imera River basin (northern Sicily, Italy). Landslides, 1-15.

Martinotti, G., Giordan, D., Giardino, M., & Ratto, S. (2011). Controlling factors for deep-seated gravitational slope deformation (DSGSD) in the Aosta Valley (NW Alps, Italy). Geological Society, London, Special Publications, 351(1), 113-131.

McColl, S. T. (2022). Landslide causes and triggers. In Landslide hazards, risks, and disasters (pp. 13-41). Elsevier.

McGrath A.G. & Davison I. (1995). Damage zone geometry around fault tips. J. Struct. Geol. 17, 1011–1024.

Meisina, C. (2006). Characterisation of weathered clayey soils responsible for shallow landslides. Natural Hazards and Earth System Sciences, 6(5), 825-838.

Mele L., Tian J. T., Lirer S., Flora A. & Koseki J. (2019). Liquefaction resistance of unsaturated sands: experimental evidence and theoretical interpretation. Géotechnique, 69(6), 541-553.

Mele L., Lirer S., & Flora A. (2020). The effect of densification on Pieve di Cento sands in cyclic simple shear tests. In Geotechnical Research for Land Protection and Development: Proceedings CNRIG 2019 7, Springer International Publishing, pp. 446-453.

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.

Meusburger, K., & Alewell, C. (2009). On the influence of temporal change on the validity of landslide susceptibility maps. Natural Hazards and Earth System Sciences, 9(4), 1495-1507.

Michoud, C., Derron, M.-H., Horton, P., Jaboyedoff, M., Baillifard, F.-J., Loye, A., Nicolet, P., Pedrazzini, A., Queyrel, A. (2012). Rockfall hazard and risk assessments along roads at a regional scale: example in Swiss Alps. Natural Hazards and Earth System Science 12 (3), 615–629.

Modoni G., Darini G., Spacagna R.L., Saroli M., Russo G. & Croce P. (2013). Spatial analysis of land subsidence induced by groundwater withdrawal. Engineering Geology 167, 59-71. https://doi.org/10.1016/j.enggeo.2013.10.014.

Montrasio, L. (2000). Stability analysis of soil-slip. WIT transactions on ecology and the environment, 45.

Morelli, S., Pazzi, V., Frodella, W., & Fanti, R. (2018). Kinematic reconstruction of a deep-seated gravitational slope deformation by geomorphic analyses. Geosciences, 8(1), 26.

Nagelisen, J., Moore, J.R., Vockenhuber, C., Ivy-Ochs, S. (2015). Post-glacial rock avalanches in the Obersee Valley. Glarner Alps, Switzerland. Geomorphology 238, 94–111. doi: 10.1016/j.geomorph.2015.02.031.

Novellino, A., Cesarano, M., Cappelletti, P., Di Martire, D., Di Napoli, M., Ramondini, M., ... & Calcaterra, D. (2021). Slow-moving landslide risk assessment combining Machine Learning and InSAR techniques. Catena, 203, 105317.

Ozturk, U., Pittore, M., Behling, R., Roessner, S., Andreani, L., & Korup, O. (2021). How robust are landslide susceptibility estimates?. Landslides, 18, 681-695.

Pánek, T., & Klimeš, J. (2016). Temporal behavior of deep-seated gravitational slope deformations: A review. Earth-Science Reviews, 156, 14-38.

Parise M. (2019). Sinkholes. In: White W.B., Culver D.C. & Pipan T. (Eds.), Encyclopedia of Caves. Academic Press, Elsevier, 3rd edition, ISBN ISBN 978-0-12-814124-3, p. 934-942.

Parise M. (2022). Sinkholes, Subsidence and Related Mass Movements. In: Shroder J.J.F. (Ed.), Treatise on Geomorphology, vol. 5. Elsevier, Academic Press, pp. 200–220. https://dx.doi.org/10.1016/B978-0-12-818234- 5.00029-8. ISBN: 9780128182345.

Parise M. & Vennari C. (2016) Distribution and features of natural and anthropogenic sinkholes in Apulia. In: Renard P. & Bertrand C. (Eds.) Eurokarst 2016, Neuchâtel. Advances in Karst Science, Springer, ISBN 978-3-319-45464-1, doi: 10.1007/978-3-319-45465-8_3.

Parise M., Galeazzi C., Bixio R., Dixon M. (2013). Classification of artificial cavities: a first contribution by the UIS Commission. In: Filippi M. & Bosak P. (Eds.), Proc. 16th Int. Congr. Speleology, Brno, 21-28 July 2013, 2, pp. 230-235.

Pellicani, R., Frattini, P., & Spilotro, G. (2014). Landslide susceptibility assessment in Apulian Southern Apennine: heuristic vs. statistical methods. Environmental earth sciences, 72, 1097-1108.

Pepe P., Pentimone N., Garziano G., Martimucci V. & Parise M. (2013). Lessons learned from occurrence of sinkholes related to man-made cavities in a town of southern Italy. In: Land L., Doctor D.H. & Stephenson

B. (Eds.), Proceedings of the 13th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Carlsbad (New Mexico, USA), 6-10 May 2013, National Cave and Karst Research Institute, p. 393-401.

Perrotti M., Lollino P., Fazio N.L., Pisano L., Vessia G., Parise M., Fiore A. & Luisi M. (2018). Finite Element–based stability charts for underground cavities in soft calcarenites. ASCE International Journal of Geomechanics, 18 (7), 04018071.

Perrotti M., Lollino P., Fazio N.L. & Parise M. (2019). Stability charts based on the finite element method for underground cavities in soft carbonate rocks: validation through case-study applications. Natural Hazards and Earth System Sciences, 19, 2079-2095.

Persichillo, M. G., Bordoni, M., Meisina, C., Bartelletti, C., Barsanti, M., Giannecchini, R., ... & Galve, J. P. (2017). Shallow landslides susceptibility assessment in different environments. Geomatics, Natural Hazards and Risk, 8(2), 748-771.

Piacentini, D., Devoto, S., Mantovani, M., Pasuto, A., Prampolini, M., & Soldati, M. (2015). Landslide susceptibility modeling assisted by Persistent Scatterers Interferometry (PSI): An example from the northwestern coast of Malta. Natural Hazards, 78, 681-697.

Pinto, F., Guerriero, L., Revellino, P., Grelle, G., Senatore, M. R., & Guadagno, F. M. (2016). Structural and lithostratigraphic controls of earth-flow evolution, Montaguto earth flow, Southern Italy. Journal of the Geological Society, 173(4), 649-665.

Richer, B., Saeidi, A., Boivin, M., & Rouleau, A. (2020). Overview of retrogressive landslide risk analysis in sensitive clay slope. Geosciences, 10(8), 279.

Rickenmann, D., (1999). Empirical relationships for debris flows. Nat. Hazards 19 (1), 47–77.

Ronchi L., Fontana A., Cohen K.M. & Stouthamer E. (2021). Late Quaternary landscape evolution of the buried incised valley of Concordia Sagittaria (Tagliamento River, NE Italy): A reconstruction of incision and transgression. Geomorphology 373, 107509. https://doi.org/10.1016/j.geomorph.2020.107509.

Rosi A., Tofani V., Agostini A., Tanteri L., Tacconi Stefanelli C., Catani F. & Casagli N. (2016). Subsidence mapping at regional scale using persistent scatters interferometry (PSI): the case of Tuscany region (Italy). International Journal of Applied Earth Observation and Geoinformation 52, 328-337. https://doi.org/10.1016/j.jag.2016.07.003.

Rosi, A., Tofani, V., Tanteri, L., Tacconi Stefanelli, C., Agostini, A., Catani, F., & Casagli, N. (2018). The new landslide inventory of Tuscany (Italy) updated with PS-InSAR: geomorphological features and landslide distribution. Landslides, 15, 5-19.

Ruff, M., & Czurda, K. (2008). Landslide susceptibility analysis with a heuristic approach in the Eastern Alps (Vorarlberg, Austria). Geomorphology, 94(3-4), 314-324.

Samia, J., Temme, A., Bregt, A., Wallinga, J., Guzzetti, F., Ardizzone, F., & Rossi, M. (2017). Characterization and quantification of path dependency in landslide susceptibility. Geomorphology, 292, 16-24.

Santucci de Magistris F. (2005). Liquefaction. Geotechnical aspects of the design in seismic areas. Italian Geotechnical Association (AGI), Patron (Eds.), pp. 99–108 (in Italian).

Santucci de Magistris F. (2006). Liquefaction: a contribution to the Eurocode from the Italian Guideline, Geotechnical Aspects of the Design in Seismic Areas. ISSMGE ETC-12 workshop, NTUA Athens, Greece, 2006.

Santucci de Magistris F. (2011). Beyond EC8: the New Italian Seismic Code. Geofizika, 28, 65–82 (http://geofizika-journal.gfz.hr/vol_28/No1/28_1_santucci.pdf)

Santucci de Magistris F., Lanzano G., Forte G. & Fabbrocino G. (2013). A database for PGA threshold in liquefaction occurrence. Soil Dynamics and Earthquake Engineering 54, 17-19 https://doi.org/10.1016/j.soildyn.2013.07.011.

Santucci de Magistris F., Lanzano G., Forte G., & Fabbrocino G. (2014). A peak acceleration threshold for soil liquefaction: lessons learned from the 2012 Emilia earthquake (Italy). Natural Hazards, 74, 1069-1094.

Sasaki Y. (2009). River dike failures during the 1993 Kushiro-oki earthquake and the 2003 Tokachi-oki earthquake. In: Earthquake Geotechnical Case Histories for Performance-based Design, pp. 131–157.

Savage, W.Z., Baum, R.L. (2005). Instability of steep slopes. In: Jakob, M., Hungr, O. (Eds.), Debris-Flow Hazards and Related Phenomena. Springer, pp. 53–79.

Scardino G., Sabatier F., Scicchitano G., Piscitelli A., Milella M., Vecchio A., Anzidei M. & Mastronuzzi G. (2020). Sea-Level Rise and Shoreline Changes Along an Open Sandy Coast: Case Study of Gulf of Taranto, Italy. Water 12 (5), 1414. https://doi.org/10.3390/w12051414.

Scardino G., Anzidei M., Petio P., Serpelloni E., De Santis V., Rizzo A., Liso S.I., Zingaro M., Capolongo D., Vecchio A., et al. (2022). The Impact of Future Sea-Level Rise on Low-Lying Subsiding Coasts: a case study of Tavoliere delle Puglie (Southern Italy). Remote Sensing 14, 4936. https://doi.org/10.3390/rs14194936.

Schädler, W. (2011). Slope movements of the earthflow type-engineering-geological investigation, geotechnical assessment and modelling of the source areas on the basis of case studies from the Alps and Apennines. Logos Verlag Berlin GmbH.

Scotto di Santo A., Forte G. & Santo A. (2018). Analysis of sinkhole triggering mechanisms in the hinterland of Naples (southern Italy). Engineering Geology 237, 42-52. https://doi.org/10.1016/j.enggeo.2018.02.014.

Sidle, R. C. (1985). Factors influencing the stability of slopes. In Proceedings of the workshop on slope stability: problems and solutions in forest management. Gen. Tech. Rep. PNW-180. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station (pp. 17-25).

Sowers G.F. (1976). Mechanism of subsidence due to underground openings. In: Subsidence over mines and caverns, moisture and frost actions, and classification. National Academy of Sciences, Washington, D.C. (ed.). 612, pp 1-8. ISSN: 0361-1981.

Spalluto, L., Fiore, A., Miccoli, M. N., & Parise, M. (2021). Activity maps of multi-source mudslides from the Daunia Apennines (Apulia, southern Italy). Natural Hazards, 106(1), 277-301.

Taalab, K., Cheng, T., & Zhang, Y. (2018). Mapping landslide susceptibility and types using Random Forest. Big Earth Data, 2(2), 159-178.

Takahashi, T. (2019). Debris Flow: Mechanics, Prediction and Countermeasures, 2nd edition. CRC Press, Balkema.

Teatini P., L. Tosi & Strozzi T. (2011). Quantitative evidence that compaction of Holocene sediments drives thepresent land subsidence of the Po Delta, Italy. J. Geophys. Res. 116, B08407. doi:10.1029/2010JB008122.

Terwilliger, V.J., & Waldron, L.J. (1991). Effects of root reinforcement on soil-slip patterns in the Transverse Ranges of southern California. Geological Society of America Bulletin, 103(6), 775-785.

Thongprapha T., Fuenkajorn K. & Daemen J.J.K. (2015). Study of surface subsidence above an underground opening using a trap door apparatus. Tunnelling and Underground Space Technology, 46, 94-103. https://doi.org/10.1016/j.tust.2014.11.007.

Tobler, D., Kull, I., Jacquemart, M., Haehlen, N. (2014). Hazard management in a debris flow affected area: case study from Spreitgraben, Switzerland. World Landslide Forum 3. pp. 25–30.

Topal, T., Akin, M., Ozden, A.U. (2007). Assessment of rockfall hazard around Afyon Castle. Environ Geol 53 (1), 191–200.

Tomás, R., Abellán, A., Cano, M., Riquelme, A., Tenza-Abril, A.J., Baeza-Brotons, F., ... & Jaboyedoff, M. (2018). A multidisciplinary approach for the investigation of a rock spreading on an urban slope. Landslides, 15, 199-217.

Tonni L., Gottardi G., Amoroso S., Bardotti R., Bonzi L., Chiaradonna A., d'Onofrio A., Fioravante V., Ghinelli A., Giretti D., Lanzo G., Madiai C., Marchi M., Martelli L., Monaco P., Porcino D., Razzano R., Rosselli S., Severi P., Silvestri F., Simeoni L., Vannucchi G., Aversa S. (2015). Analisi dei fenomeni deformativi indotti dalla sequenza sismica emiliana del 2012 su un tratto di argine del Canale Diversivo di Burana (FE). Rivista Italiana di Geotecnica, 49, 28-58.

Trigila, A., Frattini, P., Casagli, N., Catani, F., Crosta, G., Esposito, C., ... & Lari, S. (2013). Landslide susceptibility mapping at national scale: the Italian case study. Landslide Science and Practice: Volume 1: Landslide Inventory and Susceptibility and Hazard Zoning, 287-295.

Tufano R., Guerriero L., Corona M. A., Bausilio G., Di Martire D., Nisio S., Calcaterra D. (2022). Anthropogenic sinkholes of the city of Naples, Italy: an update. Natural Hazards, 1-32.

Vannucchi G., Crespellani T., Facciorusso J., Ghinelli A., Madiai C., Puliti A. & Renzi S. (2012). Soil liquefaction phenomena observed in recent seismic events in Emilia-Romagna Region, Italy. Ingegneria sismica, 2016 (3), 20-30.

Vázquez, R., Capra, L., Coviello, V. (2016). Factors controlling erosion/deposition phenomena related to lahars at Volcán de Colima, Mexico. Nat. Hazards Earth Syst. Sci. 16, 1881–1895.

Vennari C. & Parise M. (2022). A chronological database about natural and anthropogenic sinkholes in Italy. Geosciences, vol. 12, 200, https://doi.org/10.3390/geosciences12050200.

Vennari C., Salvati P., Bianchi C., Casarano D., Parise M., Basso A. & Marchesini I. (2022). AReGeoDatHa: Apulian Regional GeoDatabase for geo-hydrological Hazards. Journal of Environmental Management 322, 116051. https://doi.org/10.1016/j.jenvman.2022.116051.

Vigliotti M. & Ruberti D. (2018). Campania Grey Tuff and Anthropogenic Tuff Cavities in the Southern Metropolitan Area of Caserta (Southern Italy). Alp. Mediterr. Quat., 31, 247–251.

Volken, S. (2015). The Flims Rockslide: A New Perspective on Failure Mechanisms and Kinematics. MSc Thesis, ETH Zurich, Zurich.

Vucetic M. (1994). Cyclic threshold shear strains in soils. J Geotech. Geoenviron. Eng., ASCE, 120–12, 2208–2227.

Wang, X.L., Zhang, L.Q., Wang, S.J., Agliardi, F., Frattini, P., Crosta, G.B., Yang, Z.F. (2012). Field investigation and rockfall hazard zonation at the Shjing Mountains Sutra caves cultural heritage (China). Environmental Earth Sciences 66, 1897–1908.

Wang, X.L., Frattini, P., Crosta, G.B., Zhang, L.Q., Agliardi, F., Lari, S., Yang, Z.F. (2014). Uncertainty assessment in quantitative rockfall risk assessment. Landslides 11 (4),711–722.

Wieczorek, G.F., Glade, T. (2005). Climatic factors influencing occurrence of debris flow. In: Jakob, M., Hungr, O. (Eds.), Debris-Flow Hazards and Related Phenomena. Springer, Berlin, pp. 325–362.

Wilford, D.J., Sakals, M.E., Innes, J.L., Sidle, R.C., Bergerud, W.A. (2004). Recognition of debris flow, debris flood and flood hazard through watershed morphometrics. Landslides 1, 61–66.

Wolter, A., Gischig, V., Stead, D., Clague, J. J. (2016). Investigation of geomorphic and seismic effects on the 1959 Madison Canyon, Montana, landslide using an integrated field, engineering geomorphology mapping, and numerical modelling approach. Rock Mech. Rock Eng. 49, 2479–2501. doi: 10.1007/s00603-015-0889-5.

Zhou C., Gong H., Chen B., Gao M., Cao Q., Cao J., Duan L., Zuo J. & Shi M. (2020). Land Subsidence Response to Different Land Use Types and Water Resource Utilization in Beijing-Tianjin-Hebei, China. Remote Sensing, 12, 457. https://doi.org/10.3390/rs12030457.

SECTION B – OFFSHORE AREAS

8) Introduction

In previous deliverables (DV2.2.1 and DV2.2.2), it emerged as critical point the small number of Learning Examples (Les) dedicated to submarine landslides presented in the dataset. The underrepresentation of marine and underwater Les did not allow for the definition of a comprehensive Rationale for submarine landslides and for the related individuation of their predisposing factors.

For this reason, the purpose of this section is to address and fill this gap about the ground instability in the submerged environment. This specific analysis dedicated to the submarine phenomena, can be considered as a sort of "parallel" TK and has been coordinated by Francesco Chiocci (UNIROMA1), as **TK1** leader, and managed by RTDA and researchers from UNIROMA. Anyway, the work that will be here reported derive from numerous discussion that involved the small community of marine geologist involved in this project that belongs, besides UNIROMA, to UNIPA and OGS.

This report summarized the scientific research activities about **submarine gravitational instability** carried out in the period **October – November 2023** with the aim to produce a comprehensive work about submarine ground instability within the **Task 2.2.1** "*Identification of areas at different scales affected or predisposed to ground instabilities, either in the subaerial (a) and submerged (b) environment by existing inventories and archives –implemented and updated by EO services – and permanent and temporary geophysical observatories (dynamic mapping)"* (hereinafter referred to as **TK1**) of the **Work Package 2.2** "*State of the art and knowledge base to define impact-oriented hazard indicators*" (hereinafter referred to as **WP2**), inside the vertical spoke **VS2** "*Ground Instabilities"* of the Extended Partnership RETURN.

It should be noted that VS2 structured WP2, WP3 and WP4 by identifying the following areas of interest for each of them:

- WP2 focuses on the detection and analysis of **PREDISPOSING** factors to ground instabilities.
- WP3 targets **PREPARATORY** factors to ground instabilities.
- WP4 is centred on **TRIGGERING** and multiple geohazards cascading scenarios (**MULTI-HAZARD**).

In accordance with the definitions given within the VS2, the distinction between predisposing, preparatory and triggering factors/processes is made on a temporal basis: in fact, it means that the predisposing factors are considered invariable on the observation scale, while the preparatory factors show changes or cyclical trends during the same period. As a consequence, a trigger is considered as a process that acts in a very short and well-defined time.

The activities of **WP2** were directed in the reference period to the examination of the factors predisposing the ground instabilities, starting from a series of case studies (defined Learning Examples, LEs) which represent experiences that each partner has carried out in recent times and which include cutting-edge analyses in the theme of characterization of predisposing factors and in the spatial and temporal quantification of susceptibility.

The partner involved in the WP2 are ENEA, OGS, POLITO, UNIBA, UNIBO, UNIFI, UNIGE, UNINA, UNIPA, UNIPD and UNIROMA1. WP2 leaders are Riccardo Fanti (UNIFI) e Mario Parise (UNIBA), TK1 leader is Francesco Maria Chiocci (UNIROMA1), TK2 leader is Mario Parise (UNIBA), TK3 leader is Matteo Berti (UNIBO). 72 researchers participate in the activities of **WP2/TK1** (i.e. **TK 2.2.1**): 5 from ENEA, 3 from OGS, 6 from POLITO, 5 from UNIBA, 6 from UNIBO, 7 from UNIFI, 7 from UNIGE, 8 from UNINA, 13 from UNIPA, 8 from UNIPD and 4 from UNIROMA1.

The goal of **TK1** (Identification of areas at different scales affected or predisposed to ground instabilities, either in the subaerial (a) and **submerged environment** (b) by existing inventories and archives – implemented and updated by EO services – and permanent and temporary geophysical observatories (dynamic mapping)) and the issue of **DV 2.2.1** (Collection of inventoried events in a comprehensive integrated dataset) have been interpreted in the framework of the LEs collection. They therefore represent the "comprehensive integrated dataset" of the Deliverable and this section of the document focuses on this.

According with the main idea of the Project and of **VS2**, the learning phase had the objective of building a Rationale for preparatory processes to be used as input to the Proof of Concept (PoC). This phase has been articulated in three stages:

i) Inventory of Learning Examples (LE).
ii) Individuation of the preparatory processes analysed in each LE.
iii) Definition of a Rationale for each process, based upon the available LEs.

9) Inventory of Learning Examples (LEs)

During the first months of the project (***January – March 2023***) each partner of the Spoke carried out an internal review of its past and recent research works, with the aim of selecting the most complete case studies that allow to extract learning and principles that could be extended to other contexts. These case studies, defined "Learning Examples" (LEs), have subjects that could be focused on i) the detection and analysis of PREDISPOSING factors to ground instabilities (WP2), ii) PREPARATORY factors to ground instabilities (WP3), iii) TRIGGERING and multiple geohazards cascading scenarios. This first phase of LEs selection from the project partners is addressed as **"first call"**.

After the first call and the elaboration of the DV 2.2.1 and 2.2.2 some critical point emerged, not only in those regarding the submarine environment, and for this reason an ***Internal recall*** for other LEs was proposed. This second phase of LEs selection is addressed as "**recall**". The ***recall*** for LEs devoted to this analysis occurred from **October to November 2023** with the possibility of LEs selection also from the international bibliographic data.

For each LE, some scientific papers were stored in a repository (Windows Teams) accessible to all the institutions, in order to provide the reference for the contents of the works. The list of papers collected for WP2 is reported in Section 5.

Once the papers database has been populated, each LE has been inserted in an online inventory (one for each WPs), represented by a shared online table file. This table constituted a synoptic view of the research works, for which several information was provided by the authors of the LEs, including:

- The name/denomination of the LE (site name and/or geographical location or area of interest);
- The environment (subaerial/submerged);
- The context (mountain/hill/plain/coast/near-shore);
- The effect (landslide/subsidence/sinkhole/liquefaction);
- The scale (local/intermediate/regional);
- The analysis tools and techniques (on site monitoring/remote monitoring/deterministic analysis/statistical analysis/machine learning).

Institution	LE name	CALL		Env		Context					Effect				Scale			Tools				
		1	***2***	***A***	***W***	***M***	***H***	***P***	***C***	***NS***	***LS***	***SU***	***SI***	***LI***	***L***	***I***	***R***	***RS***	***OS***	***D***	***S***	***ML***
OGS	***Canyon Squillace (OGS_SL_1)***	X			X					X	X				X				X			
	Frana di Assi (OGS_SL_2)	X			X					X	X				X				X			X
	Canyon Cirò (OGS_SL_3)		X		X					X	X				X				X			
	Squillace gravitational complex (OGS_SL_4)		X		X					X	X				X				X			
	Crotone megaslide (OGS_SL_5)		X	X	X				X	X	X					X			X			
UNIPA	***Canyon di Palermo (PA_SL_1)***	X			X					X	X				X				X			
	Canyon di Gioiosa Marea (PA_SL_2)		X		X					X	X				X				X			
UNIROMA 1	***Canyon di Gioia (SA_SL_1)***	X			X					X	X				X				X			X
	Frana di Stromboli (with UNIBO)	X			X				X	X	X				X			X	X			X

	(SA_BO_SL_ 2)																					
	MAGIC ***(SA_SL_3)***	X			X					X	X						X		X			
	Canyon di Scaletta ***(SA_SL_4)***		X		X					X	X				X				X			
	Canyon di Var ***(SA_SL_5)***		X		X					X	X				X				X	X		X
	Etna ***(SA_SL_6)***	X	X	X	X				X	X	X					X		X	X			
	Frana di Tianjin ***(SA_SL_7)***		X		X					X	X				X				X			

Table 1*. Inventory of LEs concerning the* ***submarine environment*** *for WP2. CALL: phase of LEs selection (1-first call; 2-recall); Env: environment (A - subaerial; W - underwater). Context: M – mountain; H – hill; P – plain; C – coast; NS – near-shore. Effect: LS – landslide; SU – subsidence; SI – sinkhole; LI – liquefaction. Scale: L – local; I – intermediate; R – regional. Learning Tools: RS - remote sensing monitoring; OS – onsite monitoring; D - deterministic analysis; S – statistical analysis; ML – Machine Learning.*

The table for WP2 LEs is summarized in Table 1. During the first call, 6 LEs concerning submarine landslides were presented (1 from UNIPA, 3 from UNIROMA, 2 from OGS) that during the recall were integrated with other 7 LEs (3 from OGS, 1 from UNIPA and 4 from UNIROMA) (Table 1). The LEs selected for the WP2 are geolocalized in the map of Figure 1.

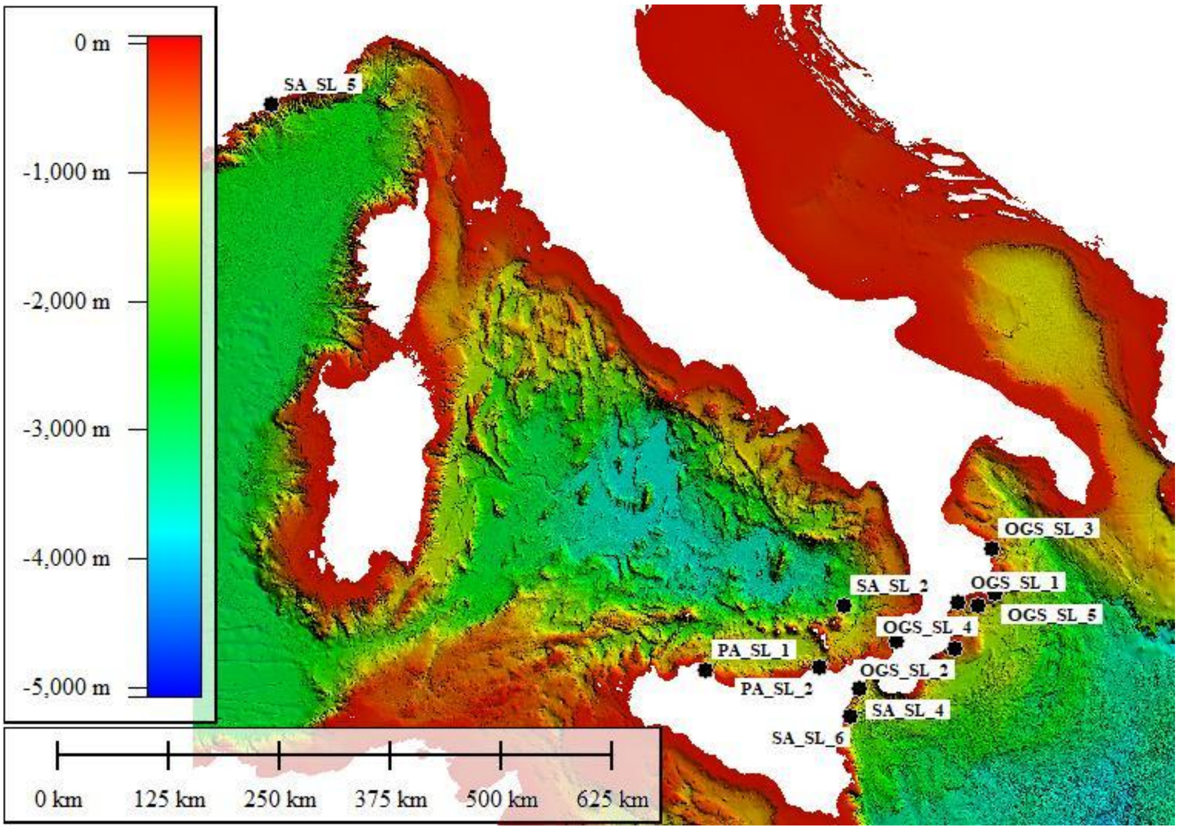

Figure 1. *Location of LEs inventoried for WP2.*

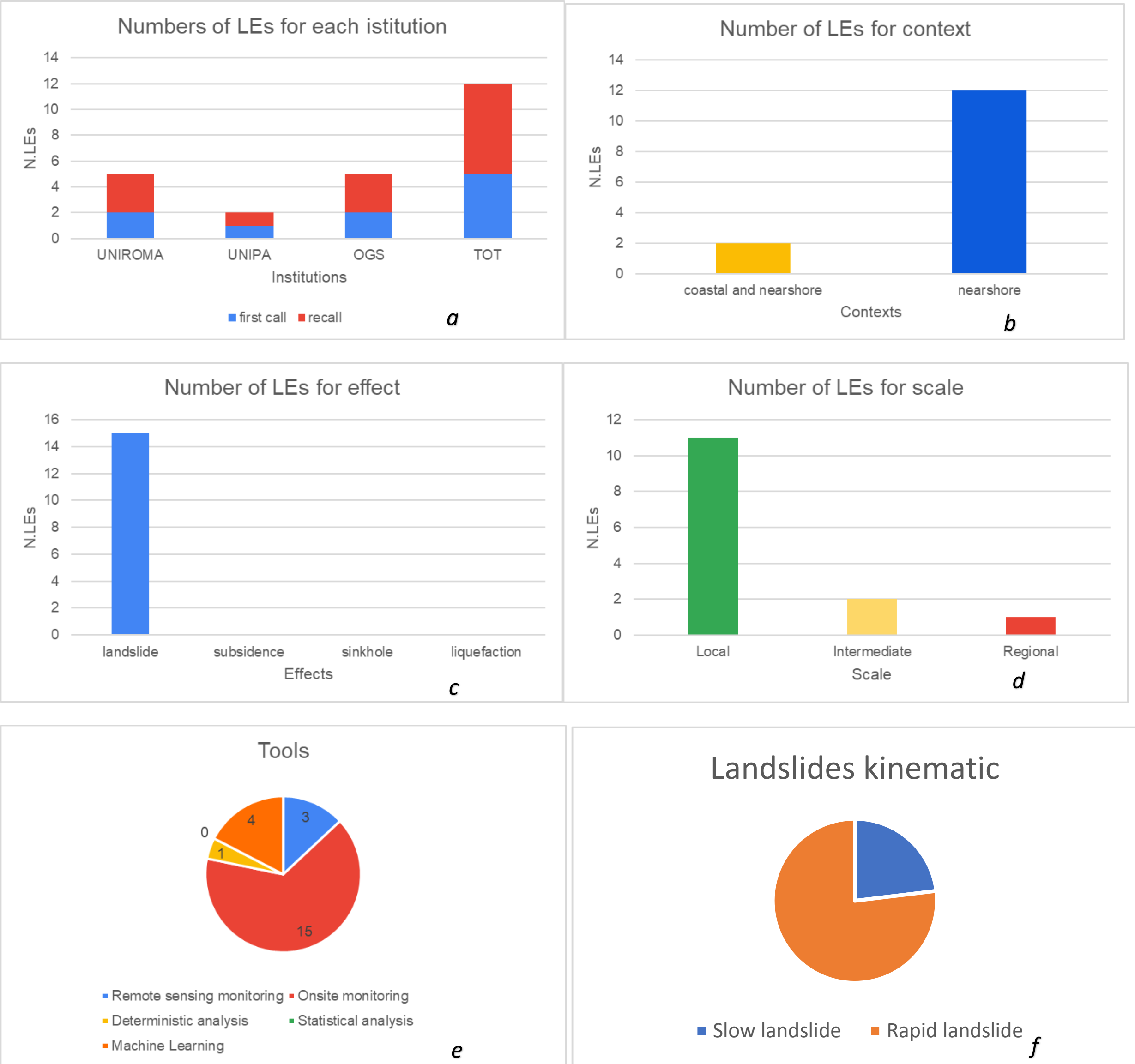

Figure 2. *Distribution of WP2 LE2 as a function of (a) Number of LEs for each institution as a function of the first call and recall. (b) Context: C – coast; NS – near-shore. (c) Effect: LS – landslide; SU – subsidence; SI – sinkhole; LI – liquefaction. (d) Scale : L – local ; I – intermediate ; R – regional, (e) Tool; (e) Landslide kinematics: Rapid vs Slow.*

10) Learning Examples (LEs) vs Predisposing Factors

After the first phase of the project, during which the LEs more suitable to describe the Predisposing Factors/Process for various instability phenomena were identified, each Partner was asked to translate the chosen examples in a more specific way providing more detailed information on the phenomenon and on the factors characterizing it. For each LE the WP2 leaders and TK leaders collected from all partners a single form whose attributes, described in the previous phase in a synthetic way with a checkbox, were filled in with in-depth descriptions (as shown in Table 1**Errore. L'origine riferimento non è stata trovata.**) to be shared among all partners in a collective online repository. In particular, these forms summarize the research work following a shared attribute scheme which includes:

1) The Partner proposing the LE (Institution);
2) The LE identification name (LE ID)
3) Site name and/or geographical location or area of interest of the LE (LE);
4) The Scale (local/intermediate/regional);
5) The Effect (landslide/subsidence/sinkhole/liquefaction);
6) The Considered Predisposing Factors (the environmental variables that have been considered in the learning example as predisposing factors);
7) The Macro-predisposing Factors (a generalization of the predisposing factors)

The LEs forms have been checked by WP2 leaders and TK leaders with the aim of verify the suitable assignment of each LE to the analysed predisposing factors/processes.

At the end of this stage, the “matrix inversion” was performed. The focus of the analysis was turned to the Factors/Processes (instead of the single LEs) quantified through the outputs of the related LEs. All the collected forms, once checked, have been combined in a single synoptic shared table to allow for an overall view of the LEs and Factors/Processes. An extract of four significant cases from the LEs inventory is shown in **Errore. L'origine riferimento non è stata trovata.**.

Then, during this control phase, WP2 leaders and TK leaders with continuous exchanges and interactions with the proposing institutions grouped the proposed predisposing factors by macro-area of afference (Macro-Factors) with the aim of starting a homogenization of the factors in order to be able to compare them between different LEs.

The Macro-categories selected for submarine ground instabilities are:

- Geology
- Geomorphology
- Seismotectonics/Volcanism
- Physical and mechanical Properties
- Groundwater/Fluid
- Erosion/Deposition

Institution	LE ID	LE	Scale	Effect	Considered predisposing factors	Macro-predisposing factors
OGS	OGS_SL_1	Squillace canyon	Local	Rapid landslide	• Seismic activity/Vertical movement • Presence of pressurized gas • Slope morphology/Topography • Hyperpicnal flow and drainage basin character • Sedimentation rate • Wave action	• Geology • Geomorphology •Seismotectonics/Volcanism • Groundwater/Fluid • Erosion/Deposition
	OGS_SL_2	Assi landslide	Local	Rapid landslide	• Seismic activity/Vertical movement • Slope morphology/Topography	• Geomorphology •Seismotectonics/Volcanism
	OGS_SL_3	Cirò canyon	Local	Rapid landslide	• Seismic activity/Vertical movement • Presence of pressurized gas • Slope morphology/Topography • Channelized Erosion • Wave action	• Geomorphology •Seismotectonics/Volcanism • Groundwater/Fluid • Erosion/Deposition
	OGS_SL_4	Squillace complex	Local	Slow landslide	• Seismic activity/Vertical movement • Slope morphology/Topography	• Geomorphology •Seismotectonics/Volcanism
	OGS_SL_5	Crotone megaslide	Intermediate	Slow landslide	• Seismic activity/Vertical movement • Slope morphology/Topography	• Geomorphology •Seismotectonics/Volcanism
	PA_SL_1	Palermo gulf	Local	Rapid landslide	• Presence of pressurized gas • Slope morphology/Topography • Seismic activity/Vertical movement	• Geomorphology •Seismotectonics/Volcanism • Groundwater/Fluid

	PA_SL_2	Gioiosa Marea canyon	Local	Rapid landslide	• Slope morphology/topography • Seismic activity/Vertical movement • Hyperpicnal flow and drainage basin character • Sedimentation rate • Littoral transport • Wave action	• Geology • Geomorphology • Physical and mechanical properties •Seismotectonics/Volcanism • Erosion/Deposition
UNIROMA	SA_SL_1	Gioia canyon	Local	Rapid landslide	• Slope morphology/topography • Faulting System/Distance to faults • Progradational stacking pattern • Sedimentation rate • Littoral transport • Wave action	• Geology • Geomorphology •Seismotectonics/Volcanism • Erosion/Deposition
	SA_SL_2	Stromboli	Local	Rapid landslide	• Lithology • Volcanic activity • Slope morphology/topography • Weak layer	• Geology • Geomorphology •Seismotectonics/Volcanism
	SA_SL_3	MAGIC	Regional	Rapid/Slow landslide	• Seismic activity/Vertical movement • Stratigraphic features • Structural features • Presence of pressurized gas • Undercutting • Previous events • Slope morphology/Topography • Hyperpicnal flow and drainage basin character • Sedimentation rate • Channel erosion • Littoral transport • Wave action	• Geology • Geomorphology •Seismotectonics/Volcanism • Groundwater/Fluid • Erosion/Deposition
	SA_SL_4	Scaletta canyon	Local	Rapid landslide	• Seismic activity/Vertical movement • Slope morphology/topography • Hyperpicnal flow and drainage basin character • Sedimentation rate • Littoral transport • Wave action	• Geology • Geomorphology •Seismotectonics/Volcanism • Erosion/Deposition

	SA_SL_ 5	Var canyon	Local	Rapid landslide	• Lithology • Slope morphology/topography • Weak layer • Presence of pressurized fluid • Shear strenght • Hydraulic properties	• Geology • Geomorphology • Physical and mechanical properties •Seismotectonics/Volcanism • Groundwater/Fluid
	SA_SL_ 6	Etna	Intermediate	Slow landslide	• Seismic activity/Vertical movement • Slope morphology/Topography	• Geomorphology •Seismotectonics/Volcanism
	SA_SL_ 7	Tianjin	Local	Slow landslide	• Lithology • Slope morphology/topography • Shear strenght • Hydraulic properties	• Geology • Geomorphology • Physical and mechanical properties • Erosion/Deposition

Table 1. Extract of four cases from the inventory of LEs and the Predisposing Factors/Process for WP2. The green fields represent the Macro-Predisposing Factors/Processes summarized by those Considered.

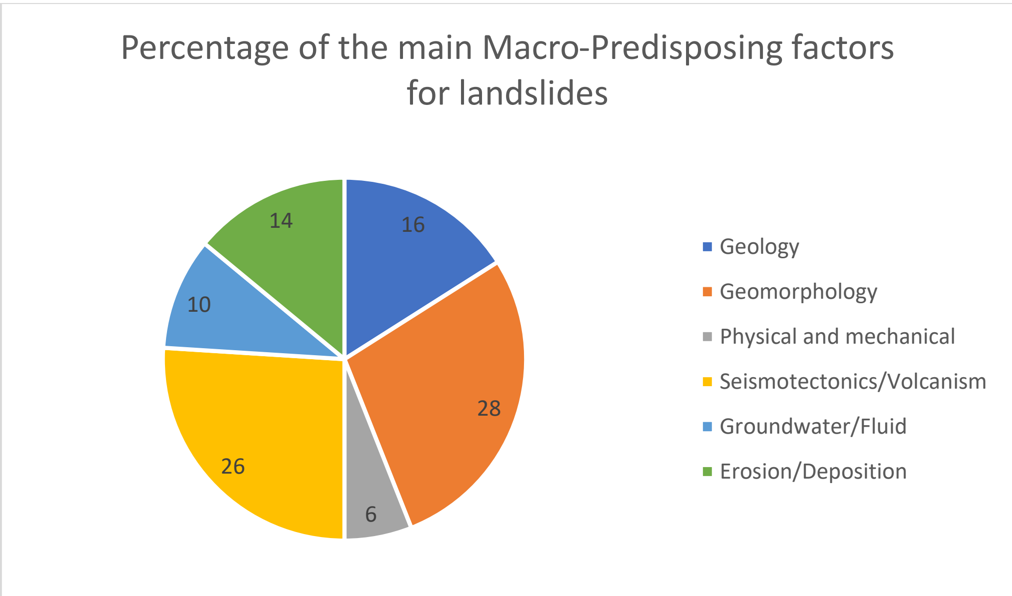

Figure 3. (a) Distribution of Macro-Predisposing Factors within the LEs.

11) Towards the Rationale – WP2 outcomes

Within the VS2, the rationalization phase took place in parallel between WP2, WP3 and WP4. To achieve this goal, a specific rationalization sheet was designed for each WP. To optimize the process, WP2 predisposing factors were analysed with a table approach, while WP3 and WP4 processes and triggers adopted a more descriptive form.

WP2 leaders and TK leaders with continuous exchanges and interactions with the proposing institutions reviewed the Considered Predisposing Factors/Process extracting the "Synthesized Predisposing Factors" (in the most logical and objective way possible) as summarized in the **Errore. L'origine riferimento non è stata trovata.**.

Successively, all the researchers specialized in submarine landslides involved in the project worked together in a shared table (Table 5) where other information about the predisposing factors where elaborated: a short description of how the factor contribute to increase the instability of a slope, the more vulnerable ambient to the specific factor, the learning examples (those proposed by the partners and other case study found in literature), the way the data about the predisposing factor is acquired and the output (how it is represented).

The shared table has been successively synthesized in Table 6. To each predisposing factors the table report the synthesis of all the method of data acquisition and the "Type of Approach" field for the output. In the "Type of Approach" field each process has been associated to a different potential level of rationalization: quantitative (i.e. through functions, empirical laws, algorithms), semi-quantitative (e.g. through severity indexes) or qualitative (e.g. through severity classes).

Table 2. Synthesized Predisposing Factors obtained from Considered Predisposing Factors/Process in ***Errore. L'origine riferimento non è stata trovata.****.*

Macro-Predisposing Categories	Synthesized Predisposing Factors
Geology	Lithology
	Structural features
	Stratigraphic features
	Progradational stacking pattern
	Weak layer
	Sedimentation rate
Geomorphology	Slope morphology/Topography
	Undercutting

	Hyperpicnal flow and drainage basin character
	Previous events
Physical and mechanical properties	Shear strength
	Hydraulic Properties
Seismotectonics/ Volcanism	Seismic activity/Vertical movement
	Faulting System/Distance to faults
	Volcanic activity
	Site effects (amplification/resonance)
Groundwater/Fluid	Presence of pressurized fluid/gas
Erosion/Deposition	Channelized Erosion
	Littoral transport
	Wave action

Table 4 Shared Predisposing Factors/Process-LE table of WP2 for the submarine ground instability. The table reports the example of the "Geology" macro-predisposing category but the same work has been produced also for the others macro-categories and relative predisposing factors.

Macro-predisposing factors	Predisposing factors	How the factor contribute to increase instability	Ambient	Learning examples	Bibliography	Data acquisition	Output
Geology	Lithology	consolidation degree, drained/undrained conditions	inner shelf/canyon head	Tianjin	Li et al., 2005	bibliography,fieldwork, cores, seafloor samples	classes
	Weak Layer	high pore water pressures,undrained conditions	ovunque	Var canyon, Stromboli, Frana di Scopello, Nidelva, Valdez, Finneidfjord	Dan et al., 2007 , Chiocci et al., 2008 , L'Hereux et al., 2010; Parson et al., 2014; Longva et al., 2003	CPT, cores, seismic section for correlations	geotechnical modellization and mechanical parameters
	Statigraphic features	rigidity contraxt	rocky coast/canyon head	Gioia canyon, Scopello	Sulli et al., 2020	seismic sections, cores	classes
	Progradational staking pattern	high slope values	inner shelf/fan delta	Var canyon	Dan et al., 2007	seismic section	degree foreset
	Sedimentation rate	high pore water pressures, high slope angle	inner shelf/fan delta/canyon head	Gioia canyon	Casalbore et al., 2019	seismic section	mm/Ka

Table 5 Rationalization from the shared Predisposing Factors/Process-LE table of WP2 for the submarine ground instability. The highlighted predisposing factors are in common with those identified for subaerial gravitational instability.

Predisposing Factors	Data representation			Data acquisition								Type of approach		
Main Factors	Areal (Map)	Linear (Map)	Punctual	Field survey	Geognostic survey	Laboratory tests	Remote sensing	Geophysical data	DEM analysis	Empirical relationships	Literature	Qualitative	Semi-quantitative	Quantitative
Lithology	X		X	X	X			X			X	X		
Structural features		X						X	X		X	X		X
Stratigraphic features	X		X					X			X	X		
Progradational stacking pattern		X						X					X	
Weak layer	X	X	X		X	X		X			X			X
Sedimentation rate	X							X			X		X	X
Slope morphology/Topography	X								X					X
Undercutting	X							X	X			X		
Hyperpycnal flow and drainage basin character	X						X		X	X	X	X		
Previous events	X	X						X	X		X	X		
Shear strenght			X		X	X								X
Hydraulic Properties					X	X								X
Seismic activity/Vertical movement	X		X	X			X	X			X		X	X
Faulting System/Distance to faults													X	
Volcanic activity	X			X			X	X			X		X	X
Site effects			X											X
Presence of pressurized fluid/gas	X	X	X		X			X			X	X	X	X
Channelized Erosion		X		X			X		X		X		X	

Littoral transport	X								X		X		X	
Wave action	X			X			X							X

12) Description of the Predisposing Factors

WPs and TKs researchers identified which predisposing factor is important for the two categories of ground instability consisting in Rapid and Slow landslides. Rapid landslides include Flows, Avalanches and Slides while Slow landslides include Creep and Deep-seated Gravitational Slope Deformations (DsGSD).

In order to strictly characterize the predisposing factors, each of them has been described by some of the researchers. The way the predisposing factor decrease the stability of a certain area has been illustrated in Table 6 for the two categories of ground instabilities, both for rapid and slow landslide.

Table 6. Extract from the shared Predisposing Factors/Process-LE table of WP2 and their related influence for rapid and slow submarine landslide.

Macro-category	Main Factors	Rapid Submarine landslide	Slow Submarine landslide
		Flows, Avalanches, Slides	*Creep, DsGSD*
Geology	Lithology	X	X
	Structural features	X	X
	Stratigraphic features		X
	Progradational stacking pattern	X	
	Weak layer	X	X
	Sedimentation rate	X	X
Geomorphology	Slope morphology/Topography	X	X
	Undercutting	X	
	Hyperpicnal flow and drainage basin character	X	
	Previous events	X	
Physical and mechanical properties	Shear strength	X	
	Hydraulic Properties	X	X
Seismotectonics/Volcanism	Seismic activity/Vertical movement	X	X

	Faulting System/Distance to faults	X	X
	Volcanic activity	X	
	Site effects (amplification/resonance)	X	X
Groundwater/Fluid	Presence of pressurized fluid/gas		X
Erosion/Deposition	Channelized Erosion	X	
	Littoral transport	X	
	Wave action	X	

Table 7. Explosion of the Predisposing Factors for rapid and slow submarine landslide.

Submarine landslide ***Fast landslide*** ***Flows, Avalanches, Slides***	
Description of the main predisposing factors	
Lithology (Geology)	The lithology of the substrate is one of the main preconditioning factors in submarine landslides. Composition, grain-size, sorting, and consolidation are lithological proprieties that directly influence other parameters (i.e shear strength, permeability, water content) strictly related to slope stability. The grain-size and sorting are very important factors since they influence the sediment permeability. The higher the permeability, and so the ability of sediments to dissipate water pore pressures (drained condition), the higher the stability of the slope. Undrained condition principally occurs in fine-grained sediments (clay, silt, mud) characterized by a low permeability that prevent the dissipation of exceeding pressures resulting in overpressured and thus instable slopes. The degree of consolidation of sediments is another important factor: it is inversely proportional to the water content and directly proportional to sediment shear strength. The higher the consolidation, the higher resistance to diving forces. For these reasons, in general soft sediments are more prone to generate submarine landslide respect to harder ones. Underconsolided fine-grained sediments are the principal actors of submarine landslides. Lithological information are obtained through coring or drilling, ROV dives and seismic facies.
Structural features Geology	Large-scale structural features are faults, folds, thrust planes. Those features typically span lengths from hundreds of meters to several kilometers. The major cause of landsliding associated to structural features is the oversteepening that can characterize the flanks of structural highs or fault scarps. Infact, the continuation below the seafloor of subareal structural highs are frequently shaped by landslides trying to restore the

	equilibrium profile. The movement along the fault plane create step-morphology (fault scarp) on the seafloor that can be characterized by high slope angle. The morphological step will act as potential sliding surfaces, enabling volumes of sediments to detach and move. These major features area identified through bathymetric data and seismic profiles.
Progradational stacking pattern Geology	Progradational stacking pattern results where sedimentation rate is high and exceeds the accommodation space available for sedimentation. This situation is very common in fan delta, delta (i.e. Gilbert-type) and on lava deltas. Sedimentation along the delta front, or slope, commonly produces large, basinward-dipping foresets with an inclination of 10°-25°, depending on the resting angle of sediment. In areas of steep offshore topography, avalanching of sediment across the delta-lip may generate even steeper foresets (30◦). In this setting, the slope angle is the main factor predisposing to instability. The progradational stacking pattern is revealed by seismic sections acquired perpendicularly to the coast.
Weak layer Geology	This is part of the stratigraphic features but, because of its relevance in the marine realm, it has been considered as a specific predisposing factor. A significant preconditioning factor for submarine landslides is the presence of a weak layer. A weak layer is composed by sediments characterized by low values of shear strength or low permeability. Such weak layers arise from variations in depositional environments, sediment origins, or changes that occurred post-deposition over geological epochs. Weak layers can be composed by clay (e.g sensitive clays), siliciclastic sediment sequence (e.g. clay-sand), volcanic tephra (e.g volcanic ash-clay) or fossiliferous sediment sequence (e.g. diatom ooze-clay). Clay-rich layers present a low resistance to shear forces, often becoming prime candidates for slip planes. Furthermore, these clay-rich layers can obstruct water flow, resulting in increased pore water pressure either within or above the layer. The presence coarse-grained layers that are prone to liquefaction during earthquakes, provide another preferential weak plane where failure may originate. The formation of water film can occur when coarse-grain sediment breaks or rearrange during the failure and pore fluid remain stuck by this interval composed by finer sediments. Notably, some of the most devastating submarine landslides have been influenced by the existence of these stratigraphic features. In the Mediterranean region the more probable weak layers consist in siliciclastic or volcanoclastic sediment sequence and can be potentially triggered in active margin or volcanic settings. Weak layer can be identified through sediment coring, CPTs, laboratory tests. Once defined, they can be areally correlated through seismic profiles.
Sedimentation Rate Geology	In cohesive sediment (prodelta mud, continental slope) sedimentation rate may create overpressure if the vertical accretion is higher than the rate of expulsion of pore water due to compaction of overburden sediment. Such process may be enhanced by the presence of organic matter (not decomposed because of the little time of exposure to oxygen rich seawater), whose decay may produce methane, so creating extra intergranular overpressure. In non-cohesive sediment, the frontal accretion of deposit (i.e., progradation) occurs trough the fast avalanching of loose granular sediment. The

	process increases the seafloor slope up to the resting angle of the sediment that is therefore characterized by a low safety factor.
Slope morphology and topography Geomorphology	The slope is the main diving force for gravitational instability. As the slope becomes steeper, gravity exerts a more pronounced downward force on rock and sediments thus causing failure and propagation. In fact, the continental slope (between 1 and 10 degrees, on average 3 degrees) host the larger part of failures that are rather uncommon on the continental shelf and abyssal plain. The steepest is the seafloor slope, most susceptible to erosive processes and the formation of submarine landslides it is. Slope also control the possibility that sliding masses evolve in gravity flow, which may erode the seafloor and entrain sediment. Topography also control instability as the presence of morphological high and unevenness often hinder the possibility of landslide or allows only small size instabilities.
Undercutting Geomorphology	Undercutting occurs when instability affects a stratified substrate and harder rocks overly soft and more erodible sediment. The removal of the foundation support unbutresses the slope and causes overhanging with consequent increase in gravitational stress, predisposing the slope to a collapse. Another effect of undercutting is the shift in sediments center of gravity: as the base of a slope or rockface is eroded away, the center of gravity of the overhanging mass might move outward, making the rock more prone to toppling or rotating outward. Furthermore, undercutting can lead to an increase in tensile and shear stresses in the overlying rock, making it more susceptible to failure. Such situation is common on volcanic coasts (where lava flows overly loose pyroclastics) and on canyon head where repetitive landslides determine the retreat towards the coast of the canyon head.
Hyperpicnal flows and basin morphology Geomorphology	In small “dirty” rivers i.e. streams with torrential regime that may experience flash floods with very high sediment/water ratio (>5-10%), the entrance to the sea of sediment-loaded mass of water may evolve in hyperpycnal flow, which interaction with the seafloor may exert shear stress and erode the bedrock and/or mobilize loose sediment. Hyperpicnal flows area generally generated by flash floods events. Flash floods occur within a few minutes or hours of excessive rainfall, a dam or levee failure, or a sudden release of water held by an ice jam. Flash floods can roll boulders, tear out trees, destroy buildings and bridges, and scour out new channels. Furthermore, flash flood-induced by heavy rains can also trigger catastrophic mud slides and debris flow that, channelized into the river, further increasing the river’s solid transport. The Mediterranean area is particularly exposed to rainfall-induced flash flood; this is due to the local climate, which is prone to short intense bursts of rainfall (hundreds of mm in few hours). In the Italian region, these events mainly occur in fall and are particularly destructive in south and north-western Italy. Areas most susceptible to the occurrence of flash floods and so hyperpicnal flows are mountainous streams and rivers. Hyperpicnal flows became relevant in preconditioning submarine landslide when the mountainous relief are very close to the coast, with steep and short subaerial valleys. This geological setting produces small drainage area with

	environment changes from mountainous to coastal with high slopes few kilometres. Most susceptible area are those where the continental shelf is narrow (<1 Km) and where the river mouth is directly connected to submarine canyons head, because is highly efficient in transporting large amounts of sediment in an environment (canyon head) that is very prone to submarine landslides.
Previous events Geomorphology	Previous landslide events can significantly influence the possibility of subsequent landslides. When mass wasting occurs, it can change the overall morphological equilibrium of the slope. Such changes might create new overhangs, reduce support for certain rock masses, or change the slope's overall angle, making it more susceptible to further failure. As well, the removal of a large rock mass during a landslide can change the stress distribution within the remaining slope. In fact, many submarine instability evolve retrogressively, i.e. propagate upslope trough the repetitive unbuttressing due to previous mass wasting. Lack of monitoring does not allow us to define if the retrogression occurs in short times (minutes/hours) of in longer times (centuries/millennia).
Shear strength Physical and mechanical characteristics	Submarine landslide commonly occur when the resisting force, i.e. the shear strength of the material, is overcome by diving forces. Sensitive soils are important weak layers and the degree of sensitivity depend on the undrained shear strength. Such parameter is fundamental for the definition of the FOS (Factor of Safety), calculated as the ratio between resisting and diving forces, that describes the stability of a slope. Generally, the shear strength in sediments increases with the grain size (low in clays and high in sand/rocks). When seabed surfaces are undercut, or deposition occur at the head of a sloping surface stability may decrease because of increasing shear stress.
Hydraulic properties Physical and mechanical characteristics	The onset of submarine landslide is linked to the soil's mechanical and hydraulic properties, mainly permeability that control the possibility to eliminate excess pore pressure. Variation of pore water pressure is in fact one of the main mechanisms of seabed instability. Increase of pore pressure can be related to an increase of fluid volume due to gas hydrate decomposition, fluid escape paroxysm or variation of water content in shallow-depth layers on the continental shelf due to rainfall maxima. In the Mediterranean area, where gas hydrate are not present in shallow waters, variations of pore pressure have to be considered principally where fluid escape features (pockmarks, mud volcano) occur and in the nearshore where large variation of groundwater level or discharging of groundwater (artesian spring sapping) may occur.
Seismic activity/Vertical movement Seismotectonics	Marine/coastal areas located in tectonically active areas may be subject to repetitive seismic stress and to vertical movement (uplift) on relatively short geological time. As for seismicity it is debatable whether seismic shaking increases or decreases shear strength of loose sediment. For non-cohesive marine soil, the vibration can cause the liquefaction of the soils, resulting in loss of the soil shear strength. On the contrary high-PGA as that associated to high-magnitude, near-filed events cause extensive mass wasting, as witnessed by the usual cable breaks due to gravity flow within canyons in the minutes/hours after the earthquake.

	Uplift and vertical movements may favour instability either creating high-gradient morphologies, lack of continental shelf and increasing sedimentation rate.
Distance to faults Seismotectonics	Marine areas close to these fault lines are more likely to experience intense PGA, elevating their failure hazard. The faulting of hard bedrock also produces loose cataclastic debris that may create weak band that may form the head or the foot of a landslide.
Site effects Seismotectonics	Specific local conditions might enhance seismic acceleration, and there's a potential for matching frequencies between seismic waves and rock slopes or blocks, leading to resonance. Soft sediment resting on hard bedrock or paleoriver valleys filled with lacustrine deposit may cause local amplification of seismic waves.
Volcanic activity Volcanotectonis	The presence of volcanic activity in the marine/coastal environment predisposes that sector to constant and continuous morphological and structural modifications favouring mass wasting. In particular, volcanoes are constructional morphologies due to the stacking of pyroclasts and lavas produced at the crater. For this reason, volcanic flanks increase in slope trough tiome and are therefore naturally pre-disposed to gravitational re-adjustment; moreover, hydrothermal activity may alter the geomechanical character of a slope predisposing it to mass wasting. Finally, heterogeneities common on volcanic deposit tend to create weak layers, horizontal discontinuities and anomalise that favours instability.
Channelized Erosion Erosion/Deposition	Submarine channels and canyons are created by turbidity currents causing seafloor erosion and removing debris produced by canyon-wall instability. Erosive processes, typical of active submarine canyon, are testified by the occurrence of upslope migrating bedforms and canyon talweg deepening, knick-points, and step-like morphology where erosion is focused at the base of the step (chute and pool). Channelized erosion operated by turbidity currents is one of the main predisposing factors in active submarine canyons.
Littoral transport Erosion/Deposition	Wind-driven littoral current controls the distribution or withdrawal and transport of sandy sediments on the beach and on the nearshore. Broader gepstrophic driven coastal current may in turn control the deposition of muddy sediment on the continental shelf and slope but they are out of the scope of the project and will not be considered. The direction of the longshore current combined with the sedimentary budget of the littoral cell and the morphology of the nearshore can contribute to the accumulation of sediments in instable areas (as canyon heads) increasing the pore pressure in the sedimentary column. In the latter case, littoral dynamics may also feed the canyon, enhancing erosion on the thalweg and possible undercutting. In some case 10-20m thick sedimentary wedge (depositional terrace) made up of loose sediment, is formed at very shallow water; such deposit made of loos material may be prone to instability.

Wave action Erosion/Deposition	The action of the waves is extremely variable as it is linked to seasonal cycles, exposure of the coast, climatic disturbances etc. Wave cyclic loading, combined pressure difference below wave crest and trough may destabilize shallow water seafloor. Such situation is not common on the Italian seas but can not be excluded.

Submarine landslide

Slow landslide

Creeps and DSGSDs (Deep-Seated Gravitational Slope Deformations)

Description of the main predisposing factors	
Lithology (Geology)	The lithology of the substrate is one of the main preconditioning factors in submarine landslides. Composition, grain-size, sorting, and consolidation are lithological proprieties that directly influence other parameters (i.e shear strength, permeability, water content) strictly related to slope stability. The grain-size and sorting are very important factors since they influence the sediment permeability. The higher the permeability, and so the ability of sediments to dissipate water pore pressures (drained condition), the higher the stability of the slope. Undrained condition principally occurs in fine-grained sediments (clay, silt, mud) characterized by a low permeability that prevent the dissipation of exceeding pressures resulting in over-pressured and thus instable slopes. The degree of consolidation of sediments is another important factor: it is inversely proportional to the water content and directly proportional to sediment shear strength. The higher the consolidation, the higher resistance to diving forces. For these reasons, in general soft sediments are more prone to generate submarine landslide respect to harder ones. Underconsolided fine-grained sediments are the principal actors of submarine slow-moving creep. Lithological information are obtained through coring or drilling, ROV dives and seismic facies.
Structural features Geology	Large-scale structural features are faults, folds, thrust planes. Those features typically span lengths from hundreds of meters to several kilometers. There is a specific connection between the development of slow-moving deformations (i.e DSGSDs) and inherited structural features. Different conditions inherited from structural features predispone to slow-moving deformation: i. Fold-related discontinuity can locally decrease the rock mass strength; ii. Bedding inclination respect to the slope inclination; iii. Lithological contrast as competent rocks over formations with ductile or plastic mechanical behavior.
Stratigraphic features Geology	Generally, most of the submarine landslide involve lithological alternation that produce vertical shear strength discontinuity. Abrupt changes in lithology can evolve into weak layers and appear to dictate the location of the failure plane. For this reason, a stratified substrate is a preconditioning factor especially for slow submarine landslides. Strong lithological contrast can occur in coincidence of stratigraphic discontinuities. On the Mediterranean continental margins, the shallower discontinuity surface is localized on the continental shelf and coincide with the erosive surface created during the last glacial maximum (when the sea level was lowered about 120 m) and successively draped by muddy sediment during the sea level rise. This surface can act as a barrier for fluid expulsion and so cause an increase in pore pressure able to destabilize the slope generating principally slow-moving instability as creep. Presence of lithological contrast or discontinuities can be revealed by seismic profile and drilling.

Weak layer Geology	This is part of the stratigraphic features but, because of its relevance in the marine realm, it has been considered as a specific predisposing factor. A significant preconditioning factor for submarine landslides is the presence of a weak layer. A weak layer is composed by sediments characterized by low values of shear strength or low permeability. Such weak layers arise from variations in depositional environments, sediment origins, or changes that occurred post-deposition over geological epochs. Weak layers can be composed by clay (e.g sensitive clays), siliciclastic sediment sequence (e.g. clay-sand), volcanic tephra (e.g volcanic ash-clay) or fossiliferous sediment sequence (e.g. diatom ooze-clay). Clay-rich layers present a low resistance to shear forces, often becoming prime candidates for slip planes. Furthermore, these clay-rich layers can obstruct water flow, resulting in increased pore water pressure either within or above the layer. The presence coarse-grained layers that are prone to liquefaction during earthquakes, provide another preferential weak plane where failure may originate. The formation of water film can occur when coarse-grain sediment breaks or rearrange during the failure and pore fluid remain stuck by this interval composed by finer sediments. Notably, some of the most devastating submarine landslides have been influenced by the existence of these stratigraphic features. In the Mediterranean region the more probable weak layers consist in siliciclastic or volcanoclastic sediment sequence and can be potentially triggered in active margin or volcanic settings. Weak layer can be identified through sediment coring, CPTs, laboratory tests. Once defined, they can be areally correlated through seismic profiles.
Sedimentation Rate Geology	In cohesive sediment (pro-delta mud, continental slope) sedimentation rate may create overpressure if the vertical accretion is higher than the rate of expulsion of pore water due to compaction of overburden sediment. Such process may be enhanced by the presence of organic matter (not decomposed because of the little time of exposure to oxygen rich seawater), whose decay may produce methane, so creating extra intergranular overpressure. This process usually drives slow movement such as creep on prodelta slope. At a larger scale, area characterized by longterm high sedimentation rates (i.e sedimentary wedges) can be characterized by slow-moving deep-seated deformations under their own weight.
Slope morphology and topography Geomorphology	The slope is the main diving force for gravitational instability. As the slope becomes steeper, gravity exerts a more pronounced downward force on rock and sediments thus causing failure and propagation. In fact, the continental slope (between 1 and 10 degrees, on average 3 degrees) host the larger part of failures that are rather uncommon on the continental shelf and abyssal plain. The steepest is the seafloor and the topography of coastal area, most susceptible to slow-moving deformations it is.
Hydraulic properties Physical and mechanical characteristics	The onset of submarine landslide is linked to the soil's mechanical and hydraulic properties, mainly permeability that control the possibility to eliminate excess pore pressure. Variation of pore water pressure is in fact one of the main mechanisms of seabed instability. Increase of pore pressure can be related to an increase of fluid volume due to gas hydrate decomposition, fluid escape paroxysm or variation of water content in shallow-depth layers on the continental shelf due to rainfall maxima. In the Mediterranean area, where gas hydrate are not present in shallow waters, variations of

	pore pressure have to be considered principally where fluid escape features (pockmarks, mud volcano) occur and in the nearshore and in the coastal area (where DSGSDs may have their initiation) where large variation of groundwater level or discharging of groundwater (artesian spring sapping) may occur. For slow-moving deformations porewater pressure and movement are generally positively correlated.
Seismic activity/Vertical movement Seismotectonics	Marine/coastal areas located in tectonically active areas may be subject to repetitive seismic stress and to vertical movement (uplift) on relatively short geological time. Slow-moving deformations in the marine environment are usually related to seismically induced increases in porewater pressures. Moreover, since these deformations are largely gravity-driven (as suggested by its name) uplift and vertical movements are important mechanisms to sustain the necessary gravitational forces of slope deformation and form DSGSD. Infact, DSGSDs are particularly common in area characterized by active uplifting movements (or where compressional phases occurred in the past).
Distance to faults Seismotectonics	A distinction is needed when defining the predisposing influences of faults for creep and DSGSDs. Marine area close to fault lines are more likely to experience intense PGA, elevating their failure hazard and generate creeps. While DSGSDs basal sliding surface is, in a certain way, a kind of thrust faults that cause compression (formation of inverse faults) at the toe of the wasting mass and extension (formation of direct faults) at its head. So, in the case of DSGSDs faults are intrinsic factor and so the distance to faults cannot be considered a preconditioning factor (since is like considering a preconditioning factor for a landslide the distance to scarp!) while for creeps they can effectively be considered a preconditioning factor.
Site effects Seismotectonics	Specific local conditions might enhance seismic acceleration, and there's a potential for matching frequencies between seismic waves and rock slopes or blocks, leading to resonance. Soft sediment resting on hard bedrock or paleoriver valleys filled with lacustrine deposit may cause local amplification of seismic waves.
Presence of pressurized fluid/gas Groundwater	Pressurized gas/fluids in the shallow layers of the seabed predispose unconsolidated sediment to instability, also in areas with even slight slopes (> 1-2°). The passage of fluids/gas through this layer breaks the already weak bonds between sediment grains, making it almost fluid-like. The presence of pressurized gas/fluid influences porewater pressures, changing the effective normal stresses, and therefore the shear strength that could be almost completely nullified. Furthermore, if the seabed is primarily composed of clays (thus particularly impermeable), the gas/fluids can create a large accumulation beneath this layer, lifting it (forming dome-like structures) or producing eruption and crater-like feature (pockmark). Even after the gas/fluids were able to reach the water column (depressurizing the subsurface), the sedimentary layer of the affected sea floor will have undergone

	significant irreversible deformations: the consequence will be the isolation (due to fracturing) of a sediment volume shaped like a lens, particularly susceptible to translational, sliding, or flowing movements. Furthermore, these mechanisms significantly amplify the effects if they occur in environments with much steeper slopes or where faults are present, as they are preferential pathways for the migration of fluids from deep seated reservoirs. In the Mediterranean area, slow-moving deformations have been often associated to variations of pore pressure due to the presence of pressurized fluid/gas.

13) Conclusions

This section of the document concerns the submarine context of the project about ground instabilities. In the previous deliverables (DV 2.2.1 and DV 2.2.2), the absence of marine and underwater LEs for the development of a thorough rationale for the associated predisposing factors was emphasized. A targeted cascade funding call led to the hiring of a new researcher with specialized expertise in the marine environment that coordinated the elaboration of this document.

The previously presented cases were indeed insufficient in various contexts and effects. The establishment of a recall ensured an increase in the Lessons Learned (LEs) reported by the project's partner institutions (UNIROMA, UNIPA, and OGS). From the recall, there was a 200% increase in LEs, demonstrating the success of this initiative even in the submarine context.

However, some critical issues persist in the submarine context and will be outlined below. Firstly, it is evident from the graph in Figure 2c that among the effects of ground instability, only "Landslides" are represented. This is because not all the effects presented occur in the submarine context, such as sinkholes that develop exclusively on land. Subsidence and liquefaction, on the other hand, are phenomena that also occur in the submarine context but are difficult to monitor and pose little danger in the underwater environment. The only effects of ground instability analyzed in the submarine context, therefore, fall within landslides.

The graphs consistently highlight that the Lessons Learned (LEs) presented primarily pertain to the local scale (11 LEs), while the intermediate and regional scales are represented by 2 and 1 learning example, respectively.

Similarly to terrestrial landslides, underwater landslides have been also classified as Rapid landslide or Slow landslide. Such a classification in an underwater environment have not same level of confidence as it is for on land-landslides, which is tied to the ability to monitor landslides and their speed with continuous or intermittent monitoring data. In the marine context, this subdivision represents an interpretation, as the speed of an underwater landslide can be measured only if it occurs simultaneously with a monitoring event. Fast and Slow landslides in the marine context are therefore distinguished considering the context in which they occur and based on the morphology of the landslide itself. From the graphs, it is evident that Rapid landslides are extensively represented in the LEs, although they primarily involve landslides at the canyon heads. In contrast, the representation of slow landslides is much lower.

Regarding landslides in the subaerial context, they have been further classified into different types of processes (e.g., debris flow, debris avalanches, rockfall, mud flow, etc.). However, a similar advancement has not yet been made for underwater landslides, as the difficulty in discriminating between various types is much greater than in the emerged environment. Especially with landslides at the heads of canyons, because of the effect of water entrainment and relative dilution of the wasting mass that is transformed into gravitational flows that do not leave a clear deposit, complicating the characterization of these landslide types.

It has also emerged that significant differences in terminology exist between the classification of landslides on land and at sea. For example, in terrestrial classification, debris flow is a channeled mass transport deposit, while in the marine environment, confinement is not taken into consideration. Moreover, within the same category, such as “Slow landslides”, there are extremely diverse types of processes, both in terms of predisposing factors and dimensions as between processes like creep and DsGSD, despite both being slow deformation processes.

As a research group focused on submarine instabilities, we believe it is important and necessary to take this challenging step forward. This would not only increase knowledge in this field but also serve the goals of the project.

14) LEs References

Institution	LE name	Bibliografia
Slow submarine landslides	*Squillace gravitational complex*	**Mangano et al. (2023)** – A new large-scale gravitational complex discovered in the Squillace Embayment (central Mediterranean): Tectonic and geohazard Implications (https://doi.org/10.21203/rs.3.rs-3101631/v1)
	Etna	**Chiocci et al. (2011) -** Continental margin large-scale instability controlling the flank sliding of Etna volcano
	Crotone megaslide	**Zecchin et al. (2018)** - The Crotone Megalandslide, southern Italy: Architecture, timing and tectonic control (https://doi.org/10.1038/s41598-018-26266-y)
Rapid submarine landslides	*Canyon Cirò*	**Ceramicola et al. (2015)** - Submarine canyon systems along the Ionian Calabrian margin, Central Mediterranean Sea
	Canyon Squillace	1) **Ceramicola et al. (2015)** - Submarine canyon systems along the Ionian Calabrian margin, Central Mediterranean Sea; 2) **Corradino et al. (2023)** - Active tectonics in the Calabrian Arc: Insights from the Late Miocene to Recent structural evolution of the Squillace Basin (offshore eastern Calabria) (https://doi.org/10.1016/j.tecto.2023.229772)
	Frana di Assi	**Ceramicola et al. (2014)** - Reconstruction and Tsunami Modeling of a Submarine Landslide on the Ionian Margin of Calabria (Mediterranean Sea) (https://doi.org/10.1007/978-3-319-04996-0_85)
	Canyon di Gioia	1) **Colantoni et al. (1992)** - Processi dinamici del canyon sottomarino di Gioia Tauro 2) **Zaniboni et al. (2014)** – Continentalmargins as a source of tsunami hazard: The 1977 Gioia Tauro (Italy) landslide–tsunami investigated through numerical modeling (https://doi.org/10.1016/j.margeo.2014.08.011) **3) Casalbore et al. (2019)** – Morphological Variability of Submarine Mass Movements in the Tectonically–Controlled Calabro–Tyrrhenian

		Continental Margin (Southern Italy) (https://doi.org/10.3390/geosciences9010043)
	Canyon di Scaletta	1) **Casalbore et al. (2011)** - Flash-flood hyperpycnal flows generating shallow-water landslides at Fiumara mouths in Western Messina Strait (Italy) (https://doi.org/10.1007/s11001-011-9128-y) 2) **Casalbore et al. (2012)** - Study of Recent Small-Scale Landslides in Geologically Active Marine Areas Through Repeated Multibeam Surveys: Examples from the Southern Italy (https://doi.org/10.1007/978-94-007-2162-3_51)
	Canyon di Var	1) **Dan et al., 2007** - The 1979 Nice harbour catastrophe revisited: Trigger mechanism inferred from geotechnical measurements and numerical modelling (http://dx.doi.org/10.1016/j.margeo.2007.06.011)
	Frana di Tianjin	**8) Li et al. (2004a) -** Slope failure in underconsolidated soft soils during the development of a port in Tianjin, China. Part 1: Field investigation (https://doi.org/10.1139/t04-089) 9) **Li et al. (2004b)** - Slope failure in underconsolidated soft soils during the development of a port in Tianjin, China. Part 2: Analytical study (https://doi.org/10.1139/t04-088)
	MAGIC	**MaGIC - Marine Geohazards along the Italian Coasts** https://www.protezionecivile.gov.it/en/approfondimento/progetto-magic-marine-geohazards-along-italian-coasts-0/
	Frana di Stromboli (with UNIBO)	1) **Chiocci et al., 2008 -** The Stromboli 2002 tsunamigenic submarine slide: Characteristics and possible failure mechanisms (https://doi.org/10.1029/2007JB005172) 2) **Casalbore et al., 2020** - Small-scale slope instability on the submarine flanks of insular volcanoes: the case-study of the Sciara del Fuoco slope (Stromboli) (https://doi.org/10.1007/s00531-020-01853-5) 3) **Romagnoli et al. (2009)** - Offshore evidence of large-scale lateral collapses on the eastern flank of Stromboli, Italy, due to structurally-controlled, bilateral flank instability 4) **Tinti et al. (2003)** - Tsunami generation in Stromboli island and impact on the south-east Tyrrhenian coasts (https://doi.org/10.5194/nhess-3-299-2003)
Institution	**LE name**	**Bibliografia**
Slow submarine landslide	***Squillace gravitational complex***	**Mangano et al. (2023)** – A new large-scale gravitational complex discovered in the Squillace Embayment (central Mediterranean): Tectonic and geohazard Implications (https://doi.org/10.21203/rs.3.rs-3101631/v1)

	Etna	**Chiocci et al. (2011) -** Continental margin large-scale instability controlling the flank sliding of Etna volcano
	Crotone megaslide	**Zecchin et al. (2018)** - The Crotone Megalandslide, southern Italy: Architecture, timing and tectonic control (https://doi.org/10.1038/s41598-018-26266-y)
Rapid submarine landslide	***Canyon Cirò***	**Ceramicola et al. (2015)** - Submarine canyon systems along the Ionian Calabrian margin, Central Mediterranean Sea
	Canyon Squillace	**3) Ceramicola et al. (2015)** - Submarine canyon systems along the Ionian Calabrian margin, Central Mediterranean Sea; **4) Corradino et al. (2023)** - Active tectonics in the Calabrian Arc: Insights from the Late Miocene to Recent structural evolution of the Squillace Basin (offshore eastern Calabria) (https://doi.org/10.1016/j.tecto.2023.229772)
	Frana di Assi	**Ceramicola et al. (2014)** - Reconstruction and Tsunami Modeling of a Submarine Landslide on the Ionian Margin of Calabria (Mediterranean Sea) (https://doi.org/10.1007/978-3-319-04996-0_85)
	Canyon di Gioia	**3) Colantoni et al. (1992)** - Processi dinamici del canyon sottomarino di Gioia Tauro **4) Zaniboni et al. (2014)** – Continentalmargins as a source of tsunami hazard: The 1977 Gioia Tauro (Italy) landslide–tsunami investigated through numerical modeling (https://doi.org/10.1016/j.margeo.2014.08.011) **3) Casalbore et al. (2019)** – Morphological Variability of Submarine Mass Movements in the Tectonically–Controlled Calabro–Tyrrhenian Continental Margin (Southern Italy) (https://doi.org/10.3390/geosciences9010043)
	Canyon di Scaletta	3) **Casalbore et al. (2011)** - Flash-flood hyperpycnal flows generating shallow-water landslides at Fiumara mouths in Western Messina Strait (Italy) (https://doi.org/10.1007/s11001-011-9128-y) 4) **Casalbore et al. (2012)** - Study of Recent Small-Scale Landslides in Geologically Active Marine Areas Through Repeated Multibeam Surveys: Examples from the Southern Italy (https://doi.org/10.1007/978-94-007-2162-3_51)
	Canyon di Var	2) **Dan et al., 2007** - The 1979 Nice harbour catastrophe revisited: Trigger mechanism inferred from geotechnical measurements and numerical modelling (http://dx.doi.org/10.1016/j.margeo.2007.06.011)

	Frana di Tianjin	**10) Li et al. (2004a) -** Slope failure in underconsolidated soft soils during the development of a port in Tianjin, China. Part 1: Field investigation (https://doi.org/10.1139/t04-089) 11) **Li et al. (2004b)** - Slope failure in underconsolidated soft soils during the development of a port in Tianjin, China. Part 2: Analytical study (https://doi.org/10.1139/t04-088)
	MAGIC	**MaGIC - Marine Geohazards along the Italian Coasts** https://www.protezionecivile.gov.it/en/approfondimento/progetto-magic-marine-geohazards-along-italian-coasts-0/
	Frana di Stromboli (with UNIBO)	5) **Chiocci et al., 2008 -** The Stromboli 2002 tsunamigenic submarine slide: Characteristics and possible failure mechanisms (https://doi.org/10.1029/2007JB005172) 6) **Casalbore et al., 2020** - Small-scale slope instability on the submarine flanks of insular volcanoes: the case-study of the Sciara del Fuoco slope (Stromboli) (https://doi.org/10.1007/s00531-020-01853-5) 7) **Romagnoli et al. (2009)** - Offshore evidence of large-scale lateral collapses on the eastern flank of Stromboli, Italy, due to structurally-controlled, bilateral flank instability 8) **Tinti et al. (2003)** - Tsunami generation in Stromboli island and impact on the south-east Tyrrhenian coasts (https://doi.org/10.5194/nhess-3-299-2003)

15) General submarine landslides references

Bloom, C. K., MacInnes, B., Higman, B., Shugar, D. H., Venditti, J. G., Richmond, B., & Bilderback, E. L. (2020). Catastrophic landscape modification from a massive landslide tsunami in Taan Fiord, Alaska. *Geomorphology*, *353*. https://doi.org/10.1016/j.geomorph.2019.107029

Bryn, P., Berg, K., Forsberg, C. F., Solheim, A., & Kvalstad, T. J. (2005). Explaining the Storegga Slide. *Marine and Petroleum Geology*, *22*(1-2 SPEC. ISS.), 11–19. https://doi.org/10.1016/j.marpetgeo.2004.12.003

Camerlenghi, A., Urgeles, R., & Fantoni, L. (2010). A database on submarine landslides of the mediterranean sea. *Submarine Mass Movements and Their Consequences - 4th International Symposium*, *28*, 503–513. https://doi.org/10.1007/978-90-481-3071-9_41

Casalbore, D., Bosman, A., Casas, D., Chiocci, F., Martorelli, E., & Ridente, D. (2019). Morphological variability of submarine mass movements in the tectonically–Controlled calabro–Tyrrhenian continental margin (Southern Italy). *Geosciences (Switzerland)*, *9*(1). https://doi.org/10.3390/geosciences9010043

Casalbore, D., Bosman, A., & Chiocci, F. L. (2012). Submarine Mass Movements and Their Consequences. *Submarine Mass Movements and Their Consequences*, 573–582. https://doi.org/10.1007/978-94-007-2162-3

Casalbore, D., Bosman, A., Chiocci, F. L., Ingrassia, M., Macelloni, L., Sposato, A., & Martorelli, E. (2016). New insights on failure and post-failure dynamics of submarine landslides on the intra-slope Palmarola ridge (Central Tyrrhenian Sea). *Advances in Natural and Technological Hazards Research*, *41*, 93–101. https://doi.org/10.1007/978-3-319-20979-1_9

Casalbore, D., Bosman, A., Martorelli, E., Sposato, A., & Chiocci, F. L. (2014). Mass Wasting Features on the Submarine Flanks of Ventotene Volcanic Edifice (Tyrrhenian Sea, Italy). *Submarine Mass Movements and Their Consequences. Advances in Natural and Technological Hazards Research. 6th International Symposium.*, *37*, 285–293. https://doi.org/10.1007/978-3-319-00972-8

Casalbore, D., Chiocci, F. L., Mugnozza, G. S., Tommasi, P., & Sposato, A. (2011). Flash-flood hyperpycnal flows generating shallow-water landslides at Fiumara mouths in Western Messina Strait (Italy). *Marine Geophysical Research*, *32*(1), 257–271. https://doi.org/10.1007/s11001-011-9128-y

Casalbore, D., Passeri, F., Tommasi, P., Verrucci, L., Bosman, A., Romagnoli, C., & Chiocci, F. L. (2020). Small-scale slope instability on the submarine flanks of insular volcanoes: the case-study of the Sciara del Fuoco slope (Stromboli). *International Journal of Earth Sciences*, *109*(8), 2643–2658. https://doi.org/10.1007/s00531-020-01853-5

Casalbore, D., Romagnoli, C., Bosman, A., Anzidei, M., & Chiocci, F. L. (2018). Coastal hazard due to submarine canyons in active insular volcanoes: examples from Lipari Island (southern Tyrrhenian Sea). *Journal of Coastal Conservation*, *22*(5), 989–999. https://doi.org/10.1007/s11852-017-0549-x

Casas, D., Chiocci, F., Casalbore, D., Ercilla, G., & de Urbina, J. O. (2016). Magnitude-frequency distribution of submarine landslides in the Gioia Basin (southern Tyrrhenian Sea). *Geo-Marine Letters*, *36*(6), 405–414. https://doi.org/10.1007/s00367-016-0458-2

Cattaneo, A., Babonneau, N., Dan, G., Déverchère, J., Domzig, A., Gaullier, V., Lepillier, B., De Lépinay, B. M., Nouguès, A., Strzerzynski, P., Sultan, N., & Yelles, K. (2010). Submarine landslides along the Algerian margin: A review of their occurrence and potential link with tectonic structures. *Submarine Mass Movements and Their Consequences - 4th International Symposium*, *28*, 515–525. https://doi.org/10.1007/978-90-481-3071-9_42

Ceramicola, S., Coste, M., Praeg, D., Migeon, S., & Zecchin, M. (2015). Submarine canyon systems along the Ionian Calabrian margin, Central Mediterranean Sea. *Submarine Canyon Dynamics in the Mediterranean and Tributary Seas - An Integrated Geological, Oceanographic and Biological Perspective. CIESM Monograph 47*, *April*, 157–163. https://noc.ac.uk/seminars/g3-seminars/submarine-canyon-systems-along-ionian-calabrian-margin-central-mediterranean

Chaytor, J. D., ten Brink, U. S., Solow, A. R., & Andrews, B. D. (2009). Size distribution of submarine landslides along the U.S. Atlantic margin. *Marine Geology*, *264*(1–2), 16–27. https://doi.org/10.1016/j.margeo.2008.08.007

Chiocci, F. L., Coltelli, M., Bosman, A., & Cavallaro, D. (2011). Continental margin large-scale instability controlling the flank sliding of Etna volcano. *Earth and Planetary Science Letters*, *305*(1–2), 57–64. https://doi.org/10.1016/j.epsl.2011.02.040

Chiocci, F. L., & de Alteriis, G. (2006). The Ischia debris avalanche: First clear submarine evidence in the Mediterranean of a volcanic island prehistorical collapse. *Terra Nova*, *18*(3), 202–209. https://doi.org/10.1111/j.1365-3121.2006.00680.x

Chiocci, F. L., Romagnoli, C., Tommasi, P., & Bosman, A. (2008). The Stromboli 2002 tsunamigenic submarine slide: Characteristics and possible failure mechanisms. *Journal of Geophysical Research: Solid Earth*, *113*(10), 1–11. https://doi.org/10.1029/2007JB005172

Clare, M. A., Le Bas, T., Price, D. M., Hunt, J. E., Sear, D., Cartigny, M. J. B., Vellinga, A., Symons, W., Firth, C., & Cronin, S. (2018). Complex and Cascading Triggering of Submarine Landslides and Turbidity Currents at Volcanic Islands Revealed From Integration of High-Resolution Onshore and Offshore Surveys. *Frontiers in Earth Science*, *6*(December), 1–24. https://doi.org/10.3389/feart.2018.00223

Clare, M., Chaytor, J., Dabson, O., Gamboa, D., Georgiopoulou, A., Eady, H., Hunt, J., Jackson, C., Katz, O., Krastel, S., León, R., Micallef, A., Moernaut, J., Moriconi, R., Moscardelli, L., Mueller, C., Normandeau, A., Patacci, M., Steventon, M., … Jobe, Z. (2018). A consistent global approach for the morphometric characterization of subaqueous landslides. *8th International Symposium on Submarine Mass Movements and Their Consequences, ISSMMTC 2018*, 455–477. https://doi.org/10.1144/SP477.15

Clarke, S. L., Hubble, T. C. T., Miao, G., Airey, D. W., & Ward, S. N. (2019). Eastern Australia's submarine landslides: implications for tsunami hazard between Jervis Bay and Fraser Island. *Landslides*, *16*(11), 2059–2085. https://doi.org/10.1007/s10346-019-01223-6

Collico, S., Arroyo, M., Urgeles, R., Gràcia, E., Devincenzi, M., & Peréz, N. (2020). Probabilistic mapping of earthquake-induced submarine landslide susceptibility in the South-West Iberian margin. *Marine Geology*, *429*(December 2019). https://doi.org/10.1016/j.margeo.2020.106296

Cukur, D., Kim, S. P., Kong, G. S., Bahk, J. J., Horozal, S., Um, I. K., Lee, G. S., Chang, T. S., Ha, H. J., Völker, D., & Kim, J. K. (2016). Geophysical evidence and inferred triggering factors of submarine landslides on the western continental margin of the Ulleung Basin, East Sea. *Geo-Marine Letters*, *36*(6), 425–444. https://doi.org/10.1007/s00367-016-0463-5

Dalla Valle, G., Gamberi, F., Foglini, F., & Trincardi, F. (2015). The Gondola Slide: A mass transport complex controlled by margin topography (South-Western Adriatic Margin, Mediterranean Sea). *Marine Geology*, *366*, 97–113. https://doi.org/10.1016/j.margeo.2015.05.001

Damuth, J. E., & Embley, R. W. (1981). Mass-transport processes on Amazon Cone: western equatorial Atlantic. *American Association of Petroleum Geologists Bulletin*, *65*(4), 629–643. https://doi.org/10.1306/2f91999a-16ce-11d7-8645000102c1865d

Dan, G., Sultan, N., & Savoye, B. (2007). The 1979 Nice harbour catastrophe revisited: Trigger mechanism inferred from geotechnical measurements and numerical modelling. *Marine Geology*, *245*(1–4), 40–64. https://doi.org/10.1016/j.margeo.2007.06.011

Embley, R. W., & Jacobi, R. D. (1977). Distribution and morphology of large submarine sediment slides and slumps on Atlantic continental margins. *Marine Geotechnology*, *2*(1–4), 205–228. https://doi.org/10.1080/10641197709379780

Fan, E. (2004). OTC 16742 Importance of Mass Transport Complexes in the Quaternary Development of the Nile. *202.120.57.205*. file://localhost/Users/nik/Documents/files_nik/scienzeTerra/nile delta/masstransport.pdf

Feeley, K. (2007). Triggering Mechanisms of Submarine Landslides, Research Report. *Northeastern University, Department of Civil and Environmental Engineering*, *0530151*, 1–45.

Gales, J. A., McKay, R. M., De Santis, L., Rebesco, M., Laberg, J. S., Shevenell, A. E., Harwood, D., Leckie, R. M., Kulhanek, D. K., King, M., Patterson, M., Lucchi, R. G., Kim, S., Kim, S., Dodd, J., Seidenstein, J., Prunella, C., Ferrante, G. M., Ash, J., … Xiong, Z. (2023). Climate-controlled submarine landslides on the Antarctic continental margin. *Nature Communications*, *14*(1). https://doi.org/10.1038/s41467-023-38240-y

Gamberi, F. (2020). Systems supplying sediment to canyon heads (SSSCHs) in the Tyrrhenian Sea: The past and the present as a key to understanding deep-sea stratigraphy. *Marine and Petroleum Geology*, *119*(August 2019), 104470. https://doi.org/10.1016/j.marpetgeo.2020.104470

Gamberi, F., Rovere, M., & Marani, M. (2011). Mass-transport complex evolution in a tectonically active margin (Gioia Basin, Southeastern Tyrrhenian Sea). *Marine Geology*, *279*(1–4), 98–110. https://doi.org/10.1016/j.margeo.2010.10.015

Gamberi, F., Rovere, M., Marani, M. P., & Dykstra, M. (2015). Modern submarine canyon feeder-system and deep-sea fan growth in a tectonically active margin (northern Sicily). *Geosphere*, *11*(2), 307–319. https://doi.org/10.1130/GES01030.1

Gamberi, F., Valle, G. D., Foglini, F., Rovere, M., & Trincardi, F. (2019). Submarine Landslides on the Seafloor: Hints on Subaqueous Mass-Transport Processes From the Italian Continental Margins (Adriatic and Tyrrhenian Seas, Offshore Italy). *Geophysical Monograph Series*, *246*, 339–356. https://doi.org/10.1002/9781119500513.ch20

Gamboa, D., Alves, T., Cartwright, J., & Terrinha, P. (2010). MTD distribution on a “passive” continental margin: The Espírito Santo Basin (SE Brazil) during the Palaeogene. *Marine and Petroleum Geology*, *27*(7), 1311–1324. https://doi.org/10.1016/j.marpetgeo.2010.05.008

Gamboa, D., Omira, R., & Terrinha, P. (2021). A database of submarine landslides offshore West and Southwest Iberia. *Scientific Data*, *8*(1), 1–9. https://doi.org/10.1038/s41597-021-00969-w

Gamboa, D., Omira, R., & Terrinha, P. (2022). Spatial and morphometric relationships of submarine landslides offshore west and southwest Iberia. *Landslides*, *19*(2), 387–405. https://doi.org/10.1007/s10346-021-01786-3

Green, A., & Uken, R. (2008). Submarine landsliding and canyon evolution on the northern KwaZulu-Natal continental shelf, South Africa, SW Indian Ocean. *Marine Geology*, *254*(3–4), 152–170. https://doi.org/10.1016/j.margeo.2008.06.001

Guillén, J. (2017). Atlas of Bedforms in the Western Mediterranean. In *Atlas of Bedforms in the Western Mediterranean*. https://doi.org/10.1007/978-3-319-33940-5

Guo, X., Stoesser, T., Zheng, D., Luo, Q., Liu, X., & Nian, T. (2023). A methodology to predict the run-out distance of submarine landslides. *Computers and Geotechnics*, *153*(October 2022), 105073. https://doi.org/10.1016/j.compgeo.2022.105073

Hart, P. E., Sliter, R., & Roland, E. (2014). *Journal of Geophysical Research : Solid Earth earthquake at Valdez*. *March 1964*, 1–15. https://doi.org/10.1002/2014JB011514.Received

He, Y., Zhong, G., Wang, L., & Kuang, Z. (2014). Characteristics and occurrence of submarine canyon-associated landslides in the middle of the northern continental slope, South China Sea. *Marine and Petroleum Geology*, *57*, 546–560. https://doi.org/10.1016/j.marpetgeo.2014.07.003

Herrmann, H., & Bucksch, H. (2014). Storm Wave. *Dictionary Geotechnical Engineering/Wörterbuch GeoTechnik*, 1317–1317. https://doi.org/10.1007/978-3-642-41714-6_197593

Hjelstuen, B. O., Sejrup, H. P., Haflidason, H., Nygård, A., Ceramicola, S., & Bryn, P. (2005). Late Cenozoic glacial history and evolution of the Storegga Slide area and adjacent slide flank regions, Norwegian continental margin. *Marine and Petroleum Geology*, *22*(1-2 SPEC. ISS.), 57–69. https://doi.org/10.1016/j.marpetgeo.2004.10.002

Hornbach, M. J., Lavier, L. L., & Ruppel, C. D. (2007). Triggering mechanism and tsunamogenic potential of the Cape Fear Slide complex, U.S. Atlantic margin. *Geochemistry, Geophysics, Geosystems*, *8*(12). https://doi.org/10.1029/2007GC001722

Hühnerbach, V., & Masson, D. G. (2004). Landslides in the North Atlantic and its adjacent seas: An analysis of their morphology, setting and behaviour. *Marine Geology*, *213*(1–4), 343–362. https://doi.org/10.1016/j.margeo.2004.10.013

Ioualalen, M., Migeon, S., & Sardoux, O. (2010). Landslide tsunami vulnerability in the Ligurian Sea: Case study of the 1979 October 16 Nice international airport submarine landslide and of identified geological mass failures. *Geophysical Journal International*, *181*(2), 724–740. https://doi.org/10.1111/j.1365-246X.2010.04572.x

Karstens, J., Haflidason, H., Berndt, C., & Crutchley, G. J. (2023). Revised Storegga Slide reconstruction reveals two major submarine landslides 12,000 years apart. *Communications Earth and Environment*, *4*(1), 2–10. https://doi.org/10.1038/s43247-023-00710-y

Kelner, M., Migeon, S., Tric, E., Couboulex, F., Dano, A., Lebourg, T., & Taboada, A. (2016). Frequency and triggering of small-scale submarine landslides on decadal timescales: Analysis of 4D bathymetric data from the continental slope offshore Nice (France). *Marine Geology*, *379*, 281–297. https://doi.org/10.1016/j.margeo.2016.06.009

L'Heureux, J. S., Hansen, L., Longva, O., Emdal, A., & Grande, L. O. (2010). A multidisciplinary study of submarine landslides at the Nidelva fjord delta, Central Norway - Implications for geohazard assessment. *Norsk Geologisk Tidsskrift*, *90*(1–2), 1–20.

Le Bouteiller, P., Lafuerza, S., Charléty, J., Reis, A. T., Granjeon, D., Delprat-Jannaud, F., & Gorini, C. (2019). A new conceptual methodology for interpretation of mass transport processes from seismic data. *Marine and Petroleum Geology*, *103*(March), 438–455. https://doi.org/10.1016/j.marpetgeo.2018.12.027

Lee, H., & Baraza, J. (1999). Geotechnical characteristics and slope stability in the Gulf of Cadiz. *Marine Geology*, *155*(1–2), 173–190. https://doi.org/10.1016/S0025-3227(98)00146-7

Lee, H. J. (2009). Timing of occurrence of large submarine landslides on the Atlantic Ocean margin. *Marine Geology*, *264*(1–2), 53–64. https://doi.org/10.1016/j.margeo.2008.09.009

Lee, H. J., Locat, J., Desgagnés, P., Parsons, J. D., McAdoo, B. G., Orange, D. L., Puig, P., Wong, F. L., Dartnell, P., & Boulanger, E. (2007). Submarine Mass Movements on Continental Margins. *Continental Margin Sedimentation*, 213–274. https://doi.org/10.1002/9781444304398.ch5

Lee, S. H., & Chough, S. K. (2001). High-resolution (2-7 (kHz) acoustic and geometric charactersof subamarine creep deposits in the South Korea Plateau, East Sea. *Sedimentology*, *48*(3), 629–644. https://doi.org/10.1046/j.1365-3091.2001.00383.x

Lee, S. H., Chough, S. K., Back, G. G., & Kim, Y. B. (2002). Chirp (2-7-kHz) echo characters of the South Korea Plateau, East Sea: Styles of mass movement and sediment gravity flow. *Marine Geology*, *184*(3–4), 227–247. https://doi.org/10.1016/S0025-3227(01)00283-3

Lee, S. H., Chough, S. K., Back, G. G., Kim, Y. B., & Sung, B. S. (1999). Gradual downslope change in high-resolution acoustic characters and geometry of large-scale submarine debris lobes in Ulleung Basin, East Sea (Sea of Japan), Korea. *Geo-Marine Letters*, *19*(4), 254–261. https://doi.org/10.1007/s003670050116

León, R., Urgeles, R., Pérez-López, R., Payo, E., Izquierdo, A. V., Giménez-Moreno, C. J., & Casas, D. (2020). Geological and tectonic controls on morphometrics of submarine landslides of the spanish margins. *Geological Society Special Publication*, *500*(1), 495–513. https://doi.org/10.1144/SP500-2019-153

Li, S., Yue, Z. Q., Tham, L. G., Lee, C. F., & Yan, S. W. (2005a). Slope failure in underconsolidated soft soils during the development of a port in Tianjin, China. Part 1: Field investigation. *Canadian Geotechnical Journal*, *42*(1), 147–165. https://doi.org/10.1139/t04-089

Li, S., Yue, Z. Q., Tham, L. G., Lee, C. F., & Yan, S. W. (2005b). Slope failure in underconsolidated soft soils during the development of a port in Tianjin, China. Part 2: Analytical study. *Canadian Geotechnical Journal*, *42*(1), 166–183. https://doi.org/10.1139/t04-088

Lo Iacono, C., Sulli, A., & Agate, M. (2014). Submarine canyons of north-western Sicily (Southern Tyrrhenian Sea): Variability in morphology, sedimentary processes and evolution on a tectonically active margin. *Deep-Sea Research Part II: Topical Studies in Oceanography*, *104*, 93–105. https://doi.org/10.1016/j.dsr2.2013.06.018

Lo Presti, V., Antonioli, F., Casalbore, D., Chiocci, F. L., Lanza, S., Sulli, A., & Randazzo, G. (2022). Geohazard assessment of the north-eastern Sicily continental margin (SW Mediterranean): coastal erosion, sea-level rise and retrogressive canyon head dynamics. *Marine Geophysical Research*, *43*(1). https://doi.org/10.1007/s11001-021-09463-9

Locat, J., & Lee, H. J. (2002). Submarine landslides: Advances and challenges. *Canadian Geotechnical Journal*, *39*(1), 193–212. https://doi.org/10.1139/t01-089

Mangano, G., Ceramicola, S., Alves, T. M., Zecchin, M., Civile, D., Del Ben, A., & Critelli, S. (2023). A new large-scale gravitational complex discovered in the Gulf of Squillace (central Mediterranean): tectonic implications. *Scientific Reports*, *13*(1). https://doi.org/10.1038/s41598-023-40947-3

Mangano, G., Zecchin, M., Civile, D., Ceramicola, S., Donato, A., Muto, F., Tripodi, V., & Critelli, S. (2022). Mid-Miocene to recent tectonic evolution of the Punta Stilo Swell (Calabrian Arc, southern Italy): An effect of Calabrian Arc migration. *Marine Geology*, *448*(August 2021), 106810. https://doi.org/10.1016/j.margeo.2022.106810

Mare, T., Colantoni, P., Gennesseaux, I., Vanney, J. R., & Ulzega, A. (1992). *Processi dinamici del*.

Martorelli, E., Bosman, A., Casalbore, D., & Falcini, F. (2016). Interaction of down-slope and along-slope processes off Capo Vaticano (southern Tyrrhenian Sea, Italy), with particular reference to contouriterelated landslides. *Marine Geology*, *378*, 43–55. https://doi.org/10.1016/j.margeo.2016.01.005

Masson, D. G., Harbitz, C. B., Wynn, R. B., Pedersen, G., & Løvholt, F. (2006). Submarine landslides: Processes, triggers and hazard prediction. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *364*(1845), 2009–2039. https://doi.org/10.1098/rsta.2006.1810

McAdoo, B. G., Pratson, L. F., & Orange, D. L. (2000). Submarine landslide geomorphology, US continental slope. *Marine Geology*, *169*(1–2), 103–136. https://doi.org/10.1016/S0025-3227(00)00050-5

Mi, Y., & Wang, J. (2021). Finite-element modeling of submarine landslide triggered by seismic loading in saturated cohesive soil deposits. *Bulletin of Engineering Geology and the Environment*, *80*(2), 951–965. https://doi.org/10.1007/s10064-020-02005-4

Micallef, A., Berndt, C., Masson, D. G., & Stow, D. A. V. (2007). A technique for the morphological characterization of submarine landscapes as exemplified by debris flows of the Storegga Slide. *Journal of Geophysical Research: Earth Surface*, *112*(2), 1–15. https://doi.org/10.1029/2006JF000505

Micallef, A., Berndt, C., Masson, D. G., & Stow, D. A. V. (2008). Scale invariant characteristics of the Storegga Slide and implications for large-scale submarine mass movements. *Marine Geology*, *247*(1–2), 46–60. https://doi.org/10.1016/j.margeo.2007.08.003

Micallef, A., Masson, D. G., Berndt, C., & Stow, D. A. V. (2007). Morphology and mechanics of submarine spreading: A case study from the Storegga Slide. *Journal of Geophysical Research: Earth Surface*, *112*(3), 1–21. https://doi.org/10.1029/2006JF000739

Micallef, A., Masson, D. G., Berndt, C., & Stow, D. A. V. (2009). Development and mass movement processes of the north-eastern Storegga Slide. *Quaternary Science Reviews*, *28*(5–6), 433–448. https://doi.org/10.1016/j.quascirev.2008.09.026

Micallef, A., Mountjoy, J. J., Canals, M., & Lastras, G. (2012a). Deep-seated bedrock landslides and submarine canyon evolution in an active tectonic margin: Cook strait, New Zealand. *Submarine Mass Movements and Their Consequences - 5th International Symposium*, 201–212. https://doi.org/10.1007/978-94-007-2162-3_18

Micallef, A., Mountjoy, J. J., Canals, M., & Lastras, G. (2012b). Submarine Mass Movements and Their Consequences. *Submarine Mass Movements and Their Consequences*, 201–212. https://doi.org/10.1007/978-94-007-2162-3

Milia, A. (2000). The Dohrn canyon: A response to the eustatic fall and tectonic uplift of the outer shelf along the eastern Tyrrhenian Sea margin, Italy. *Geo-Marine Letters*, *20*(2), 101–108. https://doi.org/10.1007/s003670000044

Milia, A., Iannace, P., & Torrente, M. M. (2017). Active tectonic structures and submarine landslides offshore southern Apulia (Italy): A new scenario for the 1743 earthquake and subsequent tsunami. *Geo-Marine Letters*, *37*(3), 229–239. https://doi.org/10.1007/s00367-017-0493-7

Minisini, D., Trincardi, F., & Asioli, A. (2006). Evidence of slope instability in the Southwestern Adriatic Margin. *Natural Hazards and Earth System Science*, *6*(1), 1–20. https://doi.org/10.5194/nhess-6-1-2006

Minisini, D., Trincardi, F., Asioli, A., Canu, M., & Foglini, F. (2007). Morphologic variability of exposed mass-transport deposits on the eastern slope of Gela Basin (Sicily channel). *Basin Research*, *19*(2), 217–240. https://doi.org/10.1111/j.1365-2117.2007.00324.x

Moscardelli, L., & Wood, L. (2008). New classification system for mass transport complexes in offshore Trinidad. *Basin Research*, *20*(1), 73–98. https://doi.org/10.1111/j.1365-2117.2007.00340.x

Moscardelli, L., & Wood, L. (2016). Morphometry of mass-transport deposits as a predictive tool. *Bulletin of the Geological Society of America*, *128*(1–2), 47–80. https://doi.org/10.1130/B31221.1

Moscardelli, L., Wood, L., & Mann, P. (2006). Mass-transport complexes and associated processes in the offshore area of Trinidad and Venezuela. *American Association of Petroleum Geologists Bulletin*, *90*(7), 1059–1088. https://doi.org/10.1306/02210605052

Mountjoy, J. J., McKean, J., Barnes, P. M., & Pettinga, J. R. (2009). Terrestrial-style slow-moving earthflow kinematics in a submarine landslide complex. *Marine Geology*, *267*(3–4), 114–127. https://doi.org/10.1016/j.margeo.2009.09.007

Mountjoy, J., & Micallef, A. (2018). Submarine Landslides. *Springer Geology*, 235–250. https://doi.org/10.1007/978-3-319-57852-1_13

Mulder, T., & Cochonat, P. (1996). Classification of offshore mass movements. *Journal of Sedimentary R*, *66*, 43–57.

Norem, H., Locat, J., & Schieldrop, B. (1990). An approach to the physics and the modeling of submarine flowslides. *Marine Geotechnology*, *9*(2), 93–111. https://doi.org/10.1080/10641199009388233

Oehler, T., Mogollón, J. M., Moosdorf, N., Winkler, A., Kopf, A., & Pichler, T. (2017). Submarine groundwater discharge within a landslide scar at the French Mediterranean coast. *Estuarine, Coastal and Shelf Science*, *198*, 128–137. https://doi.org/10.1016/j.ecss.2017.09.006

Pickering, K. T., & Corregidor, J. (2005). Mass transport complexes and tectonic control on confined basin-floor submarine fans, Middle Eocene, south Spanish Pyrenees. *Geological Society Special Publication*, *244*(May 2007), 51–74. https://doi.org/10.1144/GSL.SP.2005.244.01.04

Prior, D. B., Coleman, J. M., & Bornhold, B. D. (1982). Results of a known seafloor instability event. *Geo-Marine Letters*, *2*(3–4), 117–122. https://doi.org/10.1007/BF02462751

Puga-Bernabéu, Á., López-Cabrera, J., Webster, J. M., & Beaman, R. J. (2022). Submarine landslide morphometrics and slope failure dynamics along a mixed carbonate-siliciclastic margin, north-eastern Australia. *Geomorphology*, *403*. https://doi.org/10.1016/j.geomorph.2022.108179

Romagnoli, C., Casalbore, D., Chiocci, F. L., & Bosman, A. (2009). Offshore evidence of large-scale lateral collapses on the eastern flank of Stromboli, Italy, due to structurally-controlled, bilateral flank instability. *Marine Geology*, *262*(1–4), 1–13. https://doi.org/10.1016/j.margeo.2009.02.004

Rovere, M., Gamberi, F., Mercorella, A., & Leidi, E. (2014). Geomorphometry of a submarine mass-transport complex and relationships with active faults in a rapidly uplifting margin (Gioia Basin, NE Sicily margin). *Marine Geology*, *356*, 31–43. https://doi.org/10.1016/j.margeo.2013.06.003

Sassa, K., Canuti, P., & Yin, Y. (2014). Landslide science for a safer geoenvironment: Volume 3: Targeted landslides. *Landslide Science for a Safer Geoenvironment: Volume 3: Targeted Landslides*, *3*, 1–717. https://doi.org/10.1007/978-3-319-04996-0

Sawyer, D. E., & Devore, J. R. (2015). *M argins : Evidence for seismic strengthening*. 216–221. https://doi.org/10.1002/2015GL066603.Received

Scarselli, N. (2020). Submarine landslides - architecture, controlling factors and environments. A summary. In *Regional Geology and Tectonics: Volume 1: Principles of Geologic Analysis*. BV. https://doi.org/10.1016/B978-0-444-64134-2.00015-8

Schwehr, K., Driscoll, N., & Tauxe, L. (2007). Origin of continental margin morphology: Submarine-slide or downslope current-controlled bedforms, a rock magnetic approach. *Marine Geology*, *240*(1–4), 19–41. https://doi.org/10.1016/j.margeo.2007.01.012

Shan, Z., Wu, H., Ni, W., Sun, M., Wang, K., Zhao, L., Lou, Y., Liu, A., Xie, W., Zheng, X., & Guo, X. (2022). Recent Technological and Methodological Advances for the Investigation of Submarine Landslides. *Journal of Marine Science and Engineering*, *10*(11). https://doi.org/10.3390/jmse10111728

Smith, M. E., Werner, S. H., Buscombe, D., Finnegan, N. J., Sumner, E. J., & Mueller, E. R. (2018). Seeking the Shore: Evidence for Active Submarine Canyon Head Incision Due to Coarse Sediment Supply and Focusing of Wave Energy. *Geophysical Research Letters*, *45*(22), 12,403-12,413. https://doi.org/10.1029/2018GL080396

Strasser, M., Hilbe, M., & Anselmetti, F. S. (2011). Mapping basin-wide subaquatic slope failure susceptibility as a tool to assess regional seismic and tsunami hazards. *Marine Geophysical Research*, *32*(1), 331–347. https://doi.org/10.1007/s11001-010-9100-2

Su, M., Lin, Z., Wang, C., Kuang, Z., Liang, J., Chen, H., Liu, S., Zhang, B., Luo, K., Huang, S., & Wu, Q. (2020). Geomorphologic and infilling characteristics of the slope-confined submarine canyons in the Pearl River Mouth Basin, northern South China Sea. *Marine Geology*, *424*(March), 106166. https://doi.org/10.1016/j.margeo.2020.106166

Sultan, N., Cochonat, P., Canals, M., Cattaneo, A., Dennielou, B., Haflidason, H., Laberg, J. S., Long, D., Mienert, J., Trincardi, F., Urgeles, R., Vorren, T. O., & Wilson, C. (2004). Triggering mechanisms of slope instability processes and sediment failures on continental margins: A geotechnical approach. *Marine Geology*, *213*(1–4), 291–321. https://doi.org/10.1016/j.margeo.2004.10.011

Sultan, N., Garziglia, S., Bompais, X., Woerther, P., Witt, C., Kopf, A., & Migeon, S. (2020a). Transient Groundwater Flow Through a Coastal Confined Aquifer and Its Impact on Nearshore Submarine Slope Instability. *Journal of Geophysical Research: Earth Surface*, *125*(9). https://doi.org/10.1029/2020JF005654

Sultan, N., Garziglia, S., Bompais, X., Woerther, P., Witt, C., Kopf, A., & Migeon, S. (2020b). Transient Groundwater Flow Through a Coastal Confined Aquifer and Its Impact on Nearshore Submarine Slope Instability. *Journal of Geophysical Research: Earth Surface*, *125*(9), 1–18. https://doi.org/10.1029/2020JF005654

Sultan, N., Gaudin, M., Berne, S., Canals, M., Urgeles, R., & Lafuerza, S. (2007). Analysis of slope failures in submarine canyon heads: An example from the Gulf of Lions. *Journal of Geophysical Research: Earth Surface*, *112*(1), 1–29. https://doi.org/10.1029/2005JF000408

Sultan, N., Savoye, B., Jouet, G., Leynaud, D., Cochonat, P., Henry, P., Stegmann, S., & Kopf, A. (2010). Investigation of a possible submarine landslide at the Var delta front (Nice continental slope, southeast France). *Canadian Geotechnical Journal*, *47*(4), 486–496. https://doi.org/10.1139/T09-105

Talling, P. J., Clare, M., Urlaub, M., Pope, E., Hunt, J. E., & Watt, S. F. L. (2014). Large submarine landslides on continental slopes: Geohazards, methane release, and climate change. *Oceanography*, *27*(2), 32–45. https://doi.org/10.5670/oceanog.2014.38

Tappin, D. R. (2017). Tsunamis from submarine landslides. *Geology Today*, *33*(5), 190–200. https://doi.org/10.1111/gto.12200

ten Brink, U. S., & Geist, E. L. (2021). *On the Use of Statistical Analysis to Understand Submarine Landslide Processes and Assess Their Hazard*. 329–341. https://doi.org/10.1007/978-3-030-60196-6_23

Tinti, S., Chiocci, F. L., Zaniboni, F., Pagnoni, G., & de Alteriis, G. (2011). Numerical simulation of the tsunami generated by a past catastrophic landslide on the volcanic island of Ischia, Italy. *Marine Geophysical Research*, *32*(1), 287–297. https://doi.org/10.1007/s11001-010-9109-6

Tinti, S., Pagnoni, G., Zaniboni, F., & Bortolucci, E. (2003). Tsunami generation in Stromboli island and impact on the south-east Tyrrhenian coasts. *Natural Hazards and Earth System Science*, *3*(5), 299–309. https://doi.org/10.5194/nhess-3-299-2003

Urgeles, R., & Camerlenghi, A. (2013). Submarine landslides of the Mediterranean Sea: Trigger mechanisms, dynamics, and frequency-magnitude distribution. *Journal of Geophysical Research: Earth Surface*, *118*(4), 2600–2618. https://doi.org/10.1002/2013JF002720

Urlaub, M., Geersen, J., Krastel, S., & Schwenk, T. (2018). Diatom ooze: Crucial for the generation of submarine mega-slides? *Geology*, *46*(4), 331–334. https://doi.org/10.1130/G39892.1

Urlaub, M., Talling, P. J., & Masson, D. G. (2013). Timing and frequency of large submarine landslides: Implications for understanding triggers and future geohazard. *Quaternary Science Reviews*, *72*, 63–82. https://doi.org/10.1016/j.quascirev.2013.04.020

Van Daele, M., Versteeg, W., Pino, M., Urrutia, R., & De Batist, M. (2013). Widespread deformation of basin-plain sediments in aysén fjord (chile) due to impact by earthquake-triggered, onshore-generated mass movements. *Marine Geology*, *337*, 67–79. https://doi.org/10.1016/j.margeo.2013.01.006

Völker, D., Scholz, F., & Geersen, J. (2011). Analysis of submarine landsliding in the rupture area of the 27 February 2010 Maule earthquake, Central Chile. *Marine Geology*, *288*(1–4), 79–89. https://doi.org/10.1016/j.margeo.2011.08.003

Watson, S. J., Mountjoy, J. J., & Crutchley, G. J. (2020). Tectonic and geomorphic controls on the distribution of submarine landslides across active and passive margins, eastern New Zealand. *Geological Society Special Publication*, *500*(1), 477–494. https://doi.org/10.1144/SP500-2019-165

Watt, S. F. L., Talling, P. J., & Hunt, J. E. (2014). New insights into the emplacement dynamics of volcanic island landslides. *Oceanography*, *27*(2), 46–57. https://doi.org/10.5670/oceanog.2014.39

Wiemer, G., & Kopf, A. (2017). On the role of volcanic ash deposits as preferential submarine slope failure planes. *Landslides*, *14*(1), 223–232. https://doi.org/10.1007/s10346-016-0706-6

Xue, L., Liu, H., Li, Z., Sun, Z., Shan, H., & Jia, Y. (2023). In situ observation of wave-induced deformation of submarine landslides in tidal channel areas. *Frontiers in Earth Science*, *10*(January), 1–11. https://doi.org/10.3389/feart.2022.933031

Yoshikawa, S., & Nemoto, K. (2010). Seasonal variations of sediment transport to a canyon and coastal erosion along the Shimizu coast, Suruga Bay, Japan. *Marine Geology*, *271*(1–2), 165–176. https://doi.org/10.1016/j.margeo.2010.02.010

Zaniboni, F., Armigliato, A., Pagnoni, G., & Tinti, S. (2014). Continental margins as a source of tsunami hazard: The 1977 Gioia Tauro (Italy) landslide-tsunami investigated through numerical modeling. *Marine Geology*, *357*, 210–217. https://doi.org/10.1016/j.margeo.2014.08.011

Zaniboni, F., Pagnoni, G., Gallotti, G., Ausilia Paparo, M., Armigliato, A., & Tinti, S. (2019). Assessment of the 1783 Scilla landslide-tsunami's effects on the Calabrian and Sicilian coasts through numerical modeling. *Natural Hazards and Earth System Sciences*, *19*(8), 1585–1600. https://doi.org/10.5194/nhess-19-1585-2019

Zecchin, M., Accaino, F., Ceramicola, S., Civile, D., Critelli, S., Da Lio, C., Mangano, G., Prosser, G., Teatini, P., & Tosi, L. (2018). The Crotone Megalandslide, southern Italy: Architecture, timing and tectonic control. *Scientific Reports*, *8*(1), 1–11. https://doi.org/10.1038/s41598-018-26266-y

Zhang, M., Huang, Y., & Bao, Y. (2016). The mechanism of shallow submarine landslides triggered by storm surge. *Natural Hazards*, *81*(2), 1373–1383. https://doi.org/10.1007/s11069-015-2112-0

Zhou, Q., Li, X., Zhou, H., Liu, L., Xu, Y., Gao, S., & Ma, L. (2019). Characteristics and genetic analysis of submarine landslides in the northern slope of the South China Sea. *Marine Geophysical Research*, *40*(3), 303–314. https://doi.org/10.1007/s11001-018-9369-0

Addendum to DV2.2.3 - Rationale for the quantification of parameters measuring the proneness to ground instabilities in both offshore and onshore areas

AUTHORS

Chiara Colombero (POLITO); Filippo Zaniboni (UNIBO); Enrico Paolucci (UNIBO); Chiara Martinello (UNIPA); Giorgio Manno (UNIPA); Salvatore Martino (UNIROMA1) ***and the researchers of WP3***

Technical references

Project Acronym	RETURN
Project Title	multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate
Project Coordinator	Domenico Calcaterra UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II domenico.calcaterra@unina.it
Project Duration	December 2022 – November 2025 (36 months)

Deliverable No.	DV2.2.3
Dissemination level*	PU
Work Package	WP2.3 - Monitoring & Modelling: toward a digital twin of ground instabilities effects.
Lead beneficiary	POLITO, UNIBO, UNIPA, UNIROMA1
Contributing beneficiary/ies	ENEA, OGS, UNIBA, UNIBO, UNIFI, UNIGE, UNINA, UNIPD

* PU = Public

PP = Restricted to other programme participants (including the Commission Services)

RE = Restricted to a group specified by the consortium (including the Commission Services)

CO = Confidential, only for members of the consortium (including the Commission Services)

Document history

Version	Date	Lead contributor	Description
0.1	22.11.2023	Chiara Martinello (UNIPA) Giorgio Manno (UNIPA) Enrico Paolucci (UNIBO)	First draft
0.2	24.11.2023	Filippo Zaniboni (UNIBO) Chiara Colombero (POLITO)	Critical review and proofreading
1.0	24.11.2023		Final version

Abstract

This report is an addendum to the DV2.2.3 - *Rationale for the quantification of parameters measuring the proneness to ground instabilities in both offshore and onshore areas*. In particular, the scientific research activities carried out in the period July – November 2023 by the Work Package 2.3 (WP3) is here summarized.

WP3 focused on examining the preparatory processes to ground instabilities. This analysis was based on the learning from different approaches (on site and remote sensing monitoring data; numerical modeling and statistical analysis; machine learning techniques), collected on already deeply studied and analyzed case studies, or Learning Examples (LEs), supplied by the partner institutions. Fifteen preparatory processes (P) were identified from the inventory of LEs and at least a tool for the rationalization of each process was derived from each LE. This phase had the objective of building a Rationale for preparatory processes to be used as input to the Proof of Concept (PoC).

The activities carried out in these months have been centered on a critical review of the LEs' rationales and on an increase of the number of LEs for each preparatory process, that became necessary due to the criticalities highlighted with the deliverables 2.3.1 "*Data collection and analysis; implementation of geodatabases in advanced computing cloud systems*" and 2.3.3 "*Field-to-Num_Lab: experiencing innovative solutions for a real-time digital twin between in-site monitoring and numerical computation systems*". In detail, these criticalities are mainly linked to lack of marine and underwater LEs for the definition of a comprehensive Rationale for the related preparatory processes and to minor representation of liquefaction, subsidence, and sinkhole effects with respect to landslide studies.

With the aim of facing these issues, some actions have been undertaken and carried out: their articulation and the respective results obtained are here reported. It is worth reminding that the three WP3' tasks have worked together: for this reason, in this document the activities and their outcomes are reported as cumulatively gained from the whole WP3.

Table of Contents

List of Figures

List of Tables

1) Introduction

This document is an addendum to the DV 2.2.3 - *Rationale for the quantification of parameters measuring the proneness to ground instabilities in both offshore and onshore areas*, and summarizes the scientific research activities carried out in the period July – November 2023 by the Work Package 3 (hereafter, WP3) inside the vertical spoke VS2 "Ground Instabilities" of the Extended Partnership RETURN.

In order to carry out the planned actions, the three WP3' tasks

> **Task 2.3.1 (TK1)** "*Natural onshore and offshore field laboratories for remote and in-site monitoring of environmental forcings and deformation responses. Validation of cutting-edge sensors, technological devices, and techniques to identify and monitor precursor signals of ground instability, as well as the occurrence of ongoing deformations";*
>
> **Task 2.3.2 (TK2)** *"Numerical laboratories for digital twin reconstruction: numerical analyses devoted to quantifying the preparation parameters through multi-physical approaches based on data monitoring";*
>
> **Task 2.3.3 (TK3)** *"Deep learning and machine learning for mass wasting characterization in subaerial and submarine areas"*

have worked together: for this reason, in this document the activities and their outcomes are reported as cumulative gained from the WP3.

The general frame of **RETURN** (multi-Risk sciencE for resilienT commUnities undeR a chaNging climate) is devoted to the study of natural risks and their impacts on the anthropic and the natural context with particular attention to the effects related to climatic drivers. A detailed description of the project is out of the scope of this report and can be found at the link https://www.fondazionereturn.it/. Here it is worth recalling that, among the several natural phenomena addressed, the attention of VS2 focuses on ground instabilities, specifically landslides, sinkholes, subsidence, and liquefaction.

At present, VS2 involves 41 official researchers (13 females, 28 males) and 112 affiliated researchers (38 females, 74 males), for a total of 153 researchers from ENEA, OGS, POLITO, UNIBA, UNIBO, UNIFI, UNIGE, UNINA, UNIPA, UNIPD and UNIROMA1. From the project start, 18 researchers (RTDA) have been enrolled on RETURN (10 females, 8 males), together with 8 PhD candidates (6 females, 2 males) and 3 fellowships (1 female, 2 males).

Following the Executive Working Plan of RETURN, which was delivered as Milestone 2.1 on 31 December 2022, the institutions cooperating to the WP3 objectives are ENEA, OGS, POLITO, UNIBA, UNIBO, UNIFI, UNIGE, UNINA, UNIPA, UNIPD and UNIROMA1. WP3 leader and coordinator is Salvatore Martino (UNIROMA1), TK1 leader is Chiara Colombero (POLITO), TK2 leader is Filippo Zaniboni (UNIBO), TK3 is leaded by Filippo Catani (UNIPD).

As a premise and recall, the architecture and content of VS2 WPs related to the research activity's core is briefly summarized. The distinction between the different core WPs is made on the basis of the different factors/processes controlling ground instabilities targeted and analyzed in each of them. In particular:

- WP2 focuses on the detection and analysis of PREDISPOSING factors to ground instabilities.
- WP3 targets PREPARATORY factors to ground instabilities.
- WP4 is centered on TRIGGERING and multiple geohazards cascading scenarios (MULTIHAZARD).

The distinction between predisposing, preparatory and triggering factors/processes is based on the temporal scale of action. Predisposing factors are considered to be invariable at the scale of observation, while preparatory factors exhibit cyclical changes or trends during the same period. Finally, the trigger acts within a very short and well-defined time frame. Based on this definition, in the view of restitution of scenarios, the preparatory factors provide a "time dimension" to the quantitative evaluations of effects, allowing to consider different intensity of time-dependent variables in the analytical/quantitative models.

Inside the WP3, a first phase consisted of the collection of Learning Examples (LEs), that contributed to the identification of a set of preparatory processes (Table 1.1) aiming at classifying the phenomena involving ground instabilities and investigate techniques and approaches adopted so far to study them.

Table 1.1. Preparatory processes identified from the LEs of WP3.

Preparatory Process	**Identified PREPARATORY PROCESS**
WP3_P1	*Preparation for the detachment of soils related to physical and chemical alteration (weathering).*
WP3_P2	*Preparation for the detachment of soils related to variations in the saturation due to seasonal cumulated rainfalls.*
WP3_P3	*Preparation for the detachment of soils related to the effects of wildfires.*
WP3_P4	*Preparation for debris flows related to seasonal accumulation of debris in the high elevation feeding areas.*
WP3_P5	*Preparation related to durability of debris damming bodies in the riverbed.*
WP3_P6	*Preparation for the detachment of rock volumes related to diurnal and seasonal thermal stressors.*
WP3_P7	*Preparation for the detachment of rock volumes related to permafrost degradation.*
WP3_P8	*Preparation for coastal landslides related to climatic sea level fluctuations (sea level rise).*
WP3_P9	*Preparation for coastal landslides or at canyon heads and/or continental margins related to debris accumulation from riverbeds (deltaic systems) and subaerial processes (e.g., coastal landslides, lava flows).*
WP3_P10	*Preparation for underwater landslides, at canyon heads and/or continental margins, related to underwater solid transport under the coast (currents/waves).*
WP3_P11	*Preparation for detachment of submarine sediments related to outgassing phenomena.*
WP3_P12	*Preparation for sinkholes related to the evolution/maturation of karst phenomena.*
WP3_P13	*Anthropogenic preparation related to static loads or changes in subsurface fluid pressures or groundwater level.*
WP3_P14	*Preparation related to changes in the vegetation cover due to anthropogenic or natural causes (including vegetation diseases).*
WP3_P15	*Preparation related to pre-trigger events (e.g., seismic sequences, recurrent storm surges, cumulative intense rainfall events, landslide succession, creep and rock mass damaging).*

The analysis of this database and of the issues related to such investigation were the object of the two deliverables submitted in July 2023: DV2.3.1 "*Data collection and analysis; implementation of geodatabases in advanced computing cloud systems*" (related to TK1) and DV2.3.3 "*Field-to-Num_Lab: experiencing innovative solutions for a real-time digital twin between in-site monitoring and numerical computation systems*" (focusing on TK2 and TK3).

In the following, the actions undertaken to solve (or at least mitigate) these issues are illustrated, and their outcomes reported extensively.

2) The recall phase

2.1 Issues and priorities for each process

The activities carried out in the period July-November 2023 have been centered on a critical review of the LEs' rationales and on an increase of the number of LEs for each preparatory process. These actions have proved necessary due to the criticalities highlighted with the deliverables DV2.3.1 "*Data collection and analysis; implementation of geodatabases in advanced computing cloud systems*" and DV2.3.3 "*Field-to-Num_Lab: experiencing innovative solutions for a real-time digital twin between in-site monitoring and numerical computation systems*".

In detail, these criticalities are reported in Figure 2.1, and can be summarized as:

- lack of marine and underwater LEs for the definition of a comprehensive Rationale accounting for the related preparatory processes;

- minor representation of liquefaction, subsidence and sinkhole effects with respect to landslide studies.

DV 2.3.1 – 2.3.3: Conclusions

Critical point	***Solution to be implemented***
Lack of ***marine*** and ***underwater*** LEs for the definition of a comprehensive Rationale for the related preparatory processes (WP3) and trigger/multihazard scenarios (WP4)	***Internal recall*** for LEs devoted to these analyses and eventual target search for international bibliographic data and processing methods
Minor representation of ***liquefaction, subsidence and sinkhole*** effects with respect to landslide studies and LEs (WP3 and WP4)	***Internal recall*** for LEs devoted to these analyses and eventual target search for international bibliographic data and processing methods
Lack of coverage with sufficient LEs for ***selected WP3 preparatory processes*** (e.g. WP3_P4)	***Internal recall*** for LEs devoted to these analyses and eventual target search for international bibliographic data and processing methods

Internal Recall
July – November 2023

Figure 2.1. Critical points and proposed solutions highlighted within the deliverables DV2.3.1 and DV2.3.3.

The actions defined to mitigate or solve such issues have been articulated in the following stages:

i) critical review of the LEs' rationales collected in July, depending on their effectively suitability as input to PoC;
ii) opening the internal recall within the WP3 researchers' group for the upgrade of the already collected LEs' rationales;
iii) opening the internal recall within the WP3 researchers' group for the implementation of new LEs' rationales for the poorest represented preparatory processes;

iv) final critical review of the collected LEs' rationales;

v) sharing of the process detection tools (LEs) with the WP4, which will manage the differ tools in the PoC according to the specific environment.

Concerning action i), a detailed and critical review of the products collected for the previous deliverables shows that six preparatory processes are characterized by only one LEs' rationales (P1, P7, P10, P11, P12) or none (P4), while seven preparatory processes (P3, P6, P8, P9, P13, P14, P15) own few LEs' rationales (less than three). Moreover, some of the LEs' rationales required the translation in English from the Italian version or/and an update/integration of existing sheets to meet the PoC needs (output definition, coherence between input and output, coherence between analysis log and output). Table 2.1. List of issues and of the main priorities for the processes.Table 2.1 reports the specific issues for each process, highlighting the degree of priority through the colored scale (red: high; yellow; medium; green: low).

Table 2.1. List of issues and of the main priorities for the processes.

Preparatory Process	**Priority: HIGH – INTERMEDIATE – LOW** *Notes*
WP3_P1	*Only one LE' sheet. Consider potential reopening for empirical, semi-statistical or numerical models LEs allow estimating the THICKNESS of the alteration layer and/or the SPEED of its development*
WP3_P2	*Sufficient number of LEs, reopening is not necessary.*
WP3_P3	*Three LEs are available. Consider potential reopening for quantitative LEs*
WP3_P4	*No LE' sheet present! Reopening for any type of LE!*
WP3_P5	*Only one LE' sheet is present, but it can be generalised. Reopening is not necessary.*
WP3_P6	*Two LEs present. Consider potential reopening for quantitative LEs*
WP3_P7	*Only one LE. Consider potential reopening for quantitative LEs allow quantify temperature changes and permafrost degradation*
WP3_P8	*Two LEs present. Consider potential reopening for any type of LEs*
WP3_P9	*Two LEs present. Consider potential reopening for quantitative LEs*
WP3_P10	*Only one LE. Consider potential reopening for quantitative LEs allow quantify inshore transport dash (in the Mediterranean environment), wave motion also through numerical modelling*
WP3_P11	*Only one LE. Consider potential reopening for quantitative near shore LEs*
WP3_P12	*Only one LE. Consider potential reopening for any type of LE*
WP3_P13	*Consider potential reopening for quantitative LEs*
WP3_P14	*Consider potential reopening for quantitative LEs*
WP3_P15	*Consider potential reopening for quantitative LEs, especially for seismic sequences preparatory to the trigger, extreme rainfall events, landslides' succession, creep/rock mass damaging*

According to the issues and the main priorities for the preparatory processes, an internal recall within the researchers' group of WP3 was carried out. In particular, the following two main activities were conducted, running in parallel (beginning of September 2023 - half October 2023):

1 **Fixing the already existing LEs catalogue (call1)** by inserting the missing sheets and/or the translation from the Italian to the English version and the update/integration of existing LEs' sheets to meet the PoC needs (output definition, coherence between input and output, coherence between analysis log and output);

2 **Expanding the LEs catalogue according to the list of priorities (call2)** by the integration of the LE inventory and the upload of reference papers (before the end of September) and the rationalization of the new LEs (Mid October).

2.2 Results of the recall

At the deadline of the internal recall, the majority of the issues and priorities identified by the critical review were positively addressed.

As a priority aim, the internal recall was focused on improving the number of LEs' rationale sheets/tools for those preparatory processes with no or few cases. After the two calls (Figure 2.2), some of the preparatory processes have achieved the minimum number of three LEs' rationale tools (P2, P9, P8, P9, P11 and, P14) while other have largely overtaken the minimum cut-off (P1, P6, P3 and, P15). On the other hand, P3, P4, P7, P10 and P12 are again characterized by a very low number of LEs' rationale tools.

Process	call1	call2	TOT
P1	1	4	5
P2	2	1	3
P3	2	0	2
P4	0	1	1
P5	1	0	1
P6	2	3	5
P7	1	1	2
P8	2	2	4
P9	2	1	3
P10	1	1	2
P11	1	2	3
P12	1	0	1
P13	5	0	5
P14	3	1	4
P15	16	4	20
	40	21	61

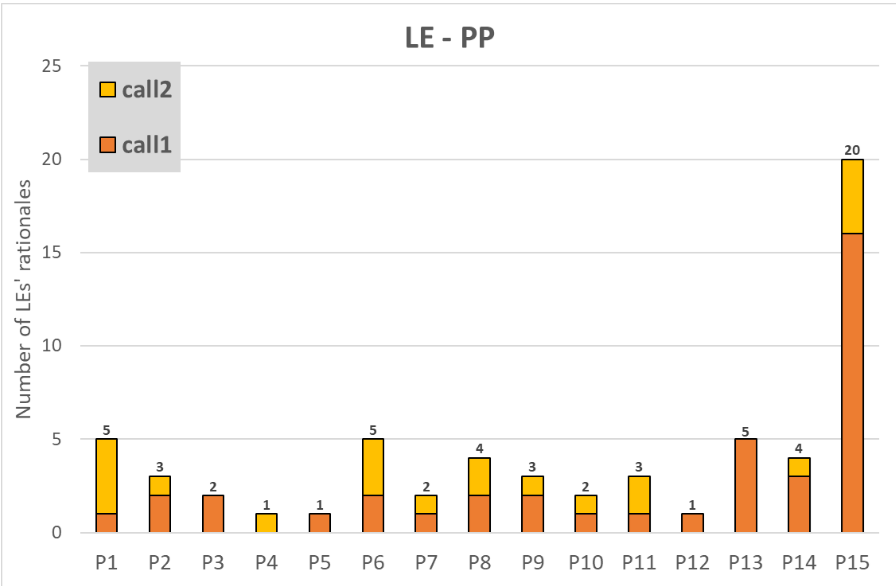

Figure 2.2. General results of the internal recall.

As a second critical point, the internal recall was focused on recovering more quantitative cases. After the calls (Figure 2.3), the quantitative approach is still the less used but, due to the general increase of the number of LEs' rationales, also an increase of the quantitative cases (passing from 6 to 14 cases) was highlighted. Furthermore, the semi-quantitative approach takes note of an increase of the number of LEs' rationales, moving from 11 to 17 cases. The qualitative analysis log is the prevalent, passing from 25 to 34 LEs' rationale tools.

	QUAL		SEMIQ		QUANT	
P	call1	call2	call1	call2	call1	call2
P1	1	1	0	1	0	2
P2	1	1	1	0	1	0
P3	1	0	1	0	0	0
P4	0	0	0	1	0	0
P5	0	0	0	0	1	0
P6	0	0	1	1	1	2
P7	1	0	0	0	0	1
P8	1	2	0	0	1	0
P9	2	1	0	0	0	0
P10	1	1	0	0	0	0
P11	1	1	1	2	0	0
P12	1	0	0	0	0	0
P13	3	0	2	0	0	0
P14	1	1	2	1	0	0
P15	11	1	3	0	2	3
TOT	**25**	**9**	**11**	**6**	**6**	**8**

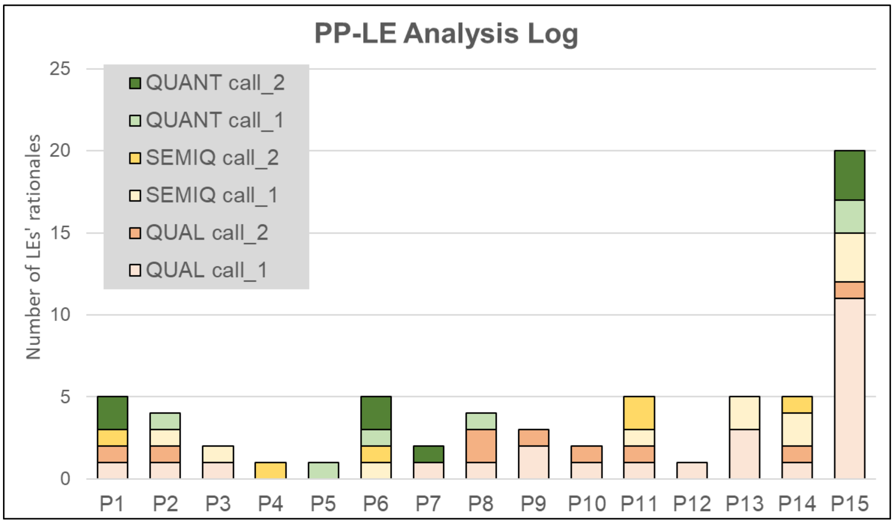

Figure 2.3. Analysis logs results of the internal recall.

In particular, among the different types of output (Figure 2.4), the restitution of outputs through classes is the most used (with 36 cases), followed by equations (with 13 cases) and indices (with 9 cases).

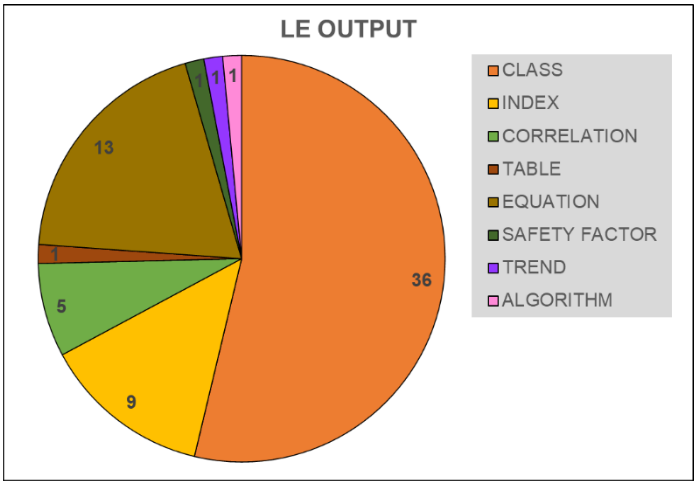

Figure 2.4. Type of output after the internal recall.

Another critical point was the collection of more LEs adopting numerical modelling (TK2) and/or machine learning (TK3) approaches (Figure 2.5). The LE' tools that use the modelling approach have increased, passing from 12 to 23, while the machine learning approach is used only in the P6 (1 case), P8 (3 cases), P14 (1 case), P15 (3 cases).

	TASK1 monitoring		TASK2 modeling		TASK3 ML	
P	call1	call2	call1	call2	call1	call2
P1	1	3	0	3	0	0
P2	2	1	1	1	0	0
P3	1	0	2	0	0	0
P4	0	1	0	0	0	0
P5	1	0	0	0	0	0
P6	2	3	1	1	1	0
P7	1	1	0	0	0	0
P8	2	0	1	1	1	2
P9	2	1	0	0	0	0
P10	1	1	0	0	0	0
P11	1	2	0	2	0	0
P12	1	0	0	0	0	0
P13	5	0	3	0	0	0
P14	2	1	0	0	1	0
P15	16	1	4	3	2	1
TOT	38	15	12	11	5	3

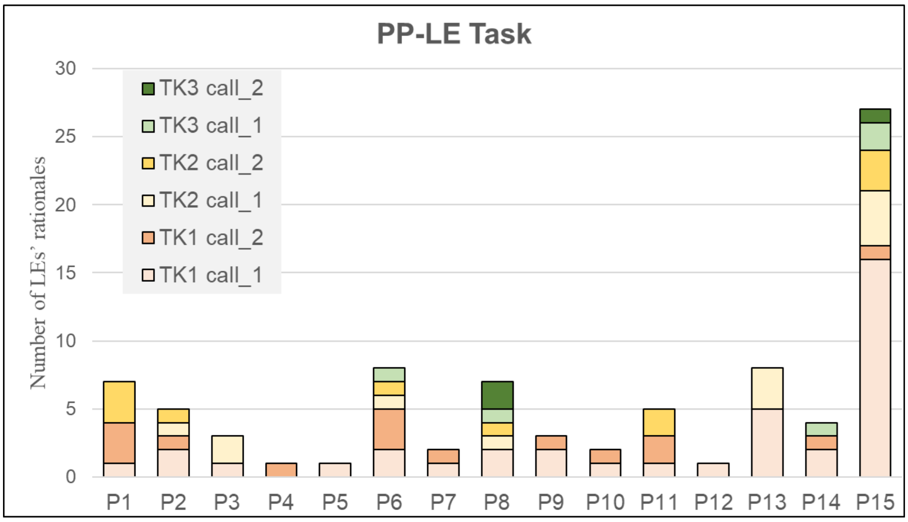

Figure 2.5. LEs' rationales subdivision among monitoring, modelling, and machine learning approaches after the internal recall.

The calls allowed to increment LEs' rationale tools related to the submarine environment (Figure 2.6), filling the gaps for the P8, P9, P10, and P11 processes, with a total number of 13 cases. Obviously, the subaerial environment is still the most studied and represented, with 51 LEs' rationale tools.

	SUBAERIAL		SUBMARINE	
P	call1	call2	call1	call2
P1	1	4	0	0
P2	2	1	0	0
P3	2	0	0	0
P4	0	1	0	0
P5	1	0	0	0
P6	2	3	0	0
P7	1	1	0	0
P8	2	2	0	2
P9	0	0	2	1
P10	0	0	1	1
P11	0	0	1	2
P12	1	0	0	0
P13	5	0	1	0
P14	3	1	0	0
P15	14	4	2	0
TOT	34	17	7	6
	51		13	

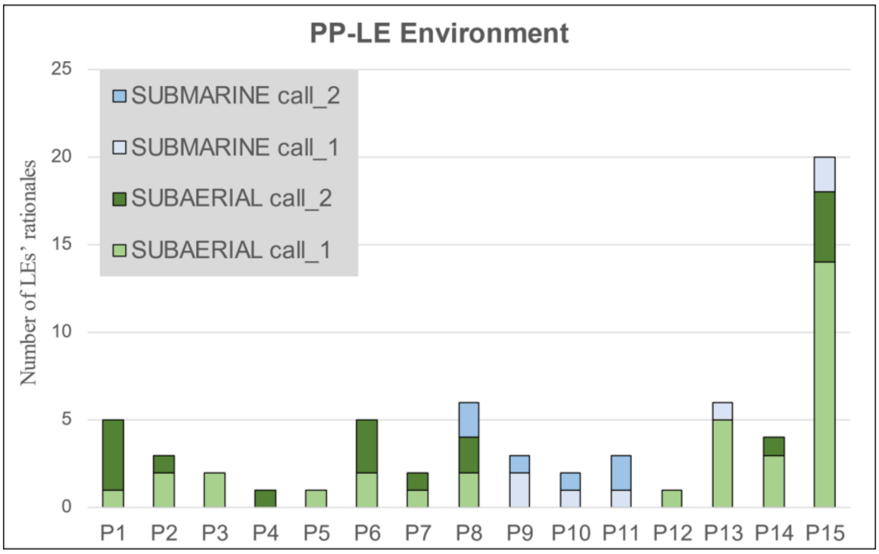

Figure 2.6. LEs' rationale tools subdivision among submarine and subaerial after the internal recall.

At the same time, the calls produced an increase of the LEs' rationales for the near shore context with a total collection of 12 LEs. The mountain context is the most studied with 32 LEs' rationale tools, followed by the hill context, with 27 cases (Figure 2.7).

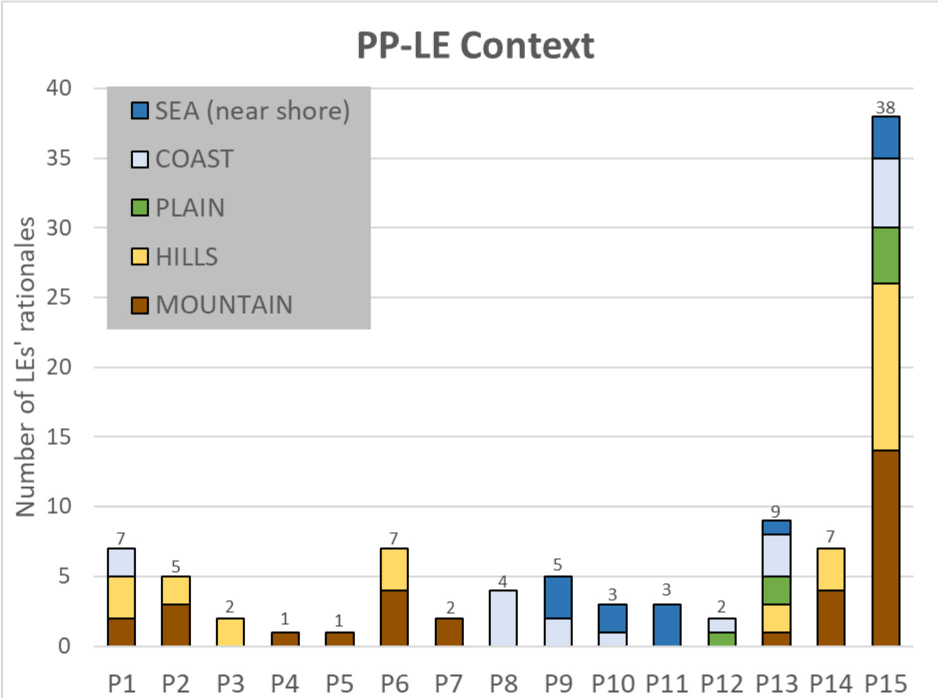

Figure 2.7. LEs' rationale tools subdivision among the different contexts after the internal recall.

One of the priorities of the calls was to add more LEs regarding liquefaction, sinkhole and subsidence effects. No increment of LEs' rationale tools for sinkhole effect is however reported after the internal recall. Even if the total number of cases is still low, 3 cases for liquefaction and subsidence are recovered, respectively (Figure 2.8).

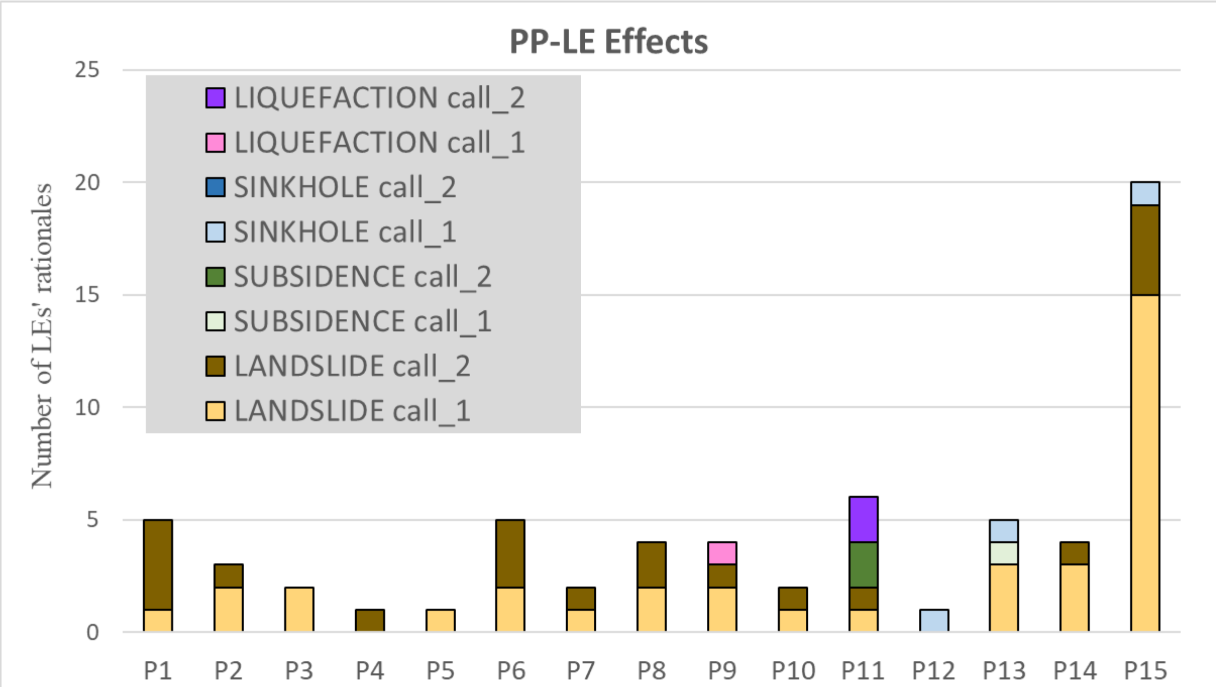

Figure 2.8. LEs' rationale tools subdivision among the different effects after the internal recall.

As regards the distribution of the LEs' rationale tools among the different tasks of the WP3, TK1 collects 31 cases, followed by TK2 with 4 cases and TK3 with 3 cases, in this reflecting also the history of the approaches to the study of natural phenomena: monitoring is the classic and first adopted investigation tool, numerical modeling improved significantly in the last two decades, and machine learning is still in its initial stage. On the other hand, the learning techniques integration are also shown: 18 cases are simultaneously studied by the TK1 and TK2; 4 cases are used by the TK1 and TK3 together (without increment after the call2); only one case is analyzed by TK2 and TK3. No cases are studied simultaneously by the three approaches (Figure 2.9).

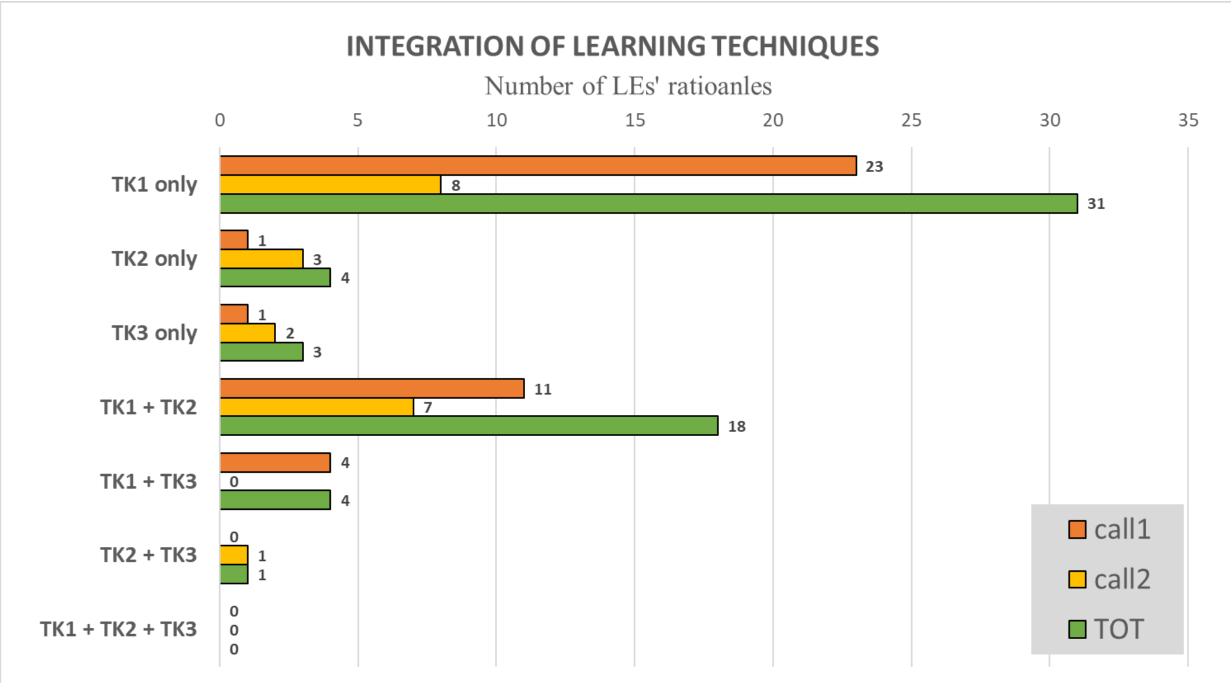

Figure 2.9. LEs' rationale tools subdivision among the different Tasks after the internal recall.

At the same time, the call1 allowed to improve the overall quality of the LEs' rationalization. In particular, with the aim to furnish a sheet effectively suitability as input to PoC, the authors have modified the LEs' rationale sheets related to each tool, improving output definition, coherence between input and output, coherence between analysis log and output. An example of upgraded sheet is reported below (Table 2.2).

Table 2.2. Example of the upgrade of the LEs' rationale tools.

PROCESS	**WP3_13** *Anthropogenic preparation related to static loads and variations of the groundwater level*
LEARNED FROM *(indicate the code of the reference LE - learning example)*	**SA_10_WP3**
3) PROCESS CONTROL PARAMETERS	1) geometry of the slope and hydraulic regime 2) physical and mechanical properties of soils (strength, stiffness, hydraulic conductivity) 3) predisposing factors: variation of the stress state and of the hydraulic regime induced by processes of excavation of the quarry slope
2) INPUT DATA TO THE RATIONALE for the analysis of the process	1) time-modification of the slope geometry induced by the excavations processes of the quarry 2) excavations combined with consolidation processes in soils related to a time-modification of the hydraulic regime in the slope
3) LEARNING METHODS (from which the input data were derived) *(on site/remote sensing monitoring – Task 1; numerical modeling – Task 2; machine learning – Task 3; specify the type/task and provide the methodological description for each input to the rationale)*	**Task 1** – on site monitoring (piezometers and inclinometers) **Task 2** – Limit equilibrium analyses and finite difference numerical 2D analyses using a coupled hydromechanical approach (u-p approach) The results indicate that the deep retrogressive failure mechanism leading to a neo-formation landslide was triggered by the pore pressure equalisation process, still occurring in the slope well after the end of quarrying.
4) APPLICABILITY CONSTRAINTS *(specify the application context/environment, highlight the spatial and temporal scale limits and the requirements for applicability)*	The scale is that of the slope. Inclination of the slope: 10 ÷ 15° with respect to the horizontal plane, with groundwater level located between 2 and 6 m depth from the ground level and failure occurring along rotational neo-formation mechanisms induced by quarrying activities at the toe of the slope. Soil characteristics: sub-Apennine saturated blue clays of medium plasticity (PI = 20 ÷ 30 %) characterized by overconsolidation ratio OCR = 3 ÷ 10 (higher values at shallow depths, lower values attained around 50 m depth).

	Hydraulic conductivity in the range of $5x10^{-11}$ and $7x10^{-11}$ m/s.
5) ANALYSIS LOGS *(specify if qualitative, semi-qualitative or quantitative)*	-semi-qualitative: the numerical analyses carried out in this case allow to define typical patterns of the instability mechanisms as compared to the monitoring results. Lesson learned is that the effect of the quarry excavation on the modification of the hydraulic regime in slopes and the consequent displacements induces by the attainment of the shear strength are characterized by a certain delay that depends on the consolidation processes.
6) OUTPUTS *(specify if categories or indexes or algorithms according to the analysis logs and provide a full description of each output)*	The retrogressive failure typically occurs along circular slip surfaces connecting the toe and the top of the slope, with a longitudinal extension within the range of 1.5÷2 times the height of the front of excavation of the quarry. The displacement rates are in the range of 4-5 mm/day and are typical of slow movements, hence the time required to reach a stabilization of the process ranges within 20÷30 years after the conclusion of the quarrying.

3) Conclusions

The WP3 activities carried out between 01/08/2023 and 30/11/2023 have been devoted to deepen the analysis of the processes preparatory to ground instabilities. This analysis was based on the learning from already deeply studied and analyzed case studies or Learning Examples (LEs). The activities carried out in the last four months have been centered on a critical review of the LEs' rationale tools delivered in July 2023 (DV2.3.1 "*Data collection and analysis; implementation of geodatabases in advanced computing cloud systems*"; DV2..3.3 "*Field-to-Num_Lab: experiencing innovative solutions for a real-time digital twin between in-site monitoring and numerical computation systems*") and on the increase in the number of LEs related to each preparatory process.

These activities have been necessary due to the criticalities highlighted within such deliverables. In detail, these criticalities were mainly linked to lack of marine and underwater LEs for the definition of a comprehensive rationale for the related preparatory processes and to a minor representation of liquefaction, subsidence and sinkhole effects with respect to landslide studies. In particular, a detailed and critical review of the products collected for the previous deliverables showed that six preparatory processes were characterized by only one LEs' rationale tool (P1, P7, P10, P11, P12) or none (P4), while seven preparatory processes (P3, P6, P8, P9, P13, P14, P15) owned few LEs (less than three). Moreover, some of the LEs' rationale sheets describing the tools required the translation in English from the Italian version or/and an update/integration to meet the PoC needs (output definition, coherence between input and output, coherence between analysis log and output).

For these reasons, an internal recall within the WP3 researchers' group was opened. This recall was focused on the upgrade of the already collected LEs' rationale tools (call1) and on the implementation of new LEs' rationale tools for the poorest preparatory processes (call2).

A general increase in the number of the LEs' rationale tools was achieved, but some preparatory processes (P3, P4, P7, P10 and P12) are still characterized by a very low number of LEs. As regards the analysis logs, the quantitative approach was implemented, passing from 6 to 14 cases.
The machine learning approach was used for 8 LEs' rationale tools while monitoring and modelling approaches recorded a higher increase of LEs.
Submarine LEs increased from 7 to 13, with a distribution in the near shore context of 12 cases.
The number of LEs' rationale tools is still low for the liquefaction and subsidence effects, while no new LEs' tools were reported for sinkholes in call2.

As a general conclusion, with the two calls, the majority of the issues and priorities identified by the critical review have been positively addressed and solved. However, it remains clear that a dedicated cascade funding call is necessary for recovering LEs' rationale tools for the preparatory processes characterized by a very low number of LEs (P3, P4, P7, P10 and P12).

On the other hand, the revision and recall activities allowed to improve the overall quality of the LEs' rationalization, furnishing tools effectively suitable as input to the Rationales and PoC. The LEs' rationale tools (LEs) were finally shared with the WP4 for the construction of the Rationale's architecture related to the different environments and contexts.

List of abbreviations

DV2.2.3	Deliverable 2.2.3 - *Rationale for the quantification of parameters measuring the proneness to ground instabilities in both offshore and onshore areas*
DV2.3.1	Deliverable 2.3.1 - *Data collection and analysis; implementation of geodatabases in advanced computing cloud systems*
DV2.3.3	Deliverable 2.3.3 - *Field-to-Num_Lab: experiencing innovative solutions for a real-time digital twin between in-site monitoring and numerical computation systems*
LE	Learning Example
P#	Process number
PoC	Proof of Concept
RETURN	multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate
TK1	Task 2.3.1 - *Natural onshore and offshore field laboratories for remote and in-site monitoring of environmental forcings and deformation responses. Validation of cutting-edge sensors, technological devices, and techniques to identify and monitor precursor signals of ground instability, as well as the occurrence of ongoing deformations*
TK2	Task 2.3.2 - *Numerical laboratories for digital twin reconstruction: numerical analyses devoted to quantifying the preparation parameters through multi-physical approaches based on data monitoring*
TK3	Task 2.3.3 - *Deep learning and machine learning for mass wasting characterization in subaerial and submarine areas*
VS2	Vertical Spoke 2 – "Ground Instabilities"
WP3	Work Package 2.3 - *Monitoring & Modelling: toward a digital twin of ground instabilities effects*