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The 1st Willy Alvarenga Lacerda lecture: New perspectives for landslide analysis and management

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Lecture

Keywords
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Landslide triggering
Landslide evolution
Multidisciplinary approach
Multiscale approach
Landslide management

Abstract

Landslides are widespread all over the world, often causing significant consequences in terms of loss of life and property damage. This explains why many scientists from Geology and Geotechnics have long been engaged in solving complex problems of both theoretical and practical interest. Geologists have systematically investigated the common characteristics of landslides proposing several classification systems, while not providing general laws for the triggering and evolution stages. Geotechnical engineers have implemented models to quantitatively analyze these stages but not to develop a general framework for typical landslide behaviors. Aimed to bridge the scientific branches dealing with landslides and based on the past efforts of many researchers all over the world, this paper focuses on deep-seated landslides developing along an existing and/or a new slip surface and multiple shallow landslides that may involve large areas in short periods of time. Considering that these phenomena are often analyzed at one single topographical scale and through monodisciplinary approaches, the paper proposes a new vision that highlights the possibility of a landslide management modern and open to the advanced technologies.

1. Introduction

Many countries around the world are threatened by landslides that often cause significant consequences in terms of loss of life and property damage. Many datasets testify to the great diffusion and consequence of landslides and among these Froude & Petley (2018) and Kirschbaum et al. (2015) provide the necessary information on the subject. Another example is the landslide risk plans developed since 1998 at an intermediate scale (1:25,000) in Italy, that is the country with the highest landslide risk in Europe, which counts about 500,000 existing and potential landslides over an area of 301,230 km^2.

The diffusion and consequences of landslides explain the efforts of scientists and authorities to improve knowledge and to manage the related risk. Focusing on the scientific aspects, several disciplines (Geology, Geomorphology, Geography, Geotechnics, Geomechanics, Hydraulics, Hydrology, Social Sciences, etc.) deepen many topics from different perspectives and with different approaches. Among these, a leading role has been played, since the past, by Geology and Geomorphology, on the one hand, and Geotechnics and Geomechanics, on the other. All of them investigate, often on a monodisciplinary basis, such a variety of issues that their statement alone is beyond the scope of this paper. Referring to the topics covered in the following sections, it is worth noting that one of the main objectives of Geology and Geomorphology is to find common characteristics of landslides, while Geotechnics and Geomechanics essentially focus on their mechanical behavior.

As regards the common characteristics of landslides, the topic is so much debated that, to date, more than 100 classification systems have been proposed in the scientific literature; the best known has been developed by Varnes (1978) and the latest one by Hungr et al. (2014). While many of these proposals are extremely useful from a technical and scientific point of view, none of them can provide insight into the laws that regulate the triggering and evolution stages of landslides.

This topic is analyzed through a variety of equation-based methods that can be essentially grouped into two different categories. The first category implements limit equilibrium equations or develops coupled or uncoupled stress-strain finite-element analyses. These models are usually applied with an extended detailed dataset on: landslide stratigraphy, mechanical properties of landslide materials, pore water pressure regime, landslide displacements and so on. The second category implements mechanical models characterized by a low number of degrees of freedom to describe the external and internal forces acting on the landslide body. These models implement complex equation systems to capture the essence of the landsliding and, in many cases, an advanced dataset is not essential. Both categories of methods are extremely useful to solve scientific and technical questions, but they cannot be used to extend the knowledge from a single phenomenon to classes of similar mechanical behaviors.

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This gap in scientific literature may lead one to believe that all landslides are unique and that it is impossible to identify common mechanical laws governing their dynamic equilibrium. In addition, the absence of a consistent bridge between the many disciplines dealing with landslides prevents the advancement of knowledge on many phenomena, especially those that often cause the worst consequences.

This paper aims to lay the foundations for progressing in the analysis and management of single deep-seated landslides, which develop along an existing and/or a new slip surface, and of multiple shallow instabilities that may involve, quite often as shallow landslides, large areas in a short period of time. To this end, the materials and methods used, the results achieved so far and the perspectives they open are discussed in the following sections.

2. Materials

Varnes (1978) classifies the landslides according to their instability features (fall, topples, slides, lateral spreads, flows, complex slides) and the materials involved in the landsliding (rock and soils). Hungr et al. (2014) provide more details on several factors, but the classification system is also based on a geomorphological description of the phenomena. This applies to many other proposals in the literature which, together with those mentioned above, represent the starting point for the geotechnical study of a single deep-seated landslide and multiple shallow instabilities. However, the predisposing and triggering factors, soil/rock properties and boundary conditions can be so different for both categories of instability phenomena as to suggest a detailed analysis for each case study to understand and model the triggering and evolution stages.

Leoroueil et al. (1996) hinted at the possibility of overcoming this vision for single deep-seated landslides. Later, the research activity developed at the University of Salerno (Italy), where the present author served as a professor of Geotechnics, has progressively outlined the possibility of passing from a heuristic to a mechanical evaluation of the landslide evolution stages. Similar attempts do not exist for multiple shallow instabilities, which encompass a wide range of phenomena often involving complex soil/rock materials.

For these two categories of landslides the following sections describe the input data implemented in the analyses, which derive from different case studies for deep-seated landslides and from a single case study for multiple shallow instabilities.

2.1 Input data for single deep-seated landslides

The landslides moving along an existing or new slip surface are divided by Leoroueil et al. (1996) into two sub-categories, which include respectively the first failure and the existing landslides. For each of them two different evolution stages are introduced, named pre-failure and post-failure for first failures and occasional reactivation and active landslides for the existing ones, Figure 1. During the failure stage, the authors hypothesize a very high velocity which decreases rapidly during the post-failure stage. For the existing landslides, they assume i) a moderately large velocity, when they are reactivated by exceptional triggering factors (i.e., earthquakes) or ii) a low velocity, if they are activated by recurring factors, such as seasonal rainfall.

As a general commentary, the authors observe that: "These four stages, with some modification depending on the type of movements, also apply to rock masses. Each of these four stages involves mechanical phenomena, controlling laws and parameters which are very different, so that Vaunat et al. (1994) came to the conclusion that it is necessary to separate these stages to understand, analyze and characterize the movements of the slopes".

These concepts have been deepened in a long-lasting research program started at the University of Salerno (Italy) in 2006 with the aim of filling the gap of knowledge for one of the most widespread type of landslides in the world. Without further relevant references in the literature, the research was developed in three key steps:

- Collecting case studies deeply investigated in the literature, regardless of the materials involved in the landsliding, the predisposing and triggering factors, the activity stages and the displacement values;
- Implementing a simple procedure to individuate common evolution stages among the landslides, apparently different from each other in the dataset;
- Finding the kinematic characteristics of the evolution stages, if any, with the aid of the fundamental laws of Mechanics and Physics.

The activities of the first step, discussed in this section, have been requiring a constant commitment which, to date, has led to identifying 18 case studies around the world, well documented in the scientific literature (Table 1).

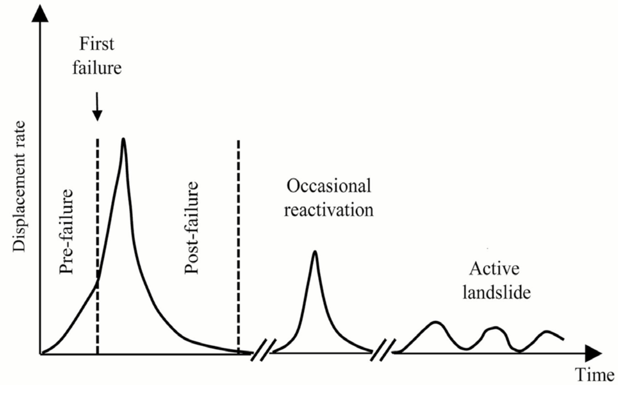

Figure 1. The landslide evolution stages introduced on a phenomenological basis [modified from Leoroueil (2001)].

Among them, 14 cases are from Europe (Italy 11, France 1, Switzerland 1, Spain 1), 3 in Asia (Japan 2, China 1), 1 in South America (Chile 1). Figure 2 provides an overview of two landslides that marked the recent history of the Italian territory as their evolution caused many casualties, huge economic damages, and the attention of mass-media over a long period of time.

The landslides in the dataset are classified according to Varnes (1978) as slides, translational slides, rotational slides, toppling, complex slides, avalanches. A similar variety of landslide triggering factors emerges from the references in Table 1 which, depending on the case, include rainfall, snow melt, rainfall and snow melt, water level fluctuation in a reservoir, excavations, earthquake. An even more marked variety is for the materials involved in the landsliding classified in the references as: rock and/or rock in different matrices, granitic gneisses, tuff, limestone, sandstones, debris, marly clay, stiff clays, clay schists, clay, volcanic grains, silt, etc. Finally, the length of the landslides (L) and the depth of the slip surface (H), Figure 3, vary in the ranges L = 340-2,000 m and H = 9.6-250 m. Often, the lowest values refer to a secondary sliding body of dimensions l and h, as schematized in the figure.

Aware that the equation-based methods (i.e., limit equilibrium methods, coupled or uncoupled stress-strain finite-element analyses, mechanical models characterized by a low number of degrees of freedom) could not be used to identify common characteristics among the selected landslides, the attention was focused on landslide displacements.

Table 1. The collected dataset (Scoppettuolo et al., 2020).

Landslide Name	Location	References
Bindo-Cortenova	Valsassina, Lecco, Italy	Secondi et al. (2011)
Castelrotto	Bolzano, Italy	Simeoni & Mongiovì (2007)
Chuquicamata	Andes, Chile	Voight & Kennedy (1979)
Fosso San Martino	Teramo, Italy	Bertini et al. (1986)
Kunimi	Japan	Shuzui (2001)
La Clapière	Southern Alpes, France	Helmstetter et al. (2004)
La Frasse	Aigle, Switzerland	Tacher et al. (2005)
La Saxe	Courmayeur, Valle d'Aosta, Italy	Crosta et al. (2014)
Montaldo di Cosola	Alessandria, Italy	Lollino et al. (2006)
Ohto	Japan	Suwa et al. (2010)
Porta Cassia	Orvieto, Italy	Tommasi et al. (2006)
Ragoleto	Licodia Eubea (Catanzaro, Italy)	Musso (1997)
Rosone	Orco river valley, Turin, Italy	Binet et al. (2007)
Ruinon	Valtellina, Sondrio, Italy	Crosta & Agliardi (2003)
Vallcebre	Pyrenees, Spain	Corominas et al. (2005)
Val Pola	Valtellina, Sondrio, Italy	Crosta et al. (2004)
Vajont	Erto e Casso, Pordenone, Italy	Nonveiller (1987)
Xintan	China	Keqiang & Sijing (2006)

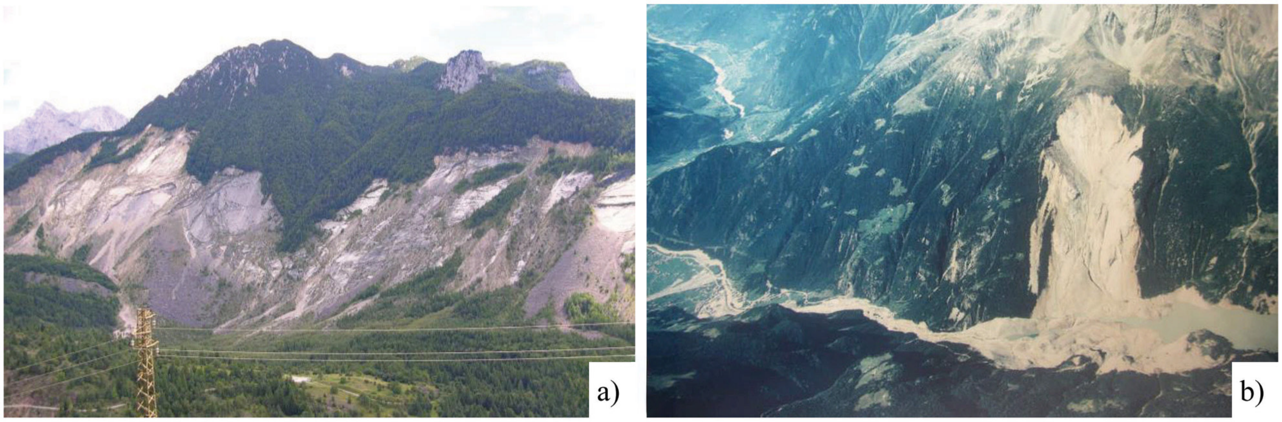

Figure 2. a) Vajont landslide (Wikipedia, 2023); b) Val Pola landslide [Studio Majone Ingegneri Associati (2023)].

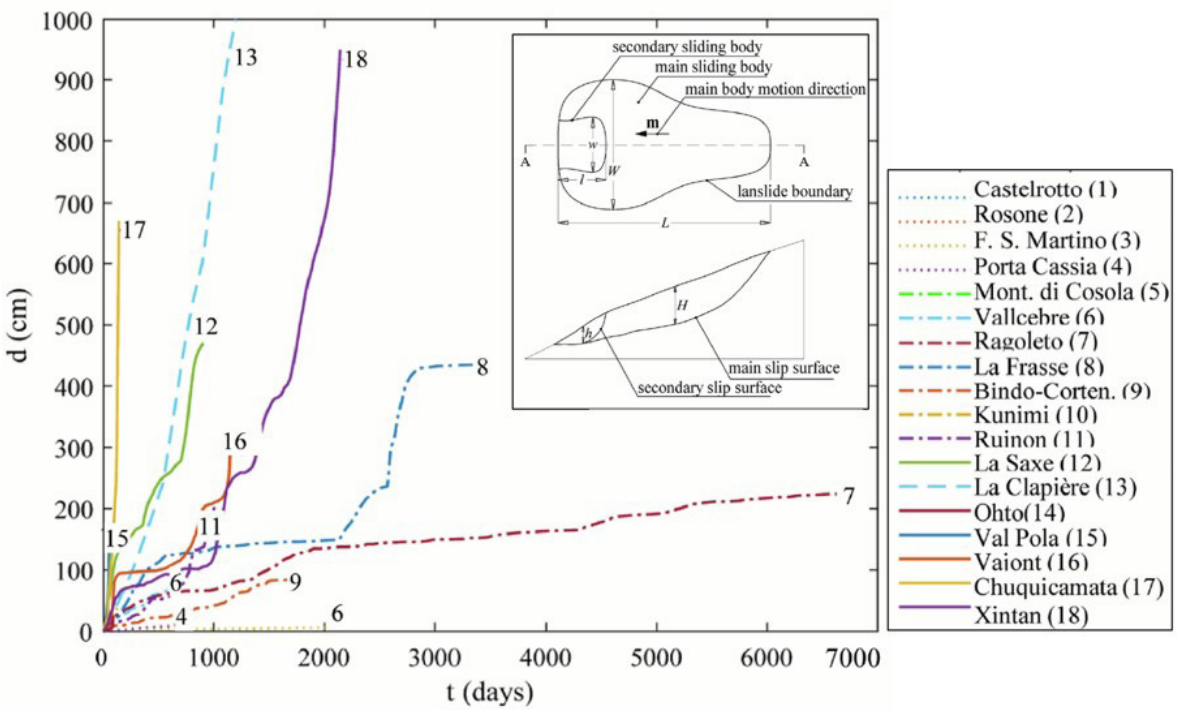

Figure 3. Geometry and dimensional displacements of the landslides in the dataset [modified from Cascini et al. (2022)].

This scientific investigation was started believing that the extent and types of displacements were linked also to the imbalance between the external and resistance forces acting on the landslide, regardless of the landslide type and the material involved. Indeed, the monitoring techniques, the historical time series, their significance and accuracy and anything else necessary for implementing the second and third key steps of the procedure were carefully analyzed before selecting each case study.

For information purposes it is noted that the displacements have been measured through: inclinometers (7), surface markers (4), extensometers (3), optical targets (2), distometer (1), crackmeters (1). In all the cases, the experimental devices are clearly described in the references (Table 1) which specify whether the measurements refer to the whole landslide body or to a part of it. The experimental data thus collected are plotted in Figure 3.

2.2 Input data for a case study of multiple shallow instabilities

This type of phenomena occurs in many geological contexts, often as shallow landslides threatening large areas in a short period of time. The slopes covered by ashy soils are among the most dangerous contexts due to the metastable behavior of these materials. However, despite the diffusion and consequences of such phenomena around the world (Cuomo, 2006), their analysis and management are far from being standardized due to: use of-monodisciplinary approaches usually implemented at a single topographical scale; oversimplification of the triggering mechanisms, predisposing factors and triggering causes; lack of historical data and input data for the geological and geotechnical analyses and so on.

This paper focuses on the case study of the Campania region (Southern Italy) currently threatened by the Vesuvius volcano, the only active volcano in the continental Europe, and in the past by other volcanic systems which both played a primary role in covering the slopes of the mountain basins in an area of about 3,000 km^2 (Figure 4a).

However, these mountain basins differ in soil covers, underlying bedrock, exposure of the slopes, geographical position, urbanization of the areas at the toe of the slopes, etc. Regardless of the differences, many mountain basins have been systematically affected in the past by catastrophic events, as that one in 1997 in Pozzano (Figure 4b), which caused four fatalities, and those in 1998 along the Pizzo d'Alvano massif (Figure 4c), responsible for 160 victims and economic damage amounting to 500 million euros.

Considering the limited knowledge at the time of the first event, detailed historical research was soon started. The first dataset on the past events was completed in the spring of 1998, almost concurrently with the second event which confirmed the very high risk threatening a large area of the Campania region. The echo of this second event in Italy and abroad, the commitment of the authorities, along with the scientific, technical and civil community made possible to acquire, during the emergency management of the event and in the following years, a large amount of data on many topics. Examples of the results achieved are provided in Figure 4d, as it concerns the historical events, and in Figures 5, 6, 7 regarding the in-situ and laboratory investigations.

Figure 5 refers to the Pizzo d'Alvano massif, for which the dataset contains the stratigraphical setting of the soil covers, the soil suction regime, the mechanical properties of the lithotypes, etc. Figure 6 refers to the Monte Albino massif, which threatens the municipality of Nocera Inferiore with various flow-like phenomena originated by shallow landslides or soil erosion due to runoff along the slopes. In detail, the figure shows the approximately 2,000 verticals investigated over an area of about 400 hectares to develop an accurate soil cover map all over the massif (Matano et al., 2016). Finally, Figure 7a refers to mountain basins of the Amalfi Coast systematically characterized by the presence of a village at the toe with the ancient ravine transformed in a paved culvert inside the urban area. The figure also provides an example of a soil cover map (Figure 7b), elaborated with the aid of the in-situ investigations, and of the analyzes that must be developed in these basins to evaluate, for the presence of the culvert, the cascading effects caused upstream by the slope instabilities triggered by critical rainfall (Figure 7c).

In conclusion, many investigations, often coordinated with each other, even if they were performed in different years and for different purposes, have made possible the investigation of many issues over a particularly vast territory. Among these issues it is worth mentioning: hydrology; soil stratigraphy relating the lithotypes to the eruption of the Vesuvius volcano; the trend of soil suction which, unlike in the past literature, links the season of the year, exposure of the slopes and bedrock underlying the soil cover into a unique framework; the mechanical properties of soils, in total and partial saturation conditions, which allow any standard or advanced geotechnical analysis; mechanisms and characteristics of the triggering and run out phenomena. It must be stressed that almost all these issues were addressed by the University of Salerno from a multidisciplinary and multiscale perspective which greatly facilitated the formulation of the proposal discussed in the following sections.

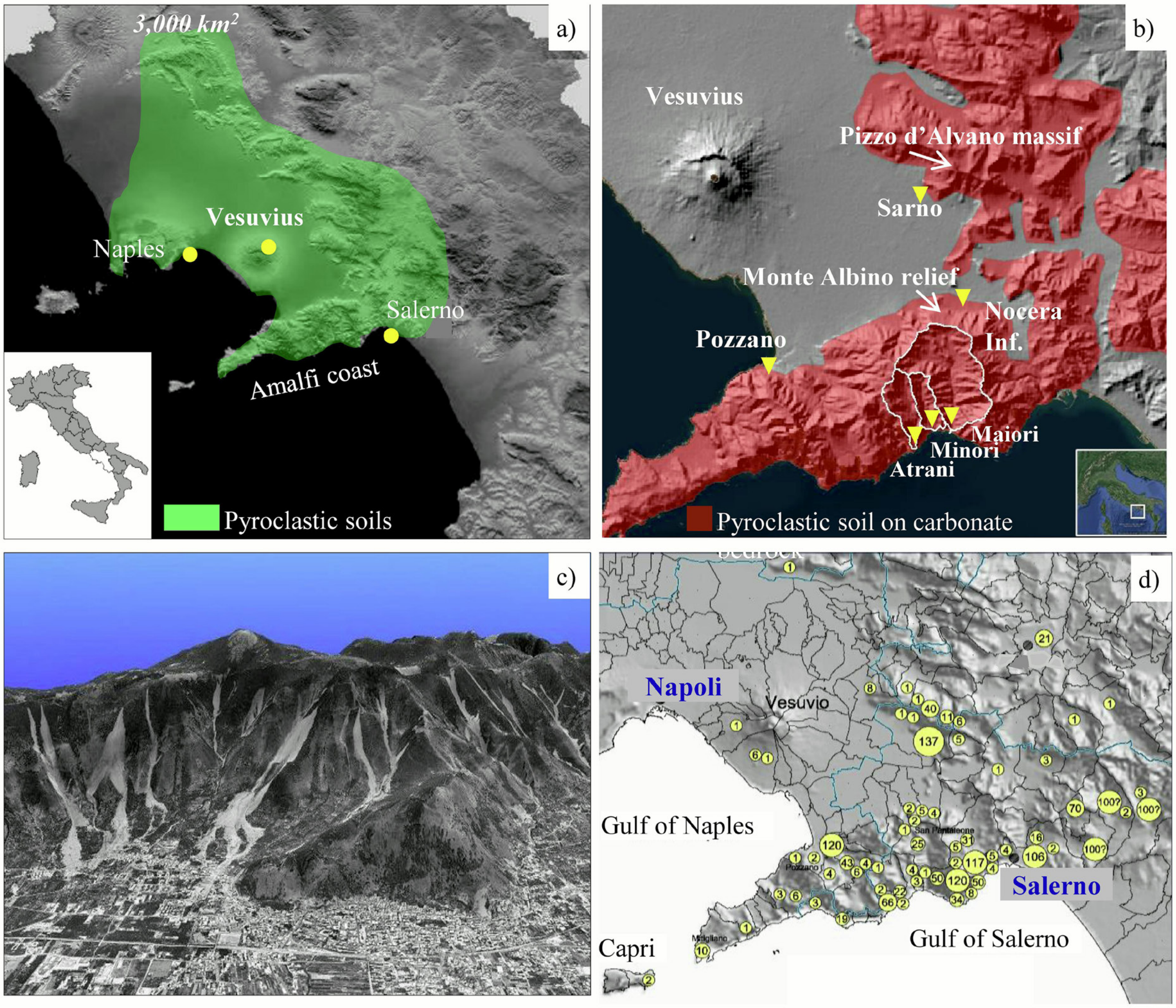

Figure 4. a) The area covered by pyroclastic soils in Campania Region (Southern Italy); b) in red the area where the pyroclastic soils cover a carbonate bedrock (Google Earth image); c) a view of the events that threatened the Sarno town [modified from Cascini (2004)]; d) victims recorded over the centuries where the pyroclastic soils mantle the carbonate bedrock [modified from Cascini (2004)].

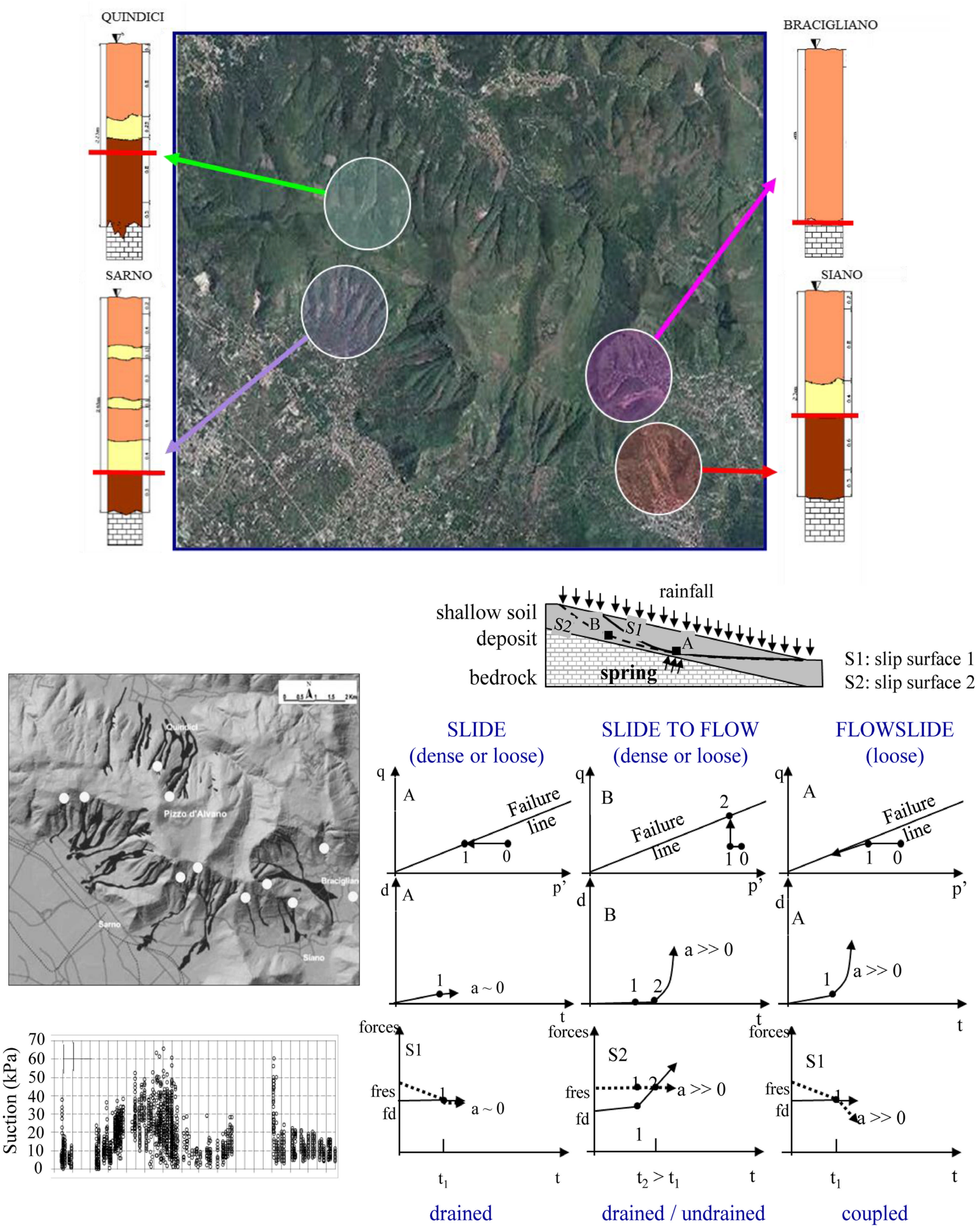

Figure 5. Examples of results provided by the in-situ and laboratory investigations at the Pizzo d'Alvano Massif [modified from Cascini (2004), Cascini et al. (2010) and Cuomo (2020)].

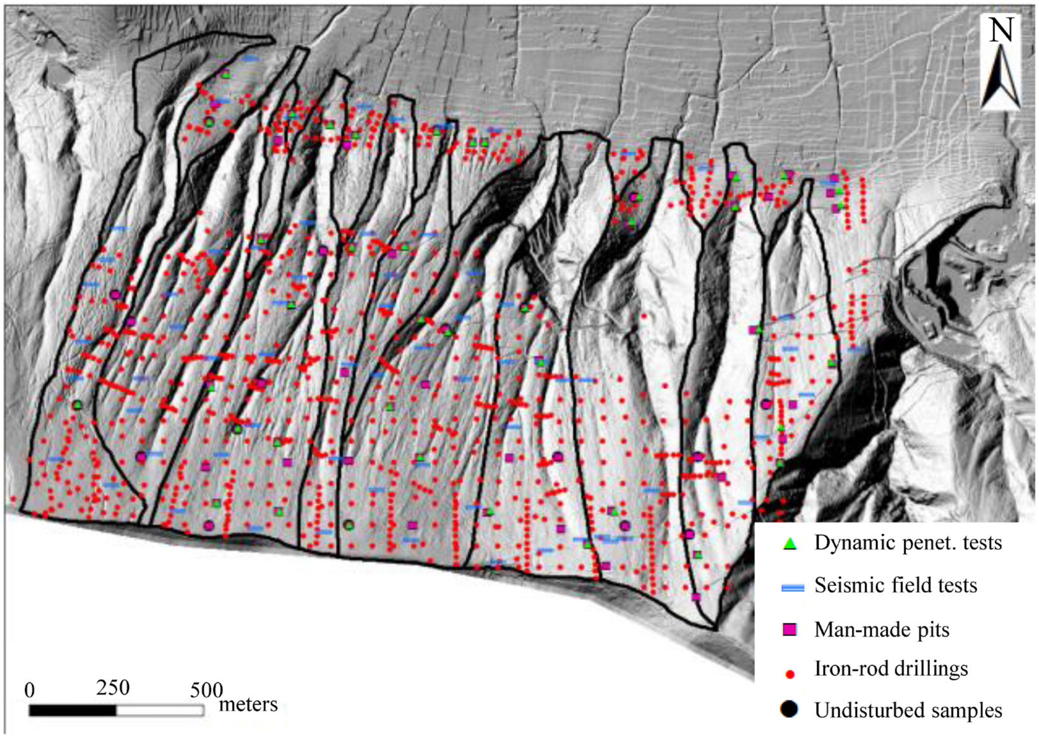

Figure 6. In-situ investigation carried out in the Monte Albino relief [modified from De Chiara (2014)].

3. Methods and results for single deep-seated landslides

The variability of the landslide displacement trends was evident from the early stages of the research, and it has grown further with the increase in the number of the selected case studies, Figure 3b. In the literature this variability is related to the difference in several factors such as: soil mechanical properties; groundwater regime; boundary conditions; landslide geometry; imbalance between external and resistance forces; and so on.

Given the inapplicability of the equation-based methods to tackle such a complex problem and confident that the landslide displacements could not have random trends, it was decided to investigate the deep essence of the problem through an innovative approach, simple schemes and consistent procedures, easily adaptable in case of partially unsatisfactory results.

Accordingly, the second and third key steps introduced in section 2.1 were addressed by grouping the displacement trend with the same prevailing evolution stage. Figure 8 collects the diagrams of landslides that, according to the references, have undergone a failure, those in which there is more than one occasional reactivation, and those in which the activity stages prevail.

These diagrams highlight i) a predominant concave shape where active stages prevail, ii) a convex shape for the other ones and iii) a totally different extent of the displacements, passing from the activity stages to occasional reactivations and failures. These observations prompted to isolate every single stage for the landslides in the dataset and this was carried out also with the aid of the triggering factors discussed in the references listed in Table 1.

The adopted procedure, explained with two examples (Figure 9), allowed the selection of 102 stages characterized by i) a linear displacement trend in correspondence with the minimum value of the triggering factors, ii) a concave trend for the active stages and iii) a convex one for occasional reactivations and first failures.

However, once the curves were distinguished in this way, the same activity stages of the landslides in the dataset were still not comparable due to the different time duration of each evolution stage and the magnitude of the displacements. Nevertheless, such a small number of displacement trends, their shape and values appeared to be non-random and potentially related to the extent of the imbalance between the external and resistance forces acting on the landslide body.

Indeed, it was decided to investigate this hypothesis through a simple procedure which, at the same time, did not obscure the essence of the problem. After several attempts, the comparison of similar stages became possible passing from dimensional to the dimensionless plan. Particularly, referring to a landslide characterized by N stages, assuming that the generic j-th activity stage is composed of n + 1 data, denoting by $d_{0,j}$ and $d_{n,j}$ the cumulative displacements at the initial and final times $t0_j$ and $t_{n,j}$ of the current stage, the dimensionless displacement $D_{i,j}$ and time $T_{i,j}$ were computed through the procedure shown in Figure 10a, $d_{i,j}$ being the displacement recorded at time $t_{i,j}$.

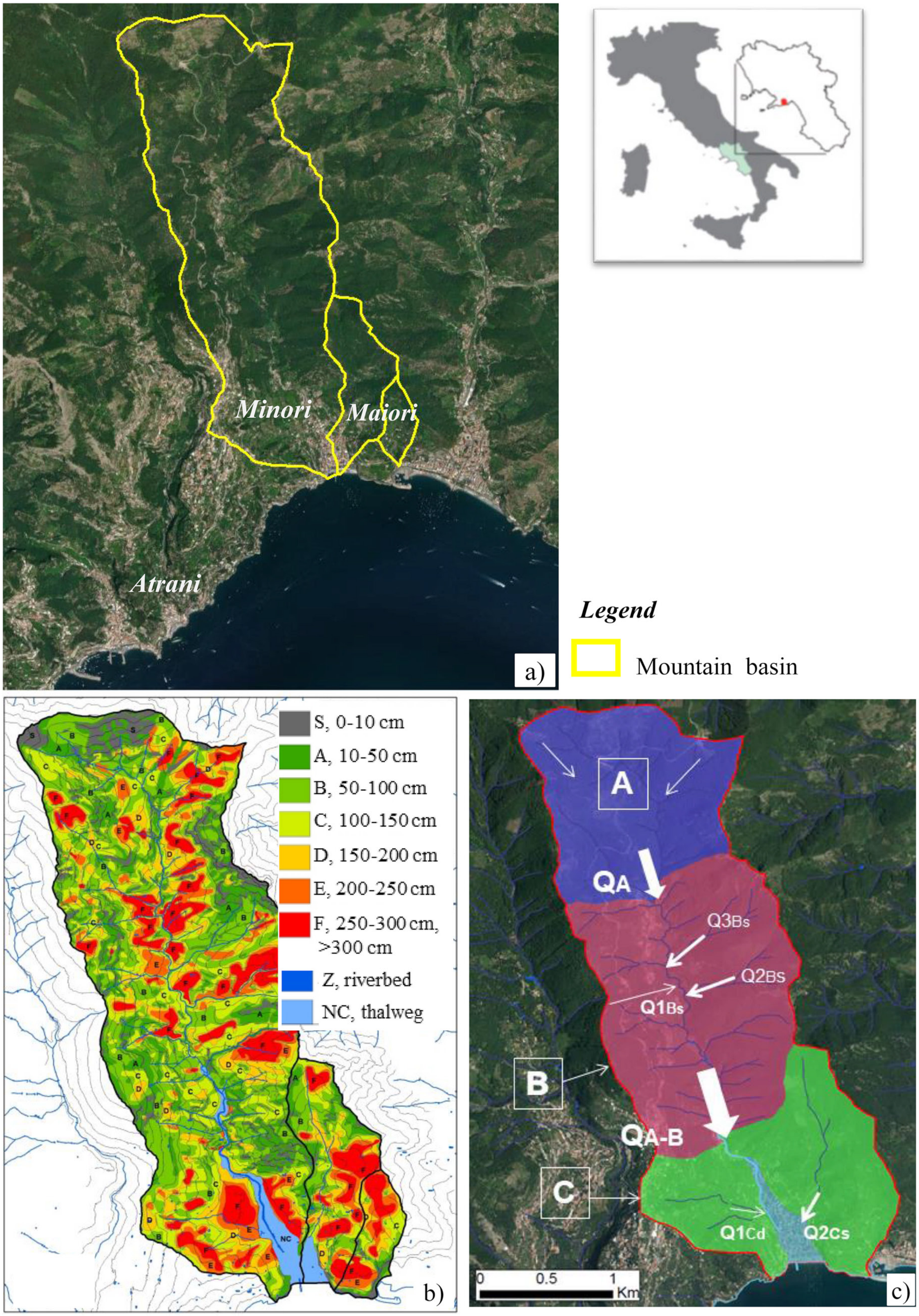

Figure 7. a) Mountain basins threatening the Minori village; b) soil cover map of the slopes in the mountain basins; c) reference scheme to analyze the cascading effects in these or similar basins.

The results obtained are plotted in Figure 10b showing that the 102 evolution stages in the dimensional plane are grouped into only 4 typical trends in the dimensionless one. Of these, 11 are linear (trend I), 66 concave (trend II), 20 convex as occasional reactivation (trend III) and 5 convex as failure (trend IV). Trend I is the diagonal of the diagram, trends II are placed above the diagonal, trends III and IV are below the diagonal being characterized by a different value of the convexity.

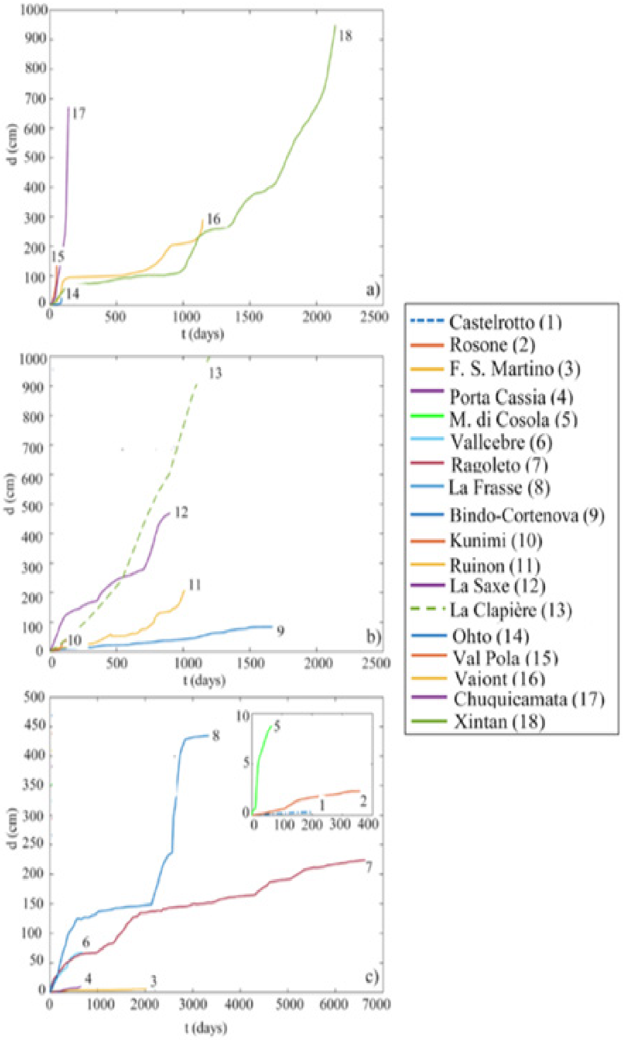

Figure 8. a) Failure events; b) occasional reactivations; c) active landslides [modified from Cascini et al. (2022)].

Scoppettuolo et al. (2020) show that the rescaled displacements defined as d/L, where d is the maximum displacement measured during a single stage and L the length of the landslide to which the experimental measures refer (Figure 3a), vary in the range from 2.5×10^{-7} to 1.4×10^{-3} for the active stages, from 2.7×10^{-5} to 2.8×10^{-2} for occasional reactivation, and are greater than 4.1×10^{-1} for failures.

It is interesting to observe that all these trends are consistent with both the landslide description in the references and the stages as defined in Figure 1. The only exception is the Vajont landslide, which according to some references [see, e.g., Alonso et al. (2010)] can be considered an existing landslide, that is a phenomenon for which Figure 1 indicates the possibility of active stages and occasional reactivations and not the failure.

4. The stability chart

The existence of a small number of trends that well interpret the 102 evolution stages of the 18 landslides in the dataset (originally all different in the dimensional space) suggested the possibility to individuate well-defined laws of mechanics for them. The lack of the input data to implement traditional and/or advanced geotechnical models led to investigate these laws through the inverse approximation of the dimensionless displacements.

The implementation of this method required first the regularization of the experimental data with a continuous function and, among those tested, the power-law function was selected as it approximated all the available in-situ measurements with an error of less than 3%. Then, the mechanical characteristics of the trends were explored through the inverse approximation of displacement $d(t)$, velocity $\dot{d}(t)$, acceleration and jerk $\dddot{d}(t)$. Notice that the

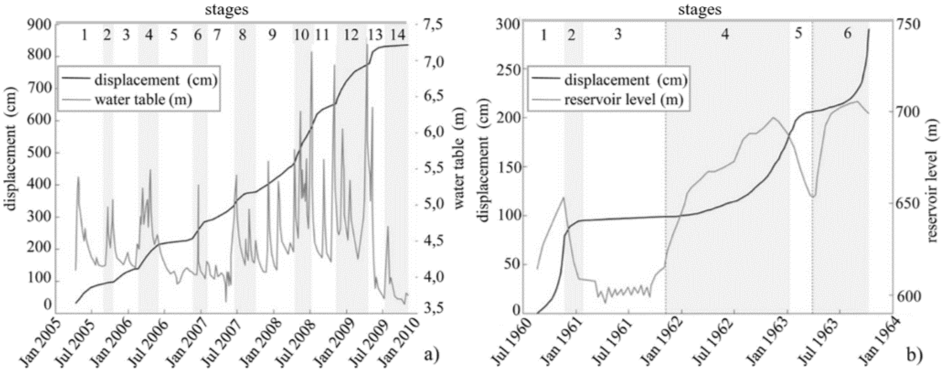

Figure 9. Isolating the activity stages through the shape of the displacement trend and the triggering factors for the case study of a) Bindo Cortenova and b) Vajont landslides [modified from Scoppettuolo et al. (2020)].

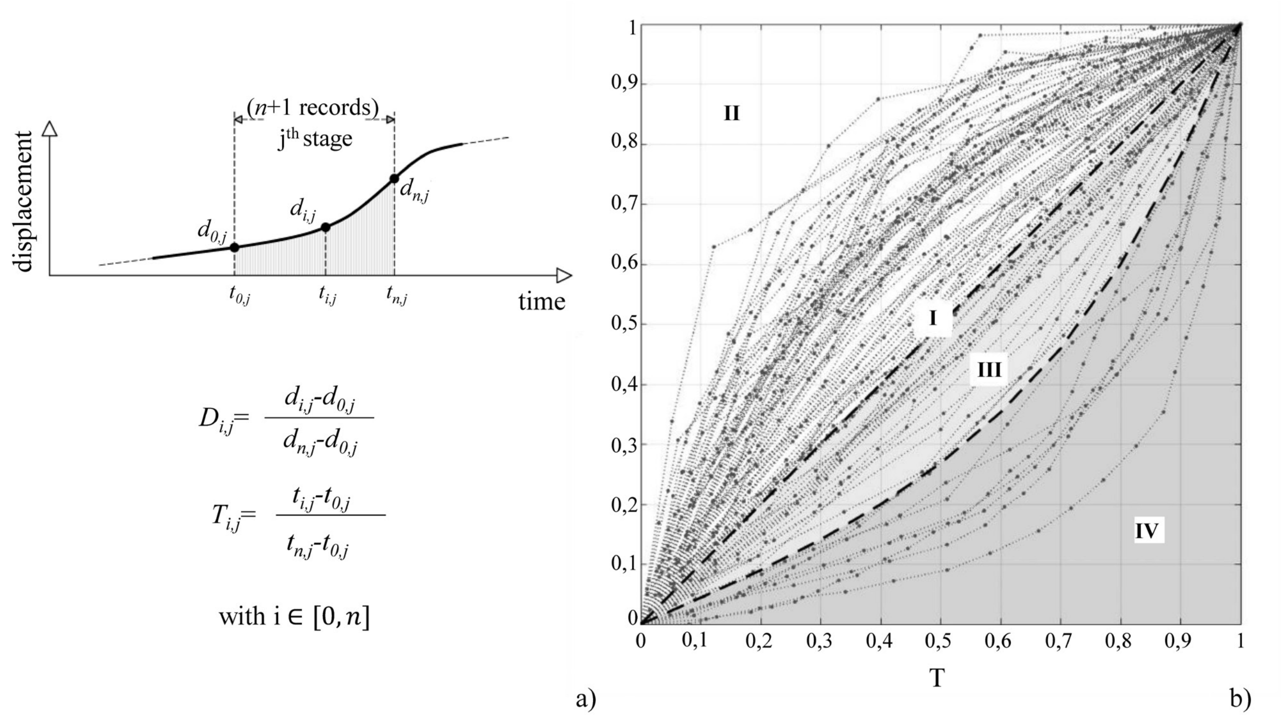

Figure 10. a) From dimensional to dimensionless displacement trends (Babilio et al., 2021); b) dimensionless displacement trends [modified from Scoppettuolo et al, (2020)].

displacement is recorded, and therefore it can be assumed to be known (and, similarly, its dimensionless counterpart), while its derivatives must be computed.

Displacements and velocities are systematically addressed in the literature. Acceleration is also analyzed by several authors, although its implementation in this paper follows an innovative approach (Babilio et al., 2021). As for the jerk, mentioned in economics and other technical fields, it is used for the first time in the study of landslides and among the first times in the resolution of Civil Engineering problems (Babilio et al., 2021).

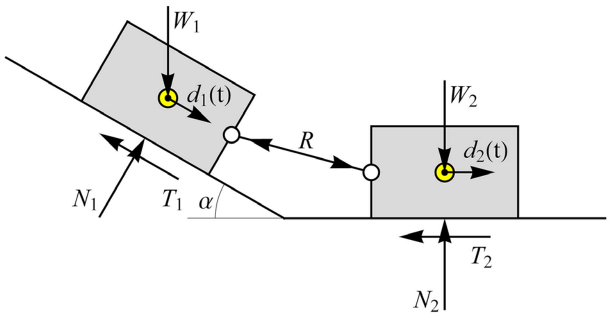

Figure 11. A reference scheme to interpret the results of the inverse analysis.

The meaning of displacement and velocity is so clear that it does not require further comment. Acceleration and jerk have an equally clear meaning through the simple scheme in Figure 11 that allows writing:

$$\begin{gathered}\ddot{d}(t)=\frac{f_{ext}(t)-f_{res}(t)}{m(t)}\,,\\ \dddot{d}(t)=\frac{\dot{f}_{ext}(t)-\dot{f}_{res}(t)}{m(t)}-\frac{\dot{m}(t)}{m(t)}\ddot{d}(t)\end{gathered} \tag{1}$$

where f_{ext} and f_{res} stand for external and resistance forces, whereas $\dot{f}_{ext}$ and $\dot{f}_{res}$ for their time derivatives. It is expected that $fres$ depends on both d (in case the sliding interface is characterized by either a hardening or a softening behavior) and $\dot{d}$ (viscous contribution).

Indeed, acceleration describes at a given instant the value of the imbalance between the forces acting globally on the landslide and a positive value implies that the external forces exceed the internal resistance in the case of constant mass. In turn, the jerk defines the trend over time of the imbalance between these forces, still in the case of a constant mass. It follows that, knowing the trend of one of the two systems of forces, the other one can be deduced, and this allows evaluating the dynamic equilibrium of the landslide and its trend within each evolution stage.

The analysis of the 102 dimensionless trends is discussed in detail in Babilio et al. (2021) and numerical results are summarized in Table 2 and Figure 12.

Table 2. Kinematic characteristics of the evolution stages [modified from Babilio et al. (2021)].

Function name	Trend I	Trend II	Trend III	Trend IVa	Trend IVb
Displacement	$D > 0\uparrow$	$D > 0\uparrow$	$D > 0\uparrow$	$D > 0\uparrow$	$D > 0\uparrow$
Velocity	$\dot{D} > 0\leftrightarrow$	$\dot{D} > 0\downarrow$	$\dot{D} > 0\uparrow$	$\dot{D} > 0\uparrow$	$\dot{D} > 0\uparrow$
Acceleration	$\ddot{D} = 0\leftrightarrow$	$\ddot{D} < 0\uparrow$	$\ddot{D} > 0\downarrow$	$\ddot{D} > 0\uparrow$	$\ddot{D} > 0\uparrow$
Jerk	$\dddot{D} = 0\leftrightarrow$	$\dddot{D} > 0\downarrow$	$\dddot{D} < 0\uparrow$	$\dddot{D} > 0\downarrow$	$\dddot{D} > 0\uparrow$

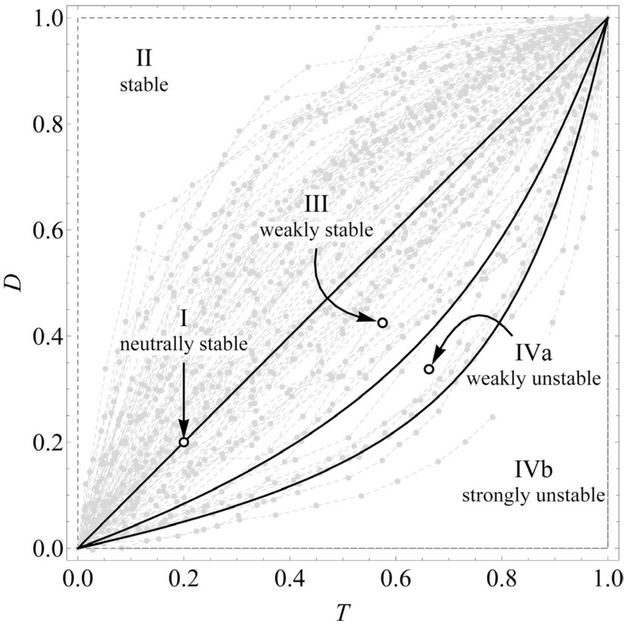

Figure 12. The stability chart [modified from Babilio et al. (2021)].

Together with the rescaled displacements provided in the previous section, the results obtained allow the following statements:

- Trend I is characterized by a positive constant velocity and zero acceleration and jerk, resulting from the perfect balance between external forces and the shear resistance mobilized along the slip surface. The exponent of the $D(T)$ function approximating the experimental data is equal to $x = 1$ that is the typical value of a landslide evolving in a neutrally stable condition.
- Trend II shows a positive decreasing velocity, a negative increasing acceleration and a positive decreasing jerk, testifying the prompt reaction of the landslide to the modification of the stress state induced by recurrent internal or external actions. The exponent of the $D(T)$ function is in between $0 < x < 1$ (concave shape of the displacement curve, testifying a typical stable condition).
- Trend III is characterized by a positive increasing velocity, a positive decreasing acceleration and a negative increasing jerk that testify the ability of the landslide to completely balance over time an exceptional and non-recurring external force. The exponent of the $D(T)$ function varies in the range $1 < x < 2$ (convex shape of the displacement curve evolving towards a concave shape, that is a weakly stable condition of the landslide).
- Trend IV is a failure condition due to the increasing value of acceleration caused by the imbalance over time between external and resistance forces. The jerk assumes a positive decreasing value for Trend IVa (the exponent of the function $D(T)$ is in the range $2 \leq x < 3$ and this highlights that the imbalance cannot exceed certain values) or a positive increasing value for Trend IVb (the exponent of the function $D(T)$ is $x \geq 3$, testifying an uncontrollable failure of the landslide that cannot be avoided by any external action).

This last trend explains the case of the Vajont landslide which, in 1960 and 1962, accelerated (stages 1 and 4 in Figure 9b) after the filling of the reservoir, and decelerated following its emptying (stages 2 and 5 in the same figure). In 1963, a third increase of the water level, slightly higher than the previous one, caused the disaster known to all (stage 6 in Figure 9b). The adopted procedure shows that the acceleration increases during all the stages while the jerk decreases in correspondence with the first two and increases during the last one. This explains why the lowering of the water level in the reservoir avoided failure during the first two stages, while disaster was unavoidable in the fatal third one. Pinyol & Alonso (2010) and Alonso et al. (2016) relate the collapse to the decay of the internal resistance caused by complex thermomechanical interaction along the slip surfaces. Hypothesis consistent with the increase in jerk and which also highlights the possible failure for an existing landslide under specific load and boundary conditions.

5. Methods and results for a case study of multiple shallow instabilities

5.1 The driving force of scientific activities

On 5-6 May 1998, over a period of approximately 10 hours, a sequence of flow-like phenomena caused 160 victims and significant economic consequences in the town of Sarno (Figure 4c) and in four other municipalities of the Campania region. The day after the disaster, the Department of National Civil Protection (DNCP) entrusted the scientific emergency management to the Geotechnical Group of the University of Salerno which, from the beginning, was supported by scientists, technicians and members of the authorities in charge of land use planning, which arrived in a few days from all over Italy (Cascini, 2003).

The extraordinary mobilization of technicians and researchers pushed the DNCP to request the zoning of the flow-like residual risk in the five municipalities, setting the deadline for the presentation on 18th May. Given the lack of experience and standards, in Italy and Europe, and the short time scheduled, it was decided to carry out essentially in-situ geological investigations and aerial photo interpretations.

The data collected were used to develop three maps, at a scale of 1: 25,000 and for the entire area of interest, respectively named the "*Geological and cover thickness map*", the "*Geomorphological Map*" and the "*May 1998 landslide map*". These maps highlighted the long run of the flows originated from shallow landslides or similar phenomena, due to the collapsibility of the soils mantling the slopes. Moreover, by overlapping these three maps (Figure 13a) it was clear that: the landslide source areas were almost all located at the same altitude along the massif; in the landslide source areas, the percentage of the mobilized soil cover was everywhere about 30% of the original one; a potential instability was evident in most of the soil covers still in place; the run out of the flow-like phenomena dated 1998 was sometimes the longest ever and sometimes not, comparing the recent with the ancient alluvial/colluvial fans.

Once the possibility of further instability phenomena in the landslide triggering areas was ascertained, it was prudently assumed that the future propagation may coincide with the areas bounded by the longest runout mapped at the base of each mountain basin (Figure 13b). It is interesting to observe that the zoning map thus elaborated (Figure 13c) confirmed its validity in the following two decades when the dataset allowed to apply more sophisticated numerical models than those implemented during the first 11 days of emergency management.

The day after the presentation of the residual risk zoning map, the DNCP asked for the zoning of the slopes susceptible to flow-like phenomena, similar to those occurred in May 1998, to be developed for the whole Campania Region (13,590 km^2) in the following three months. Not having the necessary data to provide a consistent answer to this further complex question, another working group was formed which, at the end of the activities, mapped the slopes threatening 212 municipalities in an area of 3,000 km^2 (Figure 4a) as susceptible to phenomena similar to those dated May 1998.

This high hazard in the Campania region had a so significant impact to induce the Central Government to issue the so-called "Sarno Law", which took its name from the municipality most damaged by the flows occurred in May 1998. The law imposed to all the Italian River Basin Autorities (AdB, acronym of the Italian name *Autorità di Bacino*) to zone the landslide and flood risk. This task was completed for the entire national territory in the following two years, thus allowing Italy to recover the gap accumulated over long time and to become one of the leading nations in Europe for the landslide risk zoning.

The Geotechnical Group of the University of Salerno coordinated and carried out many of these landslide-related activities in Southern Italy and, at the same time, systematically deepened many issues including the historical investigation started in 1997. This latter activity was developed through literary works, parish archives and Bourbon documents dating back to the nineteenth century (Cascini et al., 2002; Cascini & Ferlisi, 2003; Cascini et al., 2008c) which allowed the evaluation of the Societal Risk (Figure 14) in the area where the 212 municipalities are located.

The figure highlights that *i)* landslide risk is strictly related to the type of bedrock below the soil covers mantling the slopes and ii) the risk is so high in the geological context A1 as to make this area a national priority. Therefore, the University of Salerno has systematically investigated a variety of topics for the context A1, some of which are discussed below.

5.2 From practice to theory: the knowledge acquired through scientific activities

In the months following the emergency phase, the University of Salerno first identified the triggering mechanisms of the 1998 landslides through in-situ and desk investigations (Figure 15). The mechanism (M1) involved almost all the soil covers located in the so-called ZOB (Zero Order Basins) through a sequence of shallow landslides. M2, the second most widespread mechanism, was systematically caused by a small volume of soil that impacted the soil cover below causing a debris avalanche. M3 occurred in correspondence with the mountain tracks that locally increased the surface water runoff while the other three mechanisms (M4-M5-M6), partially or totally caused by erosion, have been less observed on the massif.

Once the mechanisms have been identified, the role played on M1 by the stratigraphy of the soil covering the massif and by the temporary springs, systematically recognized inside the ZOBs, was thoroughly analyzed, Figure 16. Cascini et al. (2003) and Cascini (2004) highlight that the Safety Factor (SF) provided by the limit equilibrium method is not significantly influenced by soil stratigraphy while it assumes the value $SF = 1$ only by implementing as input data the low flow rate measured for the temporary springs in the months following the events (Q = 2 L/min).

An equally relevant role of the temporary springs is demonstrated for the M2 and M3 mechanisms (Cascini et al., 2008b; Cascini et al., 2013) while the return period of the rainfalls before the event is not comparable to the slope

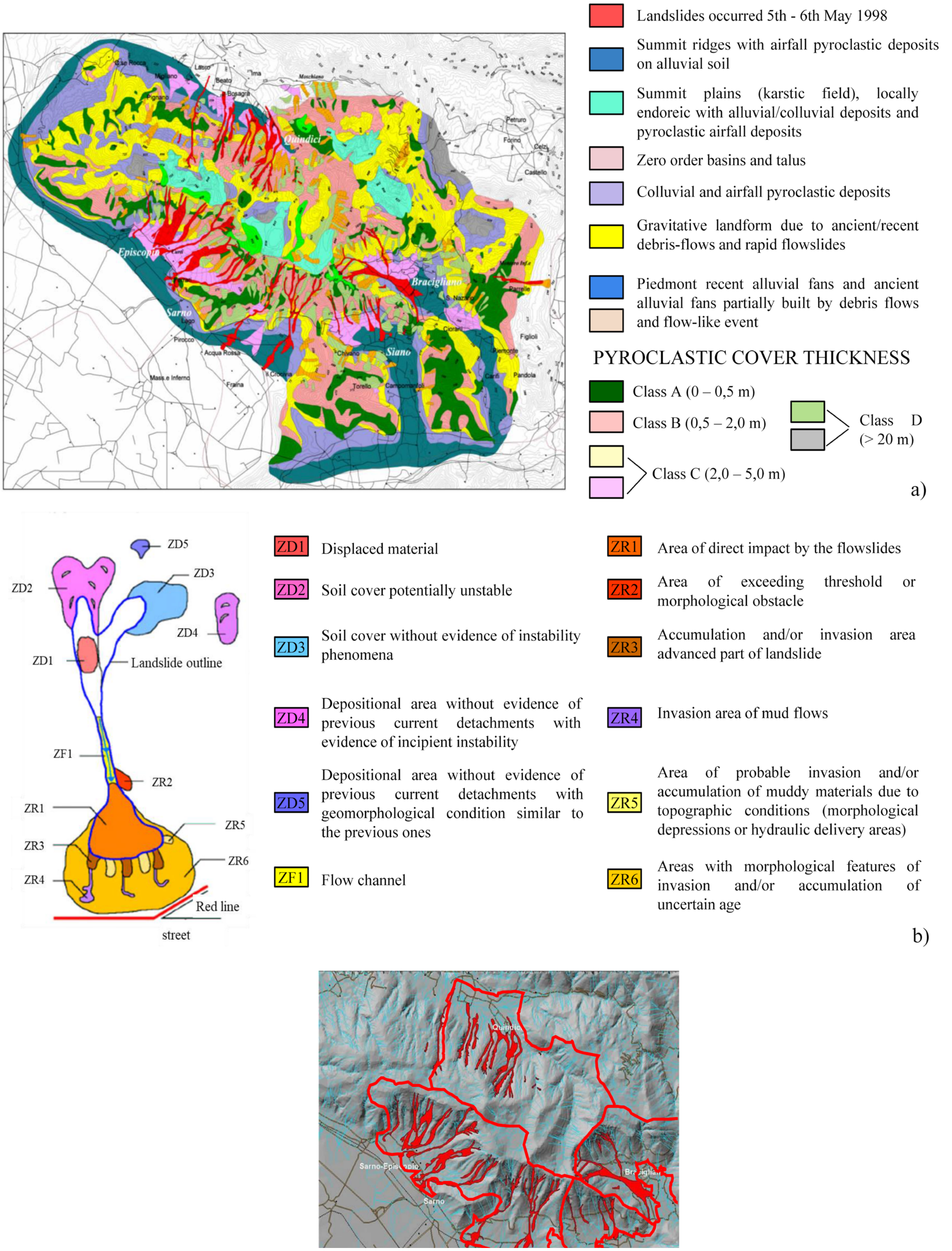

Figure 13. a) The synthesis map which overlaps the three geological maps developed with the data from the in-situ surveys [after Cascini (2004)], b) methodological scheme to zone the areas at residual risk of flowslides [after Cascini (2005)], c) the red line zoning the areas at flowslide residual risk [modified from Cascini (2004)].

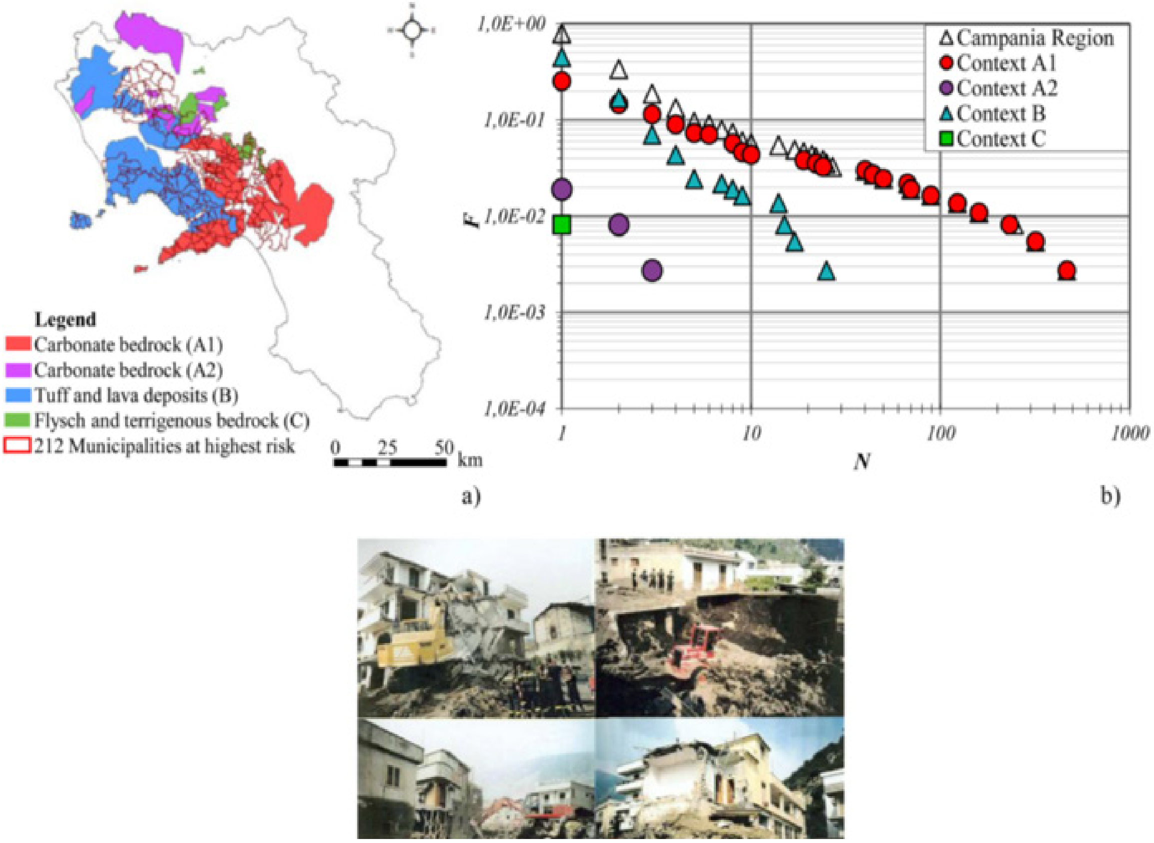

Figure 14. a) The bedrock in the area covered by pyroclastic soils, b) the Societal risk in the area of the pyroclastic soils, examples of damages to properties in the geological context A1 caused by c) the event dated 1998 along the Pizzo d'Alvano massif [modified from Cascini (2004)].

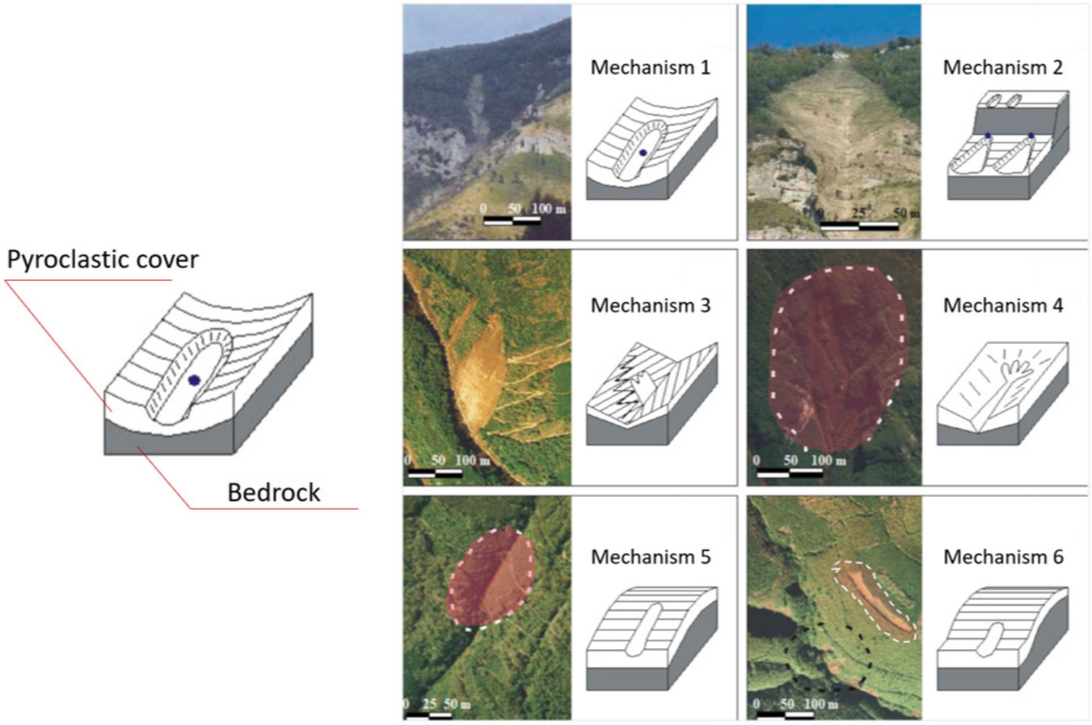

Figure 15. The triggering mechanisms along the massif affected by the event dated 1998 [modified from Cascini et al. (2008a)].

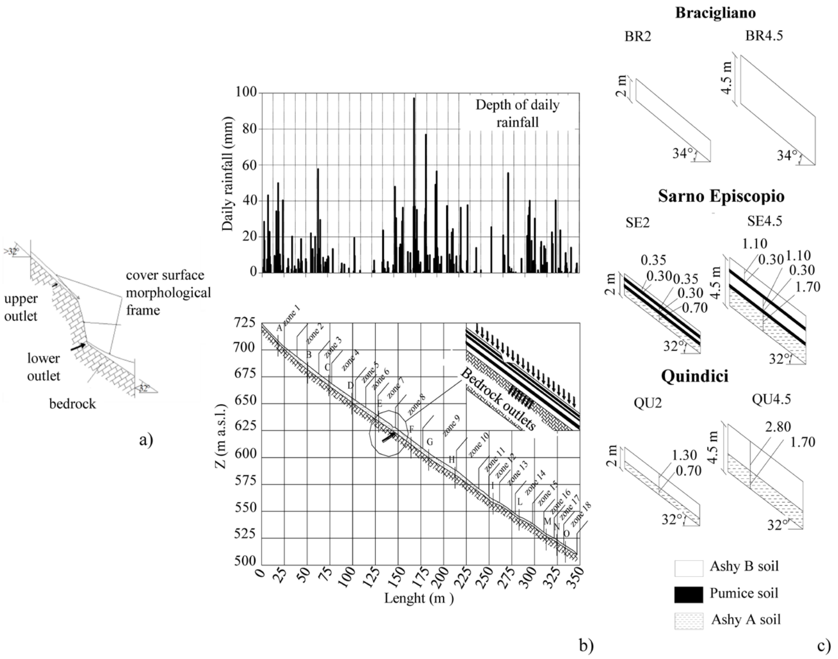

Figure 16. a) Outlets from the bedrock (Cascini, 2004), b) back-analysis of the mechanism M1 strongly influenced by the outlets in the landslide triggering areas (Cascini, 2004), c) parametric analysis of the triggering mechanisms M1 based on limit equilibrium approach [modified from Cascini (2005)].

instabilities and flow-like events, which never occurred with such intensity in the last three centuries. Together with the analysis of the hydrology of the previous years and the geological structure of the massif, this result delineates the possibility that the soil covers had been saturated from the top of the massif through the karst channels, which would have suddenly released a large amount of water accumulated in the previous years. Hypothesis, however, that is not demonstrable with engineering models.

On the contrary, the analyses demonstrate the need for a suitable model selection in order to correctly identify the areas affected by the first failure phenomena due to the mechanical and kinematic differences of the triggering mechanisms. This topic is discussed in Sorbino et al. (2010) who, back-analyzing the events dated May 1998 with distributed physically based models, compare the results obtained through two indexes that quantify the "success" and the "error" of each model in simulating the observed landslide source areas. The indexes highlight that these models can identify the areas where the mechanism M1 was observed while they fail for M2 and M3, whose characteristics cannot be captured by the differential equations they implement.

De Chiara (2014) and Ferlisi & De Chiara (2016) analyze a similar topic focusing on the Monte Albino relief, Figure 6, about 10 km far from the slopes of Sarno town, Figure 4. In such a case the detailed in-situ and laboratory investigations allowed identifying the hazards and mapping their source, evolution and deposition areas at 1:5,000 scale (Matano et al., 2016).

All the acquired elements were processed to analyze the occurrence of different mass movements (shallow landslides, erosion phenomena, etc.) which, depending on the characteristics of rainfall and the position of the triggering zones along the relief, originate flowslides, debris avalanches, hyperconcentrated flows and flash flood, so classified according to Coussot & Meunier (1996). The analyses were developed first by calibrating the rheology of the flowing masses through the back-analysis of the past events and then by estimating the hazard they originate at the toe of the slopes (Figure 17).

Moving from the Monte Albino relief to the slopes of the Amalfi coast (Figure 4a) historical data, in-situ surveys and numerical analyses show a further significant change of phenomena and consequence threatening the municipalities located at the toe of the mountain basins. The flowslides are almost completely absent and the flow-like phenomena are essentially represented by hyperconcentrated flows and flash floods, mainly occurring at the beginning of the rainy season (differently from the case of Pizzo d'Alvano massif). In almost all the municipalities, the discharge of water plus sediment originated by critical rainfalls causes the crisis of the culvert (see Section 2.2) with consequent flooding of the urban area above.

A case study testifying the serious consequences that these events may cause is dated 25 October 1954 when, starting from 1:00 p.m. and until night, more than 500 mm of rainfall were recorded, that is about half of the average yearly cumulated rainfall of the area. This extreme weather event caused 318 victims as well as severe damage in the City of Salerno and in

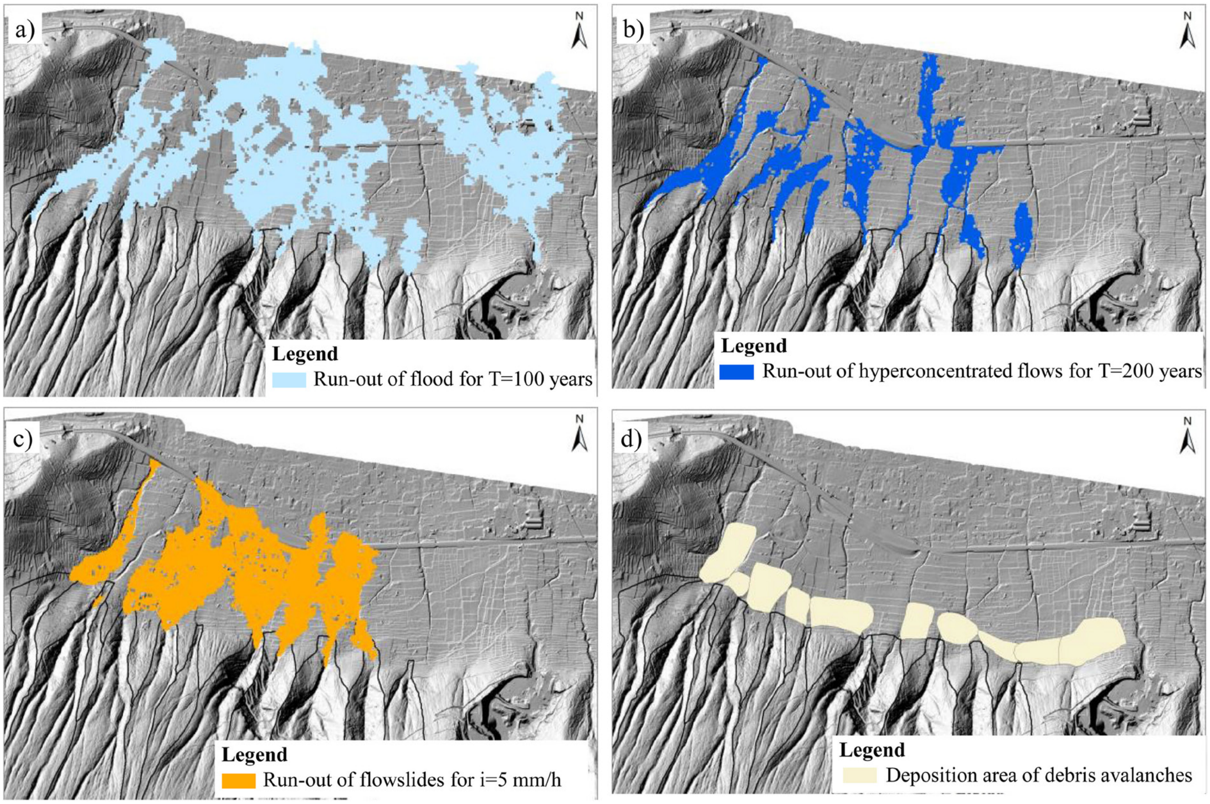

Figure 17. Numerical results provided by the propagation analysis of flow-like phenomena along the Monte Albino massif: a) flood, b) hyperconcentrated flows, c) flowslides, d) debris avalanches [modified from De Chiara (2014)].

many nearby municipalities of the Amalfi Coast. The erosive phenomena that affected the slopes of some mountain basins are analyzed in Cuomo et al. (2015), Cuomo & Della Sala (2015) while, due to the lack of many input data, the modeling of the flows that hit the inhabited centers was not developed.

However, the back-analysis of the event that occurred in 2010 in the Municipality of Atrani, Figure 4b, highlights that even not so critical rainfall can cause the flooding of the urban centre (Cascini et al., 2021). In such a case the estimated return period of the rainfall was about T = 50 years, to which correspond a cumulative water washout of 640,000 m^3 and a peak water discharge of 60 m^3/sec at the catchment outlet (Figure 18a). However, the in-situ surveys and cameras of eyewitnesses present in the area have shown that approximately 45,500 m^3 of sediments (i.e. only 7% of the water washout) were mobilized in less than 10 min (Figure 18b) by intense erosion along the slopes, originating the hyperconcentrated flow shown in Figure 18c. The combination of events increased the peak discharge of water plus sediments at the inlet section of the culvert up to the value of 180 m^3/sec (Cascini et al., 2021), equivalent to the effect expected from a rainfall with a return period of T = 200 years. As a result, the culvert was suddenly filled up and the excess volumes flooded the urban area above (Figure 18c), where caused damage and a victim.

6. Towards new frameworks for landslide analysis

While scientists from different disciplines attempt to provide general suggestions for either theoretical or applicative topics, the geotechnical community directs efforts to advance knowledge at slope scale rather than to identify classes of landslides having a similar behaviour. This is probably due to the young age of the basic principles of Geotechnics, established only 100 years ago, and to the idea that landslides require ever great insights to avoid the danger of undermining, with excessive simplifications, the reference framework built up to now with passion and competence.

The case studies discussed in this paper show that knowledge can be translated into general frameworks through a horizontal path in some cases and a vertical one in other. The path is here defined horizontal where the input data come from different case studies all analyzed in similar temporal conditions, with a monodisciplinary approach and at the same topographical scale. Vertical is instead a path for which the surveys, studies and analyses are developed with a multidisciplinary approach at different topographical scales, all correlated to each other and, where necessary, at different time scales. The benefits arising from this new analysis of landslides are discussed below.

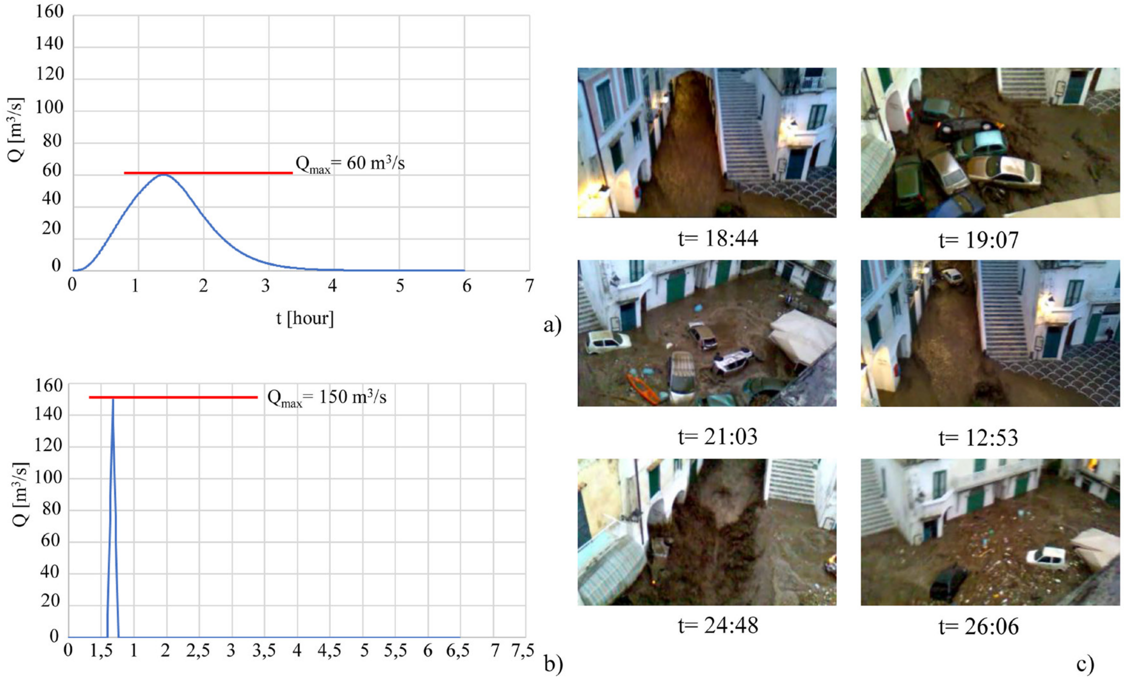

Figure 18. a) Estimated peak discharge of water and b) sediments; c) propagation in the urban area of the hyperconcentrated flow.

6.1 Single deep-seated landslides

The method proposed in Section 3, made possible by the efforts of many landslide researchers around the world, opens perspectives in practice and theory.

In practice, the identification of common dynamic characteristics of landslides allows the prediction of their evolution as described in Cascini et al. (2022) who propose two different procedures to achieve the goal. One directly processes the experimental curves while the other refers to the dimensionless displacements, as described in section 3.1. Two explanatory examples, one for each of the two proposed approaches, are reported below.

The first example is relative to the Vallcebre landslide (Corominas et al., 2005), a rainfall induced existing landslide characterized by a sequence of trends I and II. For trend II, systematically recorded during the wet season, Cascini et al. (2014a) compare the experimental measures with result from their approximation through the power law function. The comparison highlights that the first 7 data, i.e., 80 days in advance of the total duration of the activity stage, provide a satisfactory forecast of the entire set of displacements (Figure 19a).

The second example focuses on the Vajont landslide which has been analyzed through the dimensionless displacements (Figure 10b) and the stability chart (Figure 12) to estimate the equilibrium condition during each stage of the landslide evolution.

Figure 19b shows that during the first two increases of the water level in the reservoir the exponent of the power law function $D(T)$ approximating the experimental data, after a certain time, is in the range $2 \leq x < 3$, typical values of a weakly unstable condition (Figure 12 and Table 2) not evolved into failure by emptying the reservoir. The figure also shows that, during the third increase of the water level, the value of the exponent ($x > 3$) reveals, already 19 days before the disaster, the impossibility of avoiding the collapse due to the increase of both acceleration and jerk, a typical condition of a strongly unstable system (Figure 12 and Table 2).

From a theoretical point of view, the dimensionless displacement trends and the stability chart require identifying the basic governing principles and understanding whether landslides can be defined as “complex systems” as defined by Parisi (1999).

Regarding the first point, attention was focused on the approach proposed in Di Prisco & Flessati (2021) to verify whether the stability condition of these trends can be interpreted or not with Lyapunov’s theory. Cascini et al. (2023) provide promising preliminary results but there is still a long way to go due to the complexity of the topic.

As it concerns the second point, this is not the place to go deeper into the subject nor does the writer have the skills to express an opinion on how to process input data in problems involving complex systems. Despite these limitations, it is useful to stimulate the discussion through three questions: can the landslides be considered a complex system? Can the individual evolution stages of landslides, as defined in Section 3, be assimilated to a complex system? Can a complex system or part of it be governed by the laws of Physics?

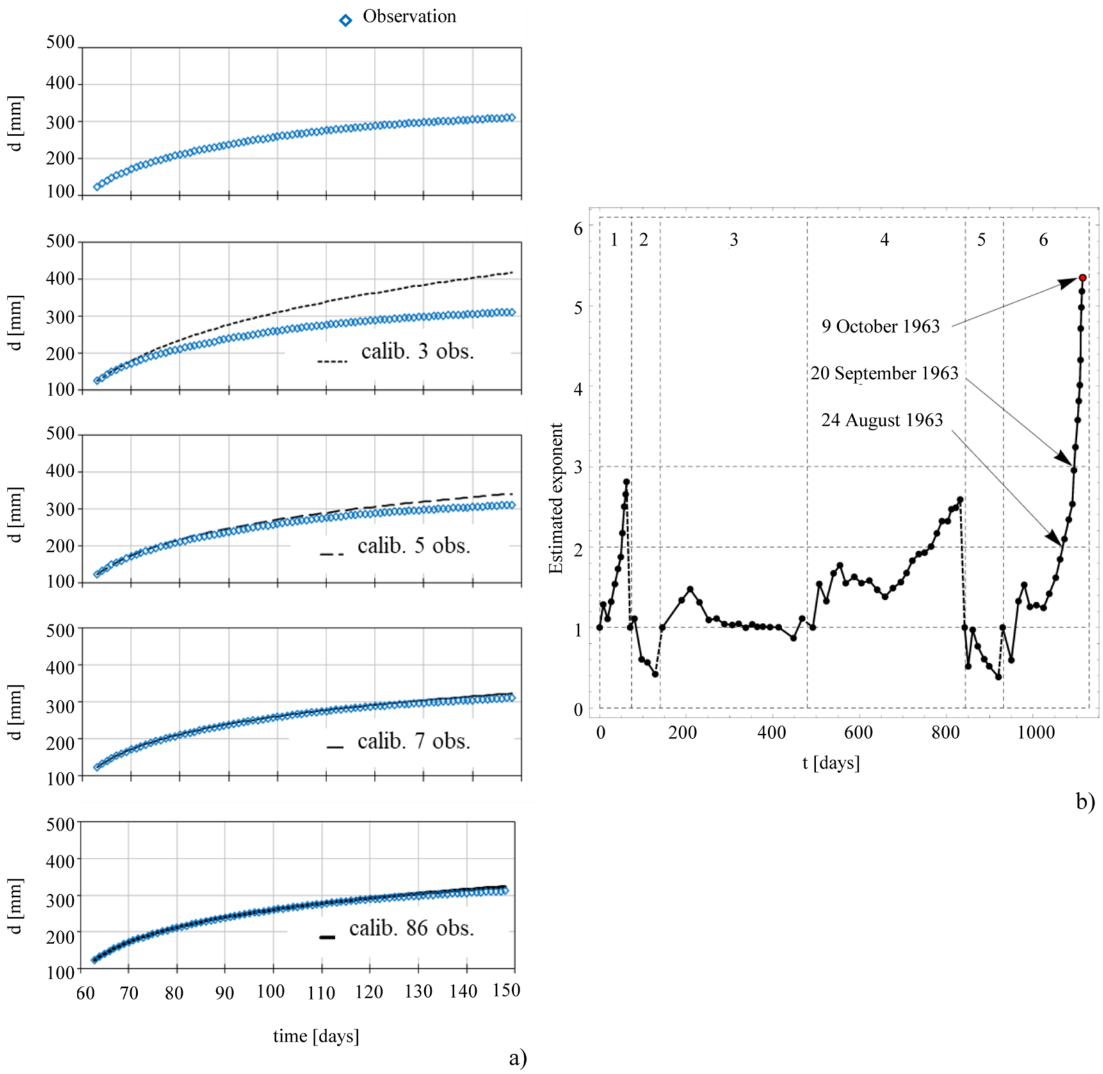

Figure 19. a) Forecasting the evolution of the Vallcebre landslide through the dimensional displacements (Cascini et al., 2014a), b) the exponent of the function approximating the dimensionless data for the last 1126 days before the collapse of the Vajont landslide [modified from Cascini et al. (2022)].

In the author's opinion, the first two questions can be answered positively since the evolution of landslides, over the years and within a single displacement trend, depends on many different interacting elements that determine their overall behavior not predictable from the study of the individual parts (Weisbuch, 1991).

The results discussed in Section 3 and simple considerations of Geology and Geotechnics indicate the possibility to provide a positive answer even to the third question, at least as regards the existing landslides. In fact, it is reasonable to hypothesize that the long geological history of these landslides has led to a geometric configuration which corresponds to a condition of stable equilibrium. Hypothesis supported by the residual shear strength systematically mobilized along the existing slip surfaces and by the linear displacements trend in the absence of external perturbations. It follows that the evolution stages represent the temporary or permanent variation of this stable equilibrium, induced by external perturbations and governed by the laws of Physics.

The author believes that the current knowledge is not sufficient to consider the previous answers exhaustive and, therefore, the questions are still open. However, it is already clear that their confirmation would furnish new theoretical perspectives for the study of landslides with extremely positive benefits as it concerns their analysis and management.

6.2 Multiple shallow instabilities

In the Campania region (Southern Italy) the risk zoning of flow-like phenomena was carried out at intermediate scale (1:25,000) with heuristic methods, i.e., the only ones capable of providing consistent replies within the mandatory deadlines set by the Authorities. Later, not having time constraints, the scientific studies were developed mainly at large (1:5,000) or detailed scale (1:1,000) implementing statistical and/or deterministic methods. In some cases, research has been developed at a small scale (<1:100,000), to complete knowledge on some issues not of direct interest to the Authorities.

In practice, the activities were carried out following the needs and objectives of the moment and, apparently, without a well-defined guiding thread. Therefore, the main questions are whether it is possible to follow a more rational path in the absence of external conditioning and which strategy to follow where these constraints exist.

With reference to the first question Cascini (2015) proposes two alternatives called respectively "bottom-up" and "top-down" approach. The first approach preliminarily analyses site-specific problems at large scale with the aid of deterministic methods; then, it generalizes knowledge to progressively larger areas through statistical or heuristic methods implemented at intermediate or small scales. The second approach follows the reverse path, initially framing the problems over large areas and at small scale with the aid of heuristic methods; then, the knowledge is deepened within sample areas of progressively decreasing extension that are usually analyzed through the statistical method at an intermediate scale and the deterministic ones at large/detailed scales.

The bottom-up approach starts from scientific-based evidence, progressively generalized through statistical and geological approaches, which gradually require an increasing expert judgment. The initial advantage is discounted with the time necessary to complete the entire path, which is generally long and, sometimes, unsustainable. An application of this approach is provided in Cascini (2015) who arrived at the generalization of the results after about 15 years.

The top-down approach certainly reduces the times of the entire process, but it requires the preliminary formulation of hypotheses whose validity must be progressively demonstrated with methods of increasing reliability. An application of this approach is illustrated in Cascini (2015) who demonstrate how it was possible to connect all the scales together in less than three years. These authors also provide guidelines to develop a consistent process that allows one to hit the target rather than progressively move away from it.

Where both approaches cannot be used, as in the case study described in the paper, it is recommended to develop, from the beginning, each step in a multiscale perspective to have, at the end of the path, a global and coordinated vision of all the issues, each analyzed with different materials and methods at different topographical scales. The framework resulting from a similar approach applied to the case study of the Campania region can be summarized as follows.

The pyroclastic covers mantling the slopes in an area of about 3,000 km^2 originate a high Societal risk in the geological context A1 systematically threatened over the centuries by events that caused victims and economic damages. The instability phenomena along the slopes of this area are triggered by critical rainfalls having different characteristics. In the hinterland the phenomena mainly occur during the wet season while moving along the coast the worst phenomena are recorded at the beginning of this season (Figure 20a). The rainfall intensity and the values of the soil suction during the hydrological year

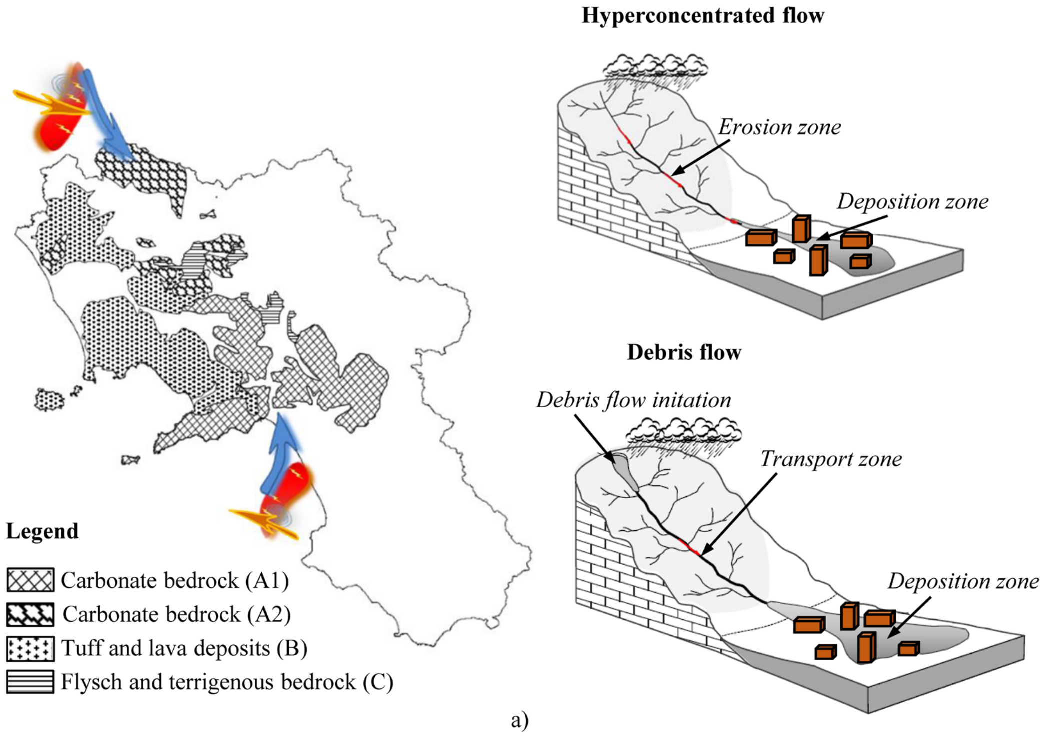

Figure 20. a) Different meteorological events causing the instability of the soil covers in the hinterland and along the Amalfi coast [modified from De Chiara (2014)]; b) different triggering and evolution mechanisms of the flows in the hinterland and along the Amalfi coast.

imply that: during the rainy season, in the hinterland, the rainfall infiltrates the soil covers originating shallow landslides that evolve into flowslides; along the coast, at the end of the dry season, erosive phenomena prevail originating flash floods or hyperconcentrated flows (Cascini et al., 2014b, 2021) with a peak discharge corresponding to a rainfall with a very high return period (Figure 20b).

In practice, this scientific evidence i) has made it possible the implementation of alarm systems, which have considerably reduced the risk to life all over the Campania region and ii) allows the mitigation of the risk to property that today appears to be only an economic problem, as the design of sustainable control works is possible thanks to the available know-how. Results, that at the beginning of the activities, were unimaginable and out of reach from a scientific and technical points of view.

7. Concluding remarks

The case studies, approaches and tools discussed in the paper show that attempts are possible to translate the impressive knowledge available on landslides into frameworks of general utility in practice, as is usually the case in much older scientific sectors than Geotechnics.

The study illustrated in Section 3 can give rise to one of these frameworks, as the evolution of single deep-seated landslides seems to be represented by a limited number of displacement trends, regardless of the geological contexts in which they occur, the soil properties of materials involved in the landsliding, the triggering factors and so on. This belief can be reinforced through the proposed method that is easy to apply and, as such, easy to use to further verify its reliability. This could establish a milestone for a class of landslides that are currently considered completely different from a mechanical point of view, while the obtained results indicate that the laws of Physics are the basis of their evolution stages.

The study outlined in Section 4 highlights the potential of the multiscale and multidisciplinary approach for studying multiple shallow instabilities that are too often analyzed in a monodisciplinary perspective. In particular, the paper proposes an approach able to connect materials and methods of different disciplines which, used together from the beginning of the cognitive process, can allow an unexpected advancement of knowledge. Moreover, sharing of knowledge, through consistent and physically based approaches, can make it possible to progress on phenomena for which the studies developed in a geological context are currently of limited interest to those carried out in another geological context.

In conclusion, the paper proposes a new vision for the analysis of landslides which, to be strengthened, requires the sharing of knowledge, implementation of coherent methods and, above all, further results to confirm some preliminary insights made possible by the efforts of a high number of researchers around the world.

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Declaration of interest

The author has no conflicts of interest to declare. The author has observed and affirmed the contents of the paper and there is no financial interest to report.

Data availability

The datasets used in the current study are available from the author upon request.

List of symbols

d:	displacement
$\dot{d}$	velocity
$\ddot{d}$	acceleration
$\dddot{d}$	jerk
f_{ext}	external forces
f_{res}	resistance forces
f_d	driving forces
$\dot{f}_{ext}$	derivative of external forces
$\dot{f}_{res}$	derivative of resistance forces
h	depth of secondary slip surface
l	length of secondary sliding body
m	main body motion direction
p'	effective mean stress
q	deviatoric stress
t	time
w	width of secondary sliding body
D	dimensionless displacement
F	cumulative annual frequency of landslides
H	depth of main slip surface
L	length of main sliding body
N	number N of fatalities due to landslides
Q	discharge
SF	safety factor
T	dimensionless time
W	width of main sliding body

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