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Definition of an Operative Methodology for the Management of Rockfalls along with the Road Network

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Abstract: Rockfalls are widespread events in mountain areas worldwide. The management of this process can be done using different approaches. In this paper, we want to analyze the procedure that can be adopted to manage a rockfall event considering the safety of infrastructure and settlements. Focusing on an Alpine region highly affected by rockfalls like the Aosta Valley Region (north-western Italy), we implemented a dedicated procedure for the road network emergency management. This procedure can be activated immediately after a rockfall, and it aims to identify the effect of the collapse, define the danger zone, plan the recovery project and propose temporary solutions for correct residual risk management until the end of the remedial works. In natural hazards, the lack of codified methods can create critical conditions and increase the responsibility of the single operators, who have to effectively manage a critical situation in a limited amount of time without a well-defined procedure. For this reason, the proposed method aims to be a first example of how a correct codification can be used for more sustainable management of this widespread phenomenon.

Keywords: rockfall hazard; landslide inventory; best-practices; decision-maker support; Aosta Valley Region

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1. Introduction

The Alpine regions are the scene of numerous rockfalls. Due to the wide unpredictable occurrence of these events, their high energy and long runout, rockfalls often cause victims and damage along with the road network [1–4].

Rockfall hazard estimation along roads is an endlessly relevant topic in literature, widely debated in recent years [3,5–9]. In Alpine territories, the high population density, the presence of many transportation corridors and touristic destinations make this problem even more important than in other mountainous areas. Due to the high socioeconomic impacts, rockfall occurrence investigation has an important role in transportation corridors' management and land use planning purposes. Governmental administrations, and local and regional authorities responsible for managing landslide risks have devised different strategies for rockfall hazard evaluation along with the road network [10–13], for more effective public transportation system management so as to improve the safety of their territories.

The Aosta Valley Region (AVR), located in the north-western of Italy, can be considered a good example of mountainous regions highly susceptible to rockfalls. In this small Alpine region, rockfalls are a natural hazard, frequently affecting the extended and branched road network, representing the more frequent type of landslide on the regional territory (regional landslide inventory, more than 23% of rockfalls) [14]. The transportation corridors of the Aosta Valley are mainly composed of roads and highways, variably crossing the Alpine territory, consisting of important communication routes with the national territory and North and South Europe countries. In addition to local residents, the road network is crossed every year by millions of tourists [15]. In this context, rockfalls represent one of the most relevant natural hazards, a primary cause of fatalities and serious damage [16].

Many attempts have been made by local and regional administrators and the AVR authorities to evaluate the rockfall hazard along with the regional road network. Nowadays, many different methodologies for natural risk evaluation have been proposed by appointed technicians and experts to support decision making in the associated risk management and mitigation. Specifically, in recent years, numerous scientific projects or inter-institutional agreements with the Aosta Valley Region authorities have been carried out, among which the most relevant are: (i) IMIRILAND [17,18], a multidisciplinary approach for quantitative risk assessment for both regional and local scale; (ii) RHRS, i.e., Rockfall Hazard Rating System [1], devoted to quantitatively define the risk associated to the road network and to identify slopes more susceptible to rockfall events that require urgent remedial works or further analysis; (iii) RO.MA., i.e., Rockfall risk Management [19], designed to assess the risk associated with rockfall and to prioritize a proper budget allocation, designed for portions of roads; (iv) Ro.S.I., i.e., Rockfall Susceptibility Index [20], part of RO.MA. methodology, which provides a numerical index of susceptibility for road sections, based on-site prompt characterization of steep rock slopes along with the road network.

However, besides the rockfall risk definition, road management during rockfall occurrence poses another major challenge, specifically in emergency management and the safety of the motorists and the passers-by. Nowadays, a codified procedure for proper management of the operative actions to be undertaken during rockfall event occurrence along a road is becoming a growing need for national and regional authorities and administrators. In the past years, some operational tools [21,22] and instruments with dedicated procedures and standardized format [23,24], have become suitable solutions for more effective management of slope instability hazards, adoptable by local and regional authorities. In this paper, focusing on the Aosta Valley Region (north-western Italy), an operative methodology for suitable road network management during rockfall occurrence has been implemented. Exploiting the know-how gained in the Cinque Terre National Park for the definition of a codified procedure for the management of the hiking paths of the UNESCO site [23], a dedicated procedure for this Alpine region has been developed, considering scientific and operative requirements. This composite procedure is functional to the definition of those actions to be applied at local scale each time where a rockfall event occurs along with the road network. The proposed operative methodology consists of a standardized protocol aimed at multi-user exploitation (e.g., public technicians, administrators, stakeholders), to the effective and efficient management of the diverse phases of an emergency. The procedure starts immediately after the occurrence of a rockfall and ends when the remedial activities have been defined and activated.

The proposed standardized and codified procedure organized in distinct phases and scenarios may represent an effective tool for local and regional authorities, providing a reasonable response to enhance suitable management of the road network that can be adopted worldwide. Adopting an appropriate risk assessment and a reduction procedure can guarantee the safeguard of motorists and more effective preservation of road infrastructure.

2. Study Area and Available Landslide Dataset

The Aosta Valley Region (AVR) is a small mountain region located at the north-western end of Italy, bordering France and Switzerland (Figure 1). The regional territory is bordered by the main peaks of the Western Alps (e.g., Cervino 4478 m, Mt. Rosa 4635 m, Gran Paradiso Massif 4061 m, and Mt. Bianco 4810 m a.s.l.), and is home to renowned national parks (e.g., Gran Paradiso National Park, Mt. Avic Park), important destinations of the mountain tourism.

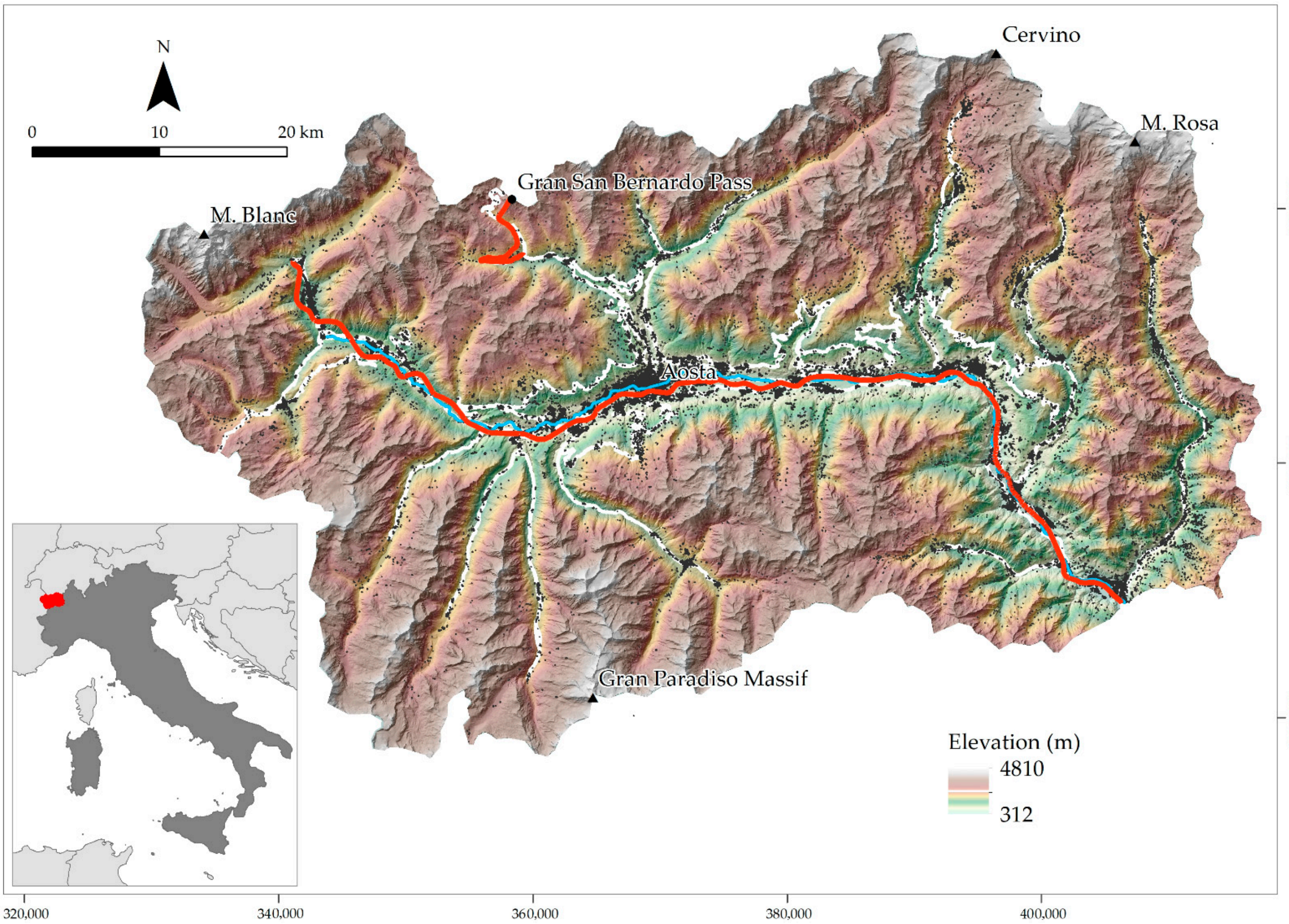

Figure 1. Relief terrain of the Aosta Valley Region study area (north-western Italy). The map shows the branched road network, with regional and municipal roads in white, the Torino-Aosta A5 highway in red, and railway in blue. The dark grey polygons represent the buildings.

This Alpine region is relatively populated compared to other mountain areas (in 2019, the number of inhabitants was 125.666 for 3261 km^2), with the main urbanized areas mainly distributed along the bottom of the valleys, and numerous small villages and localities scattered along the slopes. Historically, the AVR was considered a land of contact between Italy and the other countries of Europe, connected through important communication route and engineering works as the Gran San Bernardo and the Mont Blanc tunnels, that testifies the important interrelation between Italy and the rest of Europe. With an extension of about 2600 km, the regional road network is represented by a dense system of national and regional roads that branch off along the main valley and the secondary ones. Moreover, an important highway, the "*Torino-Aosta A5*" highway, runs along the main valley floor, parallel to the regional railway, routes of the interregional and cross-border traffic.

The geological setting of the AVR covers a complete section of the orogenic prism of the Western Alps, passing through the Austroalpine domain, the ophiolitic Piedmont zone, and the Pennidic domain [25,26]. These tectonic-metamorphic domains constitute a pile of nappes, characterized by a long-term tectonic activity and the neo-tectonic dislocation system of the Aosta-Ranzola fault system [27]. From a morphological point of view, this mountainous region is characterized by a high glacial morphodynamic footprint, superimposed by watercourses activity and gravitative phenomena [28].

Due to the complex geological and geomorphological settings, the AVR reveals a notable exposure to landslide hazards, with about 18% of the regional territory affected by gravitational processing. Slope instabilities vary in type and size from large slope gravitational instabilities as Deep-seated Gravitational Slope Deformations [29,30], complex landslides [31], up to rockfall events [32]. The regional landslide inventory, i.e., the "*Catasto Dissesti*" [33], hereinafter CD, actually collects more than 13,000 events, of which about four thousand are inherent to rockfall typology (Figure 2).

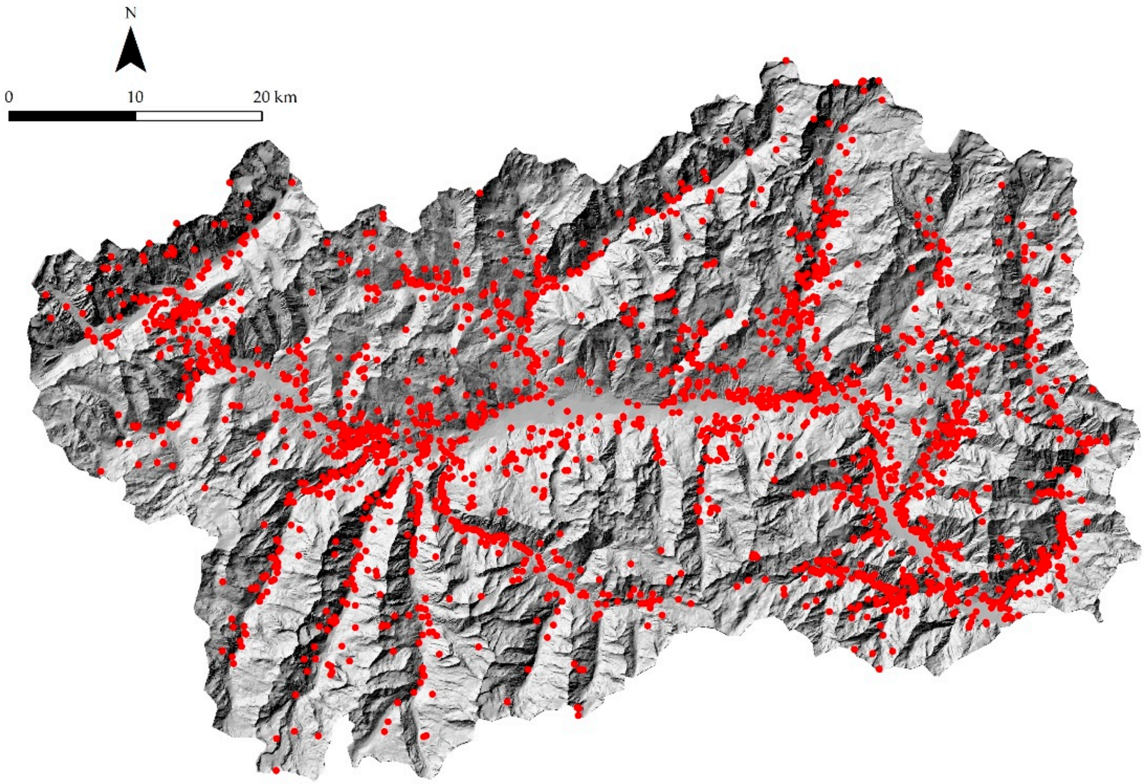

Figure 2. Rockfalls of the CD regional inventory distribution within the regional territory.

The available data and information collected in the regional landslide inventory about rockfall events cover a time span of more than eight hundred years. Rockfalls are mainly distributed along steep slopes, predominantly at medium elevation (from 1000 m to 2000 m a.s.l.), in correspondence of schistose lithologies, of the Piedmont Zone, deriving from the Piemonte-Liguria Ocean crust and Mesozoic coverage sediments [32]. The spatial and temporal distribution of the rockfall events collected in the regional landslide inventory reveals a territory highly susceptible to rockfalls, threatening urbanized areas, anthropic structures and especially the regional road network [32].

3. Methods

In this work, a new approach for proper management of rockfall impact and the related risk assessment and reduction is adopted. In particular, we focused our attention on the AVR road network to provide an effective procedure for managing rockfall effects and impacts at the local scale.

The development of the proposed methodology starts from the analysis of the materials available in the regional landslides inventory, the CD of the AVR, focusing on rockfall events, and the analysis of the existing regional scale procedure. This investigation constitutes the basis for implementing a new dedicated approach, for a local scale application, that is actually missing.

Figure 3 shows the overall methodology. The first step of our approach is the analysis of the actual data and information collection and organization at a regional scale about rockfalls. In particular, the proposed methodology focuses on the study of rockfalls which occurred in the period 2016–2020. Information about rockfall can be primarily founded in the CD. In the considered period, the CD had 711 records related to all known gravitation phenomena which occurred in Aosta Valley. Among these records, a large part corresponds to rockfalls (383 records). This primary source of data is implemented by additional information stored in a dedicated web-service, named "*Cantieri*" [34], related to technical inspections done by the geologists of the Geological Service of the Aosta Valley Administration (AVGS). The reports collected in the AVGS web-service describe the most complex events and the remedial actions and worked to reduce impacts and level of risk. Starting from this consolidated information, we organized the new procedure to apply, at a local scale, each time when a rockfall event occurs along the road network. The new approach integrates the Operative Monography (OM) tools [22] properly customized for rockfalls. Moreover, this procedure is compliant with the norms of the Italian Institution of Standardization UNI [35–42], and the international standard ISO [43].

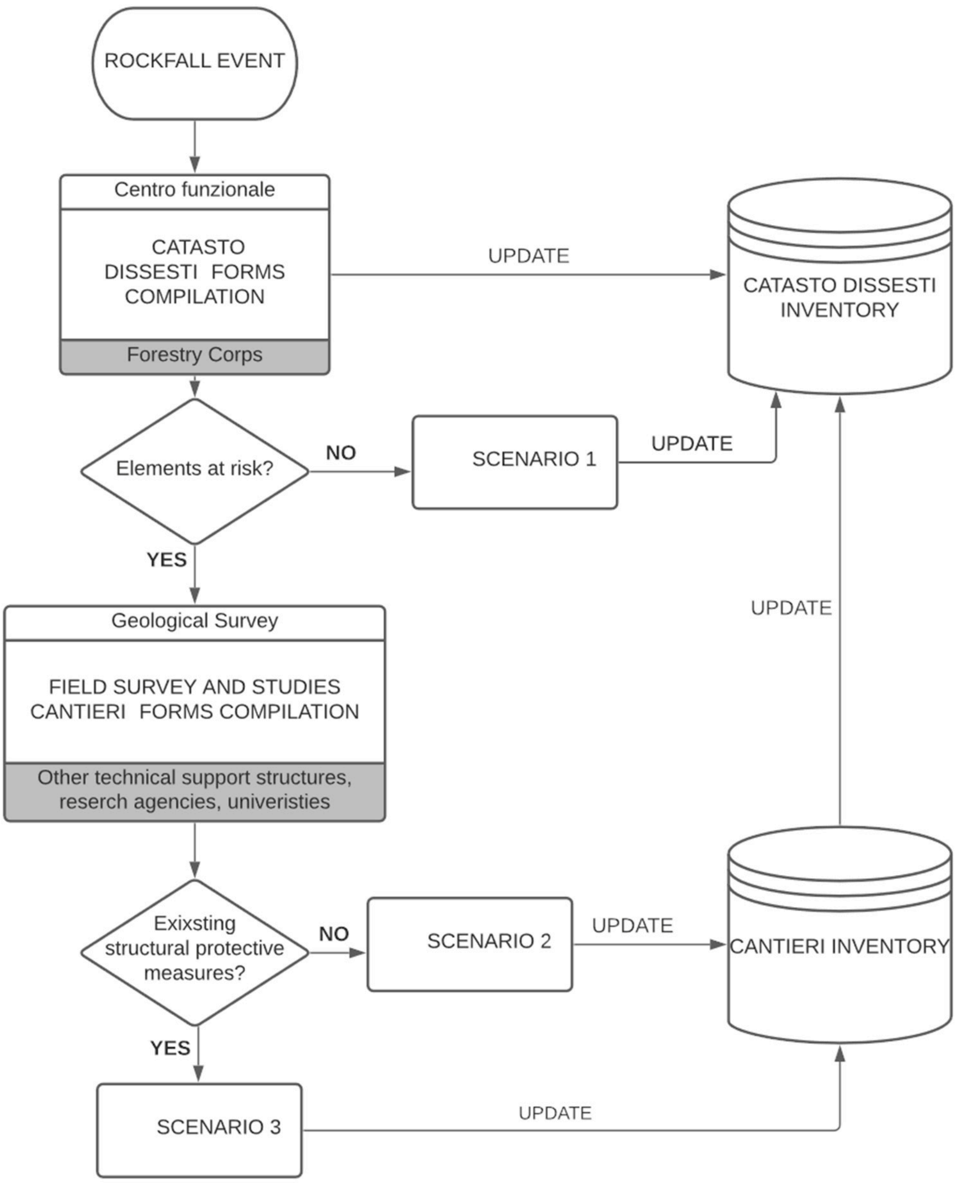

Figure 3. Scheme of the adopted methodology. The "*Catasto Dissesti*" is the official regional landslide inventory of the AVR, managed by the "*Centro Funzionale*" authority together with the Forestry Corps. "*Cantieri*" is the web-service that collects data and information about technical inspections done by geologist of the Geological Service of the AV administration, which flows into the "*Catasto Dissesti*" inventory.

3.1. Existing Regional Scale Procedure

Like many Italian regions, even the AVR has a regional landslide inventory developed to acquire all available information on the past gravitative phenomena. This register has been developed within the IFFI project (Italian landslide inventory) [14,16] and then implemented by the regional authorities. In this national project, the identification and mapping of landslides are based on standardized criteria, applied in each Italian region, mainly based on aerial photo-interpretation, collection of historical documents and local or regional existing archive, and field surveys [44]. The main purpose of this project is to provide a homogeneous database of the available data and information about landslides, following international classification standards, e.g., [45–51].

For the AVR, the IFFI inventory, actually, has merged into the CD, the regional landslide inventory consisting of a database, great source of information with a high number of records, available on a Web-GIS platform [33]. This regional database guarantees a fruitful collection and storage of the past and new landslides data and information within the regional territory. The CD is part of an operational procedure applied at a regional scale, consisting of a periodic updating of the regional landslide inventory. The update is carried out through the compilation of dedicated form by the forest stations scattered throughout the territory. The reports are compiled by an IT procedure, implemented by the "*Centro Funzionale*" [33] of the AVR, hereinafter CF, together with the Aosta Valley Forestry Corps. The current system allows for the automated acquisition of data and information relating to a specific slope instability event, acquired at first by the Forestry Corp and subsequently received by the CF, which updates the landslide inventory at regional scale.

3.2. New Local Scale Procedure

With the aim to provide an effective tool useful to policy-makers for proper road network management, a new procedure is implemented. In case of emergency due to rockfall occurrence at a specific site, an operative methodology for the definition and the scheduling of all those actions to be undertaken during the time interval between the rockfall occurrence and the remedial works' implementation was developed for local scale application.

The developed procedure identifies different scenarios according to (i) the entity of damages, (ii) the presence of elements at risk, (iii) the existence of rockfall protection. Leveraging on the large amount of data and information of the existing CD regional landslide inventory, an in-depth analysis of the rockfall typology was carried out. Specifically, a focus on the data and information about the last five years of case studies collected into the CD was made. Additional data is available in the recent web-service "*Cantieri*", i.e., an in-house service prepared by the AVGS, hereinafter CA, in charge of the technical supporting function for the regional civil protection agency. This service has been primarily developed to manage data, technical reports and information about the occurred slope instabilities of the AVR. The web-service CA automatically acquires its basic information from the rockfall and landslide event reports produced by the CF and the Forestry Corps, and through the field survey and evaluations performed by its geologists. This service has been designed to store all the information related to rockfalls and landslides, the first geological evaluations and the technical and administrative information about the further defensive works and the civil protection actions undertaken by the regional administration and municipalities. The data flow from CA is connected with the CD to update its database with the information produced during the field investigation and other data worth collecting in this latter inventory (Figure 3).

Therefore, based on previous knowledge of this mountainous region associated with the analysis of the regional landslide inventory [32], three scenarios were foreseen.

The operative scenarios provided are:

- Scenario I—the rockfall event occurs in areas where there are no previous technical studies and/or structural countermeasures and there are no elements at risk;

- Scenario II—the rockfall event occurs in areas where there are no previous technical studies and/or structural countermeasures, and it can potentially pose a risk to structures, infrastructure and human safety;
- Scenario III—the rockfall event occurs in areas where there are previous technical studies and/or structural countermeasures, and it can potentially pose a risk to structures, infrastructure and human safety.

For these defined scenarios, the procedure identified an incremental sequence of phases that are progressively activated to check the effects of the known rockfall and eventually implement a series of mitigative measures to restore an acceptable level of risk. For each scenario, the procedure defines a sequence of actions and choices to be undertaken with well-defined results associated. Actions and products are compliant with the norms of the published Italian Institution of Standardization UNI [35]. In general, the actions of the subsequent phase are based on the results of the actions of the previous phase, and the activation of the next one takes place only if the results of the previous phase do not obtain the required level of risk mitigation.

The principal identified phases in which it is possible to subdivide the period between the rockfall event occurrence and the realization of the proper remedial works are:

1. Rockfall event occurrence and establishment of the (eventual) emergency condition;
2. Implementation of a plan for the proper management of the transitional phase;
3. Design and construction of active and/or passive remedial works for risk reduction and mitigation.

The rockfall event phase starts with the event occurrence. The main element that should be considered in this phase includes the preliminary assessment of the slope stability conditions through on-site observation. Suddenly, the identification of the utmost urgent activities is required, useful for the definition of proper management of the second phase.

The second phase is the most critical. It corresponds to the time during which it is necessary to plan the actions and choices for a proper road network management. This stage aims to guarantee the safeguard of human life and infrastructure before remedial works are carried out. At this stage, the actions that reduce the risk exposure must be defined. Those actions may primarily include field inspections of the studied area to determine potential slope instabilities that may persist. In this phase, different levels of analysis may be required. Based on the degree of the rockfall event risk, the in situ analysis ranges from the simple visual inspection to an in-depth geo-structural characterization or monitoring network system implementation.

In the last phase, the design and implementation of the remedial works, with the employment of structural countermeasures (e.g., fences, walls, galleries, embankments, ditches), are foreseen. The design and selections of the various remedial works mainly depend on the public administrations' strategic choices, which should also consider the cost-effectiveness of the planned activity and the evaluated level of risk.

3.2.1. Scenario I

The application of the Scenario I (Figure 4) takes place when a rockfall involved areas without structural protective measures and where no risk elements are present close to the area affected by the event. In these cases, the event has been detected and signaled to the regional authority. Through a quick field survey, the operator in charge shall complete the form prepared to update the CD regional inventory, as required by the existing procedures. Subsequently, this procedure shall end. Considering the road network, this scenario represents the events that involve areas sufficiently far from the road network without direct involvement of the infrastructure.

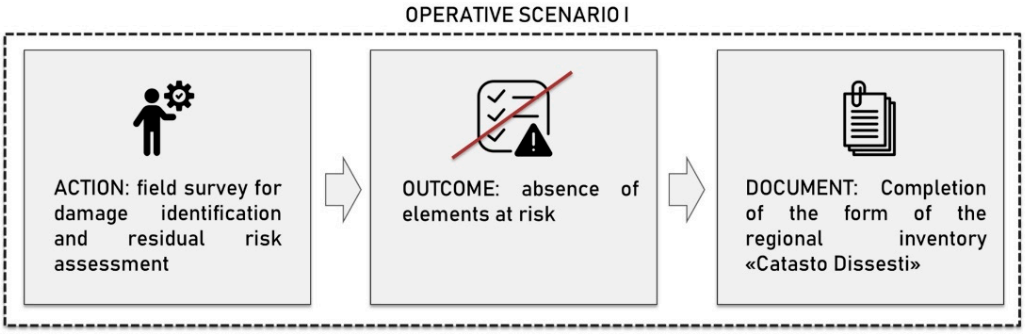

Figure 4. Scheme of Scenario I provided in the operative methodology.

3.2.2. Scenario II

Scenario II takes place in cases where the rockfall event occurs, causing damage to structures and infrastructure and posing a serious and notable risk to human safety and anthropic elements. Besides, this scenario must be activated only in cases where the rockfall event occurs in areas lacking active or passive mitigation works, and previous technical studies are absent.

Figure 5 shows the diverse insight levels of Scenario II, including the different actions planned for a specific time-scheduling. Each action has specific objectives and outcomes leading to well-defined and standardized documents, e.g., CD form, Operative Monography [22]. The document drafted at the end of each action has the function to collect, organize and manage the obtained data and information in a standard way, and to display the available data clearly. Scenario II is divided into four main actions. It is important to note that the actions of the next level are based on the results of the actions of the previous one.

Action 2.1 provides for a quick field survey immediately after the rockfall occurrence. At this stage, the operator in charge, a field geologist, identifies the caused damage and proceeds quickly to the risk assessment, through the compilation of the form predisposed by the regional authorities for updating the regional inventory. Once the presence of damage has been verified, and the residual risk has been estimated as unacceptable, Action 2.2 is started. At this stage, the main aims are the activation of the emergency activities, the identification of the area affected by the rockfall event and the definition of the proper measures for a proper risk assessment, ensuring the safety of settlements and population. The operator in charge must primarily circumscribe the area subject to rockfall event and its surroundings, which is defined as the sector involved in the emergency activities i.e., detachment area, transitional zone and accumulation zone.

For the areas specifically included in the emergency activities, the operator identifies if there are residual areas potentially unstable. Subsequently, detachment or stabilization operations are planned and carried out for the unstable portions of the observed slope. Meanwhile, activities and procedures aimed at risk mitigation during the emergency are implemented and planned. This phase of the procedure, aimed at the provisional management of the contingency, is particularly important because it has to define how the site should be managed during the period between the rockfall event and the end of the risk reduction procedure. The contingency management should consider the safety of the population and the preservation of infrastructure, but also the possibility that the area at risk could be exploited if its usage is strictly necessary. Monitoring systems or policies for the restriction of access to the site at risk are the main elements that this procedure shall consider and define.

All the collected information, data and measures are stored in the OM of Level 1, containing the background information acquired at this level. The detailed description of different level contents of the OM is provided in the following section.

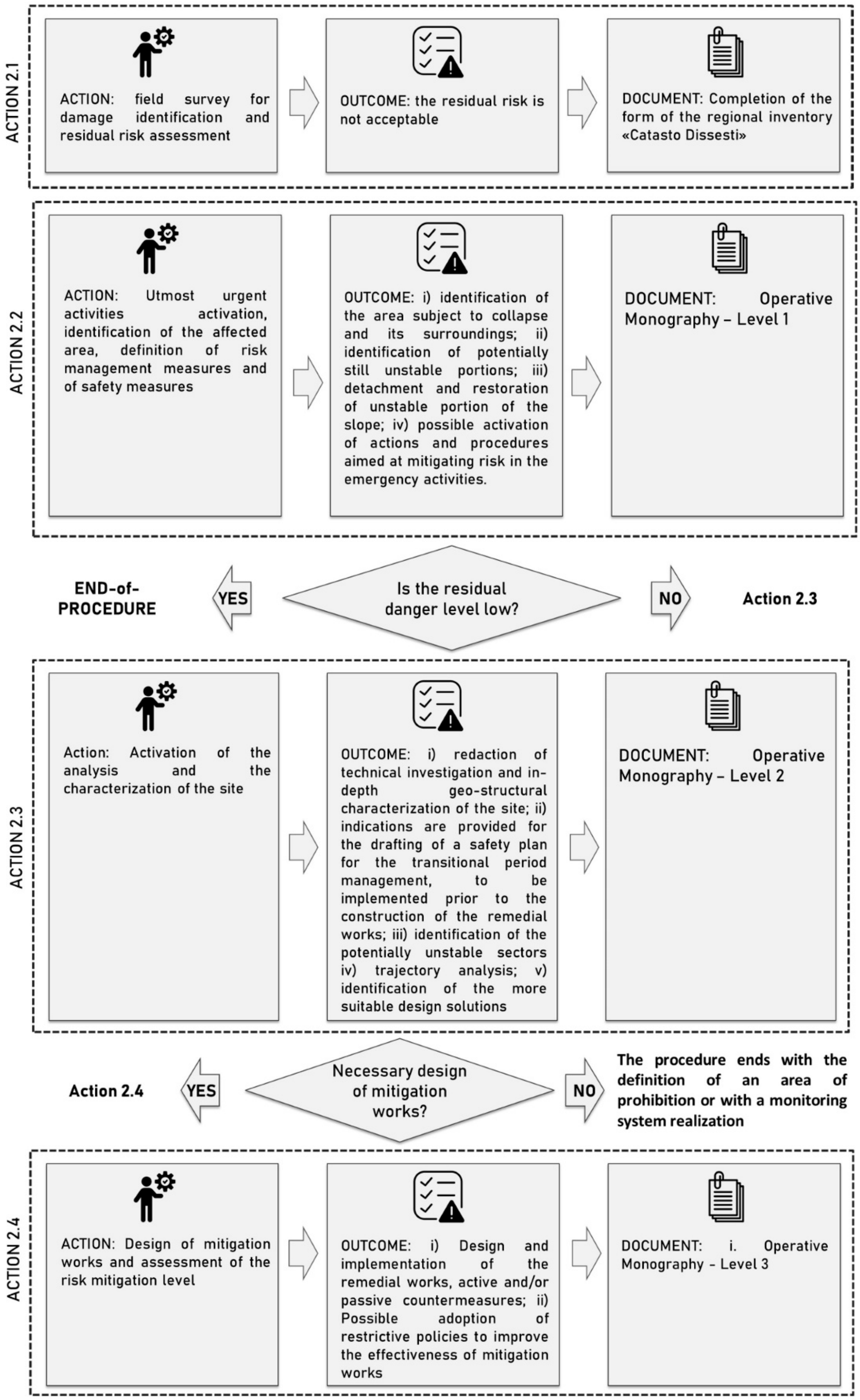

Figure 5. Scheme of Scenario II provided in the operative methodology, divided into four main actions, with the corresponding outcomes and the final document drafted for each level.

At this stage, if the residual hazard level is low or close to zero, the procedure ends. Otherwise, if the detachment and stabilization operations are not sufficient to lower residual hazard, Action 2.3 is activated.

Action 2.3 is functional to the in-depth characterization of the observed site. First, the different controlling factors (e.g., geological and geomechanical conditions, meteorological factors, natural or anthropic conditions) are investigated. Alongside, the analysis of rockfall occurrence through the geomechanical and structural characterization of the slope instability, the analysis of eventual historical traces of previous events and the application of propagation models (e.g., trajectory analysis), are carried out. Furthermore, preliminary indications, functional to drafting a contingency plan for proper management of the transitional phase before the eventual structural mitigation measures' implementation, are provided. In this way, preliminary project solutions to the risk reduction are identified and planned. The acquired information of Action 2.3 is collected in the second level of OM.

Action 2.3 ends with the evaluation of the real necessity to plan and design mitigation works. Mitigation works are often the best solution, but a cost/benefit evaluation must be considered. For this reason, there is also the possibility that the outcome of the cost/benefit analysis is that the cost of structural remedial works could not be sustainable. In this case, the procedure ends with defining a restricted area or implementing a system for residual risk management. Conversely, in cases where active and/or passive mitigation works are necessary, the next action of the procedure is activated. Action 2.4 is mainly functional for designing and constructing structural defensive measures for risk management and mitigation. The definition of the best solution for structural countermeasures is a complex task that requires a detailed on-site study. The UNI norms define how this analysis has to be performed and if the designers have to evaluate active or passive solutions or both. The final document obtained corresponds to the OM of the third level, updated concerning previous phases, including the essential information relating to the planned design choices. The final plan can consider not only the design of mitigative works, but also addition policy and restrictions that concur with the restoration of a correct level of risk.

3.2.3. Scenario III

As the previous one, Scenario III takes place in cases where a rockfall event causes damage and poses a serious risk to human safety and anthropic elements. The main difference from the previous one is that Scenario III is referred only to cases where active and/or passive mitigative works existed before the rockfalls.

Figure 6 shows the different insight levels of Scenario III, with a total of four main actions following a predetermined sequence. As in the previous scenario, each action has specific targets, and outcomes and the action of the next level is based on the results of the action of the previous one.

Action 3.1 provides for the prompt field survey immediately after the rockfall occurrence, expected in all scenarios. In this case, the operator in charge identifies the caused damage and defines the conditions of risk, through the compilation of the form to update the CD inventory. In the following action, i.e., Action 3.2, the operator in charge must delimit the area affected by rockfall events and its surroundings. For those areas specifically included in the emergency activities, the operator identifies the areas still potentially unstable. Besides, a rapid assessment of the conditions of the existing mitigation works is foreseen, to evaluate their restoration. Finally, activities and procedures aimed at risk mitigation during the emergency are implemented and planned.

Even in this scenario, specific documents, characterized by standard organization, are foreseen for each action. After Action 3.2, an OM of Level 1 is drafted, including the background information acquired at this level about geological and geomechanical characterization of the area of interest, hydrological and hydrogeological settings' characterization, identifications of elements at risk. A dedicated section must be provided for the temporary management plan as described before.

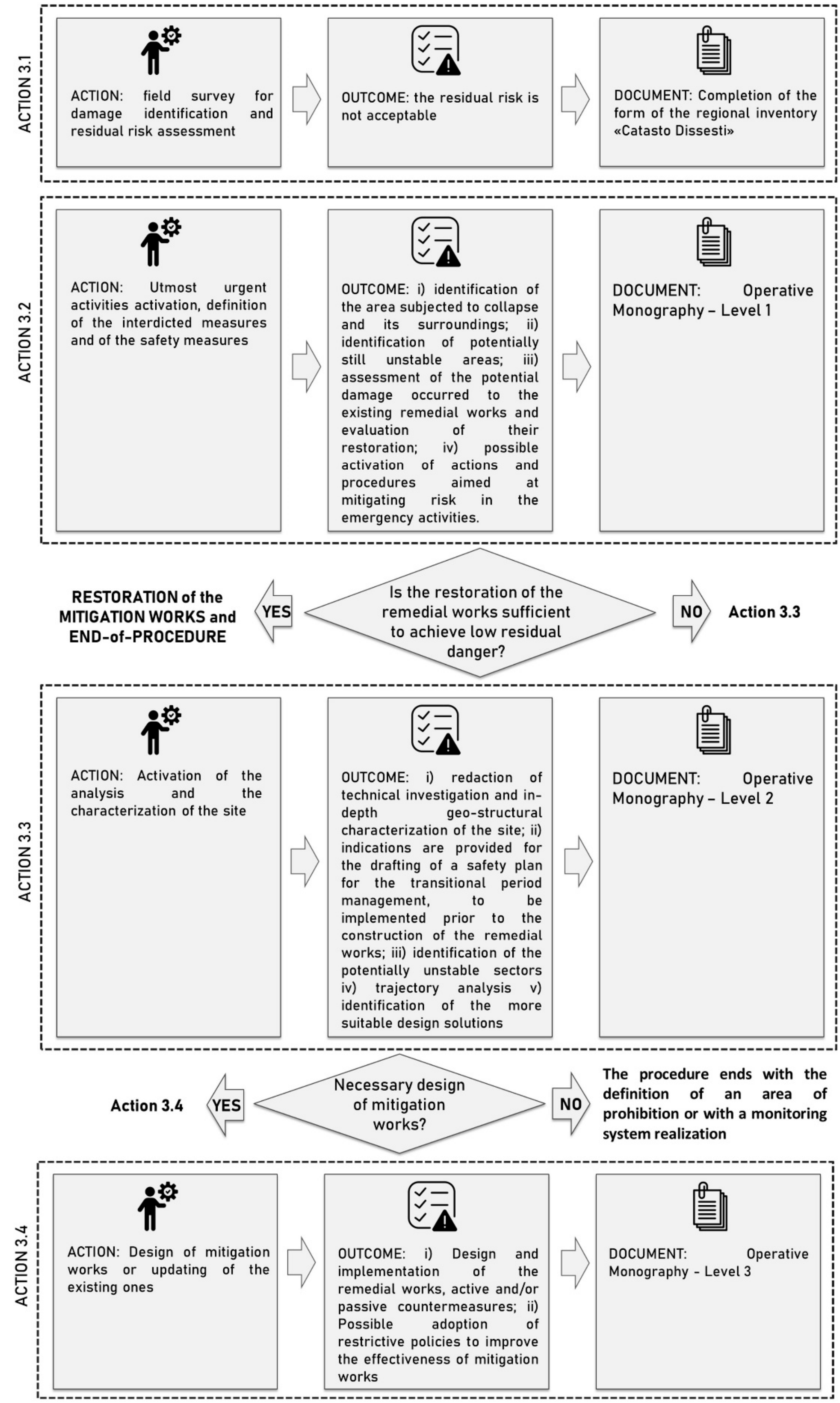

Figure 6. Scheme of Scenario II provided in the operative methodology, divided in four main actions, with the corresponding outcomes and the final document drafted for each level.

Action 3.2 ends with the identification of the possible solutions: (i) the restoration of the pre-existing mitigation works is possible, and the effect of the extraordinary maintenance of remedial works is sufficient to restore the status quo; in this case, the procedure ends with the restoration of the remedial works; (ii) in many cases since the damage suffered by the rockfall defenses is too heavy, their repair is not possible or not cost-effective, and the procedure moves onto the next action.

Action 3.3 is functional to the in-depth characterization of the observed site and is similar to Action 2.3 of Scenario II. Specifically, the operator in charge must describe the diverse controlling factors, the geomechanical and structural setting of the slope involved in rockfall events, historical events and shall carry out trajectory analysis. Furthermore, preliminary indications, functional to drafting a safety plan for proper management of the transitional phase before the eventual structural countermeasures' repairing or strengthening, are provided. In this way, preliminary project solutions to risk reduction are identified and planned.

Even in this case, a precise document is foreseen. An OM of Level 2 is drafted, including all the new information acquired at this level.

Action 3.3 ends with the evaluation of the necessity of the design of new mitigation works or the strengthening of the existing ones. As presented in Scenario II, the last evaluation that is considered before implementing the infrastructure is the cost/benefit of the proposed solution. If the outcome of cost/benefit exceeds an expected value, the procedure ends with the definition of an interdiction area, or with the implementation of a system for the residual risk management. Conversely, in those cases where active and/or passive mitigation works are necessary, the procedure moves on to the next action.

Action 3.4 is mainly functional to the design and construction of structural countermeasures for risk management and mitigation. With a specific focus on the series of UNI Norms relating to the defense works against rockfalls, the most appropriate countermeasures are designed together with the main aspects to be considered in the preliminary design and, suddenly, in the definitive and executive design levels. As presented in Scenario II, in cases where the cost/benefit analysis is not economically viable, dedicated restrictive policies can be foreseen. The final document obtained corresponds to the OM of Level 3, updated concerning the previous phases, including the essential information relating to the planned design choices.

3.3. Operative Monography Customization

In order to ensure effective management of data and information, together with the obtained results, the final documents of each action of the diverse foreseen scenarios, should be organized in a codified form. According to Giordan et al. [22], the defined document is a dedicated OM version. The OM is a standardized and easily readable document that allows immediate access to the available data and information about an event. This document, applied and tested in different geological and geomorphological contexts and for diverse types of landslides [22,23], provides a brief and constantly updated reasoned overview of a single hazardous phenomenon. The main aim is to assure a proper collection and organization of the data and information available, derived from the diverse operations foreseen by the regional administrations (e.g., CF, AVGS) during a slope instability occurrence.

Due to the multiple actions foreseen in the diverse implemented scenario, an increasing level of data and information can occur. For this reason, diverse OMs with increasing levels of depth have been proposed. Thus, this guarantees to progressively follow the envisaged actions and quickly retrieve the available information. In the defined procedure, drafting a new OM exclusively for Scenarios II and III, when a detailed in situ analysis is required. The OM has been organized in three different levels, according to the number of actions required by the procedure for correct management of the analyzed site:

- Level 1: this is the entry-level of OM that includes basic knowledge about the phenomena derived from field survey observations;

- Level 2: this second level of OM contains an in-depth analysis of geological, geomorphological, and geotechnical slope characterization, dynamic effects of rockfalls and others, for which technical studies are planned;
- Level 3: this final level is dedicated to technical specifications for remedial works design.

The OMs summarize in a standard way the main results of each action (Table 1) and, as for the actions of the scenarios, the norms of the published Italian Institution of Standardization UNI [35] should be followed. The use of OMs is important because it supports the technicians in the activation of a correct sequence of actions and results that are the base of the proposed codified procedure.

Table 1. Scheme of the OM structures for each level considered.

	Catasto Dissesti	OM Sections	OM Level 1	OM Level 2	OM Level 3
Action 1	X				
Action 2		Description of the area subject to collapse and its surroundings	X	X	X
		Description of the potential still unstable portion	X	X	X
		Description of detachment and restoration operations	X	X	X
		Description of the eventual damage to the existing remedial works and evaluation of their restoration	X	X	X
		Description of the actions and procedures aimed at mitigation risk in the emergency activities	X	X	X
Action 3		Brief summary of the technical investigation carried out in the area subject to collapse		X	X
		Description of the safety plan provided for the transitional period management		X	X
		Description of the trajectory analysis		X	X
		Description of the identified design solutions		X	X
Action 4		Synthetic description of the principal technical specifications of remedial works adopted			X
		Description of restrictive policies eventually adopted			X

In Level 1 of OMs, referring to the UNI norms, some information must be included as (i) a brief geological and geomorphological characterization of the site; (ii) the results of the eventual physical investigation carried out (e.g., field survey, on-site test); (iii) a brief engineering geological and geomechanical characterization of the source area and the slope below, up to the assets to be defended; (iv) hydrological and hydrogeological characterization of the area of interest; (v) the identification of the elements at risk. A dedicated section must be provided for the temporary management procedure. The Level 1 OM generates a document that well-summarized the basic information about the rockfall event reported in the report produced by the CF and the Forestry Corps after automatically acquired by the web-service CA and integrated by field surveys and evaluations performed by its geologists.

Moving forward with the actions foreseen in the scenarios, due to the increasing level of data and information collected, in the Level 2 OM, other data and information are managed. Specifically, always following the UNI Norms, the OM of Level 2 guarantees to quickly retrieve information about previous technical studies as historical events, geological and geomorphological settings, geomechanical survey of the slope, analysis of rockfall dynamic. In this way, geological and geotechnical investigations, eventually drafted in this phase, are briefly described and summarized in a standard mode.

Finally, in the OM of Level 3 the technical solutions chosen for the design and construction of the remedial works are critically summarized, and also in this case the UNI Norms are followed.

4. Results

The implemented operative methodology has been well-proven in the AVR. The analysis of the CD dataset in the period 2016 – 2020 revealed 711 records related to all the known gravitative phenomena which occurred in Aosta Valley territory. Among them, 383 records report rockfall events. This primary source of data has not been sufficient for a correct definition of the type of scenario of each occurred event. For this reason, we also considered the additional information included in the technical reports done by the AVGS geologists collected by the web-service CA [34].

A total of 219 cases on a total of 383 rockfall events fall under Scenario I, 149 cases fall under Scenario II, while only 15 cases are in Scenario III. Figure 7 shows the distribution of the inventoried rockfalls of the last five years in the three scenarios.

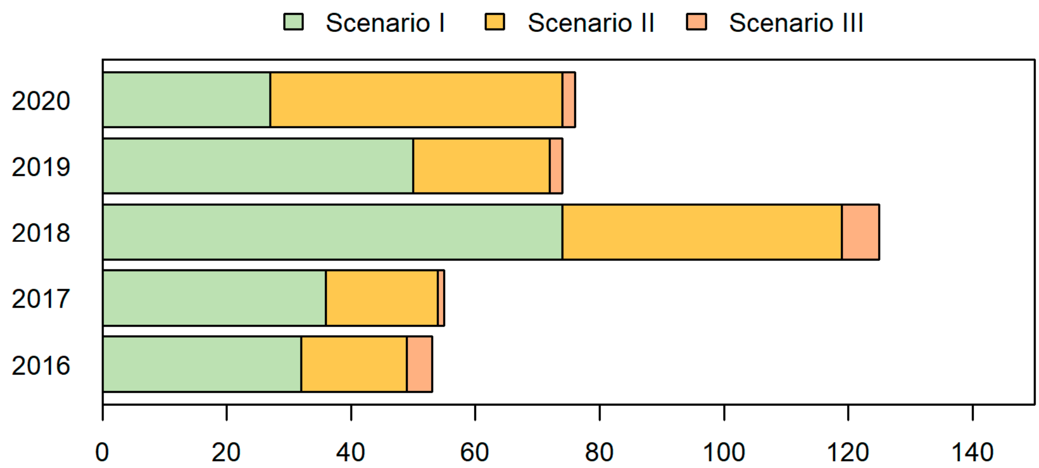

Figure 7. Bar graph of the rockfall events that occurred between the 2016 and 2020, collected in the "*Catasto Dissesti*", distributed in the three provided scenarios.

According to Figure 7, the recorded trend is regular in the past five years, with the majority of cases falling into Scenario I, between 60 and 70% per year. Scenario II follows with a percentage variable from 30 to 35% per year. A much smaller percentage, varying from 2 to 8%, is recorded for Scenario III. The only exception is recorded for the year of 2020, with about 40% of the cases falling in Scenario I and about 60% in Scenario II.

In Figure 8, we present an example of rockfall belonging to Scenario I, which occurred in the locality of Trajo, close to the renowned tourist resort of Cogne. The rockfall occurred in October 2017. The source area is located at the sub-vertical cliffs upstream of the regional road, at the foot of which debris talus, partially vegetated and wooded, sporadically fed by large blocks. The rockfall occurred in two stages and involved a significant volume (i.e., 8000 mc), causing a cloud of dust, which compromised the visibility in the valley floor for about 30 min. The rock material broke down in two directions due to local morphology. The predominantly coarse materials spread over the rocky crags, without directly affecting anthropic structures and infrastructure, except the local path network. In this case, no damage has been reported, and there are no elements at risk close to the area affected by the event. It should be noted that the phenomenon has not led to the interruption of essential services. In this case, an immediate field survey by the AVGS with the updating of the CD regional inventory, was carried out.

This event occurred in an area without structural countermeasures and has produced effects that do not constitute a risk for human safety and anthropic infrastructure, well representing a case of application of Scenario I.

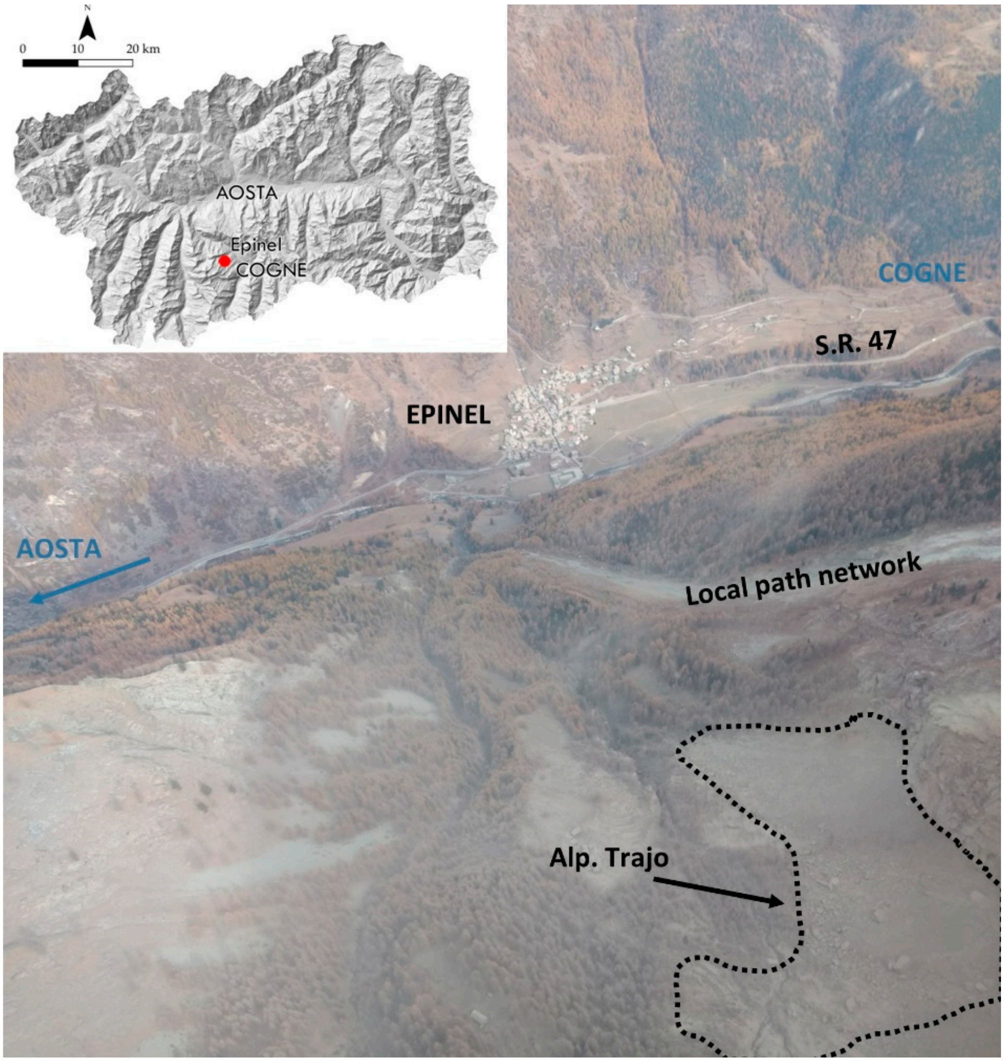

Figure 8. Example of rockfall event inventoried in the CD manageable in Scenario I, which occurred in the locality of Trajo, close to Cogne town and involving the local path network.

Figure 9 presents a case study accounted in Scenario II. The rockfall occurred in the locality of Plan Chécrouit, close to the renowned tourist resort of Courmayeur, in February 2020. The source area consists of a rock cliff located along the southern slope of the Mont Chétif, from which a volume of about 800–1000 m^3 has detached. Based on the technical report available in a study [34], it appears that most of the blocks stopped along the talus at the base of the slope. However, some stone blocks of about 300–400 m^3, due to the high kinetic energy, continued the fall along the slope, damaging some tall trees. There were several blocks, following two distinct trajectories, impacting on a stretch of a dirt road, and creating a hole about 10 m deep. The blocks have reached and damaged some ski facilities (e.g., ski slopes, chairlift, electric cabin). Due to the hazard looming on the anthropic structures and infrastructure, and threatening human safety, the local authorities have proceeded as a precaution to delimit the area affected by the rockfall, as well as the neighboring sectors, by means of a fence.

In the field report, available on CA, the geological assessment focuses on identifying potentially still unstable portions, analyzing the source area, and referable to Action 2.2. Specifically, a geo-structural characterization of the source area has been reported to identify predisposing conditions for triggering new rockfalls. The AVGS suggests an in-depth geological, geo-structural and trajectographic analysis of the area subject to collapse and its surroundings based on the observations made. This is intended to assess the implementation of proper design solution for risk mitigation and define if the residual risk is acceptable, as scheduled in Action 2.3. Finally, due to the risk posed to diverse anthropic infrastructure, the local authorities adopted some restrictive policies, as planned at the end of Scenario II within Action 2.4.

This event occurred in an area without structural countermeasures and has produced effects that pose a risk for human safety and anthropic infrastructure, which led to the adoption of restrictive policies. This case well represented an application of Scenario II.

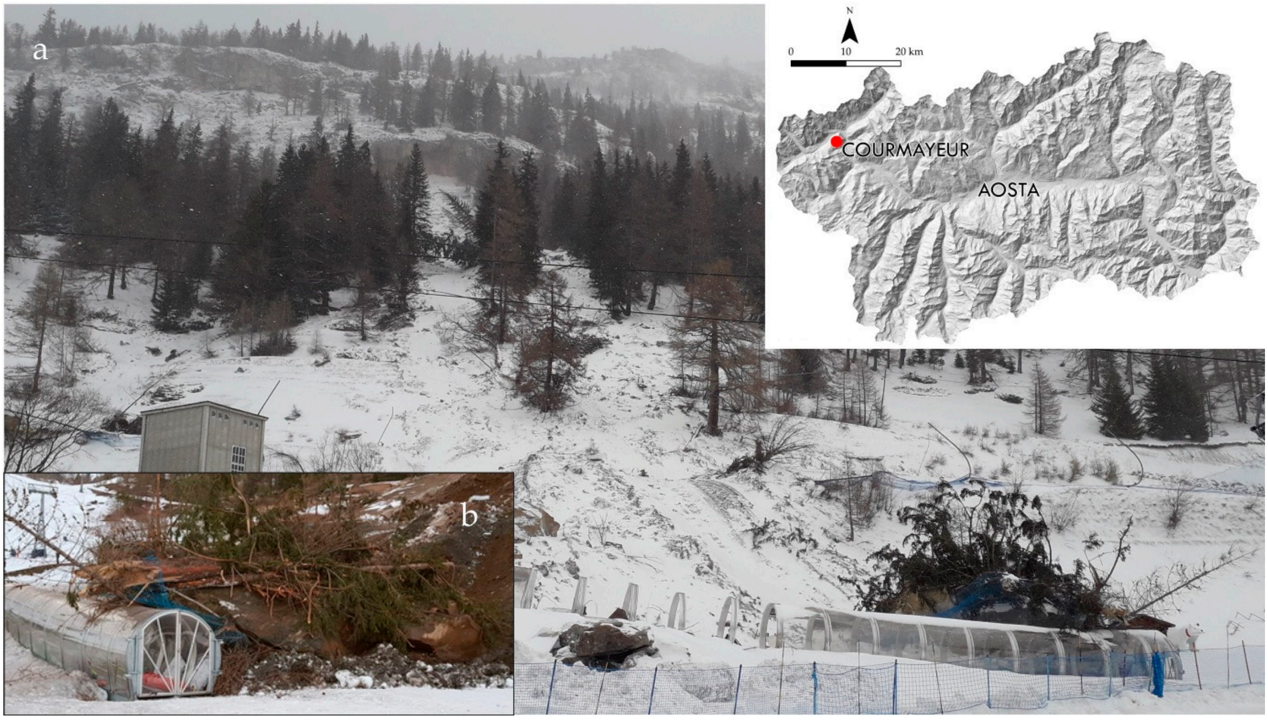

Figure 9. Example of rockfall event analyzed in CA and inventoried by the CD manageable in Scenario II, which occurred in the locality of Plan Chécrouit, close to Courmayeur town: (**a**) source area of the rockfall event; (**b**) damage recorded to the ski facilities of the Mont Chétif.

Finally, Figure 10 shows a case study which can be classified as Scenario III. The rockfall occurred in the locality of Escarra, in the Brusson municipality, in November 2016. The source area consists of a rock cliff immediately above the Escarra hamlet, from which a volume of about 50–70 m^3 has detached. Some blocks rolled and bounced up to reach the existing defensive structure embankment for buildings' rockfall protection. The rockfall impacted at different heights on the uphill extrados and the lateral cliff of the rockfall embankment, without totally compromising and breaching the rockfall protection.

In the field report, the high propensity to failure of the sub-vertical cliff is emphasized, analyzing the area subjected to collapse and its surrounding, and quickly surveying the damage that occurred to the existing remedial works, as scheduled in Action 3.2. It should be noted that for this event, there are already technical reports, drafted in the framework of the planning of the interventions to protect the town of Escarra. The previous studies focused on an in-depth geological, geomorphological, and geo-structural characterization of the area of interest, analyzing the previous rockfall events in this area, leveraging on terrestrial laser scanner and direct investigations of the cliff. All these analyses well describe the actions planned in Action 3.3.

The field report outlines for this event the urgent and unavoidable need to restore the functions of the existing work, without the implementation and design of new remedial works, de facto concluding Scenario II at Action 3.3.

This event occurred in an area with existing structural countermeasures and technical studies, constituting a serious risk for human safety and anthropic structures and infrastructure, well representing a case of application of Scenario III.

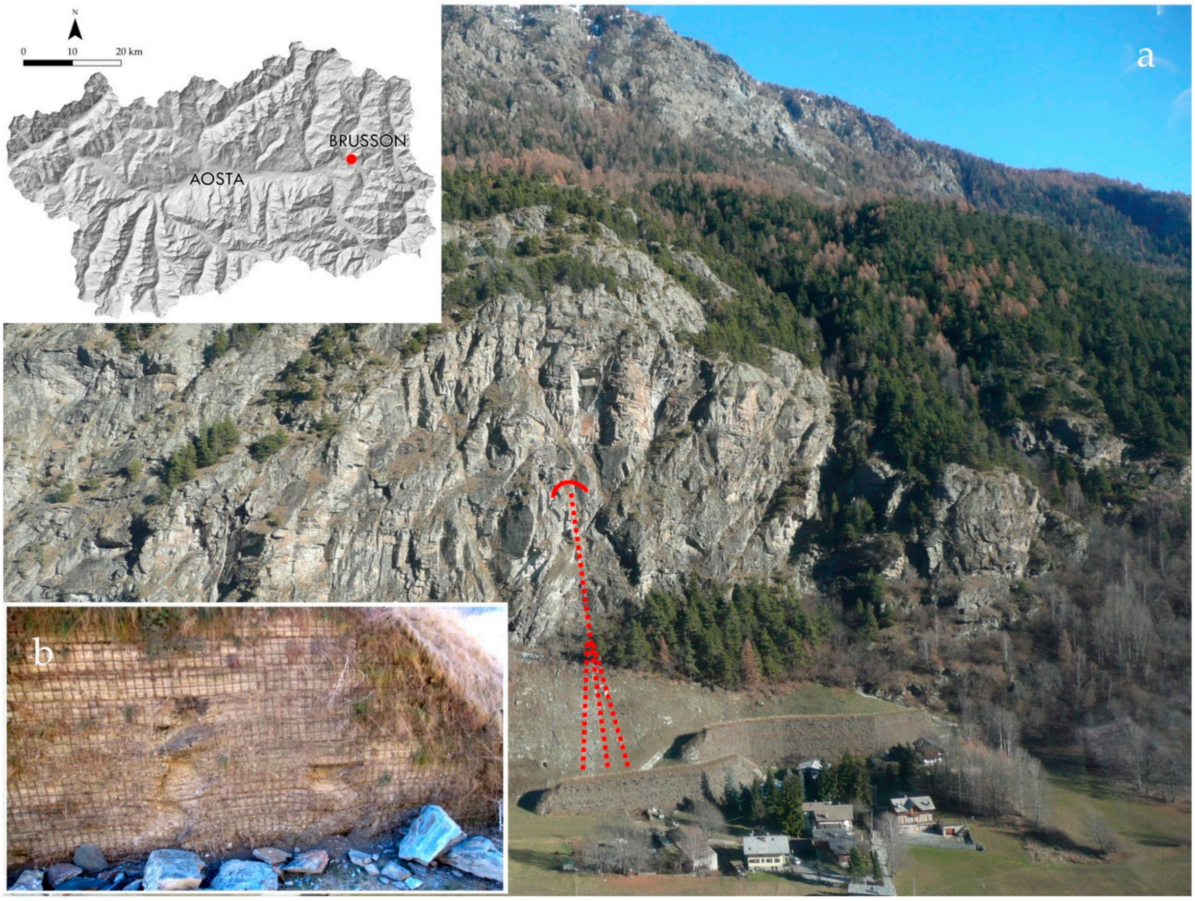

Figure 10. Example of rockfall event inventoried in the CD manageable in Scenario III, which occurred in the locality of Escarra, in the Brusson municipality (Ayas Valley): (**a**) source area of the rockfall event; (**b**) damage recorded to the existing embankment, located immediately above the Escarra hamlet.

5. Discussion

Like all the inhabited mountainous areas, rockfalls are a complex problem to tackle even in the AVR. The road network of this mountainous territory, composed of strategic highways, a railway and a dense network of regional and municipal roads, is highly spatially and temporally affected by rockfalls, as testified by the extended CD regional landslide inventory [33]. This regional inventory is a powerful cartographic database populated by the AVR authorities in the IFFI project framework [31] that actually represents a fundamental element for the management of all acquired information about slope instabilities, which occurred in the AVR territory. A detailed analysis of CD pointed out that the morphological characteristics of the AVR make its territory a typical environment where the adverse combinations of steep slopes and complex geological and structural settings, make the slopes along the roads highly sensitive to rockfall events [32].

Internationally, road management safety in case of rockfall occurrence poses a major challenge in emergency management. In the international literature, there are various risk assessment procedures aimed at a correct rockfall risk evaluation and management in mountain areas [52–54] or sites with cultural and geological heritage [55–57]. These procedures are based on the use of diverse instruments and tools like terrestrial photogrammetry [58,59], terrestrial laser scanner (TLS) [60–63], and uncrewed aerial vehicles [64–66]. In this framework composed of many various methodologies and instruments, technicians and administrators are working to the implementation of regional or national guidelines [67,68] for the landslide risk assessment, providing useful information for the definition of operative solutions aimed at correct and effective land protection and planning.

Beyond the numerous risk assessment methodologies and strategies, one of the most critical points is the proper management of the period between the rockfall occurrence and the remedial work implementation. Often complex and difficult, this period represents a key element for defining more effective and efficient risk management and a future improvement of the resilience of the territory. Correct risk management and an improvement of the resilience of the territory could be pursued only using a codified procedure defining a sequence of actions and results that must be achieved to ensure an acceptable risk level, consistent with the current emergency situation. More generally, a codified procedure for a proper administration of the operative actions to be undertaken during a rockfall event along the road is becoming a growing need not only for AVR but for the majority of the national and regional authorities and administrations, which manage territories affected by rockfalls. The availability of codified activities is important for adopting a standardized approach and for the interoperability of regional and local administrators, operatives and geoscientists. The final goal is more sustainable and well-organized management of the rockfall related to the emergency phases.

Taking examples from other fields of application, in which a standard protocol is mandatory [69,70], we started to consider that the use of defined methodologies and protocols is an important element event in managing slope instabilities and, more generally, in engineering geology applications. Analyzing the other fields of applications, where the adoption of a standardized approach is common, we also realized that this attitude is important during emergencies when the time for the definition of possible response is limited, and the availability of a codified procedure helps decision-makers in the organization of the correct sequence of actions and supports them with a clearer definition of duties and responsibilities. If we consider, in particular, the rockfall events, it is important to note that the implementation of a proper and efficient procedure is not easy because of the high variability in terms of data, pre-existing conditions, and elements at risk. This extreme variability is not a characteristic of rockfall but, more generally, represents a common point of many types of landslides [22,23]. For this reason, the correct approach should be based on a detailed analysis of the characteristics that can be used to define different kinds of rockfall and different scenarios. In AVR the analysis of the CD database certified that the AVR is characterized by many rockfalls that, unfortunately, sometimes can involve infrastructure and represent high-risk conditions. The CD provides a good basis of data, in schematic form, very useful for quickly describing the known phenomena as well as geological and geo-structural contexts. To obtain more detailed information about the events that occurred in the last five years, this work also focused on the available technical reports stored in another database of the AVR authorities called CA. The combined analysis of these two databases gave us the possibility to check not only how many rockfalls were identified and registered in the considered time interval, but also the impact of these events and the countermeasures adopted by the regional and local authorities. The results obtained by observing the last five years of CD dataset pointed out that 57% of inventoried events occurred in areas that do not seem to be able to constitute a risk for human safety and infrastructure; in these cases, the regional authorities used the CD to describe and catalogue the known phenomena. In the other 43% of occurred events, the AVGS had to make an additional analysis because the rockfalls involved elements at risk and created a critical condition that required countermeasures. Instead, about 39% of the rockfall events occurred in areas where there were no previous technical studies and/or structural countermeasures. Finally, only a small percentage (4%) corresponds to rockfall events, which occurred in areas where there are previous technical studies and/or structural countermeasures. The presence of elements at risk and the preexistence of infrastructure aimed to stabilize the slope or reduce the effects of the impact are the two elements that we adopted to define the three different scenarios that are the bases for the proposed procedure.

Starting from these scenarios, we developed and tested a new operative methodology for managing rockfall impacts and the definition of temporary and permanent mitigation actions. The implemented method combines regional and local-scale approaches. The regional approach is based on the well-known CD regional landslide inventory. The local scale approach considers a procedure composed of a sequence of activities aimed at defining the road map for a correct management of the residual risk assessment and the definition of the mitigation strategy. This part of the methodology has been implemented and tested to fill in the gap due to the current lack of internationally standardized and well-defined procedures for the local management of rockfall related emergencies and critical conditions. The local scale procedure is composed of a sequence of levels subdivided into several actions. Following this sequence of actions, we proposed an incremental process that can allow efficient and effective road network safety management. Moreover, it is important to note that each scheduled action corresponds to specific outcomes. The defined procedure is developed in a progressive sequence of actions and outcomes, where the next level's action is based on the previous action results. Besides, for the correct management of the increasing number of data and information, the OMs were coupled with the methodology, using the same incremental approach. OMs supply a standard and easily readable document that, properly customized for rockfall typology, guarantees immediate access to data and information about any single event observed. Three OM levels have been codified, with an increasing level of detail to assure a fruitful collection and organization of the data, following the progressive increase of the multiple actions foreseen in each scenario. Moreover, to make the operative methodology compliant to the national standards and current regulations, both actions and products, i.e., OMs, refer to the Italian Institution of Standardization's UNI norms.

6. Conclusions

The Alpine regions are exposed to several rockfall events, which cause serious problems in the land protection and, specifically, in the road network management, to protect drivers and passengers, pedestrians and the infrastructure. A proper definition of choices and priorities to be applied along a communication route during the emergency phases is a key aspect for a more effective rockfall risk management and mitigation. To achieve this goal, regional and local administrators and decision-makers need a real operational tool allowing an operative and flexible guideline for rockfall risk management along with the road networks.

This work has established the feasibility of an operative methodology to be activated immediately after a rockfall event, during the interval between the rockfall occurrences and for the implementation of the remedial works. Leveraging on the Aosta Valley Region (north-western Italy), a small Alpine territory widely affected by rockfalls, we developed and tested this operative methodology to be applied to the road network emergency management. Starting from the existing procedure applied at a regional scale and based on the CD regional landslide inventory, a new local scale procedure was developed, providing a new event-scale regulation associated with the existing regional procedure. By exploiting the large amount of data and information contained in CD, and in the other regional database CA, we analyzed events over the last five years, and defined three distinct scenarios. Defined scenarios were defined considering several key aspects such as the degree of damage, the presence of previous technical reports and/or active or passive remedial works and structural mitigative measures. A detailed description and outlining of the diverse actions to be undertaken for each established scenario were performed, identifying an incremental sequence of phases to be activated in progression to check the effects of rockfall occurrence, associated with a series of measures aimed to restore an acceptable level of risk.

The presented operative methodology allows for immediate screening of the emergency by providing useful guidance for allocating funds. The final goal is to increase the resilience of the system by fixing those sectors that have no previous interventions, and the sectors needing reinforcement of the interventions done in recent decades. This procedure represents a useful tool for regional and local authorities and administrators, providing a reasonable response to enhance a proper administration of the road network, by scheduling the appropriate risk management measures, and to guarantee a tolerable or acceptable risk level for the safety of road, infrastructure and traffic, which is also applicable in other mountain areas of the world.

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Data Availability Statement: "*Catasto Dissesti*" data is available in a publicly accessible repository that does not issue DOIs. This data can be found here: https://catastodissesti.partout.it/ (accessed on 16 March 2020). For "*Cantieri*" data restrictions apply to the availability of these data. Data was obtained from Geological Service of the Aosta Valley Region and are available from the Geological Service of the Aosta Valley Region on reasonable request.

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