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Ground investigation: a tool for landslide risk mitigation of infrastructures

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Abstract

Recent monitoring experiences for bridges in Central and South Italy have shown that it is not common for bridges to be directly damaged by landslides phenomena in their vicinities, either because their siting was very carefully selected at the origin or because appropriate protection measures have been taken to reduce geological risk to acceptable levels. In the first case, periodic visual inspections of the manufacts may suffice to monitor possible consequences of ground instability phenomena, but in the second case monitoring of the infrastructure and of the ground is the only possible tool to evaluate the existence of a landslide-structure interaction which can influence its performance and safety. Ground investigation is a fundamental activity for landslide monitoring and analysis, and this is specifically true when a landslide-infrastructure interaction problem needs to be investigated and assessed. By discussing the results from case studies recently inspected, this paper shows how the knowledge of the physical processes and the monitoring of selected parameters are the first irreplaceable tools to mitigate risks associated with instability phenomena interacting with sensitive infrastructures.

Keywords: geological risk mitigation; ground investigation of active slopes; monitoring of slope-bridge interaction ;

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1. Introduction

Linear infrastructures, roads, railways and pipelines are very vulnerable to landslides. This is particularly relevant in a landslide-prone territory, like Italy, that hosts large part of European mapped phenomena. For this reason, landslide risk mitigation for bridges and viaducts is a highly relevant issue. Some recent events are exemplars to outline the problem: in 2015, the re-activation of the Scillato landslide (Sicily) greatly damaged the Himera viaduct of the Palermo-Catania motorway; in 2019, a section of the Turin-Savona A6 motorway was affected by a landslide that irreparably damaged the viaduct called “Madonna del Monte”; in 2020 the bridge crossing the river Magra collapsed due to long term displacements of one abutment caused by a landslide in the Northern Apennines.

However, within a systematic monitoring programme of infrastructures, the observation of a number of bridges in Central and South Italy has shown that, thanks to an accurate siting selection at the origin, it is not common for bridges to be damaged by the presence of landslides in their vicinities. Also, when the bridge-landslide interaction could not be avoided, appropriate protection measures were implemented to reduce geological risk within acceptable levels. When the landslide risk is negligible, periodic visual inspection may suffice to guarantee safety against ground instability phenomena; otherwise, when the landslide risk is not negligible, monitoring of the infrastructure and of the ground is the only possible tool to evaluate the existence of a landslide-structure interaction problem which can influence its performance and safety. In this framework, ground investigation is a fundamental activity for landslide monitoring and analysis, and this is specifically true when landslide-infrastructure interaction needs to be investigated. In the conception of the new generation of Eurocode 7 (prEN 1997:2023), ground investigation comprises several activities that include studies to address the geology of the site, site inspections, intrusive and non-intrusive site investigations, monitoring of the structure and terrestrial or satellite interferometry, monitoring with probes into the ground to describe ground deformations and groundwater flow, to be possibly linked to environmental parameters. However, for the purpose of a general preliminary classification of existing bridges to locate the most critical cases and to orderly program remedial interventions, a thorough ground investigation may be disproportionate, and the question arises of how to calibrate the investigation to reach a sufficient knowledge of the bridge and its behaviour in relation to possible slope instabilities to ensure that the assessment of landslide hazard is reliable.

2. The multilevel approach for risk assessment of Italian bridges

Since the disastrous failure occurred to the suspended bridge over the Polcevera River in Genova in 2018, many actions have been undertaken by the Italian Ministry of Infrastructures to minimize the risk of occurrence of other catastrophic failures in the road network across the country. As the first step, a procedure, outlined in specific Guidelines, was made mandatory by law to manage existing bridges along the Italian national roads and motorways network (Linee Guida Ponti Esistenti, 2022, hereafter indicated as LG 2022).

According to this Guideline, a multilevel approach shall be followed to improve the knowledge of the actual condition of the many bridges existing along the network, in order to classify bridges based on the most significant risks, to plan monitoring activities for some of them and to perform a full safety and performance analysis of those structures that classify as critical according to given criteria. The multilevel approach for risk analysis and management of existing bridges is summarized in the flow chart of Figure 1 reproduced from LG 2022.

Subsequently, for all existing bridges and viaducts the first three levels of the procedure (Level 0, Level 1, and Level 2) lead to the assignment of the Class of Attention, hereafter denoted as CdA, through the quantification of four different specific risks, namely structural, seismic, geological (i.e. for landslide) and hydraulic. Following the classical definition of risk, each specific risk is expressed by means of a qualitative estimate of hazard, vulnerability, and exposure; for geological/landslide risk, susceptibility is considered instead of hazard to distinguish from other natural phenomena for which a probability of occurrence can be defined. The CdA results from the combination of the above four specific risk assessments.

Level 2 analysis for the assignment of CdA for landslide risk requires the separate evaluation of susceptibility, vulnerability and exposure levels, all of which range from “Low” to “High” with five possible classes, taking into account several prescribed primary and secondary factors, as shown in Table 1.

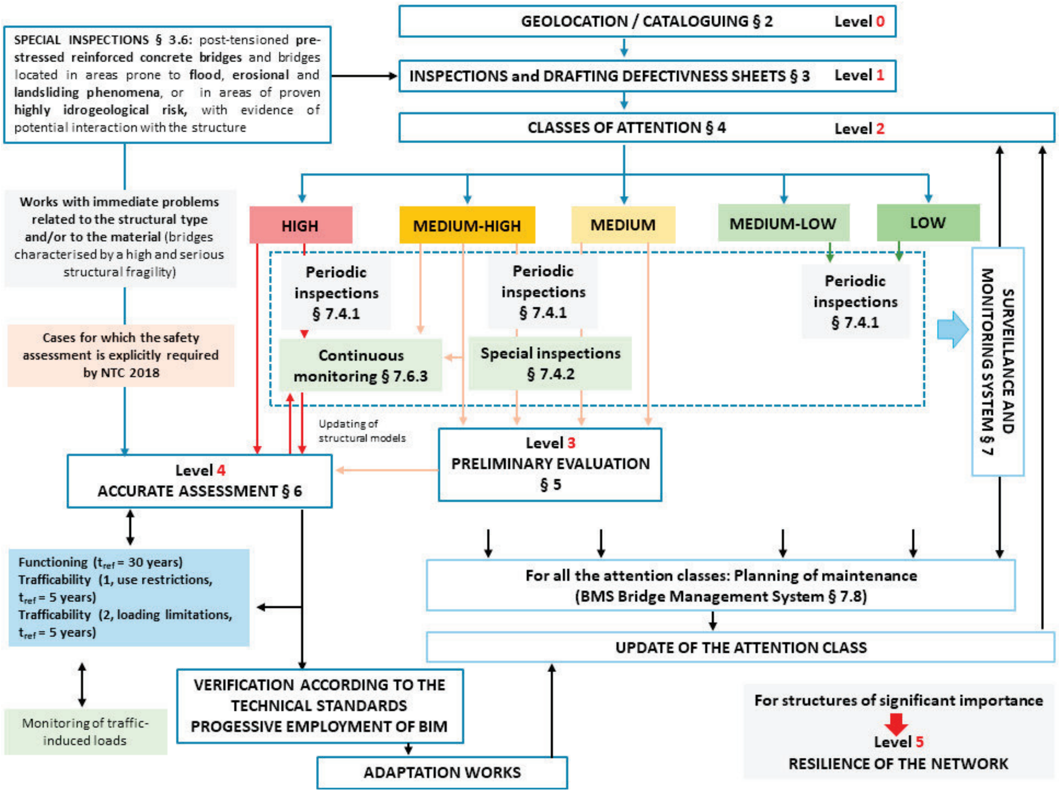

Figure 1 Flow chart summarizing the multilevel approach for risk analysis and management of bridges.

Of the three, the estimate of susceptibility class is the most complex, due to the many uncertainties involved in quantifying the primary descriptors of slope instability phenomena, and is typically based on existing risk maps of the area and a visual inspection only. These descriptors are: a) the magnitude, which quantifies the volume of the potential mobilized mass ranging from a very small volume of 10^2 m^3 to an extremely large volume of 10^6 m^3; b) the rate of displacement that, following the classification of Varnes (1984), ranges from extremely slow to extremely fast; c) the state of activity to be assessed as active, inactive or stabilized for phenomena that are certain and strongly critical, critical or scarcely critical, and phenomena recognized as possible only.

Table 1 Primary and secondary factors for the assessment of the Class of Attention for landslide risk

	Primary factors	Secondary factors
SUSCEPTIBILITY	Slope Instability (magnitude, displacement rate, state of activity)	Model uncertainty
VULNERABILITY	Structural scheme and robustness of the bridge, type of foundations	Extension of the interference between landslide and bridge
EXPOSURE	Traffic frequency and length of the spans	Existence of alternative route. Type of the obstacle to be bypassed. Consequence of failure

As regards the maps, the Italian territory has been systematically mapped for geological risk mitigation since 1998, after the so-called “Sarno decree” (Decreto-Legge,1998). By law, each regional district has provided a detailed picture of landslide phenomena distribution at 1:25,000 scale. Another source of information comes from satellite observations and specifically from the European Ground Motion Service (EGMS) provided by Copernicus, the Earth observation component of the European Union’s Space Programme.

Once the class of slope instability has been determined, the secondary factors for determining the susceptibility class are taken into account as illustrated in the flow chart of Figure 2; in particular, after considering slope instability, quality of the evaluation and presence/absence of mitigation measures are considered, resulting in an overall evaluation of susceptibility.

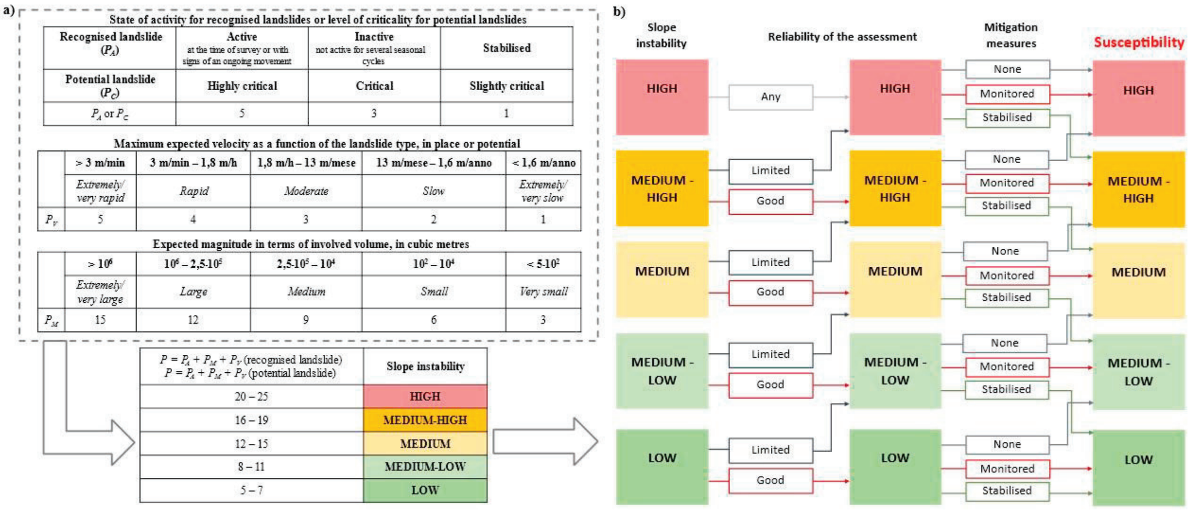

Figure 2 a) parameters and their numerical values which contribute to the evaluation of the slope instability class; b) flow chart for the evaluation of the susceptibility class for geological / landslide risk.

The vulnerability of a bridge with respect to landslide risk is assigned by combining its structural vulnerability with an evaluation of the actual interference between structural components in contact with or embedded in the ground, i.e. abutments and foundations, with the instability phenomenon. This interference can be either limited to the approach embankment, (the earth structure that links the bridge to the ground), or include parts or all the foundations. The structural vulnerability depends on the structural characteristics; in this respect, isostatic structural schemes can accommodate some displacements without showing damage but have fewer resources than more constrained structural schemes; materials or schemes that favor the fragile types of rupture are considered highly vulnerable, etc. Finally, exposure is linked to the actual use of the bridge in terms of number and type of vehicles per unit of time, i.e. traffic frequency and type, this latter influencing the intensity of actions.

All the above are then combined to derive the CdA of the bridge with respect to "landslide risk" as shown in Figure 3. Similar combination tables are available for the remaining susceptibility classes, i.e. Medium, Medium-low, and Low.

*Class of susceptibility: **HIGH***

		Class of exposure				
		High	Medium-High	Medium	Medium-Low	Low
Class of vulnerability	High	High			Medium-High	
	Medium-High	High		Medium-High		
	Medium	High	Medium-High			
	Medium-Low	Medium-High				Medium
	Low	Medium-High			Medium	

*Class of susceptibility: **MEDIUM-HIGH***

		Class of exposure				
		High	Medium-High	Medium	Medium-Low	Low
Class of vulnerability	High	High	Medium-High			
	Medium-High	Medium-High				Medium
	Medium	Medium-High			Medium	
	Medium-Low	Medium-High		Medium		
	Low	Medium-High	Medium			

Figure 3 Classification of bridges for landslide risk: example given for High and Medium high landslide susceptibility.

3. Practical application of the Multilevel approach to landslide risk: L2 analysis

With the purpose of testing this procedure for a significant number of bridges, the FABRE consortium has been commissioned by ANAS (the largest Italian company for roads and motorways) to estimate the CdA of a thousand bridges. To this aim, many national universities and research groups have been involved in testing the multilevel approach. In detail, 20 bridges and viaducts located in the Marche Region and 10 in the Emilia Romagna Region

(Figure 4) were assigned to this research unit of Università Politecnica delle Marche for landslide risk assessment. The work was organized with desk studies on the existing design and execution documentation of each bridge and with on-site visual inspections by a team comprising geotechnical engineers and geologists with the aim to evaluate the Class of Attention for landslide risk (Level 2). This work is still ongoing, but a clear picture of the possible landslide-bridge interference for the considered sample set is already emerging.

Within the logic of the multilevel approach, the Class of Attention for landslide risk is only one component of the overall Class of Attention to be assigned to a bridge, which will indicate the safety management actions. The combination of the Class of Attention assigned for each of the four specific risks may result in an overall Class of Attention that does not necessarily imply the need for in-depth analyses of Levels 3 and 4. Level 4 is the only one that directly calls for a full safety verification of the infrastructure, including monitoring of the superstructure and of its components, foundations, and abutments, as well as any possible interference with unstable slopes or with erosive currents. In Figure 4a the spatial distribution of the CdA for landslide risk resulting from Level 2 evaluation is reported, together with the schematic geological map derived from Barchi et al. (2001).

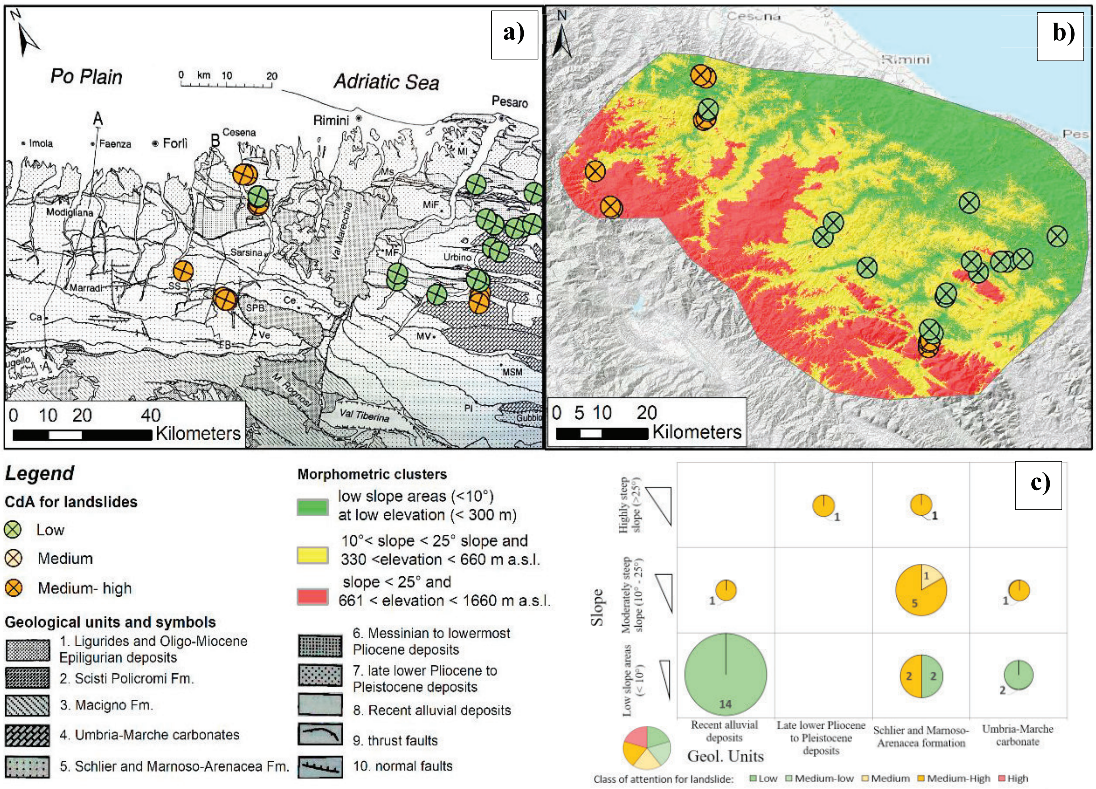

Figure 4 a) Schematic geological map (modified from Barchi et al. 2001), with indication of the CdA for landslides; b) Morphometric map based on slope and elevation parameters; c) Case studies categorized by the geological units outcropping in the area, classes of slopes and the CdA for landslides.

No bridges or viaducts were allocated in the High attention class for landslide risk, 11 were allocated in the Medium-High class, 1 in the Medium class and 18 in the Low class. It is worth noting that most bridges with Low CdA are located on alluvial deposits. For the Medium CdA a significant dataset is not available, while Medium-High CdA is frequently attributed to bridges located on consistent deposits of clastic rocks, mainly composed by alternations of sandstone and pelitic layers (ratio of sandstone to pelitic levels S/P < 1/3). In Figure 4b, the morphometric map derived from the ISO cluster unsupervised classification (performed using the software ArcGIS 10.8, ESRI) is shown. Respectively, three classes are derived by coupling the slope with the elevation parameter, derived from the Digital Elevation model (10x10 m cell size, DEM) of Tinitaly (Tarquini & Nannipieri, 2012). As a result, most of the bridges with Medium-High CdA (orange class in Figure 4a) are in areas characterized by high elevation (> 661 m a.s.l.) and steep slopes (> 25°), while Low CdA bridges are generally located in flat, low elevation areas (slope < 10°, elevation < 300 m). An exception to this rule is reported for some viaducts (upper left orange circles in Figure 4a) which are attributed moderate landslide risk (P3 hazard level of the Hydrogeological Master Plan of Italy, PAI). In fact, although they are located on flat and low slope areas, the P3 landslides involve the pelitic lithofacies of Marnoso-Arenacea formation and the Colombacci formation (sandstone/pelites < 1/3) (Schlier and Marnoso-Arenacea unit in Figure 4a). A comparative representation of all study data is shown in Figure 4c.

As a result of this evaluation, no structures were directly considered for the Level 4 analysis which requires a full verification of the actual stability and performance of the bridge. Many bridges/viaducts were classified with Medium-High CdA and so, according to the multilevel approach, a "preliminary analysis" of Level 3 is prescribed to clarify whether a full "safety verification" shall be undertaken or if a more detailed inspection and monitoring of the infrastructure is sufficient to maintain its efficiency. Focusing on landslide risk only, it is important to consider that the Class of Attention is the result of a very preliminary analysis of the bridge, based on desk studies of existing documentation and on-site visual inspection, although this analysis is typically made by technical experts, presumably well trained in mapping geomorphological features and in design for slope instability problems, the extent to which the method ensures a reliable and effective representation of landslide risk is questionable. This is particularly relevant when, as it occurred for most of the examined cases, the existing documentation does not include the original design reports where results of site inspections and ground investigations may be found.

4. Discussion

The application of the LG2022 to several bridges and viaducts allowed to highlight some difficulties in the evaluation of the Class of Attention for landslide risk. A general observation is the lack of the original project of the bridge in several cases. Since these are works carried out by public administrations, the project is always stored in some archive. Given the relevance of information included in the project it is expected that a more intense effort will be dedicated to this issue by the bridge's owner.

A first problem is the evaluation of the so-called "potential landslides". LG2022 defines a potential landslide as a phenomenon that does not exist at the time of the inspection, but in which the geological, geomorphological and geo-mechanical properties of the slope determine a potential risk of landslide activation. This evaluation has to be made at Level L2, a phase in which such a judgement is often very hard due to lack of information from existing documentation. The operative comment to LG2022 provided by ANSFISA gives some instructions to this aim by saying that the potential landslide is a phenomenon that is possible to recognize on site but not yet studied. This definition is not particularly helpful for the assessment of potential landslides as defined in LG2022. It may be useful to point out that the definition of a potential landslide has been extensively considered in the "*Guidelines for landslide susceptibility, hazard and risk zoning for land use planning*" (Fell al., 2008) in which a comprehensive list of situations where landsliding is potentially an issue is outlined. This list covers a very large spectrum of possibilities in which a potential landslide should be considered; for example "steep slopes degraded by recent forest logging, forest fire and/or construction of roads" in situations where possible sliding is dictated by topography, "slopes in highly sensitive weak clays or thick silt deposits" and "steep natural slopes in regions affected by large earthquakes or concentrated rainfall" where possible sliding is controlled by geological and geomorphologic conditions, etc.. Such an extended and detailed list could provide assistance to locating potential landslides, defining with more accuracy how to judge and weigh the different phenomena, without leaving the responsibility of assessing susceptibility to the expert on the basis of a simple visual inspection, which is furthermore hampered by the difficulty in accessing the bridge sites.

A second aspect of interest is that the overall CdA is obtained by combining the four different specific risks (structural, seismic, geological - i.e. for landslide - and hydraulic). Given the major role assigned to the structural and foundational CdA, it is possible that a Medium-High or Medium CdA for landslide alone does not ensure, as expected, a more detailed scrutiny of the landslide risk by programming ground investigation and/or monitoring. Even when the global CdA indicates the execution of a preliminary verification (Level 3), ground investigation is not clearly considered. although a thorough investigation of the bridge and of the surroundings appears appropriate.

Regardless of the experience of the assessors and the objective information available from official risk maps of the area, Level 2 classification for landslide risk is unavoidably susceptible to large errors, due to the lack of direct investigation of the characteristics of the landslide phenomenon potentially interacting with the bridge. In fact, all information is external whereas parameters needed for "expert judgment" should be obtained by probing the ground below the surface using intrusive direct ground investigation and monitoring or by indirect methods such as geophysical prospecting. In the absence of direct investigations, the ability to interpret the field evidence is essential and the presence of geologists with experience in geomorphologic surveys is therefore very important. In the absence of the appropriate documentation from the original project, the assessment of landslide susceptibility should include the preparation of a geomorphological map at a local scale (1:2,000/1:5,000) as it is usually carried out for designing new linear infrastructures. This operation could also be useful to confirm the reliability of small-scale maps and would allow to include more relevant details (e.g. a deposit of limited thickness). In fact, due to the inhomogeneous covering of geological maps at detailed scale in the whole country (1:10,000 – 1:25,000), valuable geological data are sometimes missing.

Although in a different context, the management of safety of the gas pipeline network in Italy may be considered as a reference to follow when implementing measures to minimize the so-called "geological risk" for linear infrastructures that interact with landslide-prone areas. The management of safety for gas pipelines is provided by the UNI-EN-1594:2013. The suggested procedure follows a kind of multilevel approach, but with some variations with respect to the one adopted for bridges. Specifically, a potentially active area has to be investigated first through external observations such as aerial (or satellite nowadays) imagery and geological and geomorphological surveys. In the presence of indications of soil movement, a strict geotechnical survey is always prescribed to obtain information on depth and extension of the landslide, rate and direction of the movement, soil stratigraphy, groundwater, and geotechnical properties. The idea in this specific case is therefore to use ground investigation and monitoring as a tool for mitigation of the landslide hazard for the pipeline. With some similarities, the draft of the new Eurocode 7 (prEN 1997:2023) also clearly considers ground investigation as a means to reduce the probability of occurrence of failures when a link between the amount of investigation and the geotechnical category of the construction is prescribed, this latter depending on a combination of complexity of the geotechnical situation and consequences of a failure event. Further ground investigation is prescribed with increasing complexity of the geotechnical situation, and the specific case of ground-structure interaction is considered in the higher class of complexity.

Adopting the above logic, to support and provide justification of the assessed Class of Attention for landslide risk, it would be therefore advisable to program even a very light ground investigation and monitoring of the bridge/viaduct and the surrounding ground to confirm the many assumptions needed to quantify susceptibility. This further insight should be carried out at least where there has been assigned a High, Medium High and Medium CdA for landslide risk. Specific periodic inspections to investigate possible evidence of interaction between a landslide phenomenon and the bridge should be programmed, pending the execution of a more detailed evaluation supported by ground investigation. With such methodology, the possibility that an infrastructure whose CdA for landslide hazard resulted high from Level 2 assessment could be wrongly considered at risk, or alternatively completely ignored, in the full scrutiny of the road network, is minimized.

5. Conclusive remarks

From first experiences with the application of the multilevel approach to manage safety of existing bridges, some insights have been presented in the paper, focusing on the evaluation of the landslide risk of the Level 2. As expected, the evaluation of Class of Attention for landslide risk is not straightforward due to the low quality of information that are available at Level 2 and due to the need of considering both active and potential phenomena by carrying out a desk study and a visual inspection only. The lack of *in-situ* ground investigation makes the evaluation of landslide risk very difficult and uncertain. To improve the quality of the evaluation, the participation of an expert in geomorphological survey appears very useful. Also, the possibility to program even a very light ground investigation based on a detailed geomorphological map (scale 1:2,000/1:5,000) should be preliminary to the periodic inspections when information from previous ground investigation is not available and the landslide susceptibility resulted not low from the assessment of the Level 2.

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