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Insights into Landslide Interaction with Bridges and Viaducts: Lessons from Italian Case Studies and Database Analysis

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Abstract

The study of landslides and their impacts on infrastructure has assumed an increasingly significant importance in recent years. Landslides, along with floods and earthquakes, are natural disasters responsible for severe socioeconomic and human losses. Italy, with its complex geological and geomorphological structure, has historically experienced a high occurrence of landslides caused by both natural and human factors. Notably, viaducts and bridges are frequently affected by landslides that may produce damage to their structural components or, in the most severe cases, complete collapse. To analyze the complex mechanisms of interaction between a bridge and a landslide, a comprehensive database of case studies concerning bridges located in Italian territory, which have been inspected by various Universities participating in the FABRE Consortium, has been implemented. Such database records detailed information related to the examined structures, in compliance with the "Guidelines for the classification and management of risk, safety assessment, and monitoring of existing bridges" (provided by the Italian Ministry of Infrastructure and Transport). First, the database contains information regarding the presence or absence of landslides that may partially or fully interact with the structures under analysis. Secondly, it provides specific kinematic details about the type of landslide movement, its activity status, volume, and velocity. Finally, information about landslides and interacting bridges are used to evaluate susceptibility, vulnerability, and exposure classes associated with landslide risk. This assessment helps define the corresponding Attention Class (AC), as per the definition in the Guidelines. Most importantly, a thorough analysis of the case studies collected in the database has led to the development of significant statistical insights, revealing the relevance of different recurrent landslide features in the assignment of the landslide AC to viaducts. This contribution aims at enhancing the comprehension and the effective management of landslides within Italy's road infrastructure.

Keywords: Lanslides; Bridges, Interactions; Database, Risk Assessment

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1. Introduction

The geological and geomorphological structure of Italy exhibits a profound complexity that, over the years, has led to numerous slope instability phenomena, influenced by both natural and anthropogenic factors. A wide number of studies have been devoted in the past, exploring different typologies of landslides, such as deep-seated landslides (Guerricchio, 2022; Galeandro et al., 2013), shallow landslides (Salciarini et al., 2006; Ponziani et al., 2011; Cernuto et al., 2023), earth and debris flows (Ceccato et al., 2018; Gabrieli & Ceccato, 2016; Doglioni et al., 2020), and rockfalls (Salciarini et al., 2009).

In recent years, Italy has witnessed landslide events resulting in significant damages and, eventually, structural collapses. An emblematic example is the case of Albiano Magra bridge, as outlined by working group of the Italian Ministry of Infrastructure immediately after the failure and scientifically deepened by Farneti et al. (2022), where the earth pressure behind the East abutment, combined with the landslide movement of the slope on which the bridge rested, was identified as the probable cause of its collapse. Similarly, the Himera viaduct in Sicily, cited by Lo Iacono et al. (2017), experienced damage to four of its piers due to a landslide, causing a rotation and the subsequent resting of the northern section of the viaduct onto the southern one. Guerricchio and Melidoro, (1981) analysed the case of the Serra railway viaduct in Basilicata, where a landslide induced the tilting and displacement of a lateral pier of the viaduct, creating a height difference of about one meter in the underlying railway.

Fig. 1. A) Albiano Magra bridge; b) Himera Viaduct, c) Serra railway viaduct.

It is evident that landslides, under specific circumstances, can cause significant structural damages, mainly due to the displacements or rotations of the foundation of bridge piers and/or abutments. Other crucial effects on viaduct safety can result from the impact of landslides (including debris flows or rockfalls) affecting various structural elements – decks, piers, abutments, etc. Therefore, the study of landslides and their subsequent effects on the safety of interacting infrastructures is a topic of growing importance, as highlighted by Wang et al. (2018) and Lu et al. (2012). Given Italy's historical susceptibility to landslides, it becomes essential to deepen the understanding of the interaction features between these ground movements and infrastructures.

In this context, 331 bridges in Italy have been selected and analysed as part of the FABRE Consortium activities. A notable percentage of these exhibit interactions with landslide phenomena, whether recognized or potential. A comprehensive database was created, specifically designed to collect data on these bridges in accordance with the "GuideLines (GL) for the classification and management of risk, safety assessment, and monitoring of existing bridges", as provided by the Italian Ministry for Sustainable Infrastructure and Mobility (MIMS, 2022). This database not only catalogues the infrastructures but also provides detailed information on the presence and characteristics of associated landslide movements. It includes information on the type of landslide, the state of activity, volume, and velocity, adhering to the scheme "landslide and hydraulic form" for the Analysis of Level 1 of the bridge, as defined by the GL. One of the primary features of this tool is its capability to automatically analyse and categorize infrastructures in terms of susceptibility, vulnerability, and exposure to landslide risk, assigning the respective Attention Class (AC). From a thorough analysis of the database, significant statistics were generated, offering an immediate portrayal of the most common conditions and higher-risk scenarios, facilitating a swift understanding of the most recurrent issues in bridge safety related to landslides.

2. Database structure

The database has been developed in MS Access format and gathers all the information related to the structures inspected by various Research Units curing the activities of the FABRE Consortium. It also encompasses details on observed or potential landslide phenomena that could interfere with these structures. Currently, the database lists 331 viaducts, located within the Italian territory. The database is organized into 9 sections (as depicted in the graphical representation of Fig. 2). The first five sections are dedicated to the census of the structures, in accordance with the MiMS Guidelines. The data collected in these 5 sections include essential information on the structure; location; state of conservation of the structure; importance of the connecting road; geometric characteristics; details on the abutments; details on the piers; details on the deck; monitoring activities; road network information; and a list of documents to classify the landslide AC.

The next three sections focus on defining the geological context of the area where the infrastructure is located, assessing the potential presence or absence of landslide risks, and characterizing the kinematic of interfering landslides. Specifically, these sections cover the following critical aspect: the level of landslide risk; geomorphological context; type of landslide; distribution of activity; morphometry; activity, magnitude, expected velocity; and extent of interference.

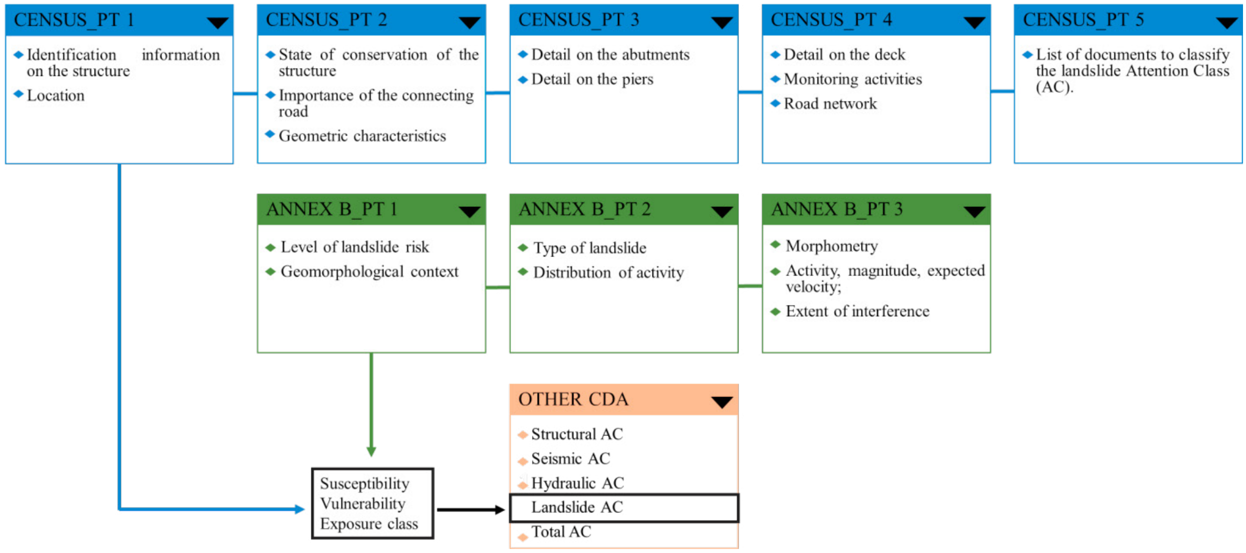


Fig. 2. Database Organization.

Based on the data entered in the previous sections, the database automatically determines the susceptibility, vulnerability, and exposure class for landslides, which in turn defines the landslide-AC. The very last section summarizes the outcome of the landslide-AC, together with the structural-, seismic-, hydraulic-, and overall-AC for each considered structure.

3. Data analysis

The database includes 331bridges and viaducts, located in various regions of Italy. They are not homogeneously distributed along the Italian peninsula but they can be considered as a comprehensive representation of the whole bridge population in the Country. Among the 331 viaducts analysed, 72 exhibit a landslide-AC more severe than "Low", meaning that at least one recognized or potential landslide interferes with them.

As indicated by the MiMS Guidelines, the landslide-AC definition is based on factors such as susceptibility, vulnerability, and exposure. These are defined through the integration of primary and secondary parameters, as explicitly outlined in Tab. 1.

Table 1. Parameters needed for the determination of landslides-AC.

	Primary parameters	Secondary parameters
Susceptibility	Slope instability (Magnitude, Velocity, Activity state)	Evaluation uncertainty Mitigation measures
Vulnerability	Type/robustness of the bridge and type of foundations	Extent of interference
Exposure	Average daily traffic level and span length	Presence of Road alternatives Type of bypass Strategic importance of the structure

The statistical analysis reveals that among the 72 viaducts with interacting landslide phenomena, 60% exhibit High *susceptibility*, 29% fall into the Medium-High category, while a minority vary between Medium and Low, as depicted in the first graph of Fig. 3. Concerning *vulnerability*, as illustrated in the central graph of Fig. 3, 53% of the cases belong to a High category, with the remaining percentages distributed between Medium-High and Low. In terms of *exposure*, the data shows that 46% of the cases are classified as Medium, 32% as Medium-Low, and a minimal fraction, 1%, as High (left graph of Fig. 3). It should be noted that the most frequent *exposure* categories fall in Medium and Medium-Low. This is because its definition is closely related to structural information, unlike susceptibility and vulnerability, which are linked to specific factors characterizing the landslide.

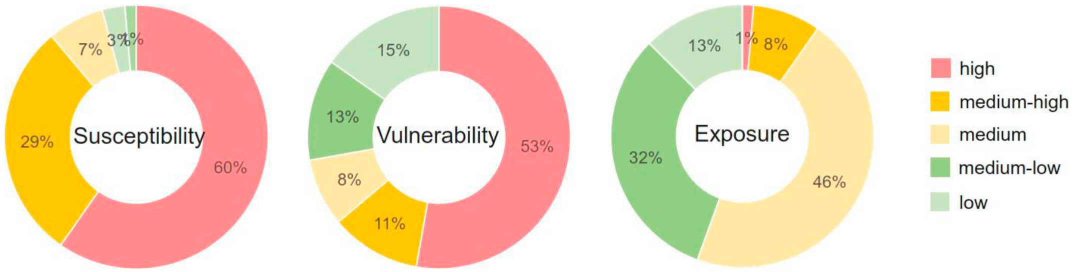


Fig. 3. Distribution of the different categories for Susceptibility, Vulnerability and Exposure to landslides for the 72 viaducts interfering with landslides.

The landslide-AC is determined through the combination of susceptibility, vulnerability, and exposure categories. As previously indicated, among the total of 331 cases, only 72 showed an interaction with landslides, which automatically implies that the remaining 262 cases automatically fall into the Low AC category (78%), as depicted in Fig. 4. Furthermore, this figure highlights that the 5% of the analysed viaducts are classified within the High landslide-AC, while in most cases where a landslide is identified, this is associated with a Medium-High landslide-AC (11%).

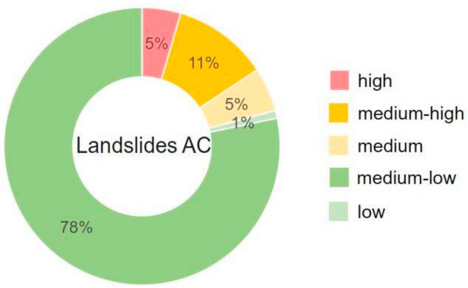
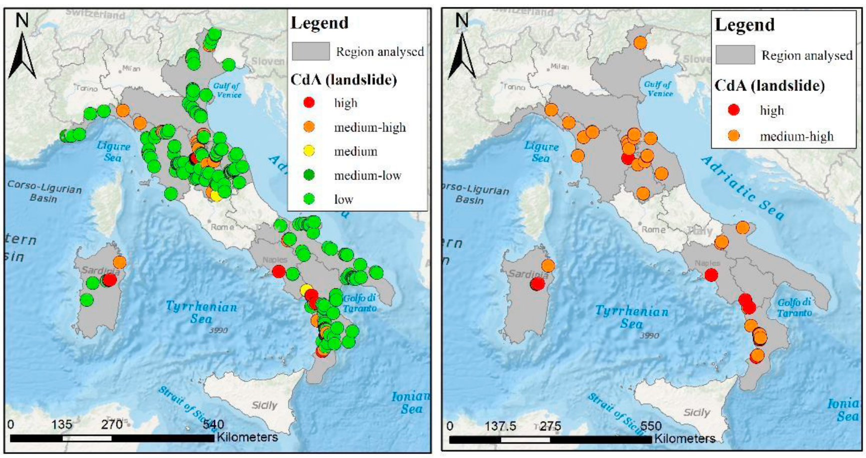


Fig. 4. Landslide-AC distribution for the overall sample of viaducts considered in Italy.

Fig. 5a shows the map of Italy illustrating the locations of the 331 viaducts with their assigned landslide-AC, distinguished by colour based on the category (from Low to High). In Figure 5b, only the viaducts classified with a landslide-AC ranging from High to Medium-High are shown.



a) b)

Fig. 5 Map of Italy illustrating the locations of: a) the 72 viaducts with and assigned landslide-AC higher than Low, distinguished by color based on the category; and b) the viaducts classified with a landslide-AC ranging from High to Medium-High.

3.1 Correlations between landslide-AC and landslide variables

To establish a correlation between the landslide-AC and the pertinent variables defining landslide features, an additional statistical study was performed, focusing on the subset of 72 cases where one or more landslides interfere with the structure. The aim was to obtain a comprehensive understanding of the conditions that occur more frequently and the impact of relevant parameters describing landslides on the assignment of the landslide-AC categories. The selected variables under investigation were categorized into subgroups following the MiMS Guidelines, as illustrated in Tab. 2.

Table 2. Classification of the variables considered.

Magnitude parameter on volumetric basis in m^3 (PM)	Maximum expected velocity parameter (PV)	Extent of interference	Type of phenomenon	Site morphology
-Very large (> 10^6)	-Very rapid (> 3 m/min)	-Total	-Rockfall	-Crest
-Large (2.5 · 107 - 10^6)	-Rapid (1.8 m/h- 3 m/min)	-Partial (abutment or piers)	-Topple	-Steep slope (> 25°)
-Medium (10^4 - 2.5 · 107)	-Moderate (13 m/month - 1.8 m/h)	-Approaching zones	-Rotational Sliding	-Moderately steep slope (10° - 25°)
-Small (10^2 - 10^4)	-Slow (1.6 m/year - 13 m/month)		-Translational Sliding	-Gentle slope (0 - 10°)
-Very small (< 5 · 10^2)	-Very slow (< 1.6 m/year)		-Debris Flows and Avalanches	-Horizontal
			-Viscous and Translational Flows	-Plain at the base of slopes
			-Complex	
			-Deep-seated Gravitational Phenomena	
			-Combined	

Fig. 6 shows the frequency of landslide volumetric magnitude (PM) grouped by the landslide-AC. The most severe landslide-AC (High) is observed for the two highest PM categories (Very Large and Large); the Medium-High landslide-AC is primarily associated with the three central PM categories (from Large to Small); the Medium landslide-AC is principally related to the last three PM categories (from Medium to Very Small), and, finally, the Medium-Low landslide-AC is exclusively associated to the Very Small PM category. This underscores that the PM category directly affects the estimation of the landslide-AC: the larger the volume, the more critical the landslide-AC becomes.

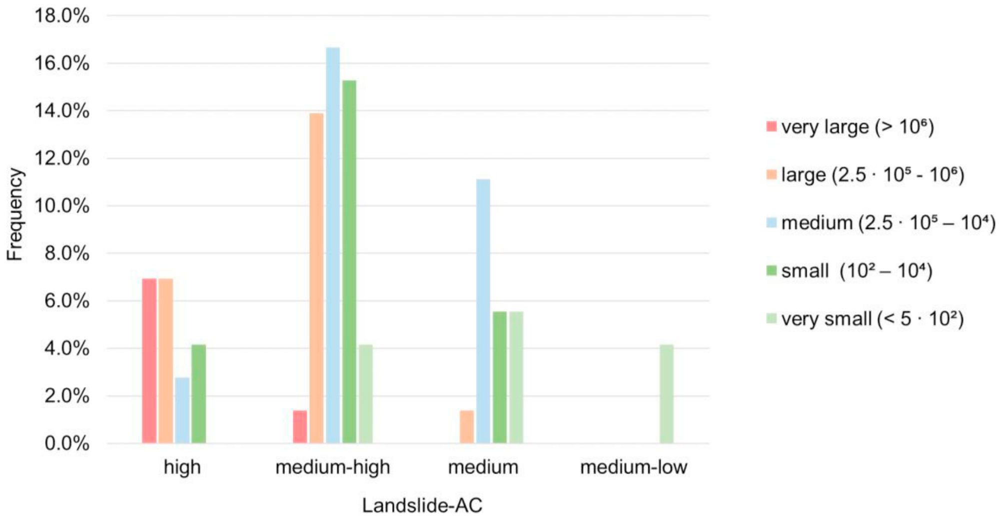


Fig. 6. Distribution of landslide volumetric magnitude (PM) for different landslide-AC levels.

Similarly, we investigated the correlation between the landslide-AC and landslide maximum expected velocity (PV) as depicted in Fig. 7. Although a clear relationship is not apparent, it's essential to highlight a significant pattern. There is a notable prevalence of landslide interacting with the examined viaducts when the landslide velocity is classified as Very Low (< 1,6 m/year), representing over 53% of the total considered case studies. As a consequence, this category is notably prevalent in the two most critical landslide-ACs, assigned to a High or Medium-High, and is also relevant in the Medium landslide-AC. Thus, we can speculate that the Very Low PV category is associated with landslides involving significant volume, capable of producing a more severe landslide-AC due to their associated sizing. On the contrary, rapid landslides generally have smaller volumes (for example rainfall-induced shallow landslides, sometimes evolving into debris flows, or rockfalls) and, in principle, they can produce a less severe landslide-AC because of the smaller associated size. Indeed, from Fig. 7 it is evident that the two less critical landslides-AC categories (Medium, and Medium-Low) are associated with Rapid or Very Rapid phenomena.

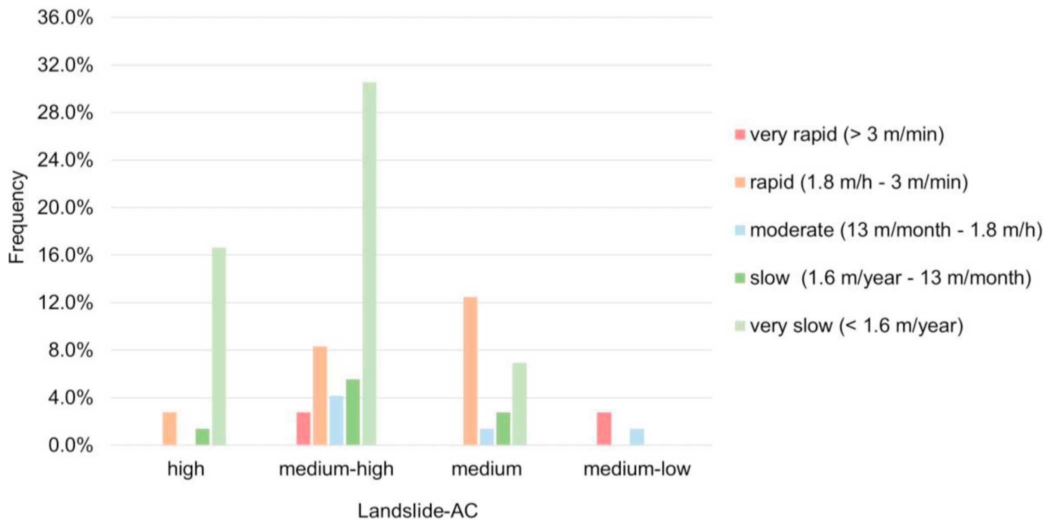


Fig. 7. Distributions of landslide maximum expected velocity (PV) for different landslide-AC levels.

Of considerable interest is the histogram presented in Fig. 8, which highlights the correlation between the landslide-AC and the extent of interference of the landslide with the infrastructure From this analysis it emerges that a total interference between the landslide and the infrastructure leads to an assignment of the landslide-AC in the most severe category (High). However, the presence of cases with a partial interaction is noteworthy, particularly contributing to the Medium-High landslide-AC category, meaning that the role of partial interference is still relevant in bringing the landslide-AC evaluation toward the most severe categories. Conversely, the presence of a landslide in the approaching zone typically leads to the less severe landslide-AC category (Medium-Low). This observation emphasizes the pivotal role of the specific extent of interference in determining the severity of the landslide-AC, with total interference presenting the highest risk, partial interference contributing to a significant risk, and the presence of a landslide in the approach zone resulting in a comparatively lower risk.

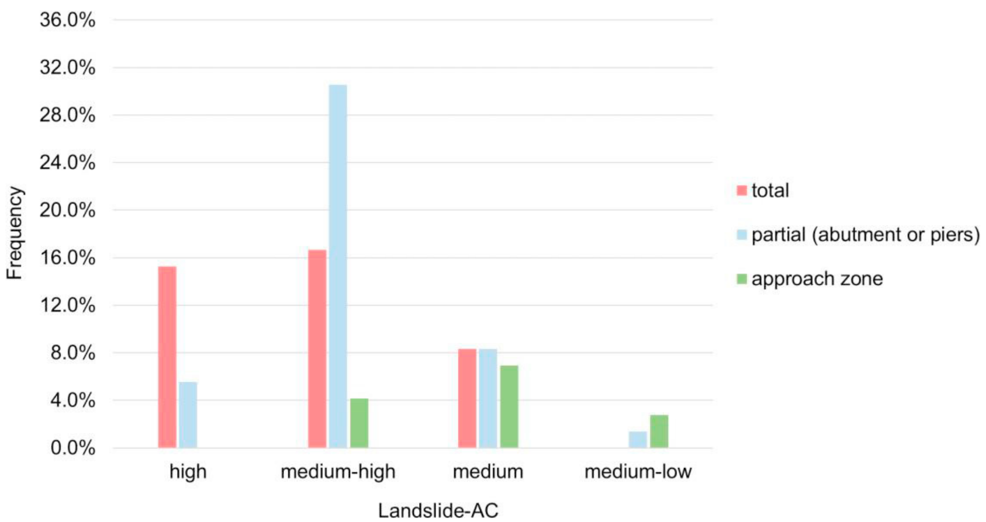


Fig. 8. Distribution of the extent of interference of the landslide with the infrastructure for different landslide-AC levels.

Subsequently, an analysis was conducted to correlate different types of landslides with the assignment of the landslide-AC (Fig. 9). It is evident that when combined landslides occur, incorporating different types such as rotational slides, translational slides, and complex slides, the associated landslide-AC tends to fall within the most severe categories (from Medium to High). However, it is worth noting that the "combined landslide" category is the most frequent (46%) one in the considered sample of viaducts interacting with landslides and this can affect the results of the statistical analysis introducing a bias due to the over-representation of a single category.

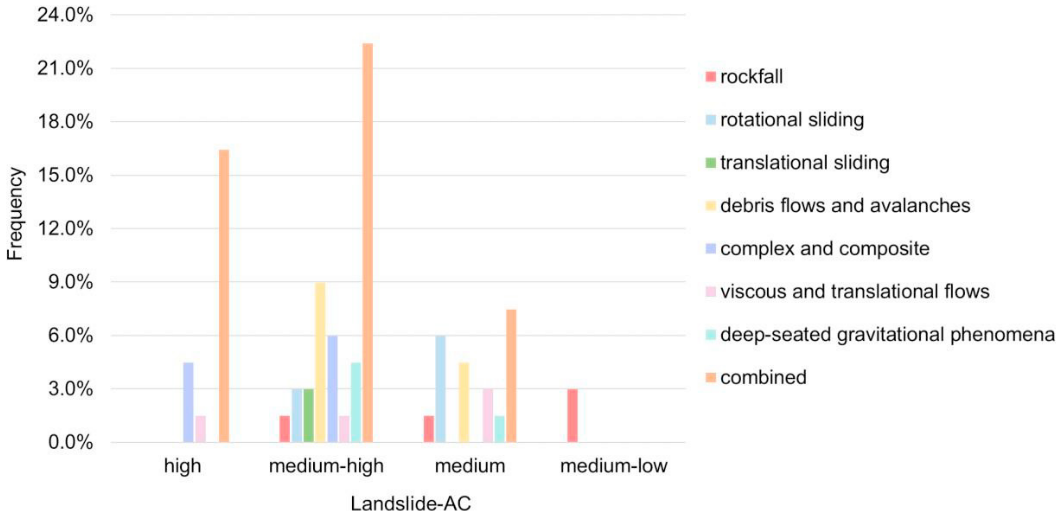


Fig. 9. Correlation between the landslide-AC and the different types of landslides.

Finally, the correlation between the local morphology and landslide-AC was examined (Fig. 10). It emerges that a clear correlation between the steepness of the slope and the severity of landslide-AC is not predictable. The category of a "Moderately steep slope" is the most frequent one (42 %) in the considered sample of viaducts interacting with landslides and this is predominant in the two central categories of landslide-AC (Medium, and Medium-High), but it is also present in the most severe one (High). It is worth noting that the "Gentle slope" category, characterized by sub-horizontal topography, is the second category in the population for the three most severe classes (High, Medium-High, and Medium). This implies that even sub-horizontal topography can be associated with a severe landslide-AC.

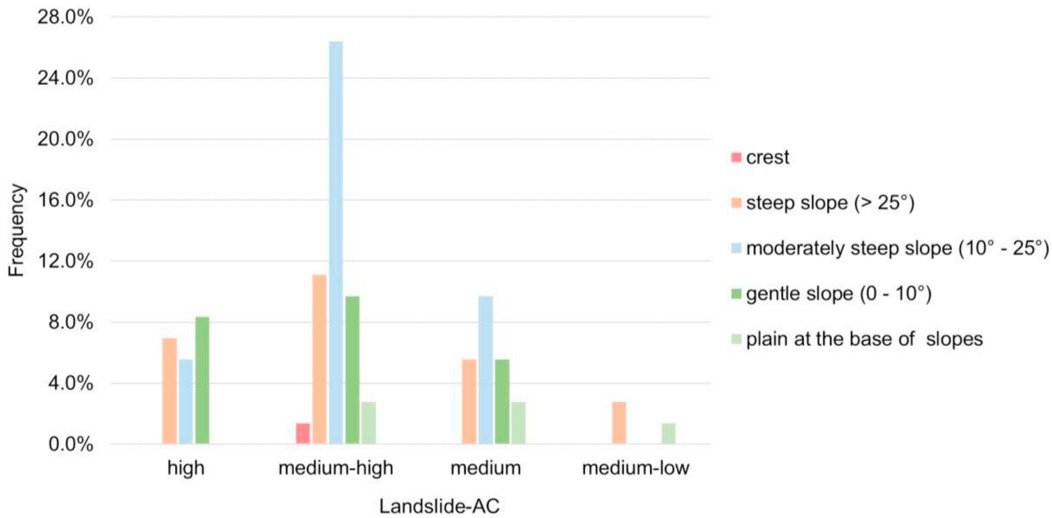


Fig. 10. Correlation between the landslide-AC and the local topography.

4. Conclusions

This study, conducted as part of the FABRE Consortium activities, has provided a comprehensive analysis of 331 bridges in Italy with a specific focus on their interactions with landslide phenomena. The creation of a detailed database, structured in accordance with the MiMS Guidelines, has allowed for a thorough examination of the susceptibility, vulnerability, and exposure of these bridges to landslide risk. Although the investigation carried out so far is limited to bridges and viaducts lying only in some Italian Regions, it may be reasonably considered as representative of the Italian territory.

The database, developed in MS Access format, categorizes the viaducts into different sections, covering essential information about the structures, their geographical context, and details on recognized or potential landslide movements. Among the key findings, 72 out of the 331 viaducts were identified to have interactions with landslides. The statistical analysis revealed that 60% of these cases exhibited "High" susceptibility, with corresponding vulnerability and exposure categories contributing to an understanding of the overall risk.

A geographical representation of the viaducts and their assigned landslide-AC was presented, showcasing the distribution of risk across Italy. Further statistical studies delved into the correlation between landslide-AC and various parameters defining landslide features, such as volumetric magnitude, maximum expected velocity, extent of interference, types of landslides, and local morphology. These analyses provided valuable insights into the factors influencing the severity of landslide-AC assignments.

The results indicated a direct relationship between the volumetric magnitude of landslides and the severity of landslide-AC, emphasizing that larger volumes correspond to more critical AC classifications. Additionally, the study highlighted the significance of landslide velocity, the extent of interference, and the types of landslides in influencing the risk assessment. The analysis of local morphology demonstrated that even sub-horizontal topography could be associated with a severe landslide-AC.

Overall, this research aims to contribute to a better understanding of the risk associated with the interaction between landslides and bridges in Italy. The findings underscore the importance of considering a range of parameters in landslide risk assessments, offering insights that can inform mitigation strategies and enhance the resilience of critical infrastructure.

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