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Landslide-bridge interaction: Insights from an extensive database of Italian case studies

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A R T I C L E I N F O

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A B S T R A C T

Despite the wealth of documented case studies, systematic approaches to correlate landslide characteristics with the damage they cause to bridges are rare. The correlation is challenging due to the complexity of landslides, which can vary in movement types, volume, velocities, materials, and orientations. Additionally, the lack of universally applicable models to forecast bridge responses in case of landslide interaction adds complexity. Recognizing the urgency of addressing this challenge, various countries, including Italy, have introduced guidelines and strategies to manage infrastructure risks and enhance safety. Efforts are underway to develop practical tools for authorities and infrastructure managers, encompassing factors influencing bridge response, especially under the action of natural hazards. This article presents a database of landslide-bridge interactions in Italy, developed under the FABRE Consortium. The database was compiled by analysing 382 bridges across 12 Italian regions. The article explores correlations between landslide characteristics and risk classification for bridges, defined as "Landslide Class of Attention" (L-CoA). The analysis shows that landslide volume is directly correlated with L-CoA severity, with larger volumes leading to higher classifications. Very slow-moving landslides are prevalent in high-risk L-CoA categories, suggesting they are associated with significant volumes and severe consequences. Complete interference between landslides and infrastructure poses the highest risk, while partial interference also contributes significantly. Combined landslides tend to result in more severe L-CoA classifications. The findings underscore the importance of better understanding the interactions between landslides and bridges, to develop predictive models and mitigate the risks posed by landslides to infrastructure in Italy and beyond.

1. Introduction

Italy is renowned for its complex geological and geomorphological features and has historically experienced a significant extension

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and frequency of landslides, triggered by a combination of natural and anthropogenic factors. While extensive research has explored various types of landslides— from deep-seated to shallow [1–5], and from debris flows [6–8] to rockfalls [9] — the interaction between landslides and critical infrastructure, such as bridges, has emerged as a significant area of concern. The recent scientific literature reports numerous examples of damaged bridges in Italy due to interactions with landslides, showcasing prominent cases like the Himera Viaduct in Sicily [10], the Albiano Magra bridge in Tuscany [11], the Ginosa Bridge in Puglia [12], the Vallone-Chiusa bridge in Campania [13], the Serra railway viaduct in Basilicata [14]; [15], the Ischia del Basento Bridge in Basilicata [16], and many others. However, there remains a notable gap in systematically connecting the characteristics of landslides to the corresponding impacts on bridge stability. Addressing this gap is critical for improving resilience and preventing future hazards.

Recent studies have provided a wealth of case-specific data, highlighting structural damage and, in extreme cases, collapse. As documented by Lo Iacono et al. (2017), on April 10th' 2015, four piers on the north side of the Himera Viaduct, located along the A19 Palermo-Catania highway in Sicily, suffered severe damages caused by a rotational landslide (Fig. 1). The piers underwent rotation, leading to a section of the north viaduct tilting towards the south viaduct. Extensive analysis conducted by Moretto et al. [17] indicates that rainfall, and the subsequent rise in pore-water pressure, served as triggering factors for the landslide.

The collapse of the Albiano Magra bridge stands as a prominent example of the interaction between landslides and bridges. In this instance, the bridge's failure (Fig. 2) was attributed to a combination of earth pressure exerted behind the East abutment and the movement of the landslide affecting the bridge structure. Initially outlined by the working group of the Italian Ministry of Infrastructure, this situation underwent further detailed investigation by Farneti et al. [11].

Another relevant case, recently studied in the scientific literature by D'Ambrosio et al. [12], concerns the Ginosa Bridge, located at the border between the Puglia and Basilicata regions, in southern Italy. Here, an extremely slow landslide involved the clayey slope adjacent to the bridge's right abutment. This phenomenon resulted in significant damage, particularly to the right abutment, causing substantial consequences for the integrity of the concrete arch and the stability of the left abutment, evident through profound cracks (Fig. 3).

In a study conducted by Budetta et al. [13] in the Campania region, an event on January 26th' 2014, marked the partial reactivation of the previously dormant Vallone Chiusa translational landslide. This event led to the collapse of two piers, followed by the downward vertical displacement of the bridge deck.

Guerricchio & Melidoro [14] and Geremia et al. [15] examined the case of the Serra railway viaduct in Basilicata, where a landslide caused the tilting and displacement of a lateral pier, resulting in vertical displacement of about 1 m (Fig. 4). The railway was opened on October 28th' 1929, and only a few years later, the bridge began to exhibit worrying signs of instability, manifesting in the bending of the railway tracks. The progressive deformation of the six arches of the bridge led to the suspension of rail traffic starting from March 1st' 1952. A study conducted in the area revealed a Deep-Seated Gravitational Slope Deformation (DSGSD) involving the northern side of the structure. It is believed that the calcareous block, which anchored the bridge on this side, is implicated in the DSGSD, occurring along a listric sliding surface [18] at its base. The discrepancy in mechanical response between the terrigenous and calcareous deposits is considered one of the main factors contributing to the landslide that resulted in the bridge's collapse.

Doglioni [16] presented a partially collapsed bridge at the toe of the slope going from the plateau of Ferrandina down towards the north-east in the valley of river Basento, in the area of Ischia del Basento. As can be noted in Fig. 5, it is evident how the bridge was stressed with a pushing stress, which progressively compressed the bridge, until it was damaged up to collapsed. This collapse resulted from nearly 70 years of accumulated minor displacements, stemming from the landslide affecting the slope located in that area.

Research progress has underscored the complexity of these phenomena. For instance, landslide-induced bridge failures are highly dependent on variables such as movement type (e.g., rotational or translational slides), volume, material composition, and speed. The Varnes classification (Fig. 6) and subsequent refinements by Hungr [19] have provided a foundational framework, but translating these classifications into predictive models for bridge failure is still a major challenge.

The interaction mechanisms between landslides and infrastructure—whether through abutment sliding, undercutting, or direct impact on bridge piers—demonstrate substantial variability, complicating efforts to establish clear preventive measures. As illustrated in Fig. 7, this concern pertains to whether landslides affect the viaduct longitudinally (as depicted in Fig. 7a) or transversely (as depicted in Fig. 7b), with variations observed in different instances. Among the main interaction mechanisms between a bridge and a landslide, we can identify a) abutment sliding parallel to the bridge direction, b) abutment sliding perpendicular to the bridge direction, c) undercutting of the abutment foundation, d) impact or sliding of a landslide onto a bridge pier, e) sliding of the pier foundation, f) rockfall onto the deck, g) landslide affecting the entire bridge. Numerous case studies outlined in international literature emphasize that all types of interference just described have the potential to cause severe damage ([20,21]; L. A. Rødvand et al., 2019; [22,23]).

Fig. 1. The Himera viaduct in Sicily [10].

Fig. 2. The Albiano Magra bridge.

Fig. 3. The Ginosa Bridge [12].

Fig. 4. The Bridge of the Calabro-Lucana Railways and the evolution of the uplift of the pile and arch deformation (D'Ambrosio et al., 2024).

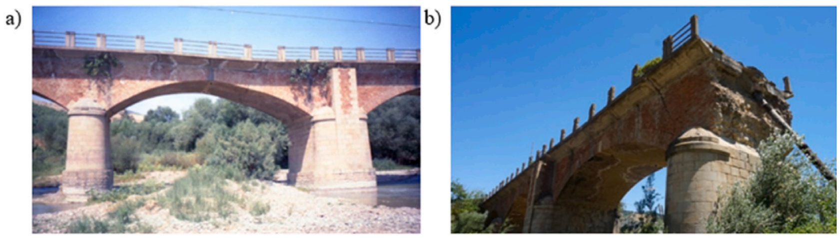

Fig. 5. a) Deformed arch of the bridge before the collapse; b) Arch of the bridge after the collapse [16].

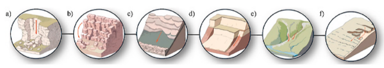

Fig. 6. The Representation of landslide movement types: a) Fall, b) Topple, c) Translational sliding, d) Rotational sliding, e) Lateral spread, f) Flow.

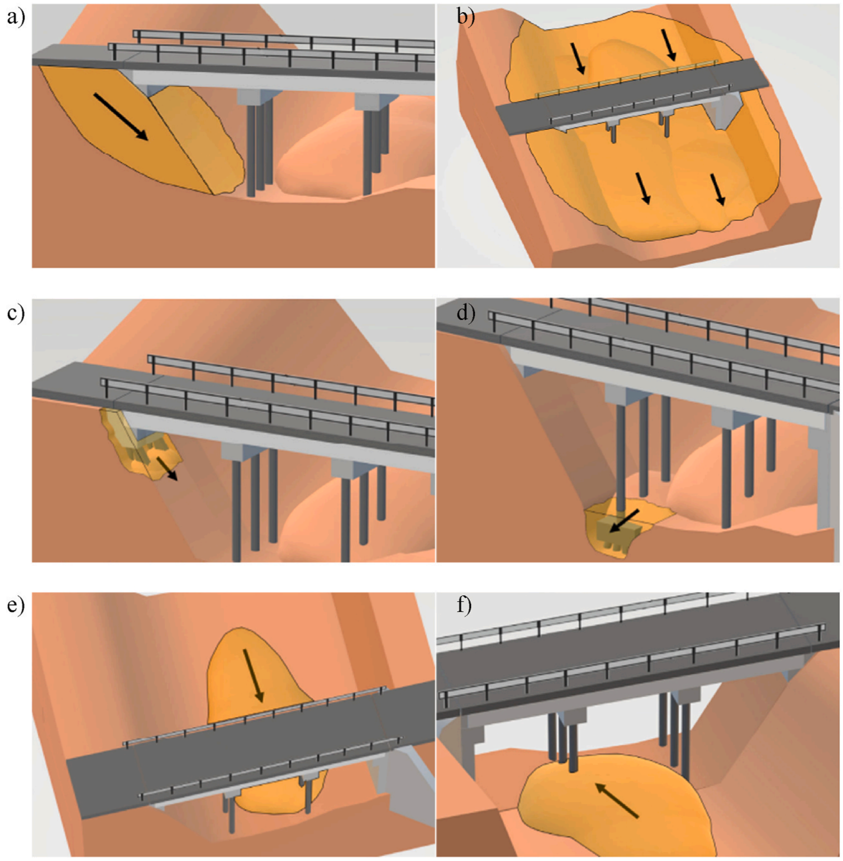

Fig. 7. Global kinematics involving the bridge a) longitudinally or b) transversely; c) longitudinally due to abutment erosion; d) transversely due to erosion at the base of the piers; e), f) transversely due to landslide impact or debris flow.

Progress has been made in recent years through international studies (e.g., Ref. [24]), which have compiled case studies of bridge-landslide interactions globally, offering valuable insights into recurrent failure conditions. However, there remains a pressing need to apply these findings systematically across national infrastructures.

One of the primary scientific questions lies in correlating the vast range of landslide dynamics with bridge vulnerability, especially in terms of velocity thresholds and material behaviour. Despite the existence of classification systems, the variability in outcomes—ranging from minor displacements to catastrophic collapse—demands further investigation into the mechanisms that dictate such diverse results.

This research addresses these critical gaps by focusing on the Italian context, where the FABRE Consortium has spearheaded efforts to collect and analyse data on bridges affected by landslides. FABRE Consortium was established in 2020 (https://www.consorziofabre.it/), with the signing of its founding deed by various universities and research institutions located in Italy. FABRE promotes and coordinates the involvement of its member universities and research institutions in scientific activities within the fields of Civil Engineering and Architecture, with a particular focus on the evaluation of bridges, viaducts, and other structures.

The goal of the present work is to gain insights into the relationships between specific landslide characteristics and the resulting safety classification level of the structure. To achieve this aim, a comprehensive database that integrates information utilized by the Italian Guidelines (GL) for assessing the safety classification of existing bridges was developed. By integrating landslide typologies, activity status, and velocity data into a comprehensive database, this study advances the field's understanding of susceptibility and vulnerability factors in bridge safety. The resulting framework enables a more precise classification of infrastructure risk, highlighting common high-risk scenarios and recurring issues that demand further attention from both the scientific community and infrastructure managers. The work presented herein not only provides a detailed analysis of past failures but also raises key scientific questions about the broader application of landslide typologies and predictive models in real-world infrastructure management, with the ultimate goal of preventing future hazards and enhancing bridge resilience in Italy and beyond.

2. Italian Guidelines for bridge classification and safety assessment

To monitor and improve the safety of bridges in Italy, the Ministry of Infrastructures recently approved the new "*Guidelines for the classification and management of risk, safety assessment, and monitoring of existing bridges*". These guidelines adopt a structured, multilevel approach, as depicted in Fig. 8. The process begins with an initial phase of conducting a census of the structures to be analysed and proceeds to determining a synthetic parameter called Class of Attention (CoA), which provides a classification of bridges based on their safety levels. This classification serves as the basis for conducting safety verification, as prescribed by the methodology. As detailed in the Guidelines [25], the multilevel approach is developed into six levels, each marked by increasing levels of detail and complexity.

The lower three levels (L0, L1, L2) operate on a territorial macro-scale and lead to the assignment of an Overall Class of Attention (O-CoA) through the quantification of four specific sources of risk, namely: structural, seismic, landslide, and hydraulic/scour risk (Fig. 9). The subsequent levels (L3, L4, L5, shown in Fig. 8) focus on a smaller subset of structures, providing increasingly detailed assessments, with Level 5 dedicated to structures requiring comprehensive analyses. This work will focus on these first three levels, as they are critical for assigning the Landslide Class of Attention (L-CoA).

At Level 0, an inventory of all structures is created, cataloguing their primary characteristics through the collection of available information and documentation. In Level 1, which applies to the structures listed in Level 0, direct visual inspections and rapid surveys are carried out, examining the structure's condition along with the geomorphological and hydraulic characteristics of the surrounding area. The aim is to identify the state of deterioration, the main structural and geometric features, and potential risks from landslides or hydrodynamic actions. Level 2 is the core of the approach, as its results form the basis for subsequent evaluations and the classification of attention classes. This stage determines the CoA for each bridge based on hazard, vulnerability, and exposure parameters, derived from the previous levels. For landslide risk, the term "susceptibility" is employed instead of "hazard" to focus exclusively on spatial prediction, neglecting the temporal component due to the challenges of defining event occurrence probability.

The susceptibility, vulnerability, and exposure indicate the structure involvement in landslide phenomena, integrating both primary and secondary data, as specified in Table 1. Here, while the vulnerability and exposure parameters correlate closely to structural data, susceptibility primarily relates to landslide phenomena.

More specifically, the vulnerability of a bridge with respect to landslide risk combines structural vulnerability with an assessment of the actual interaction between the possible landslide event and the structure. Exposure parameters, such as daily traffic level, span length, presence of road alternatives, the type of bypass, and the strategic importance of the structure, follow definitions analogous to those associated with Structural- and Seismic-CoA.

When assessing landslide susceptibility (Fig. 10), it is essential to define slope instability through the combination of three parameters deducible from documentation or on-site observations. These parameters are then integrated with secondary parameters to achieve a comprehensive susceptibility assessment.

Among the fundamental parameters to define slope instability, there is the *"state of activity"* (P_A or *"degree of criticality"*, P_c), which can vary among active, inactive, or stabilized for recognized landslide phenomena, or evaluated as highly critical, critical, or slightly critical for potential landslides. A landslide could be defined as "actual" if it has been accurately mapped and documented. On the other hand, it could be classified as "potential" if it is acknowledged but not yet thoroughly studied, and if during field inspections, it is possible to observe weak recent precursor signs or identify evident precursor signs like those suggested by the Landslide Phenomena Inventory in Italy (I.F.F.I.) for detecting potential landslides.

The other important parameters for slope instability include the *"magnitude"* (P_M), which quantifies the volume of the potentially mobilized mass by considering the landslide area and its sliding surface, and is classified from extremely large to very small according

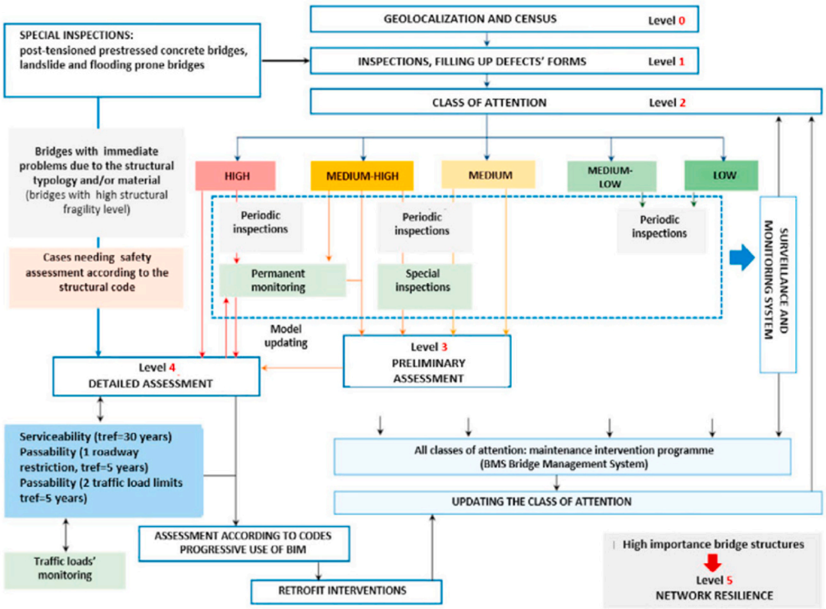

Fig. 8. Guidelines multilevel approach (MIMS, 2020).

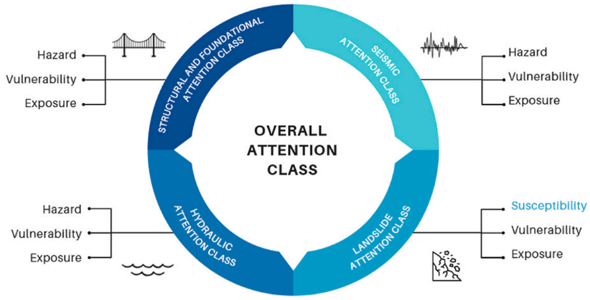

Fig. 9. The classification method for the determination, for each bridge, of the "Overall Class of Attention" (CoA).

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

	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

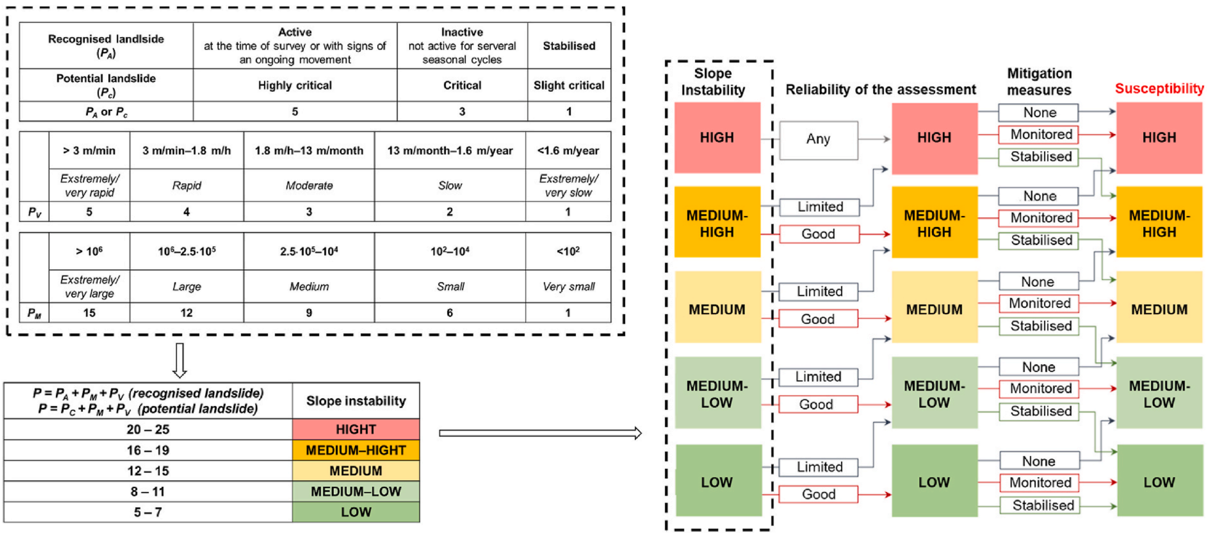

Fig. 10. Susceptibility class definition.

to Guidelines (MIMS, 2022), and the "*maximum expected velocity" (P_V)* based on the landslide type, categorized from extremely slow to extremely rapid according to Varnes' classification (Varnes, 1996). These parameters are determined using available documentation provided by the operators or by consulting the landslide inventory (I.F.F.I.) or other cartographic sources.

To rank the level of slope instability, the guidelines propose a point-based system that assigns numerical values to the three main parameters, as shown in Fig. 11. The instability level assessment is developed based on the sum of the values associated with the parameters: $P = P_A + P_M + P_V$ for recognized landslides and $P = Pc + P_M + P_V$ for potential landslides.

After determining the slope instability class, the information is combined with secondary factors, including the quality of the assessment and the presence/absence of mitigation measures. This combination leads to an overall assessment of susceptibility. Finally, by combining susceptibility, vulnerability, and exposure, the L-CoA is obtained.

3. The database

The systematic procedures outlined in the Italian Guidelines for bridge classification provided a valuable opportunity to gather a

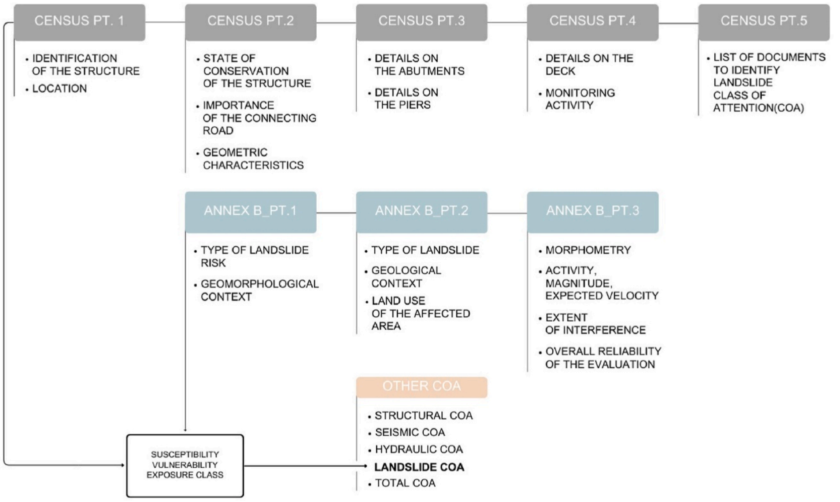

Fig. 11. Database structure.

substantial number of case studies from across the Country. This endeavour led to the creation of a comprehensive database containing pertinent information regarding landslide-bridge interactions. In the current version of the database, a sample of 382 bridges and viaducts has been included, spanning across 12 regions of Italy involved in the collection process. These structures underwent inspections by various Institutions as part of the activities carried out by the FABRE Consortium.

The database is organized into 9 sections, as illustrated in the graphical representation in Fig. 11. The initial five sections are dedicated to the inventory (census) of structures, in adherence to the Italian Guidelines. These sections encompass essential details about the structure, such as its location, conservation status, significance of the connecting road, geometric characteristics, abutment and pier details, deck particulars, monitoring activities, road network information, and a compilation of documents for classifying L-CoA.

The subsequent three sections are dedicated to delineating the geological context of the region housing the bridge, evaluating the possible presence or absence of landslide risks, and characterizing the kinematics of disruptive landslides. These sections specifically address key aspects including the level of landslide risk, geomorphological context, landslide type, distribution of activity, morphometry, activity magnitude, expected velocity, extent of interference, and overall reliability of the evaluation.

These pieces of information are useful for defining the so-called “primary” and “secondary” parameters, whose combination allows for the assessment of susceptibility, vulnerability, and exposure related to landslide risk. The approach employed for determining the L-CoA involves a method based on classes and logical operators: logical flows guide the transition from the classification of primary and secondary parameters to the classification of susceptibility, vulnerability, and exposure factors, ultimately leading to the determination of the L-CoA. The primary and secondary parameters identified as relevant for determining L-CoA are listed in Table 1. Finally, the concluding section provides a summary of L-CoA, along with Structural-, Seismic-, Hydraulic-, and Overall-CoA for each analysed structure. Based on the data entered in the preceding sections, the database automatically determines landslide susceptibility, vulnerability, and exposure, thereby defining the L-CoA.

The geographic distribution of the bridges inspected in this study is depicted in Fig. 12a, with the examined regions highlighted in grey. For each analysed region, there are five columns representing the number of inspected bridges, differentiated by colour according to the level of attention associated with landslide risk, ranging from “High” to “Low”. Additional information regarding samples per

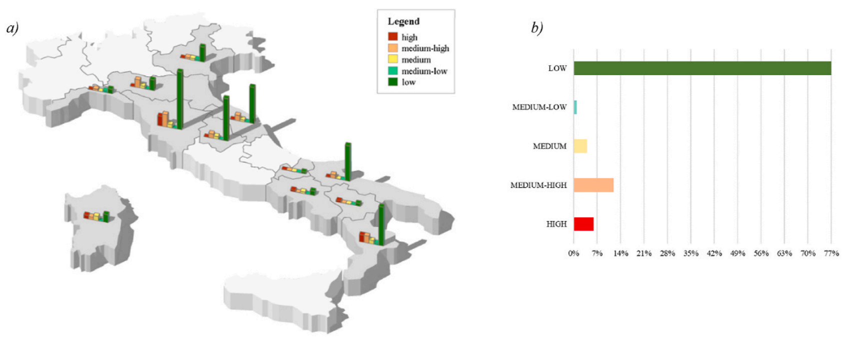

Fig. 12. (a) Map of Italy illustrating the regions interested in the bridge inspections and (b) the final L-CoA distributions.

region and their respective L-CoA classifications is presented in Table 2.

From a preliminary analysis of the data, it emerges that out of the 382 bridges and viaducts examined, 23 % exhibit a L-CoA higher than "Low" (Fig. 12b). This 23 % represents the subset of bridges interacting with landslide phenomena, whether already recognized or potential.

3.1. Sample selection for analysis

Fig. 14 shows the exam of the percentage distribution of the considered cases interacting with landslides in terms of susceptibility (a), vulnerability (b), exposure (c), and O-CoA (d) categories. Among the 86 bridges (23 % of the total sample of 382) that exhibit a landslide condition of attention (L-CoA) higher than "Low" (as shown in Fig. 13), the analysis reveals that 66 % exhibit high susceptibility, 22 % falls into the medium-high category, while a minority varies between medium and low susceptibility, as depicted in Fig. 14a.

Concerning vulnerability, as illustrated in Figs. 14b and 57 % of the cases are classified as high vulnerability, with the remaining percentages distributed among medium-high and low vulnerability. In terms of exposure, as shown in Fig. 14c, the data shows that 45 % of the cases are classified as medium, 33 % as medium-low, and a minimal fraction, 4 %, as high exposure. It is worth noting that the most frequent exposure categories fall into medium and medium-low, primarily because their definition closely relates to structural information, unlike susceptibility and vulnerability, which are linked to specific factors characterizing the landslide. From the combination of susceptibility, vulnerability, and exposure categories, the landslide risk attention class is derived, as described in Section 2. Fig. 14d demonstrates that in the presence of landslide phenomena interfering with bridges and viaducts, mostly a medium-high landslide risk attention class is obtained, with a further 26 % classified in the High category.

3.2. Some relevant examples of database compilation

While specific details regarding the analysed case studies cannot be shared due to the presence of sensitive data, certain cases documented in the database of bridges and viaducts interacting with landslide phenomena merit particular attention owing to their complexity and direct impact on infrastructure. Consequently, the distinctive characteristics of interest within these phenomena will be described, with specific details schematically depicted in Fig. 15, aligning with the specifications outlined during the database compilation. Additionally, this Section aims to give an example of the database compilation and of the typical case studies included within it. A significant example is depicted in Fig. 15a, where the bridge is potentially affected by three instability phenomena, resulting in direct effects on its structure. The IFFI cartographic analysis identified two landslide movements with undefined kinematics, but presumably attributable to "Rotational/Translational Sliding", along with a landslide phenomenon upstream of the structure, classifiable as "Rockfall/Topple". Moreover, both the area where the bridge abutment is located and the areas where the three piers are situated are characterized by active or quiescent landslide phenomena. The surrounding environment of the infrastructure exhibits complex morphological dynamics constantly evolving. The movement of superficial deposits can be attributed to poor soil characteristics, groundwater circulation patterns, and steep terrain slopes, with intense meteorological events and earthquakes capable of triggering such phenomena. During the inspection activities within the scope of FABRE operations, interventions for slope stabilization were observed at the structure, including the construction of a retaining wall around the piers (as shown in Fig. 15a) and the use of gabions filled with stone to stabilize the excavations made for the construction of the bridge piers. Another notable case is depicted in Fig. 15b, where the bridge is directly affected by an extended landslide, involving both one abutment and the bridge piers, with the interference area located at the base of the slope. During the inspection, mitigation measures for landslide containment were identified, such as the use of stone-filled gabions; however, their effectiveness appears compromised (Fig. 15b). Another emblematic case is highlighted in Fig. 15c, where the bridge is directly involved in a landslide phenomenon classifiable as "Rotational/Translational Sliding". This phenomenon affects an area characterized by uncultivated land with bushy vegetation where the viaduct is located. During the inspection, significant signs of structural deterioration were observed. A deep diagonal crack was identified at the base of the abutment 2 wall of the bridge, along with partial detachment of concrete wedges in the parapet wall zone (Fig. 15c). These

Table 2
Numbers of cases inspected by region and their associated L-CoA.

Region	high	medium-high	medium	medium-low	low
Basilicata	1	–	–	–	2
Calabria	7	7	3	1	43
Campania	1	–	1	–	4
Emilia Romagna	–	8	2	–	11
Liguria	–	1	–	1	4
Marche	–	5	1	–	40
Molise	–	–	–	–	1
Puglia	–	3	–	–	39
Sardegna	3	2	4	–	8
Toscana	10	13	3	–	81
Umbria	–	4	2	–	47
Veneto	–	1	1	1	16

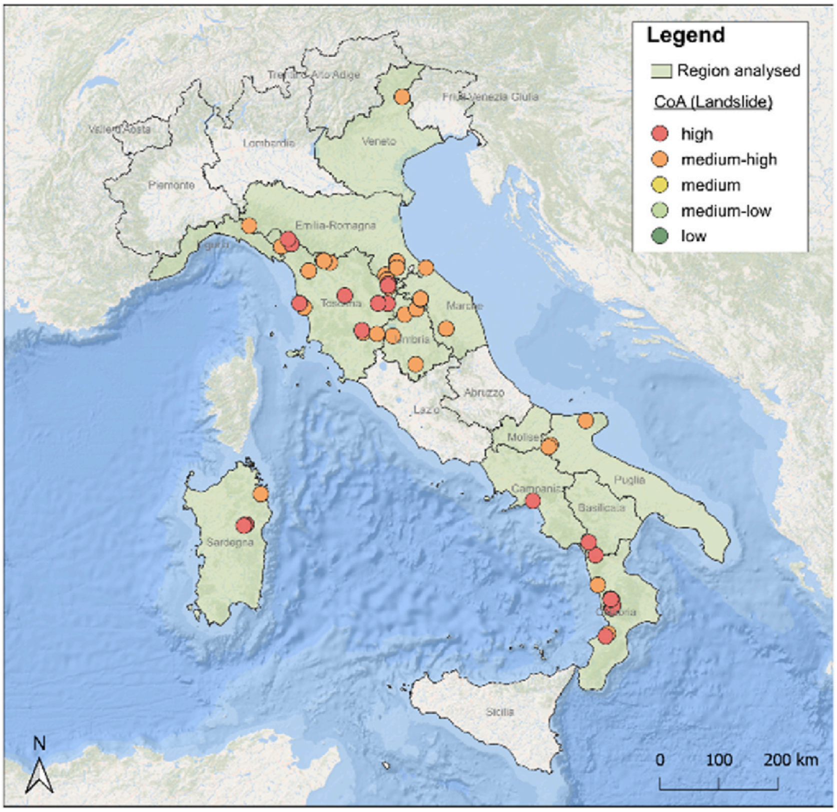

Fig. 13. Position of the viaducts classified with a L-CoA ranging from High to Medium-High.

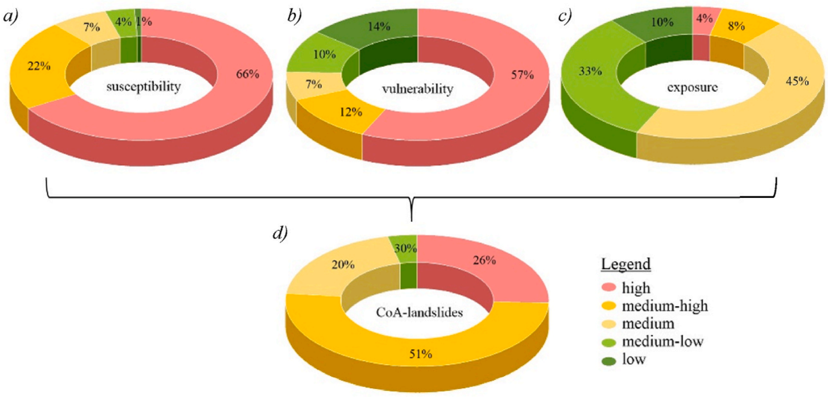

Fig. 14. Distribution of the (a) susceptibility, (b) vulnerability, (c) exposure and (d) O-CoA categories across the considered viaducts affected by landslides.

lesions appear to be the result of an ongoing landslide movement, causing a progressive shift of the foundations of abutment 2 towards abutment 1. Another case, depicted in Fig. 15d, shows the direct interference between a landslide and two piers of the viaduct. During the inspection, numerous signs of movement were also detected on the retaining structure of the embankment upon which the viaduct access ramp is founded. Specifically, it was observed that in the cultivated area, there are counter-slopes and bulges, typical of slow and shallow slides involving fine-grained soils.

4. Database analysis

Given all the challenges mentioned in the previous sections, the objective of this work is to clarify to the best extent possible, the common conditions and characteristics of landslides that contribute to the definition of a specific L-CoA category for the structure.

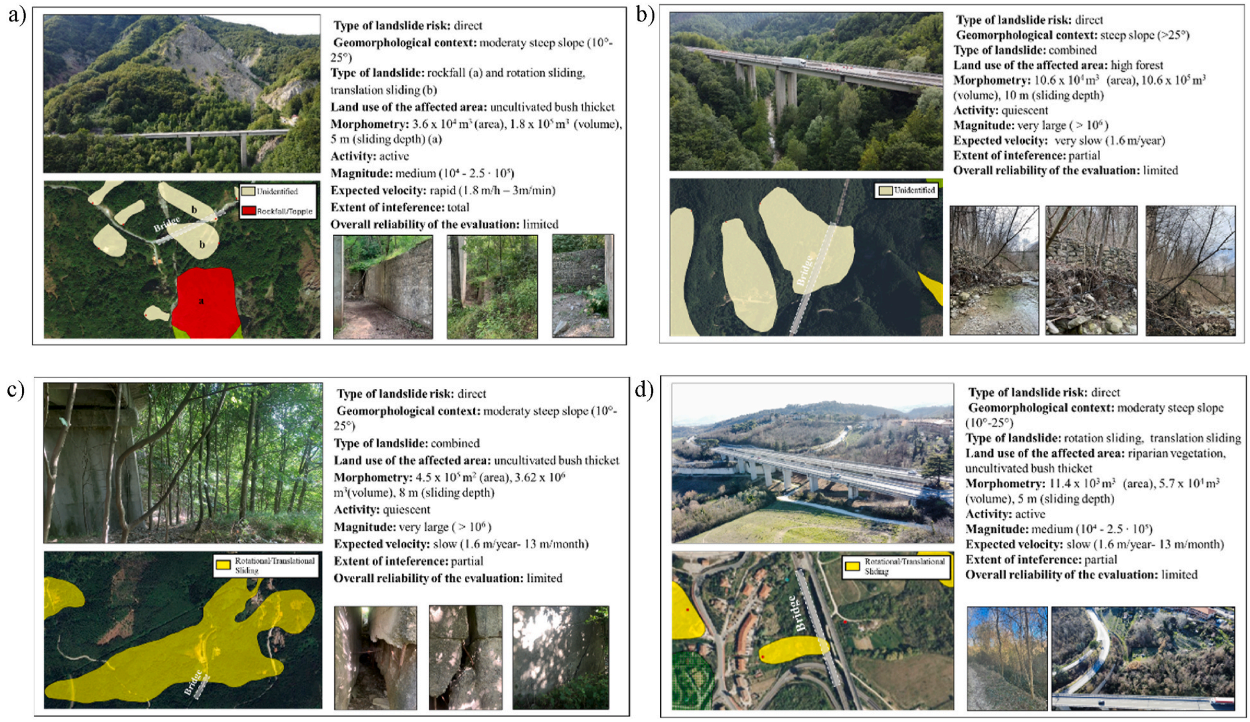

Fig. 15. Interference of the bridge with different types of landslide phenomena and interventions for slope stabilization observed at the structure.

To this end, database analyses were conducted to assess the relationship between the L-CoA of the considered structures — those experiencing interference with one or more landslides — and the variables defining the landslide key features, subdivided into the subgroups listed in Fig. 16.

Specifically, a set of variables defining landslide characteristics were considered. These include the magnitude parameter on a volumetric base (P_M), which represents the mobilizable volume ranging from Very large to Very small; the expected maximum velocity parameter (P_V), indicating the maximum speed the landslide could reach during its movement, ranging from Very rapid to Very slow. The type of interaction between the landslide phenomenon and the bridge was categorized as total, partial, or proximity landslides, thus affecting the approach zone. Ultimately, the type of landslide phenomenon was distinguished, such as rotational sliding, complex or compound phenomena, and the involvement of multiple combined landslide events. Finally, the morphology of the site where the infrastructure and landslide occur was also considered for this purpose.

Additionally, to quantitatively assess the rank of correlation between the L-CoA and the considered ordinal variables, the Spearman correlation coefficient, ρ, has been computed [26]. The Spearman correlation coefficient is defined as the Pearson correlation coefficient between ranking variables and can be computed as:

$$\rho = 1 - \frac{6\left(\sum_{i=1}^{n} d_i^2 + \sum_{j=1}^{n} \frac{t_j^3 - t_j}{12}\right)}{n(n^2 - 1)}$$

where: d_i is the difference between the two ranks of each observation; t_j represents the jth tie length and n is the number of observations.

The Spearman's rank correlation coefficient indicates the direction of association between the independent variable X (e.g. P_M and the dependent one Y (i.e. L-CoA). It is positive when Y tends to increase as X increases, and negative when Y tends to decrease as X increases. The correlation degree is labelled as follows (Table 3):

Fig. 17 displays the distribution of landslide volumetric magnitude (P_M) across different Landslide Classes of Attention (L-CoA) categories: high, medium-high, medium, and medium-low. The P_M values are grouped into five categories based on volume (from very large to very small). For the High L-CoA, the frequency distribution shows a significant presence of very large landslides (black bars) compared to other categories, indicating that areas classified as high-risk experience a higher proportion of massive landslides. Some smaller events are also present but less frequent. The Medium-high L-CoA class exhibits a more diverse range of magnitudes, with medium (grey) and large (dark grey) landslides having the highest frequencies. However, small events are also noted, indicating a broad distribution of landslide sizes in this category. In the Medium L-CoA the distribution shifts towards small and medium-sized landslides, with large and very large events becoming much less frequent. This suggests a moderate risk level primarily driven by smaller landslides. To finish, in the Medium-low L-CoA most events are small and very small (light grey bars), suggesting that low-risk

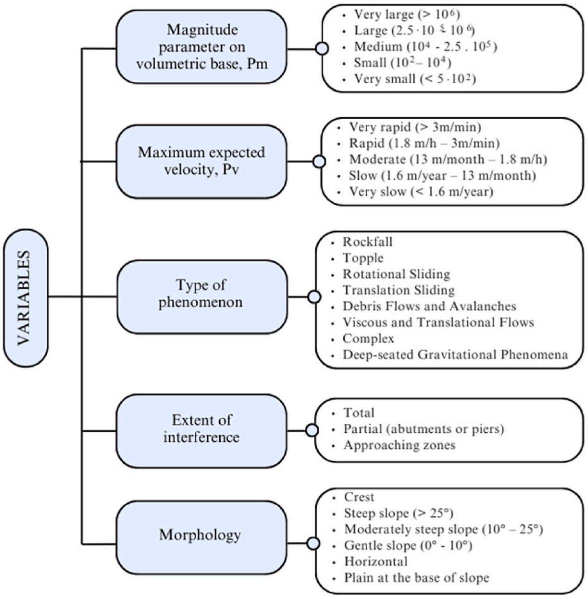

Fig. 16. Considered variables and their classification.

Table 3
Spearman coefficient value and related correlation degree.

Grading Standards	Correlation Degree
$\rho = 0$	no correlation
$0 < \lvert\rho\rvert \leq 0.20$	very week
$0.20 < \lvert\rho\rvert \leq 0.40$	weak
$0.40 < \lvert\rho\rvert \leq 0.60$	moderate
$0.60 < \lvert\rho\rvert \leq 0.80$	strong
$0.80 < \lvert\rho\rvert \leq 1.00$	very strong
1.00	monotonic correlation

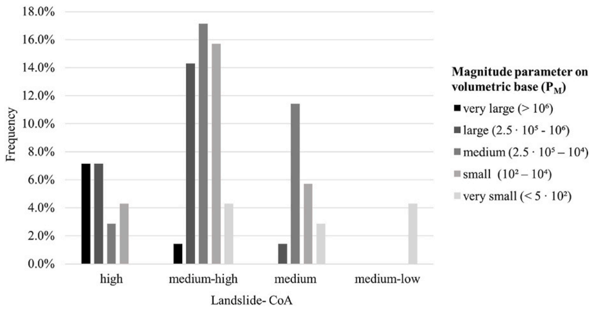

Fig. 17. Distribution of landslide volumetric magnitude (P_M) for different L-CoA.

areas are predominantly affected by less impactful landslides, with minimal presence of larger events. These observations are confirmed by Spearman's rank correlation coefficient that is $\rho = 0.49$, indicating a moderate correlation between landslide size and bridge safety level.

Fig. 18 depicts the frequency distribution of the landslide maximum expected velocity parameter (P_V) across different L-CoA. The P_V values are categorized into 5 groups based on the speed of the landslide (from very rapid to very slow) While a distinct relationship may not be immediately evident (the Spearman's rank correlation coefficient ρ is 0.378; indicating a weak correlation), it is crucial to emphasize a significant pattern. A notable prevalence of landslides interacting with the examined viaducts emerges when the landslide velocity falls into the Very Slow category (<1,6 m/year), accounting for over 53 % of the total considered case studies. Consequently, this category is notably predominant in the two most critical L-CoA classifications, categorized as High or Medium-High, and also holds relevance in the Medium L-CoA classification. Thus, we can speculate that the Very Slow P_V category is associated with landslides

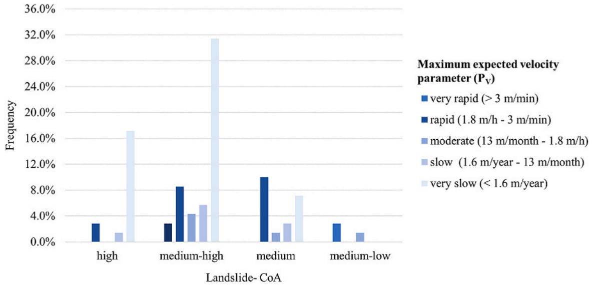

Fig. 18. Distribution of landslide maximum expected velocity (P_V) for different L-CoA.

involving significant volume, capable of producing a more severe L-CoA 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 L-CoA because of the smaller associated size. This is confirmed by the moderate negative correlation coefficient between volume and landslide velocity ($\rho = -0.571$). Analysing further the graph of Fig. 21, the Medium-high L-CoA class shows the highest variability in landslide velocities, with very slow movements (very light blue) being dominant, followed by some moderate and rapid events. The very rapid category is present but at a lower frequency. In the Medium L-CoA, the most frequent landslides are slow-moving (light blue), with some moderate and very slow events. There are only a few rapid or very rapid events in this category, indicating that landslides in this group tend to be slower. And, to finish, in the Medium-low L-CoA, very slow landslides dominate, with very few occurrences of faster movements.

Fig. 19 shows the distribution of the extent of interference caused by landslides across different L-CoA categories. The extent of interference is divided into three categories: approach zone (refers to landslides affecting the approach areas to the structure); partial (refers to landslides affecting specific bridge elements like abutments or piers); and total (refers to landslides impacting the entire structure). Total interference is most prevalent in the High L-CoA category, highlighting the high-risk nature of these structures for being completely affected by landslides. Partial interference is dominant in medium-high risk L-CoA, indicating that specific elements like abutments or piers are more vulnerable. Conversely, when a landslide occurs in the approaching zone, it tends to result in a less severe L-CoA category (Medium-Low). This observation underscores the crucial role of the specific degree of interference in determining L-CoA severity. As expected, complete interference poses the highest risk, partial interference contributes significantly to risk, whereas the presence of a landslide in the approach zone results in comparatively lower risk. Despite this distribution, Spearman's rank correlation coefficient is $\rho = 0.39$, indicating a weak correlation between the extent of interference and the risk level for the structures. This weak correlation may be partly due to the fact that most of the interference is concentrated in the medium-high and high-risk categories, reducing the variation in the data across different risk classes. With such a skewed distribution, it is difficult to obtain a strong correlation, as the variability within the lower-risk classes is limited.

Following this, an analysis was conducted to explore the correlation between various types of landslides and the assignment of L-CoA (as depicted in Fig. 20). It is evident that when combined landslides occur, including various types such as rotational slides, translational slides, and complex slides, the resulting L-CoA tends to fall within the most severe categories, ranging from Medium to High. However, it is important to note that the “combined” landslide category is the most frequent in the sample of viaducts interacting with landslides under consideration (48 %). This aspect that can affect the results of the database analysis introducing a bias due to the over-representation of a single category.

Lastly, the correlation between local morphology and L-CoA was investigated (as illustrated in Fig. 21). Here, a clear correlation between slope steepness and L-CoA severity cannot be readily anticipated ($\rho = 0.005$; i.e. very weak correlation). The category of "Moderately steep slope" is the most prevalent (43 %) in the considered sample of viaducts interacting with landslides, predominantly falling within the two central categories of L-CoA (Medium and Medium-High), but also present in the most severe category (High). Notably, the "gentle slope" category, characterized by sub-horizontal topography, contributes significantly to the population for the three most severe classes (High, Medium-High, and Medium). These findings suggest that even sub-horizontal topographies can be

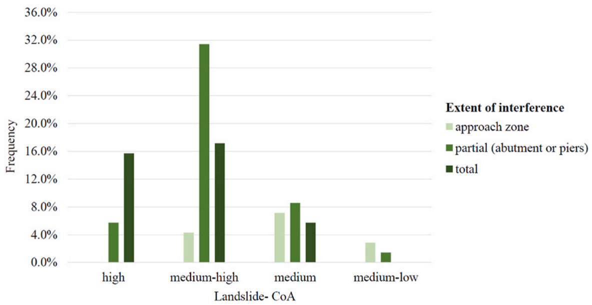

Fig. 19. Distribution of landslide extent of interference for different L-CoA levels.

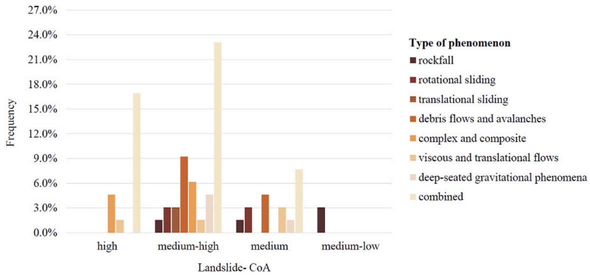

Fig. 20. Distribution of landslide types for different L-CoA levels.

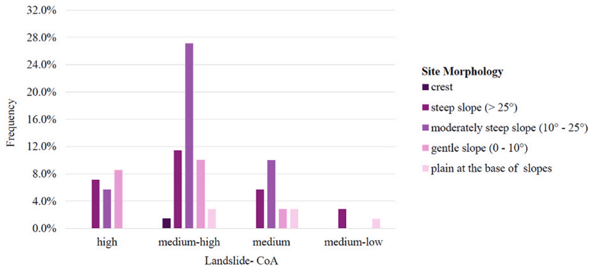

Fig. 21. Distribution of local slope morphology for different L-CoA levels.

associated with elevated levels of L-CoA, prompting the need for a critical reassessment of the parameters commonly used to evaluate risk. Factors such as soil composition, anthropogenic activities, and weather conditions may play a more significant role than slope steepness alone. These observations highlight the importance of further investigation to fully understand the complexity of interactions between local morphology and structural stability in landslide-prone areas.

5. Conclusions

Italy's intricate geological and geomorphological characteristics have historically led to a significant occurrence of landslides, impacting critical infrastructure such as bridges and viaducts. The recent scientific literature has documented numerous instances of damaged bridges across Italy due to interactions with landslides, indicating the pressing need for comprehensive understanding and effective mitigation strategies.

The systematic procedures mandated by Italian Guidelines for bridge classification provided an opportunity to compile a comprehensive database on landslide-bridge interactions. This effort, undertaken within the FABRE Consortium, involved inspections of 382 bridges and viaducts across 12 regions of Italy. It employs a method based on primary and secondary parameters to determine the L-CoA, which reflects susceptibility, vulnerability, and exposure to landslide risk. Initial analyses indicate that 23 % of inspected bridges have a L-CoA higher than "Low," highlighting their interaction with landslide phenomena. Focusing on this 23 % sample of bridges interacting with landslides, deeper dives into the database revealed various levels of correlation between landslide features and L-CoA.

- Correlation between landslide volume and Class of Attention (L-CoA). The study highlighted a direct correlation between landslide volume and L-CoA severity. Larger landslides tend to result in higher L-CoA classifications, indicating a greater risk to infrastructure. This finding emphasizes the importance of considering the potential volume of a landslide in risk assessments.
- Influence of landslide velocity. Although no linear relationship emerged between landslide velocity and L-CoA, the study revealed that very slow landslides are prevalent in high-risk L-CoA categories. This suggests that slow landslides, while not immediately perceived as dangerous, can significantly impact infrastructure due to their often considerable volume.
- Importance of the extent of interference. Complete interference between landslides and infrastructure represents the highest risk. Partial interference also contributes significantly to risk, while the presence of a landslide in the approach zone poses a relatively lower risk. This finding underscores the importance of evaluating the extent of interaction between a landslide and infrastructure, such as bridges, during risk analyses.
- Criticality of combined landslides. Combined landslides, which involve multiple types of movement, tend to result in more severe L-CoA classifications. This highlights the need to account for the complexity of landslide phenomena during risk assessments, as the combination of different movement types can significantly increase the danger.
- Lack of direct correlation between slope angle and L-CoA. Contrary to expectations, the study did not find a direct correlation between slope gradient and L-CoA severity. Even gently sloping terrains can be associated with high L-CoA. This suggests that risk

assessment should not rely solely on slope gradient but must consider a broader range of factors, including soil type, vegetation cover, and weather conditions.

The research conducted contributes to bridging the gap in understanding landslide-bridge interactions, providing valuable insights for infrastructure management and safety enhancement. Continued interdisciplinary efforts and innovative approaches are essential for developing robust predictive models and mitigating the risks posed by landslides on infrastructure in Italy and beyond.

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CRediT authorship contribution statement

Diana Salciarini: Writing – original draft, Supervision, Methodology, Conceptualization. **Erica Cernuto:** Writing – original draft, Visualization, Investigation. **Giulia Capati:** Writing – original draft, Visualization, Investigation. **Francesca Dezi:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Lorenzo Brezzi:** Writing – review & editing, Investigation. **Fabiola Gibin:** Writing – review & editing. **Fabio Gabrieli:** Writing – review & editing, Investigation. **Stefano Stacul:** Writing – review & editing, Investigation. **Angelo Doglioni:** Writing – review & editing. **Arianna Lupattelli:** Writing – review & editing. **Nunziante Squeglia:** Supervision, Methodology, Conceptualization. **Vincenzo Simeone:** Supervision, Conceptualization. **Paolo Simonini:** Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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