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GIS-Based Analysis of Landslide and Bridge Data for Risk Assessment

Chiara Bellosguardo^a, Fabiola Gibin^a, Riccardo Ceccato^a, Sandro Rossato^b, Fabio Gabrieli^{a,*}

^a*Department of Civil, Environmental and Architectural Engineering, University of Padova, Via Marzolo 9, Padova 35131, Italy*

^b*National Research Council, Institute of Geosciences and Earth Resources, Padova, 35127, Italy*

Abstract

The study of the interaction between road networks and landslides is crucial for assessing the risk posed by these phenomena to transportation infrastructures. In particular, the risk associated with interactions between landslides and bridges or viaducts can be quantified through the concept of “Landslides Class of Attention” (L-CoA). This study aims to develop methodologies for deriving key susceptibility and vulnerability factors in cases of landslide–bridge interactions within a vast area. The geographic area selected to test the effectiveness of the procedures is the Province of Belluno, (Italy). The proposed procedures enable the extraction of parameters essential for determining the L-CoA across a large number of infrastructures. To achieve this, the databases related to the existing landslides and bridges are integrated and analysed within a GIS environment. The primary databases used are the IFFI inventory of landslides in Italy and OpenStreetMap, which provides extensive information about bridges. These datasets are processed to extract parameters necessary for the L-CoA evaluation, such as bridge length and crossed entity, while additional parameters, including landslide magnitude and velocity, are derived by applying relationships from the literature. Information not directly obtainable from the databases can be supplemented through databases of selected infrastructures. Given the large number of identified interactions, statistical analyses can be performed to investigate how various factors influence the L-CoA. The adopted approach also allows for the extraction of parameters not directly required for L-CoA assessment, such as the orientation of the bridge relative to the landslide direction or the slope of the landslide. These additional data enable further statistical evaluations aimed at identifying potential correlations between the characteristics of the interacting elements and their corresponding L-CoA.

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* Corresponding author. Tel.: +39-049-827-7994.

E-mail address: fabio.gabrieli@unipd.it

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1. Introduction

In Italy, the interaction between road networks and landslide movements represents one of the major risk factors for transport infrastructures, particularly for bridges and viaducts, which may suffer even severe damage up to collapse, especially in conjunction with extreme natural events (Scala et al., 2025). Paradigmatic examples of interaction with landslide movements include the Albiano Magra bridge in Tuscany (Farneti et al., 2022), the Himera viaduct in Sicily (Lo Iacono et al., 2017) and the Serra railway bridge in Basilicata (Geremia et al., 2015). This issue represents a critical problem also at the global scale (Gabrieli et al., 2025a). In order to quantify and manage the critical issues related to the safety of bridges and viaducts, the Italian Superior Council of Public Works has developed and approved the “*Guidelines for the classification and management of risk, the safety assessment and the monitoring of existing bridges*” (MIMS, 2022).

The Guidelines propose an integrated approach that makes it possible not only to determine the risk associated with landslide phenomena, but also to assess structural, seismic, and hydraulic risks, providing a unified tool for evaluating the safety conditions of infrastructure assets. In particular, landslide risk is expressed through a parameter known as the “*Landslide Class of Attention*” (L-CoA), which considers both the structural typology of the bridge and the characteristics and level of knowledge of the landslide. Information on the bridge and the landslide is used to derive susceptibility, vulnerability, and exposure classes, which, when combined, allow estimation of the L-CoA (Gabrieli et al., 2025b). The parameters used to determine the L-CoA for each individual infrastructure are obtained from available documentation and from data collected on site through targeted inspections aimed at identifying precursory signs on the structure and in the surrounding area.

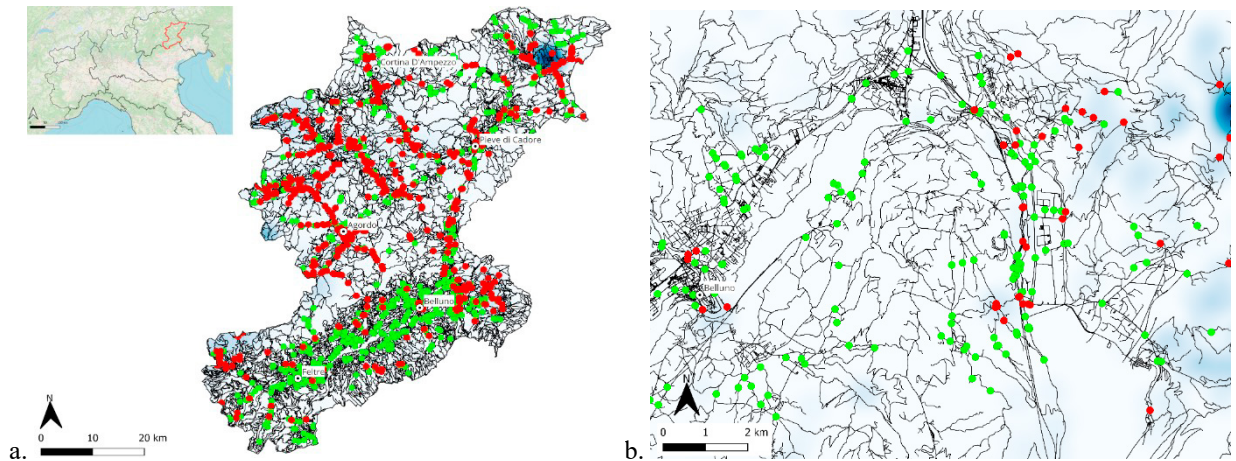


Fig. 1. Map of bridges, landslides and road network in the Province of Belluno: (a) bridges affected by landslides (red), bridges not affected by landslides (green) and heatmap of landslide concentration (blue); (b) map detail.

The study area considered in this work (the Province of Belluno) is predominantly mountainous, covers an area of 3610 km² (of which 13% is affected by landslides), and is characterized by a road network exceeding 13600 km, with numerous bridges and viaducts located in landslide-prone areas (Fig. 1). In this context, with a bridge density on the order of 0.4 bridges/km², it is evident that the phase of risk assessment of these structures can be very demanding in terms of time and costs for the managing authorities. The aim of this study is therefore to develop simplified preliminary classification procedures that allow rapid identification of intervention priorities based on the definition of specific vulnerability indicators (Gecchele et al., 2019).

The analysis is carried out starting from the collection of available cartographic data on bridges and landslides. The main sources of information used in this analysis are the “IFFI” Catalogue (<https://idrogeo.isprambiente.it/app/iffi>),

integrated with information from the “PAI” Catalogue (<https://idrogeo.isprambiente.it/app/pir>) for landslides, and OpenStreetMap for road infrastructure. Additional information was derived from the Provincial Soil Map, maps of mean annual and monthly precipitation, and digital terrain elevation models (DTM).

Following the definition of various characteristics of bridges and viaducts at the provincial scale, a sufficiently large dataset was obtained, making it possible to carry out preliminary analyses. To this end, descriptive analyses, cluster analyses, and correlation analyses between the properties of landslide and bridge samples were developed, with particular attention to the group of bridges affected by landslides.

2. Information collection phase

For the collection of the parameter values required for the calculation of the L-CoA and for carrying out subsequent statistical analyses, information from various maps and GIS-based databases related to the area of interest was considered. In particular:

- IFFI (Italian Landslide Inventory): contains points and polygons representing, respectively, uncartographable landslides (e.g. rockfalls) and cartographable landslides, along with information on the type of movement;
- PAI (Hydrogeological Asset Plan): contains additional polygons delineating landslide phenomena, including indications of potential transit and deposition areas, and classified according to hazard level;
- OpenStreetMap (OSM): contains the complete road and railway networks with the location of bridges, as well as the network of watercourses and valleys;
- TINITALY: the digital elevation model of the Italian territory with a density of 10,000 points/km²;
- BIGBANG80: raster maps related to total monthly precipitation and mean annual precipitation for the period 1951–2024;
- Soil Map (2018): divides the Italian territory into areas with homogeneous land cover characteristics;
- Map of AADT values of the main road infrastructures.

This information is useful for the calculation of primary and secondary parameters and for estimating the L-CoA with regard to landslides. Conversely, data related to the structural characteristics of bridges are limited and do not allow the extraction of some primary vulnerability and exposure parameters. Furthermore, in OSM the coverage of the bridge network is not complete: for example, out of a sample of 21 bridges inspected in the Province of Belluno, only 14 (i.e. 67%) were recorded in OpenStreetMap. Despite the limitations of the bridge database obtained from OSM, it was nevertheless possible to derive useful information for the calculation of the L-CoA and for carrying out preliminary statistical analyses.

3. Data extraction and processing

The extraction of parameters related to bridges and landslides was carried out using the Model Designer of the QGIS software (2025), which allows to define and execute a sequence of logical and geometric operations to be performed on the input layers. The main advantage of this procedure lies in the possibility of extending it to any other geographical area of the Italian territory, provided that the same databases used in the study are available.

Due to the characteristics of inputs and to combine different data sources, for data extraction and processing, some assumptions were adopted, which are described below for a few steps considered particularly significant:

- Step 1: bridge elements are converted from polylines to polygons with a width of 5 m, considered a reasonable estimate of the width of the infrastructures under consideration;
- Step 6: the magnitude of landslides is calculated, for landslides in the IFFI catalogue with a defined areal extent, using the relationships (Larsen et al., 2010):

$$V = 10^{(1.145 \pm 0.008)} A^{(-0.44 \pm 0.02)} \quad \text{for landslides in soil material}$$

$$V = 10^{(1.35 \pm 0.01)} A^{(-0.73 \pm 0.03)} \quad \text{for landslides in rock materials;}$$

The velocity of landslides is derived by comparing the velocity classes reported in the landslide movement classification of Cruden and Varnes (1996), the landslide categories in the IFFI catalogue and the velocity classes defined in the Guidelines. In particular, landslides are assigned the maximum velocity value of the class to which they belong in order to adopt a more conservative estimate. For landslides in the PAI catalogue, which have a more uncertain mapped area, the magnitude is calculated as the sum of the magnitudes of intersecting IFFI catalogue landslides (if present). The velocity, in turn, is assigned as equal to the maximum velocity of the intersecting IFFI landslides. It should be noted, however, that for PAI catalogue landslides that do not intersect any IFFI landslides (about 78% of the total) no velocity or magnitude value can be assigned;

- Step 7: the intersection between a bridge and a landslide is considered “complete” if more than 50% of the bridge area is contained within the landslide polygon; “partial” if it intersects the landslide within a distance of 10 m from it and an “approach zone” if the intersection occurs within a distance of 100 m from the landslide;
- Step 8: the interaction between a bridge and a landslide is classified, based on the angle formed between the direction of the bridge and that of the landslide, as “parallel” ($\alpha < 30^\circ$), “oblique” ($30^\circ < \alpha < 60^\circ$) or “perpendicular” ($60^\circ < \alpha < 90^\circ$);
- Step 9: to obtain the extreme events index (e), for each j -th month of the n years of the reference period, the mean (μ_j) and the standard deviation (σ_j) of the monthly precipitation ($P_{i,j}$) are calculated and the resulting values are combined using the relationship:

$$e = \frac{\sum_{j=1}^{12} \left(\sum_{i=1}^n \max \left(0, \frac{P_{i,j} - \mu_j - \sigma_j}{\sigma_j} \right) \right)^2}{\sum_{j=1}^{12} \left(\sum_{i=1}^n \max \left(0, \frac{P_{i,j} - \mu_j - \sigma_j}{\sigma_j} \right) \right)} ;$$

the values of mean annual precipitation and of the extreme events index assigned to landslides are the average of the values of the cells they occupy.

Tab.1. Description of the steps.

Step	Description	Outputs
1	Groups bridges (polylines) that constitute a single structure by applying a buffer with a width of 5 m	Number of bridges
2	Determines the length and azimuthal direction of the bridges by calculating the distance between the polygon vertices and its orientation	Bridge length, bridge direction
3	Determines, by intersection, the elements crossed by the bridges (roads subdivided by type, rivers and valleys)	Crossed elements
4	Assigns to the bridges the AADT values from the corresponding road network	AADT
5	Calculates the mean slope and the propagation direction of landslides from the IFFI and PAI catalogues by overlaying the landslide area onto the DEM raster	Landslides slope, landslides direction
6	Calculates the magnitude and velocity of landslides using literature-based correlations, considering the landslide area, the surface type (obtained from the Soil Map) and the type of movement	Landslides magnitude, landslides velocity, landslides surface type
7	Identifies the bridges that intersect landslide areas and assign to each intersection the corresponding interference class	Bridge–landslide interference class
8	Compares the directions of bridges and landslides to determine the relative bridge–landslide angle	Relative bridge–landslide angle.
9	Assigns to each landslide the values of mean annual precipitation and the extreme events index, calculated as the average within the landslide area	Annual precipitation, extreme events index

For an available subset of bridges affected by landslides along the main road routes, data were also derived on the percentage and absolute changes in kilometres travelled and travel times (in minutes) spent on the network by users in the event of bridge closure, with reference to the current traffic situation. This information is useful for the assessment of some of the secondary exposure parameters of the bridges.

Once the above steps were applied, two separate tables were obtained, one for bridges and one for landslides, containing the attributes derived for each element.

4. Statistical analyses

The integration of the bridges and landslides database and the application of the steps developed in the GIS environment made it possible to derive a large amount of data, which was used for statistical evaluations. Landslide samples were analysed using descriptive statistics in order to perform preliminary assessments. To identify any distinctive properties of bridges affected by landslides compared to those not involved in landslide phenomena, the descriptive statistics for bridges were complemented with cluster analyses. Finally, correlations between the characteristics of bridges affected by landslides and those of the landslides were investigated, with particular attention to the relative bridge–landslide direction. MS Excel and Minitab software were used to perform the statistical analyses. A total of 1484 bridges and viaducts were considered, of which at least 41% interact with landslides.

4.1. Descriptive statistics of landslides

The descriptive statistics considered most significant for characterizing the landslide sample concerned the hazard level (PAI Catalogue), the type of movement (IFFI Catalogue), as well as magnitude and velocity. To obtain statistically meaningful results, the first two analyses compared the entire sample of landslides in the study area with the subset affecting road or railway bridges; the latter two analyses refer only to the group of landslides that intersect bridges.

With regard to the classification of landslides based on the type of movement, it emerges that the majority of landslides in both groups considered are characterized by a rotational/translational sliding mechanism.

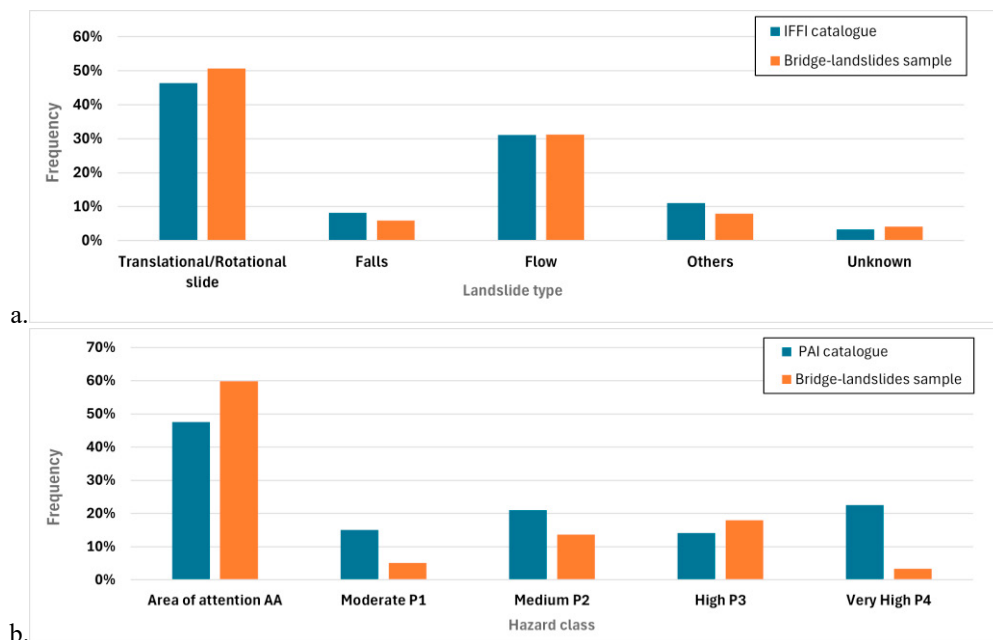


Fig. 2. (a) Frequency of landslide types of movement and (b) frequency of landslide hazard classes.

The frequencies of the different types of movement mechanisms show an overall similar distribution between landslides in the IFFI Catalogue and those intersecting bridges (Fig. 2a). Indeed, the application of a χ^2 test returns a p-value of 0.134, indicating that the observed differences between the two distributions are not statistically significant. However, among the categories that contribute most to the χ^2 statistic is rapid flow, which is overrepresented in the sample of landslides intersecting bridges. This type of movement is particularly difficult to define and, consequently, complex to study in the context of bridge-landslide interactions.

A similar analysis was conducted for landslides in the PAI Catalogue to evaluate differences between the two samples based on hazard class (Fig. 2b). In this case, discrepancies between the class frequencies in the two considered samples are more evident. Most PAI Catalogue landslides that intersect bridges (79%) are characterized by a hazard class lower than “medium”; however, if only the more detailed IFFI landslide catalogue were considered, 117 landslides present only in the PAI Catalogue would be excluded, of which 20% fall into the “high” and “very high” hazard classes.

The distribution of landslides according to magnitude class shows that about half of the landslides intersecting bridges fall into the “medium” category. However, it should be noted that for non-mappable landslides in the IFFI catalogue, the area, and therefore the magnitude, was defined arbitrarily: the extent was assigned the maximum value expected for a non-mappable landslide, 10000 m², as the real area is unknown. Consequently, for this group of landslides, the magnitude is classified as “medium,” but some elements of the group may actually have a smaller extent and fall into the “small” magnitude category.

Considering landslides that involve bridges in terms of velocity class, most fall into intermediate categories: “slow” (29%), “moderate” (57%), and “fast” (34%). It is important to note that velocity classes were assigned based on the type of movement and the landslide slope, but other factors may influence this characteristic of the landslide; therefore, the velocity class obtained may not correspond to the actual one in some cases.

4.2. Cluster analysis of bridges

Cluster analyses were carried out on the bridge sample to investigate whether there are characteristics that distinguish bridges affected by landslides (610 bridges) from those not affected by landslides (874 bridges). For this purpose, the types of crossed elements and network categories were considered.

To evaluate the relationship between bridge involvement in landslides and the type of crossed element, river or another road, frequency tables were produced (Fig. 3), in which a value of 1 indicates the presence of the element and a value of 0 indicates its absence; both absolute values and percentages with respect to the total number of bridges are reported.

		waterway	
		0	1
landslide	0	148 (10%)	726 (49%)
	1	53 (3%)	557 (38%)

a.

		road	
		0	1
landslide	0	729 (49%)	145 (10%)
	1	542 (37%)	68 (4%)

b.

Fig. 3. (a) Landslide-crossed waterway intersection frequency table and (b) landslide-crossed road frequency table.

Comparing the results for bridges affected by landslides with those not involved in the phenomenon, no significant differences were observed.

The relationship between road network type and bridge involvement in landslide phenomena is not consistent with the size of the two bridge samples across all infrastructure categories. In particular, when normalized by network length, the number of bridges belonging to the main road categories, motorway, primary and secondary, is slightly lower in the sample of bridges affected by landslides than in the sample of bridges not affected by the phenomenon, which nevertheless represents the most numerous group. Therefore, infrastructures of greater importance are characterized by a higher incidence of landslide phenomena compared to bridges belonging to lower-category roads.

In the histogram (Fig. 4), based on OpenStreetMap classification, road categories with similar relevance are grouped together, resulting in three road network types.

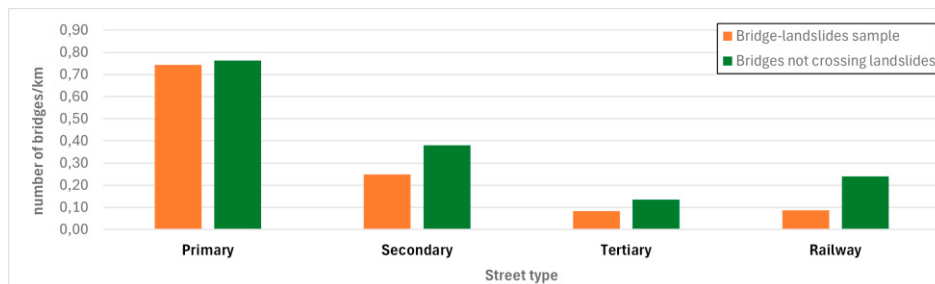


Fig. 4. Number of bridges/km crossing landslides and not crossing landslides divided according to network types.

4.3. Correlations between bridge and landslide characteristics

To determine the existence of correlations between the characteristics of bridges affected by landslides and the landslides involving them, Chi-square, Kruskal–Wallis, and Spearman statistical tests were applied, depending on the nature of the variables involved and the assumptions required by each test. The analyses were performed for several pairs of variables, with particular attention to correlations involving the angle between the bridge direction and the landslide direction. Among the statistically significant correlations (p -value < 0.05), only those with plausible physical meaning were considered.

The association between the bridge-landslide interference class and the relative bridge-landslide angle (Cramér's $V = 0.02$) shows that the observed frequency of “complete” interference is higher than the expected frequency in cases of orthogonal intersection; conversely, for the group of bridges parallel to the landslide propagation direction, the observed frequency for the same interference type is lower than expected.

From the correlation between the relative angle and the presence of a river as the crossed element (Cramér's $V = 0.03$), it emerges that the group of bridges perpendicular to the landslide direction and not crossing a river has a higher-than-expected frequency; the same characteristic is observed for the group of bridges parallel to the landslide and crossing a river.

The correlation between landslide slope and the relative angle ($\epsilon^2 = 0.01$) indicates that the mean landslide slope is highest (25°) for interactions classified as “oblique” and lowest (20°) for “parallel” interactions.

Additional correlations considered of interest were obtained by examining various pairs of variables.

The association between landslide slope and the bridge–landslide interference class ($\epsilon^2 = 0.03$) shows that the mean slope of landslides involved in “complete” bridge-landslide intersections is 20° , it is 21° for “partial” intersections and reaches 25° when the bridge lies within the “approach zone”.

A strong correlation exists between the absolute change in kilometres travelled by users relative to the baseline scenario (i.e. normal bridge operation) and road type ($\epsilon^2 = 0.4$). In particular, higher-importance roads exhibit larger absolute increases in kilometres travelled compared to lower-category roads. A similar result is obtained when considering the absolute change in travel time (minutes spent on the network) relative to the baseline scenario and road type.

5. Conclusions

The study demonstrated that, starting from appropriate landslide and bridge databases, it is possible to derive many of the parameters required for the evaluation of the L-CoA, which can then be integrated with data collected in the field. This information can also be useful for developing further analyses and for identifying recurring patterns of bridge-landslide interaction or correlations. However, some of the databases considered present critical issues: for example, not all bridges in the road network are catalogued in OpenStreetMap, while in the IFFI Catalogue non-mappable landslides do not report information on their extent, which is necessary for determining landslide magnitude.

Nevertheless, through suitable assumptions, it was still possible to exploit the available data and carry out preliminary assessments.

The statistical analyses conducted on landslides highlighted the most common movement types and hazard classes among those involving bridges. In contrast, the comparison between bridges affected by landslides and those not involved did not reveal distinctive characteristics that would allow the two groups to be clearly separated; however, it was observed that bridges belonging to major road infrastructures exhibit a higher incidence of landslide phenomena compared to other road categories. The correlations identified between bridge characteristics and landslide characteristics were statistically significant but, in most cases, weak. It should also be considered that some correlations involve parameters estimated in an arbitrary manner, such as the magnitude of non-mappable landslides, and therefore may not fully reflect reality. The only correlation that proved to be both significant and robust concerns parameters calculated under scenarios different from the baseline and road type: in particular, the increase in kilometres travelled and travel times for major infrastructures is substantial, especially when combined with the higher incidence of landslide phenomena compared to other road categories.

The study therefore proved useful in developing a method that enables the assessment of the characteristics of a large number of bridges and landslides and of the interactions between them. Moreover, it made it possible to highlight both the limitations and the potential of the open-source databases used, as well as of the assumptions adopted. Based on field inspections, it will be possible to integrate the information derived from the databases and to confirm or further investigate the statistical analyses in order to identify additional relationships among the variables.

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