*Proc. of the 9th International Symposium on Geotechnical Safety and Risk (ISGSR)*
*Edited by* Zhongqiang Liu, Jian Dai and Kate Robinson
*Published by* Research Publishing, Singapore.
doi: 10.3850/GRF-25280825_isgsr-118-P087-cd

# STATISTICAL ANALYSIS OF LANDSLIDE RISK ASSESSMENT PARAMETERS FOR BRIDGES AND VIADUCTS UNDER NEW ITALIAN GUIDELINES

Fabio Gabrieli, Fabiola Gibin, Alessandro Scala, Luca Simoni, Lorenzo Brezzi, Paolo Simonini

*Department ICEA, University of Padova, via Ognissanti 39, 35129 Padova, Italy*
*E-mail: FG: fabio.gabrieli@unipd.it, FG: fabiola.gibin@phd.unipd.it, AS: alessandro.scala.1@studenti.unipd.it, LS: luca.simoni.1@studenti.unipd.it, LB: lorenzo.brezzi@unipd.it, PS: paolo.simonini@unipd.it*

In July 2022, following the tragic collapse of the Morandi Bridge in Genoa, Italy, the Italian Ministry of Infrastructure and Transport approved new *Guidelines for the Classification and Management of Risk, Safety Assessment, and Monitoring of Existing Bridges* (GLs). These guidelines aim to systematically evaluate and classify the safety of bridges and viaducts, providing a reliable tool to estimate a Class of Attention (CoA) for each structure, thereby identifying those requiring special precautions and maintenance. The GLs employ a multi-level approach across four risk areas: structural, seismic, hydraulic, and landslide. Each risk area is evaluated based on hazard/susceptibility, vulnerability, and exposure. For landslide risk, susceptibility is determined by parameters such as the state of activity, unstable volume, and characteristic speed of the landslide, along with secondary parameters like assessment reliability and existing mitigation measures. Vulnerability includes factors like average span, construction material, static scheme, type of foundation and structure-landslide interaction. Finally, exposure considers average daily traffic, maximum span length, and the strategic importance of the infrastructure. Given the methodical and standardized nature of the new regulation and the limited experience with it, this paper presents a statistical study based on generating around 10,000 synthetic cases of landslide-bridge interactions to evaluate their impact on Landslide-CoA outcomes. The study identifies trends, potential imbalances, and the sensitivity of parameters in landslide risk assessment. The study focuses also on specific case scenarios, comparing results for structures interacting with large, slow-moving landslides with those for structures potentially affected by rockfall phenomena characterized by smaller volumes but much higher impact velocities, examining their different effects on Landslide-CoA levels. Findings suggest potential improvements to the calculation methods and potential enhancements of the new guidelines, contributing to safer and more reliable infrastructure management.

*Keywords*: landslide-bridge interaction, landslide risk assessment, bridges and viaducts, landslide susceptibility, Italian guidelines, statistical approach.

## 1. Introduction

The vast Italian infrastructure heritage of bridges and viaducts requires continuous monitoring and appropriate oversight to ensure the safety of the structures and the protection of the people using them. To achieve this objective, in 2022, the Italian Superior Council of Public Works issued the *Guidelines for Risk Classification and Management, Safety Assessment, and Monitoring of Existing Bridges* (GLs) (MIMS 2022). These guidelines aim to assign a Class of Attention (CoA) to each structure, thereby prioritizing risks, enabling timely interventions on those structures requiring urgent maintenance, and ensuring continuous oversight of the entire infrastructure network. The guidelines adopt a multi-level and multi-risk approach. The structure undergoes progressively detailed evaluations based on the assigned CoA. Initially, information is gathered about the structure and the context, followed by a preliminary inspection by experts. The CoA then defines the evaluation pathway, including further assessments, precision requirements, and inspection frequency.

This longitudinal approach is complemented by a cross-sectional evaluation, as the various levels of safety assessment are applied to four distinct risks: structural, seismic, hydraulic, and landslide-related. Each risk is evaluated in terms of hazard (or susceptibility for landslide risk, as it only considers spatial factors), vulnerability, and exposure. Subsequently, through matrix-based combinations, the risk levels are integrated to define a single CoA. The Italian guidelines are among the first regulations to incorporate the evaluation of four risks into a single methodological approach. Given their significant impact and recent implementation, these guidelines require careful monitoring and revision for continuous improvement, ensuring an effective and reliable risk assessment.

This article examines landslide risk, focusing on the factors influencing the corresponding CoA for structures. This risk is particularly critical for bridges, as landslides often manifest years after construction (Farneti et al., 2023). Moreover, their impact on the structure is difficult to estimate since bridges are not designed to withstand such loads. This could lead to a distorted assessment of the overall risk attributed to the structure.The statistical study conducted aims to analyze the Italian normative and highlight any imbalances or biases toward specific CoAs, which may sometimes result in landslide risk overestimation. Such insights will allow for improvement proposals. To this end, 10,000 synthetic bridge-landslide interaction cases were generated by extracting combinations of primary and secondary parameters based on various criteria. The resulting distributions of susceptibility, vulnerability, exposure, and landslide-CoA were then evaluated. Finally, since two critical parameters in the evaluation are landslide volume and velocity, two specific scenarios were analyzed: a large-scale, slow-moving landslide and a small-scale, rapid-flow landslide. This analysis aimed to assess the impact of these recurrent cases on the final risk assessment outcomes.

## 2. Generation of synthetic bridge-landslide interaction cases

In the GLs, susceptibility evaluation initially considers the landslide activity state or criticality level, the mobilized volume, and the velocity. Each of these primary parameters is assigned a value (ranging from 1 to 5 for *activity state/criticality level*, from 1 to 5 for *landslide average expected velocity*, and from 3 to 15 for *landslide volume*). Subsequently, these values are summed to derive an additional parameter called "*slope instability*." This parameter is then adjusted to account for the presence of *mitigation measures* and the uncertainty regarding the *reliability of the assessment*. Based on this, a *susceptibility class* for the landslide event is assigned. Vulnerability, on the other hand, is primarily determined by the characteristics of the structure: *structural scheme*, *main constructive material*, *span length, number of spans*, and *foundation type*. Additionally, the contribution of the *interference extent* is considered, which evaluates the interaction between the landslide and the structure. Finally, for exposure, the *average daily traffic level* and the *average bridge span* are taken into account. Secondary parameters include the type of *crossed entity*, the availability of *alternative routes*, and the *strategic importance* of the structure.

Susceptibility, vulnerability, and exposure are each characterized by a value ranging from low to high, divided into five distinct levels, and these are subsequently combined to determine the final landslide-CoA.

To verify the reliability of the method introduced in the GLs, 10,000 combinations of primary and secondary parameters were statistically sampled and artificially generated (i.e., 10,000 synthetic bridge-landslide interaction cases). The results were then compared with the real sample of bridges affected by landslides observed during inspection activities (Salciarini et al. 2024).

To achieve this, certain indices were first parameterized, such as mitigation measures (0 if absent, 1 if monitored, 2 if stabilized) or the type of crossed entity (ranging from 0 to 2 based on importance). Primary parameters were then considered, taking into account their respective scores (e.g., volume ranging from 3 to 15, velocity from 1 to 5). An algorithm was developed to calculate susceptibility, vulnerability, and exposure classes according to the logical frameworks outlined in the guidelines, ultimately determining the landslide-CoA.

To test the performance of the new guidelines, it is possible to apply an exhaustive approach that explores the space of all possible solutions (i.e., all combinations of parameters) or an informed approach that takes into account the actual distribution of the various parameters (e.g., the fact that larger landslides are also less frequent). For this purpose, the synthetic parameter extraction for subsequent analysis was conducted using two methods: uniform sampling and sampling based on the actual distribution of landslide parameters. In the first case, velocity, magnitude, and activity state values of the landslide were randomly sampled. In the second case, random sampling was performed in accordance with the actual distributions of landslide volumes in the Italian territory (Brunetti et al. 2009) and landslide velocities derived from the Italian Landslide Inventory (ISPRA, 2024).

## 3. Discussion of results and comparison with real data

The distribution of the obtained classes was analyzed, first in terms of susceptibility alone (Figure 1a) and then globally as landslide-CoA (Figure 1b).

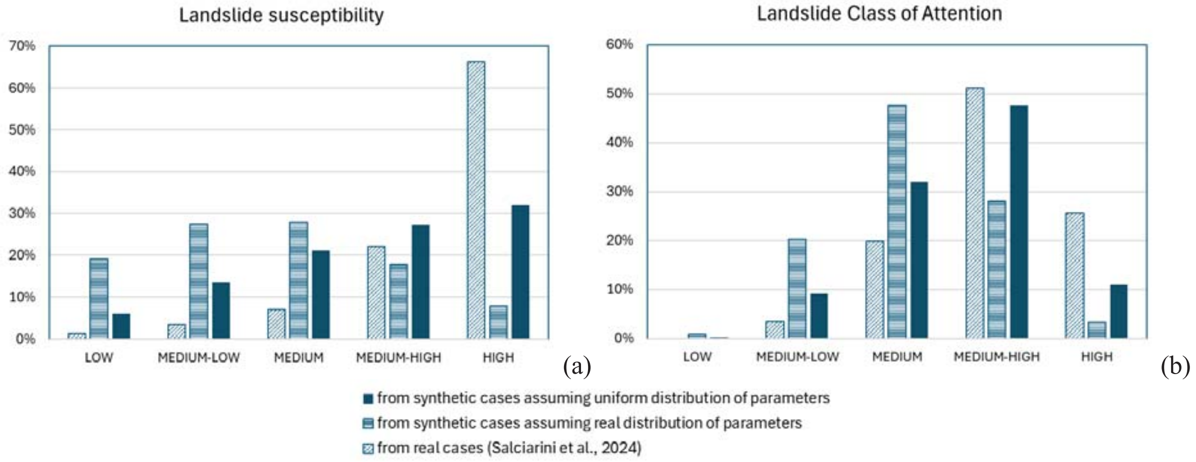

Fig. 1. (a) Susceptibility and (a) CoA obtained by analyzing the data from the random sample (i.e., uniform distribution of parameter values), the sample with real distributions of landslide volume and velocity, and the data from field inspections.

As observed, the susceptibility class distribution for the 10,000 random cases shows a monotonically increasing trend with higher criticality levels: lower susceptibility classes are significantly less frequent than higher ones, with only 6% of cases falling into the low susceptibility class. This random value distribution highlights a tendency to produce high susceptibility values, primarily due to the combination of primary parameters determining slope instability. Conversely, in the 10,000 cases generated using the actual frequency distribution of landslide volumes and velocities derived from the analysis of all cataloged landslides in Italy, the susceptibility values are notably different, focusing more on medium and medium-low levels. However, comparing these two synthetic results with real data—i.e., the measured sample of bridges affected by landslides—the situation shifts further. For these real cases, there is a clear peak in the frequency of high susceptibility (66% compared to 32% in the random sample), with a consistently increasing trend as susceptibility levels rise. The fact that the real distribution yields high susceptibility levels aligns with the prevalence of large landslides (39%, of which 98% have extremely low velocity). These scenarios tend to overestimate susceptibility parameters, regardless of velocity levels. Similarly, rapid landslides, typically very small or small in size, also predominantly lead to high or medium-high susceptibility levels. In practical applications of the GLs, there is a risk that the lack of documentation and the presence of dense vegetation may result in “assessment reliability” being set to "limited," increasing the susceptibility class by one level. Additionally, the absence of mitigation measures - often observed in real applications - further contributes to more critical susceptibility classes.

The resulting distribution of landslide-CoA (Figure 1b) shows a frequency peak for medium and medium-high classes across all three cases, with low-level CoAs being residual, unlike high-level CoAs, which range from 4% to 26%. However, there is a notable discrepancy among the three datasets: real bridge-landslide interaction cases show a higher frequency of medium-high levels (Salciarini et al. 2024), as do those from the random sample. Conversely, using the data derived from the actual distribution of landslides across Italy more frequently results in a medium-level CoA. This trend is attributable to the abundance of "large" and "extremely large" landslides in the sample, while statistically, these should be less represented when considering the Italian landslide catalog. This discrepancy may partially result from a documentation bias - the tendency to identify and analyze only landslides of a certain magnitude, as noted by McColl and Cook (2023). At the same time, it is plausible that while smaller landslides are more frequent, only those with high magnitude significantly interact with bridges and viaducts (Gabrieli et al. 2024).

Moreover, inspector evaluations may tend to slightly overestimate risk for safety reasons, leading to even higher final values and potentially undermining the purpose of the multi-level approach and the prioritization of structures requiring urgent intervention. Overly cautious estimates could increase the number of bridges requiring more detailed evaluations, creating challenges in management and economic sustainability.

It is likely necessary to mitigate the evaluation framework by carefully analyzing the parameters contributing to susceptibility, vulnerability, and exposure, to achieve a reliable landslide-CoA.

## 4. Comparison between different landslide scenarios

To deepen the analysis, the CoA was evaluated for two specific scenarios that are the most represented in the sample of bridges affected by landslides: a slow, deep-seated gravitational movement and a rapid small-volume flow. The first type of landslide is primarily characteristic of the Apennine slopes, occurring in cohesive soils. The second type, in contrast, is typical of both Alpine and Apennine environments, with incoherent materials or volcanic matrix and steep slopes.

A large landslide characterized by slow to very slow velocities (“Scenario 1”) was analyzed, fixing the volume parameter within a range of 12 to 15, the highest possible values, while velocity was set between 1 and 2. Subsequently, a second case of a fast-moving landslide with small dimensions (“Scenario 2”) was tested. In this case, velocity was constrained to values between 4 and 5 (maximum values), and volume was set between 3 and 6, relative to the maximum of 15. For both scenarios, the focus was on the susceptibility of the landslide.

These two landslide types were selected because they represent extreme cases that can occur, both of which could disastrously impact the viaduct, as documented in other bridge-landslide interaction cases worldwide (Brooker et al. 1993; Cruden et al. 2012; Lu and Zhang 2012). The resulting CoA distributions for the two scenarios are shown in Figure 2.

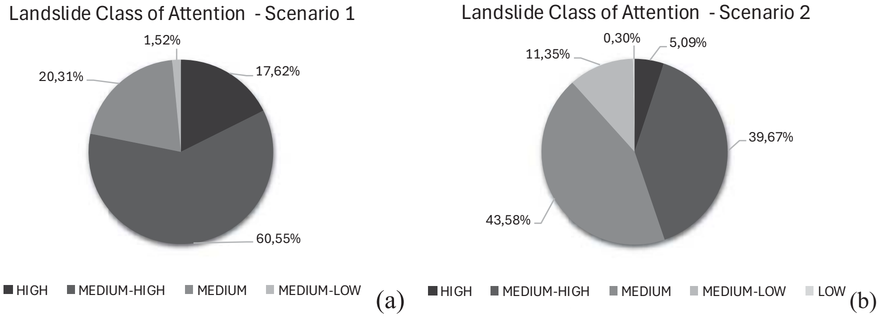

Fig. 2. Distribution of landslide-CoA for (a) Scenario 1 and (b) Scenario 2.

In Scenario 1 (slow landslides with large volumes), the CoA distribution predominantly falls into higher classes. In particular, medium-high and high classes show an increase of nearly 20% compared to simulations with all random values and 45% compared to those obtained using real distributions. This highlights the significant impact of volume in susceptibility calculations. In this scenario, the low class disappears entirely, while the medium-low class is present in only 1.52% of cases. In Scenario 2 (rapid landslides with small volumes), the final distribution is lower than in the previous scenario, with nearly 44% of cases reporting a medium CoA. In this scenario, the lowest class reappears, though at a very reduced percentage (0.30%).

These findings indicate that, according to the GLs, scenarios involving bridges interacting with large, slow-moving landslides are generally more hazardous and urgent than those involving rapid phenomena. While the volume of material involved in the landslide plays a critical role in the interaction with the structure and can cause significant damage, slow velocities generally allow for timely interventions. Conversely, in the case of rapid landslides, such as debris flows or rockfalls, once triggered, there is virtually no time to intervene. High velocities result in significant impact forces, even when associated with smaller volumes, potentially leading to catastrophic outcomes. In both scenarios, monitoring is of paramount importance. For slow-moving landslides, monitoring should primarily focus on the bridge to detect early signs of structural distress. For rapid phenomena, attention should be directed towards the surrounding area to identify precursor signs or predisposing factors that may indicate the potential onset of sudden, high-speed events.

## 5. Conclusions

Italy is characterized by more than 630,000 cataloged landslides (ISPRA, 2024). Special attention must be given to landslides that impact or potentially threaten infrastructure, due to the significant economic and social consequences they may entail. The new GLs for assessing the safety of existing bridges introduce an integrated approach to evaluating structural conditions, including landslide risk assessment. Given their recent implementation and limited application, these guidelines require ongoing review with a critical approach to ensure accurate CoA determination.

This study focused on analyzing two sets of approximately 10,000 synthetic cases of bridge-landslide interaction, generated through the extraction of primary and secondary random parameters, as well as parameters based on the Italian landslide inventory. These were then compared with real cases to identify trends in susceptibility, vulnerability, exposure, and CoA classes. It was observed that the distribution of landslide CoA tends toward medium or medium-high levels, primarily influenced by susceptibility and exposure. To ensure effective prioritization of interventions, the evaluation method must be refined, balancing a precautionary approach with a more detailed analysis of parameter values.

Finally, the analysis of two prevalent landslide scenarios highlighted how slow landslides with large volumes tend to produce more critical CoA levels compared to rapid, small landslides. In both cases, it remains crucial to promptly identify potential landslide hazards and implement a monitoring system capable of anticipating catastrophic events.

**Acknowledgement**

This work was financially supported by FABRE Research Consortium for the evaluation and monitoring of bridges, viaducts, and other structures.

## References

Brooker, E. W., and R. B. Peck (1993). Rational design treatment of slides in overconsolidated clays and clay shales. *Canadian Geotechnical Journal*, *30*(3), 526-544. https://doi.org/10.1139/t93-045

Brunetti, M. T., F. Guzzetti, and M. Rossi (2009). Probability distributions of landslide volumes. *Nonlinear Processes in Geophysics* 16, 179-188. https://doi.org/10.5194/npg-16-179-2009

Cruden, D. M., C. D. Martin, S. Thomson, and B. G. N. Miller (2012). A moderate velocity landslide with immoderate consequences. *Landslides and Engineered Slopes: Protecting Society through Improved Understanding, (ed.) E. Eberhardt, C. Froese, AK Turner, and S. Leroueil*, 355-360.

Farneti, E., N. Cavalagli, M. Costantini, F. Trillo, F. Minati, I. Venanzi, and F. Ubertini (2023). A method for structural monitoring of multispan bridges using satellite InSAR data with uncertainty quantification and its pre-collapse application to the Albiano-Magra Bridge in Italy. *Structural Health Monitoring*, *22*(1), 353-371.

Gabrieli, F., F. Gibin, L. Brezzi, E. Cernuto, A. Lupatelli, D. Salciarini, E. Mammoliti, F. Dezi, S. Stacul, N. Squeglia, A. Doglioni, V. Simeone, and P. Simonini (2024). Lessons from international case studies on bridge-slide interaction problems. *Procedia Structural Integrity*, 62, 506–513. https://doi.org/10.1016/j.prostr.2024.09.072

ISPRA. Inventario dei Fenomeni Franosi in Italia (IFFI). Roma: Istituto Superiore per la Protezione e la Ricerca Ambientale; 2024. In Italian. Available from: https://beta.idrogeo.isprambiente.it/app/iffi

Lu, Y. E., and L. M. Zhang (2012). Analysis of failure of a bridge foundation under rock impact. *Acta Geotechnica*, *7*, 57-68. https://doi.org/10.1007/s11440-011-0156-1

McColl, S. T., and S. J. Cook (2023). A universal size classification system for landslides. *Landslides* 21, 111-120. https://doi.org/10.1007/s10346-023-02131-6

Ministry for Sustainable Infrastructure and Mobility (MIMS), Ministerial decree 204 on 01.07.2022. Guidelines for the classification and management of risk, the safety assessment and the monitoring of existing bridges, Italy. *G.U. Serie Generale n. 196 (2022) 8–23, 2022.*

Salciarini, D., E. Cernuto, G. Capati, F. Dezi, L. Brezzi, F. Gibin, F. Gabrieli, S. Stacul, A. Doglioni, A. Lupattelli, N. Squeglia, V. Simeone, and P. Simonini (2024). Landslide-bridge interaction: Insights from an extensive database of Italian case studies. *International Journal of Disaster Risk Reduction*, *114*, 104983. https://doi.org/10.1016/j.ijdrr.2024.104983