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Understanding Landslide–Bridge Interactions Through a Comprehensive Analysis of a Global Case Study Database

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Abstract: Infrastructures such as bridges and viaducts are exposed to numerous natural hazards that can compromise their safety and stability over time. Among these risks, interactions with landslides can pose significant threats, as landslides can introduce new loads onto the existing structure that were not accounted for in the original design. Landslides exert forces with a significant horizontal component that may impact the supports, piers, or directly on the bridge deck, leading to deformations and, in extreme cases, collapse. This work presents the development of a database containing 41 international case studies on interactions between landslides and bridges or viaducts. These events are classified according to key parameters such as landslide velocity, volume, and the type of interaction with the infrastructure. The analysis of the cases reveals recurring patterns in interaction and damage mechanisms, offering a deeper understanding of the most common conditions under which these interactions occur. The study's findings highlight the importance of implementing preventive strategies and monitoring systems to mitigate the impact of landslides—whether slow-moving or rapid—on these infrastructures. Furthermore, the research underscores the need for more accurate risk assessment tools, considering that climate change may increase the frequency and severity of extreme weather events capable of triggering landslides.

Author keywords: Landslide–bridge interaction; soil–structure interaction; bridge health monitoring; bridge management system; risk assessment

Introduction

Bridges and viaducts are often located in geomorphologically complex areas, where road or railway paths must overcome obstacles such as valleys or rivers. Over their service life, these structures are not only subject to the inevitable progressive degradation of their materials and components but are also exposed to a range of natural hazards, including earthquakes, floods, and landslides. Therefore, it becomes essential to assess the durability of such structures not only based on the properties of their materials but also in relation to their natural surroundings.

Landslides, in particular, can compromise the functionality and stability of a bridge by introducing external quasi-static or dynamic forces that alter the boundary conditions and loads considered during the design phase.[1] These new loads, characterized by a predominant horizontal component, can induce stresses and deformations in the bridge structure and, in some cases, lead to collapse.[2] Landslides are complex and difficult-to-predict phenomena, as they are associated with a combination of factors, including environmental drivers (rainfall, snowmelt, temperature variations, and infiltration processes), geological and geomorphological settings, and the characteristics of the involved soils (low permeability or strength, internal erosion, alteration phenomena, and viscous behavior).[3]

The identification and delineation of landslide-prone areas, as well as risk mapping, have only recently been systematically conducted, particularly due to the widespread availability of increasingly detailed satellite imagery and data. Consequently, in most cases, incipient movements or potential instability conditions for a bridge are unknown before its construction or are underestimated. In the absence of such information, the effects of gravitational phenomena may not become immediately evident even after the bridge

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enters service and may only manifest over time through signals in the surrounding area or directly on the bridge, such as deformations, displacements, or cracking in the structure. It is evident that if these earth or rock movements are very "intense" and/or sudden, or are not adequately monitored and mitigated, they can cause significant damage.[4]

To assess the risk level of a bridge interacting with a landslide, it is necessary to understand its initial condition, the degree of damage, and its degradation rate, as well as consider the possibility of a paroxysmal evolution in response to extreme environmental events.[5,6] To this end, it is essential to evaluate the interaction modes and the factors controlling the phenomenon, as well as possible temporal evolutions, based on the historical record of the bridge–landslide interaction case.[7] In the literature, some studies have focused on individual structures affected by landslides[8,9] and on describing advanced monitoring systems for specific risk assessment.[10] Other studies have considered a series of bridges damaged or collapsed due to earthquakes,[11] typhoons,[12] structural degradation, or hydraulic phenomena.[13] However, to the best of the authors' knowledge, there is currently no database or systematic approach to studying bridge–landslide interaction cases.

To address this gap, a data collection effort has been initiated on case studies of bridges and viaducts that collapsed or were damaged by landslides. The analysis of 41 international cases revealed common patterns in damage mechanisms. By classifying these events and identifying key factors such as landslide velocity, volume, movement direction, and type of interaction with the structure, it was possible to derive considerations and correlations between variables. Analyzing past events and the factors controlling these mechanisms is essential for understanding landslide risk in relation to soil–structure interaction problems and for developing effective monitoring and mitigation strategies.

Database Creation

To identify the most common types of interactions between different types of bridges or viaducts and various landslide phenomena and to understand their mechanisms, a database was created to compile case studies from the international literature. From the preliminary research phase, only 41 cases were deemed adequately documented and therefore considered complete; cases (frequent) where the documentation pertained only to the landslide or only to the structure were excluded, as this would not have allowed proper cataloging of the type of interaction and would not have produced reliable results in subsequent evaluations.

The database was developed using Microsoft Access, which enabled efficient organization of the collected data through forms, with fields containing descriptive, numerical, and categorical information, as well as maps and both terrestrial and satellite images. Six macro-classes of information were identified for each record:

1. Information on the structure's location (e.g., its coordinates in terms of latitude and longitude, the surrounding area's morphology, the type of crossed elements, etc.).
2. Data on the landslide type, the area's geological context, the mechanical parameters characteristic of the lithotypes, the depth, and the slope of the detachment surface.
3. Data on monitoring techniques installed to detect pre- and post-landslide conditions and to record any changes.
4. Data on landslide characteristics, such as area and volume dimensions, movement velocity, and type of movement.
5. Data on the geometric and structural characteristics of the bridge (e.g., length, height, number of piers, type of road it supports, type of structure, year of construction, and history of the structure).
6. Details on the interaction between the structure and the landslide, the observed damage, and any stabilization or bridge maintenance interventions carried out following the landslide event.

For the variables considered most significant in the database analysis, key categories were identified according to the classification outlined in Table 1.

The sources of documentation for bridge–landslide interaction cases were primarily scientific articles and technical reports. These were supplemented with project drawings, photographs, and maps. Additional information was derived from satellite and multi-temporal imagery, as well as newspaper and magazine articles. All this information was used to populate the fields of the database. In cases where data were unavailable or incomplete, the authors and collaborators of the original studies were contacted.

Significant informational gaps emerged in certain areas, such as groundwater conditions (95% of missing data), the mechanical properties of landslide materials (90% of missing data), the types of foundations for each substructure (50%), post-damage or collapse interventions (35%), and the predisposing and triggering factors of the landslide (34%).

Sample Analysis

Volumes, velocities, and types of landslides interacting with bridges

When comparing the analyzed sample with the overall population of landslides in Italy (data from the IFFI Inventory, 2023) and the European landslide database,[14] it emerges that the predominant type of landslide, according to Cruden and Varnes[15] classification, is "slides" (translational and/or rotational). This pattern is also evident in landslide databases that do not necessarily involve bridges (Fig. 1). However, in the sample of landslides interacting with bridges and viaducts, the percentage of slides is significantly higher (71% compared to 47%), while other types of landslides, such as "falls" and "flows," represent only 5% and 10% of cases, respectively (Fig. 1).

Most of the landslides cataloged in the interaction cases with bridges exhibit "very slow" kinematics (44% of cases),

Table 1. Variables considered in the analysis of the bridge–landslide database

Variable	Categories
Bridge typology	• Arch • Continuous girder • Simply supported girder • Other • Unknown
Materials	• Concrete (prestressed and reinforced) • Steel • Masonry • Composite (RC + steel, RC + masonry) • Other • Unknown
Interaction	• Partial (1 pier/multiple piers) • Partial (abutment + one/some piers) • Total • Unknown
Construction time	• $T < 1945$ • $1945 < T < 1980$ • $T > 1980$ • Unknown
Landslide type	• Falls • Flows • Slides • Complex • Unknown
Landslide size	• Small ($>10^2$ m^3) • Medium ($>10^4$ m^3) • Large ($>2.5 \times 10^5$ m^3) • Extremely/very large ($>10^6$ m^3) • Unknown
Landslide velocity	• Extremely slow (<16 mm/year) • Very slow (>16 mm/year) • Slow (>1.6 mm/year) • Rapid (>1.8 m/h) • Extremely/very rapid (>3 m/min) • Unknown
Landslide direction	• Orthogonal • Parallel • Oblique • Unknown
Triggering factor	• Heavy rainfall • Another natural factor • Anthropic action • Combination factor • Unknown
Type of damage	• Loss of functionality/partial collapse • No loss of functionality/monitored • Total collapse • Unknown

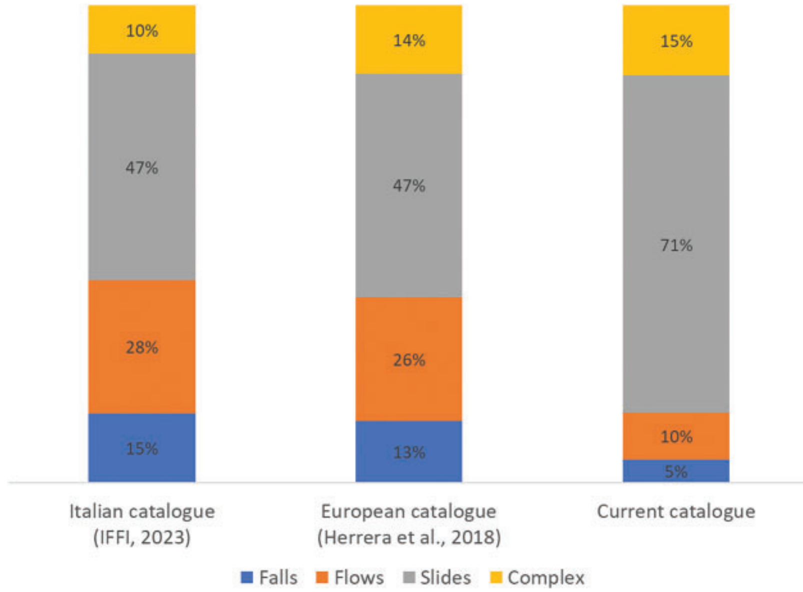


Figure 1. Comparison of the distribution of landslide types in the Italian and European landslide catalogs with the bridge–landslide sample

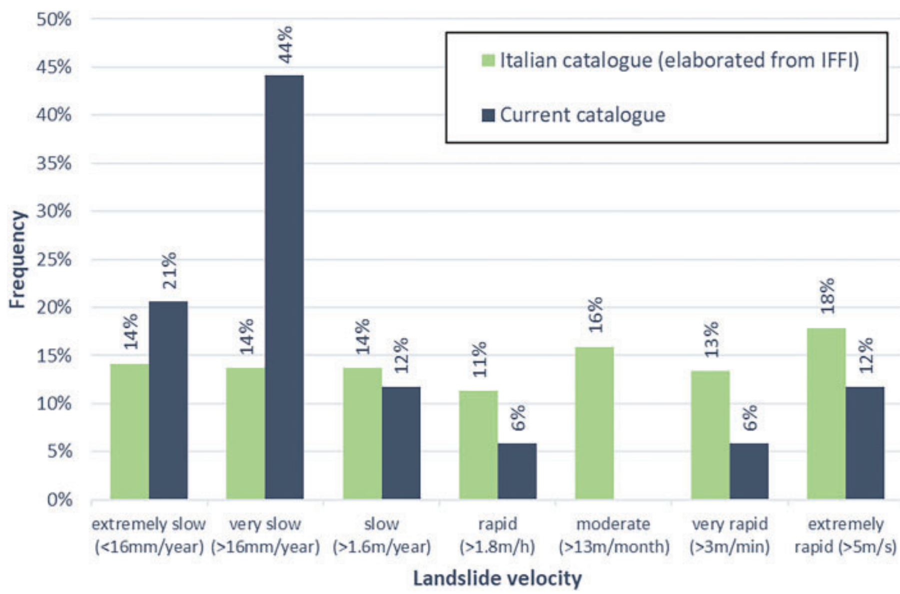


Figure 2. Comparison of estimated landslide velocity distribution from the Italian IFFI landslide catalog with the bridge–landslide sample

consistent with the prevalence of creep and translational and/or rotational sliding mechanisms in cohesive soil matrices (Fig. 2). In general, movement speeds below 1.8 m/h were recorded in 77% of cases. A similar result emerges from data on 86 bridges interacting with landslides in Italy, [16,17] where "very slow" landslides account for 56% of cases. By contrast, when analyzing the Italian IFFI landslide catalog and estimating maximum expected velocities based on landslide types,[18] a more uniform distribution is observed, with each velocity class representing approximately the same proportion of landslides (between 11% and 18%) This discrepancy is likely due to the fact that rapid landslides have a lower probability of interacting with point infrastructure such as bridges. Rapid landslides typically cross valleys transversally, and correctly designed bridges can span these areas without experiencing physical interaction. Conversely, slow-moving landslides can affect both the abutments and piers of a bridge, interacting transversally and/or longitudinally. Moreover, slow landslides are harder to detect due to their low movement speeds, which may cause displacements and deformations on the structure long after its construction.

Regarding landslide volume distribution, landslides interacting with bridges tend to have large volumes (average volume 6.5×10^3 m^3), with a prevalence of "extremely/very large" landslides (>10^6 m^3) and a decreasing frequency for smaller volumes (Fig. 3). This sharply contrasts with

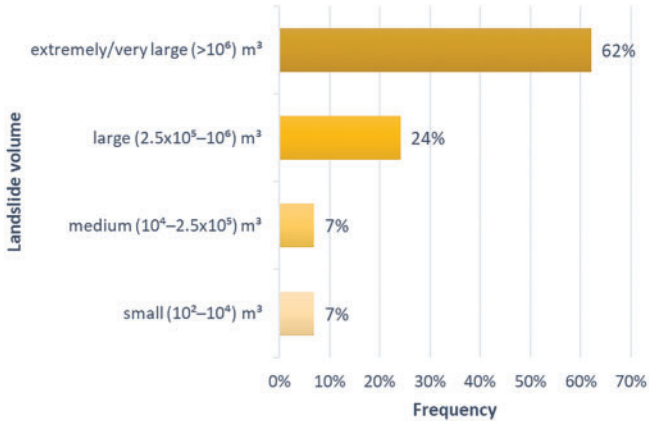


Figure 3. Distribution of landslide volumes in the bridge–landslide database

the probability density distributions of landslide volumes obtained from many other landslide datasets,[19] where smaller landslides are far more common, and larger ones are rarer, following a power-law distribution:

$$f(V) = kV^{-\alpha} \tag{1}$$

where f(V) is the frequency of landslides with volume V, k is a scale- and context-dependent constant, and α is the exponent representing the slope of the distribution.[20] In most studies, α varies between 1.0 and 1.9, with an average of about 1.3, indicating that for each order of magnitude increase in volume, the frequency decreases by 1.3 orders of magnitude.

The opposite trend observed in the distribution of landslide volumes interacting with bridges—where larger landslides are more frequent—suggests that only such large landslides are capable of affecting these structures. Smaller landslides, though more widespread overall, tend not to cause significant damage to critical infrastructure like bridges and viaducts. Additionally, this type of landslide may be underrepresented in the database due to documentation bias: smaller, non-damaging landslides are often undocumented, as noted by McColl and Cook.[21]

Interaction mechanisms

The wide variety of bridge and landslide types results in a vast range of possible interaction scenarios, further amplified by the specific characteristics of each case study. However, the interaction mechanisms can be synthesized into five main categories. For each category, common characteristics can be identified in terms of the bridge elements involved, the type and speed of the landslide, and the evolutionary nature of the phenomenon. A classification that provides a summary, though not entirely exhaustive, of these categories is presented in Table 2.

For each of these mechanisms, the distinctive characteristics will now be detailed, accompanied by the presentation of paradigmatic case studies.

Pressure on bridge abutments

In newly constructed bridges, most horizontal forces (both longitudinal and transverse) are typically accounted for during the design phase and absorbed by specific reinforcements on the abutments and/or mitigated through devices such as expansion joints, sliding supports, and seismic isolators or dampers. However, additional forces caused by the interaction between the structure and a landslide can still occur.

For example, a landslide may overload the bridge abutments with longitudinal pressure, creating unexpected compression stress. This can lead to joint displacements, deck arching, or, in severe cases, the deck sliding out of position and sudden failure. Alternatively, transverse pressure can add a shear component, causing cracks in the abutments and deck, slippage at the supports, and displacement at the joints.[22]

Often, horizontal pressure (longitudinal and/or transverse) is accompanied by settlements, differential settlements, and permanent deformations. Furthermore, under identical conditions, rigid structures and geometries subjected to horizontal loads tend to experience brittle failure without warning, while more deformable structures exhibit ductile behavior, often showing clear warning signs before collapse.[16] Due to the geometry of abutments and decks, which are generally stiffer transversely, transverse pressures are better tolerated than longitudinal ones.

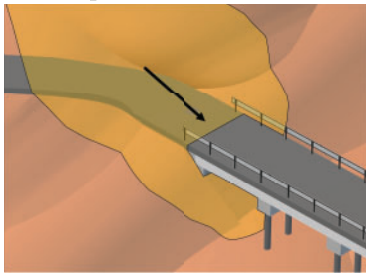
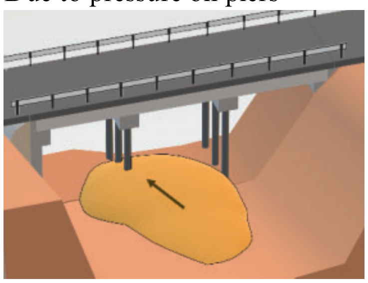
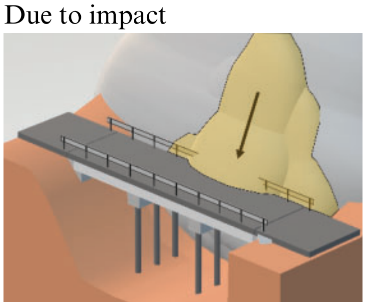
Moreover, in many existing bridges, the abutments—compared to the piers—tend to have shallower or even surface-level foundations. This is due to lower vertical design loads. Older bridge foundations were primarily designed to bear vertical loads, and it is not uncommon to find deep foundations with inadequate or poor reinforcement. Additionally, bridges constructed before seismic design codes were adopted are more susceptible to the effects of bridge–landslide interactions.

One of the most dramatic examples of bridge–landslide interaction due to abutment pressure is the collapse of Viaduct 1 of the Caracas–La Guaira Highway in Venezuela (Fig. 4). This large reinforced concrete arch bridge, completed in 1953, connected the capital to the international airport. It was affected by a major landslide (4.3 Mm^3 volume) that was first observed after an earthquake in 1967 and reactivated by heavy rainfall in 1987. Over time, the landslide exerted significant longitudinal and transverse pressure on the viaduct's abutments, causing abnormal arching of the structure by several tens of centimeters.[23]

Despite attempts to relieve stress by cutting the intrados, adding new joints, and reinforcing the structure with anchors and drainage systems, the bridge collapsed in 2006.[8] Fortunately, the slow movement and specific geometry of the bridge allowed warning signs to be detected, enabling continuous monitoring and the closure of the bridge before its collapse. This case highlights both the challenges of stabilizing very large landslides and the effectiveness of continuous monitoring in reducing the risk of severe damage.

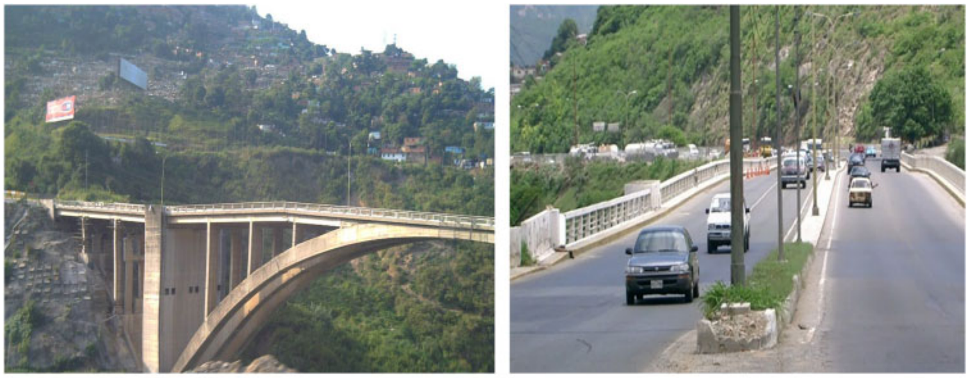
Another significant example, similar in mechanism and speed, is the sudden collapse of the Caprigliola Bridge, also known as the Albiano Magra Bridge,[24,25] in Tuscany,

Table 2. Classification of bridge–landslide interaction mechanisms

Interaction mechanism	Main elements involved	Prevalent landslide type	Prevalent evolutionary nature	Paradigmatic case studies
Due to pressure on abutments 	Abutments and deck	Translational slides, rotational slides, creep, DSGSD, and slow and medium-slow landslides	Progressive or paroxysmal	Caracas–La Guaira Bridge (Venezuela)[8]
Due to pressure on piers 	Piers and deck	Translational slides, rotational slides, creep, DSGSD, and slow and medium-slow landslides	Progressive or paroxysmal	Micheletti Viaduct (Italy)[9]
Due to impact 	Piers, abutments, and deck	Rapid landslides such as debris flows, rockfalls, and collapses	Paroxysmal	Chediguan Bridge (China)
Due to erosion, undercutting, and foundation undermining 	Piers and abutments	Slow landslides and rapid landslides such as mudflows and debris flows	Progressive or paroxysmal	Skjeggestad Bridge (Norway)
Due to actions on anchoring structures	Anchors	Slow and medium-slow landslides	Progressive or paroxysmal	

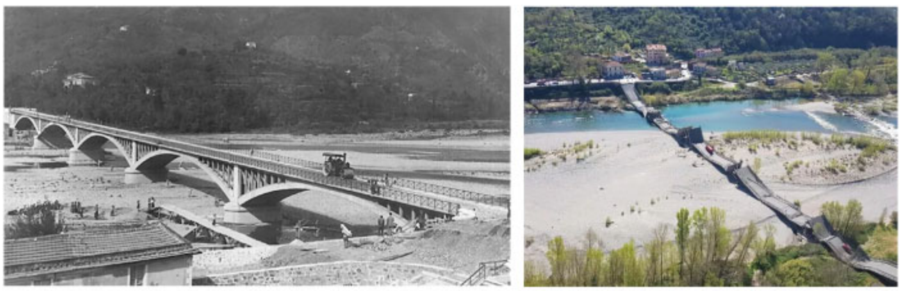
Italy (Fig. 5). This bridge, originally built in 1908 and reconstructed in 1949, collapsed without apparent warning, leaving no opportunity for interventions or traffic closures. Fortunately, the collapse occurred in April 2020 during the COVID-19 lockdown, preventing casualties.

Subsequent analysis of pre-existing InSAR data and other investigations revealed that a slow-moving landslide had been exerting longitudinal pressure on the eastern abutment for some time. In this case, the arching of the deck due to longitudinal pressure was smaller (about 3 cm in 7 years) than in the Caracas–La Guaira Bridge due to differences in bridge geometry and pier-to-deck constraints. This case underscores the challenges of detecting precursor signals,



(a) (b)

Figure 4. Lateral and frontal views of Viaduct 1 of Caracas–La Guaira (Venezuela) before its collapse on March 19, 2006, showing significant deck arching



(a) (b)

Figure 5. Caprigliola Bridge (Italy), (a) under construction and (b) after its collapse on April 8, 2020

especially when ground deformations are minimal and difficult to observe using conventional methods.

Another noteworthy case is the Serra di Lagonegro Viaduct.[26] This arched railway viaduct, inaugurated in 1929, experienced issues from the outset due to the elevation of its first pier by approximately 40 cm in less than 10 years (Fig. 6). This was caused by the sliding of a large limestone block beneath the town of Lagonegro.[27] Deformations eventually became so severe that it was impossible to adjust the track alignment, leading to the bridge's closure.

Figure 6. Current view of the Serra di Lagonegro railway bridge in Italy

Thrust on bridge piers

A landslide can exert pressure on the foundations of bridge piers and, either directly or indirectly, on the piers themselves, causing displacements and/or rotations.[28] Depending on the bridge geometry and the degree of constraint between the foundations and piers or between the vertical elements and the deck, this mechanism can alter the load distribution at supports, create overstresses in the superstructure, and lead to irreversible structural deformations, potentially compromising the bridge's stability. The height of the piers can amplify these effects: small displacements or rotations at the base or in the foundation often result in significant displacements at the pier heads, on the bridge bearings, and consequently on the deck.[9] Unlike thrusts on abutments, pier thrusts, given the same displacement rate, are more easily detectable due to the amplification of effects with height. Piers can tilt either downslope or upslope, depending on the relative depth of the sliding surface with respect to the foundation plane (Fig. 7).

The severity of the thrust depends on the slope inclination, the volume of the unstable mass, the water table height, and the degree of soil saturation. Thanks to the asymmetry of foundation plans, transverse thrusts are generally better tolerated and less frequent than longitudinal ones. Transverse movements of piers are common in hillside bridges, where the maximum slope direction is perpendicular

Figure 7. Examples of downslope pier rotation for the Himera Viaduct, Italy

to the bridge's direction, making it plausible for sliding surfaces to pass beneath the foundation plane. In such cases, deep foundations can enhance structural stability by reducing deformation magnitude and acting as a reinforcement against landslide movement.

A significant example of this type of mechanism is documented in Li County, China, where an ancient landslide affecting a highway bridge was reactivated due to slope reprofiling and intense rainfall (Fig. 8). Inclinometer measurements identified multiple sliding surfaces at depths of 12 and 28 meters, while the bridge experienced settlement rates of 1–2 cm/year vertically and 10 cm/year horizontally.[29]

Another example is the Micheletti Viaduct in Italy, affected by a slow-moving landslide that gradually pushes several piers downslope.[9] The viaduct, located on a hillside, crosses a DSGSD (deep-seated gravitational slope deformation) and smaller secondary landslides with sliding surfaces always beneath the foundation plane. Seven out of 27 piers are experiencing displacements with maximum rates of 4–10 mm/year and upslope rotations, causing the pier heads to move closer to the slope. Despite the ongoing movement, the viaduct has remained operational due to low displacement rates, which allow for precise monitoring and periodic rehabilitation. This case highlights the importance of continuous monitoring and maintenance in managing large landslides with slow but consistent movements over time.

Impact mechanisms

Impact mechanisms can be broadly divided into two categories of landslides: debris or mudflows and rockfalls.

In the case of debris or mudflows, the flow exerts impulsive forces on bridge elements located in the valley bottom, such as piers. If the bridge span is modest or the bridge is low relative to the flow thickness, abutments and decks may also be affected. This type of impact involves dynamic forces, which combine with drag and static forces. The drag force from a debris flow, similar to water flow, is proportional to the flow velocity (up to a critical value), density, and the cross-sectional area of the piers exposed to the current. [30,31]

If the landslide directly impacts the substructure or the bridge deck, it can cause damage, such as cracks or fractures that may even affect load-bearing structures. In extreme cases, it can lead to the sudden partial or total collapse of the structure. Landslides causing this mechanism are classified as rapid or very rapid (>3 m/min).

The second category includes rockfalls and block falls, which may impact both piers and decks. The impact force depends not only on the pre-impact kinetic energy (determined by velocity and mass) but also on the rigidity of the impacting mass and the rigidity of the impacted elements. For the same mass and velocity, a single rock block transmits more energy than loose debris.

Impact mechanisms are particularly insidious as they are typically triggered by highly unpredictable, paroxysmal events often associated with intense and/or persistent rainfall, though sometimes they result from progressive degradation processes that suddenly become rapid and violent. In the case of debris and rock avalanches, they can originate from masses of soil and rock (dry or saturated) located far from the bridge and move at high speeds downhill, sustained by a collisional and turbulent flow regime. Identifying and mapping initial detachment areas is challenging and uncertain, even with appropriate risk maps. Similarly, the runout length and path of these flows depend on numerous unpredictable factors. For rockfalls, uncertainty in trajectory can be partially reduced using statistical approaches.

One example of debris flows impacting bridges is the Minbaklu Bridge[32,33] in Taiwan. In August 2021, heavy rains

Figure 8. Landslide along the Wenchuan-Maerkang highway, Li County, China. (a) Aerial view of June 2020 and (b) April 2023 after reprofiling and stabilization works (courtesy of Kun He, adapted from Du et al.[29])

Figure 9. Minbaklu Bridge during the collapse caused by a mudflow on August 7, 2021

from Typhoon Lupit caused 3 million m^3 of material to detach from Mount Silabaku, reaching the bridge 6 km downstream (Fig. 9). The enormous mudflow reached road level, pushing two bridge spans downstream and causing its collapse. The initial landslide area was not identified before the event, though subsequent studies revealed that seismic signal analysis combined with geological data could have helped identify the detachment niche.[34]

Another significant case is the G213 Taiping Middle Bridge in China, which was impacted by two severe debris flows—one in 2011 and another in 2019—ultimately leading to its total collapse (Fig. 10). The first debris flow, exceeding 500,000 m^3, triggered by exceptional rainfall, caused a 12 cm displacement of the bridge, prompting mitigation measures that proved insufficient when a larger debris flow (600,000 m^3) struck again in 2019. This case underscores the devastating potential of rapid-moving landslides, particularly debris flows, and the limitations of current mitigation measures in addressing high-energy, rapid events.

A slower impact mechanism was documented by Wang et al.:[36] a 2.5 million m^3 landslide that struck five piers of the LX high-speed railway viaduct near Xining in central China in September 2022 (Fig. 11). The most damaged pier rotated downslope and suffered a transverse displacement of about 7 meters. The rotational landslide occurred nearly a month after a rainy period and was attributed to the cyclical wetting and degradation of gypsum rock and mudstone layers.

A rockfall impact mechanism is documented on the Valsugana state highway in Italy, where approximately 100 m^3 of rock detached from a cliff in January 2024 (Fig. 12a). A boulder exceeding 100 tonnes, after breaching protective rockfall nets, bounced onto the railway and struck the road bridge deck laterally, displacing it by about 5 cm from its supports. A similar case, but with a different outcome, involved the Chediguan Bridge in China. In July 2009, following a landslide, a 130-ton boulder struck one of the bridge piers, demolishing it and causing the collapse of the deck (Fig. 12b).[37]

Erosion, undermining, failure, and scour mechanisms at the base of piers and abutments

The flow of watercourses, as well as mud and debris flows, are known to contribute to localized erosion at the base of piers, exposing foundations and increasing the bridge's instability or risk of collapse due to a loss of load-bearing capacity.[13] Additionally, strength degradation in low-quality soils can lead to foundation sliding, even in nearly flat terrains. For example, bridges and viaducts in riparian or lacustrine environments built on highly compressible or expansive clayey soils or on peatlands are particularly vulnerable. Groundwater fluctuations, snowmelt infiltration, and wetting–drying cycles can trigger ion exchanges and chemical alterations that cause early strength degradation.

One such challenging material is quick clay, primarily found in postglacial regions of North America, Scandinavia, and Russia.[38] These clays present significant risks of foundation failure and sliding.[39] Similarly, gypsum and evaporite formations[40] are prone to dissolution, swelling, internal erosion, and karstification upon hydration, posing instability challenges. Other problematic soils include fine sands, poorly consolidated silts, expansive clays, and shale clays. For instance, the wetting, swelling, and alteration of shale clays exposed along major rivers in North America and Canada have caused stability problems in bridges.[41]

In such cases, the presence of shallow or deep foundations anchored into more stable layers, as well as soil reinforcement and stabilization techniques, can be critical to the stability of bridge piers and the overall structure.

An example of such interaction mechanisms is the landslide that caused the partial collapse of the Skjeggestad Bridge in Norway in February 2015 (Fig. 13). The bridge spans a watercourse, with pier foundations embedded in a thick layer of quick clay more than 5 m deep. Despite relatively gentle local slopes and deep foundations, the load

Figure 10. G213 Taiping Middle Bridge (China) after the first debris flow in 2011 and following its complete collapse in 2019[35]

Figure 11. Landslide at the LX high-speed railway viaduct near Xining (China) on September 15, 2022 (courtesy of Ye Chen and Kongming Yan, adapted from Wang et al.[36])

Figure 12. (a) The Pescatore Viaduct in Italy, impacted by falling rock blocks on January 12, 2024. (b) The Chediguan Bridge (China) collapsed following the impact with a boulder (July 25, 2009)

from backfill materials deposited uphill triggered a sliding movement that undermined one pier.[42] After demolishing the bridge's southern carriageway, the reconstruction plan included soil stabilization and new reinforcement measures to ensure the structure's long-term safety.

Mechanisms involving bridge anchoring structures

Beyond damaging the bridge itself, landslides can also impact other load-bearing elements, such as suspension bridge anchors, potentially rendering the infrastructure unusable or causing rapid collapse. This is the case of the Peace River suspension bridge, which was affected by the sliding and detensioning of the north anchorage and finally collapsed in 1957.[41,43] Though less common, these mechanisms are tied to the type and structural configuration of the bridge and remain potentially disastrous.

Figure 13. The Skjeggestad Bridge (Norway), affected by pier sliding on February 2, 2015

Damage to the structure and phenomenon evolution

The evolution of bridge–landslide interaction phenomena can be categorized into two main types: progressive evolution and paroxysmal evolution (Fig. 14). In the first case, the landslide activates gradually, progressively accelerating the curve of the natural degradation process. In the second case, the natural deterioration of the structure is compounded by one or more degradation acceleration events, worsening the bridge's condition and bringing it closer to collapse.[5] These events are usually linked to significant environmental phenomena (e.g., intense rainfall and earthquakes) that trigger the reactivation or new activation of landslide movements.[6] Naturally, intermediate evolutions between these two types also exist.

Progressive events (Fig. 14a) are typically associated with slow-moving landslides in cohesive soils. Damage manifests gradually, initially without evident or dangerous effects on the bridge structure. However, over time, the forces accumulated by the landslide (both horizontal and vertical) may accelerate, particularly when accompanied by material degradation, soil saturation, and creep phenomena. In this context, structural deformation or failure does not occur suddenly but can be detected well in advance through active

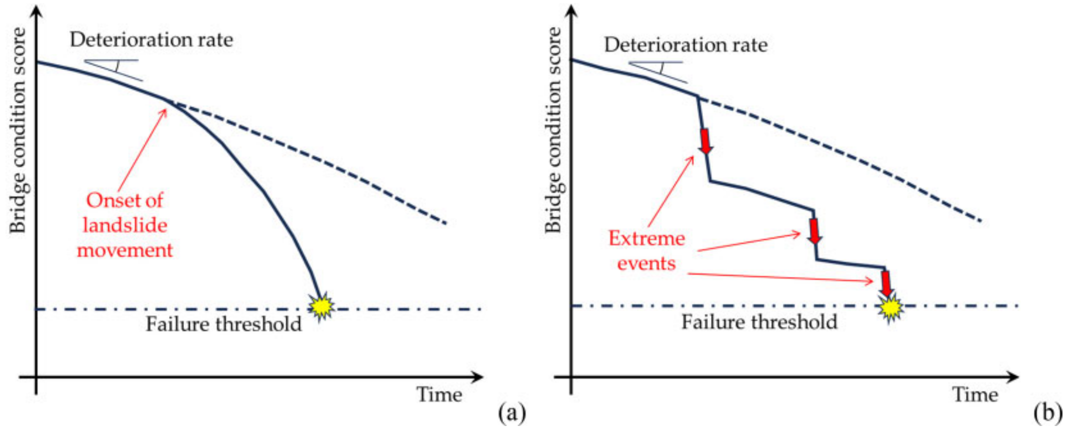


Figure 14. (a) "Progressive" and (b) "Paroxysmal" evolution of bridge degradation over time

monitoring systems, enabling preventive interventions such as reinforcement of foundations or critical bridge elements, particularly when landslides are of modest size.

Paroxysmal events (Fig. 14b), on the other hand, are characterized by rapid and often violent evolution triggered by extreme events such as heavy rainfall, earthquakes, or sudden thermal variations. These landslides are usually associated with less cohesive soils or phenomena such as rockfalls, debris flows, or block falls, which can exert rapid and destructive pressure on the bridge structure. In these cases, bridge degradation occurs abruptly and can lead to partial or total collapse, making preventive action difficult or impossible. Paroxysmal landslides typically exhibit nonlinear behavior, where the increase in damage is exponential relative to time and external stress intensity, leading to catastrophic degradation.

In both cases, triggers or resurgence can result from prolonged or intense rainfall events, though activation in seemingly "dry" conditions—pointing instead to progressive chemical or physical degradation of rocks or soils—is not uncommon. For instance, ongoing degradation of rock formations, particularly when subject to cycles of wetting and drying.

With reference to the level of damage caused by the two types of evolutionary mechanisms (Fig. 15), data on bridges affected by landslides show that total structural collapse is much more likely in paroxysmal events (71% of cases) than in progressive evolution cases (12%), which more often result in limited damage (85%).

This highlights that slow deformation phenomena affecting bridges, while generally causing less severe damage for the same displacement, are more likely to be mitigated through reinforcement, drainage, and continuous monitoring strategies. Reinforcement primarily aims to increase the threshold for incipient instability and is effective in small to medium landslides. Drainage, in addition to increasing material resistance by reducing pore pressures, aims to prevent paroxysmal evolution following extreme events. Monitoring quantifies damage levels over time and estimates the residual risk to the structure using predictive models.[10]

Regarding the combined effect of landslide velocity and mobilized volume, it is noteworthy that a correlation exists

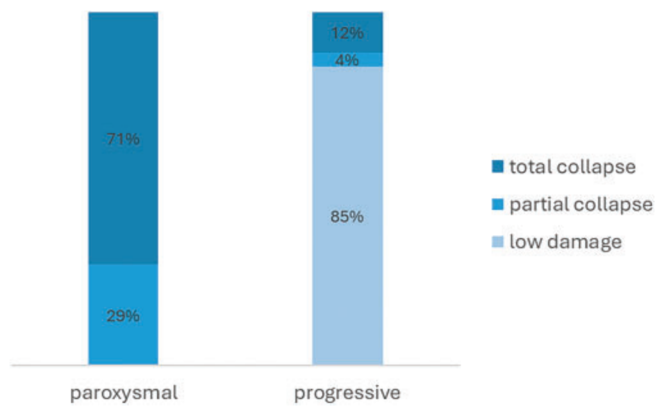


Figure 15. Probability of damage evolution in bridge–landslide interaction mechanisms: paroxysmal vs. progressive

between these factors and observed damage levels, classified as a binary variable (low-damage vs. high-damage) (Fig. 16). Data analysis for bridges affected by landslides shows that landslides with velocities >1.6 m/year and volumes exceeding 10^6 m^3 lead to high damage levels (total structural collapse) in 100% of cases; conversely, slow, small landslides result in damage at most classified as "partial collapse" in 100% of cases.

Rapid landslides of modest volume or slow landslides with significant volumes, however, lead to severe damage in 33% and 21% of cases, respectively. Nonetheless, the greater intrinsic hazard of rapid landslides—due to higher unpredictability—calls for increased attention, as they often lack warning signs and frequently prevent timely corrective interventions, monitoring, or alerting.

In general, these aspects underscore how landslide velocity and volume act synergistically as fundamental variables influencing expected damage levels. With more data available, they can provide a solid basis for developing fragility curves tailored to different types of bridge–landslide interactions.

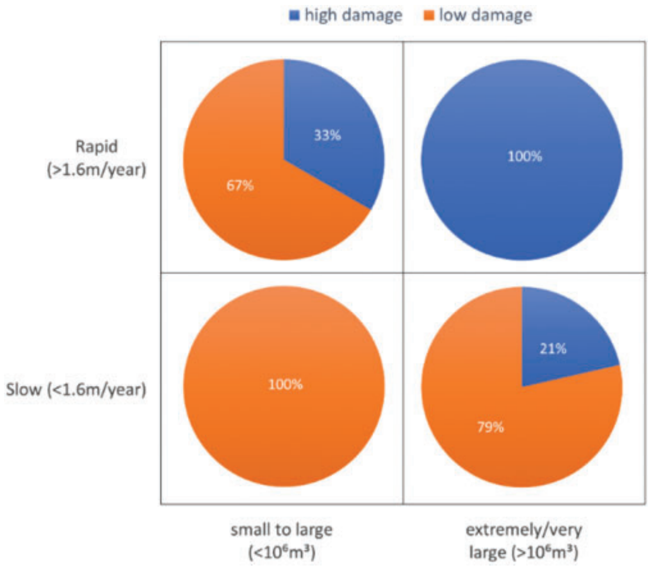


Figure 16. Distribution of damage levels based on landslide volume and velocity for analyzed bridge–landslide cases

Conclusions

Landslides pose a significant natural hazard to the stability of bridges and viaducts, particularly in mountainous areas and specific geological contexts where foundation soils may be particularly poor, or geological and geotechnical conditions are especially conducive to instability. The risk associated with these events is heightened by the difficulty in defining a comprehensive geological and geotechnical model of the phenomenon, encompassing the delineation of the unstable volume, the evolution of the event, and the movements and trajectories of the masses, as well as uncertainties about the timing and triggering mechanisms. These uncertainties also affect the assessment of the forces and deformations that the bridge may be subjected to, complicating the identification of effective solutions.

Existing bridges exposed to landslides must endure external loads with unusual intensity and direction compared to the loads considered during the design phase, which can lead to bridge collapse.

This study developed a database of international case studies on bridge–landslide interactions, serving as a valuable resource for understanding the challenges of managing these events for both existing bridges and new constructions. The database identifies recurring patterns in landslide–structure interactions, providing a foundation for analyzing key factors influencing damage, such as landslide velocity and volume. Four primary types of interactions were identified: forces on piers, forces on abutments, impacts, erosion or scouring, and other mechanisms affecting anchorages.

Analysis of the sample revealed that landslide volume and velocity are critical factors in the evolution of structural damage. Rapid and intense interaction phenomena are the most challenging to predict and are often associated with extreme events. In contrast, slow or medium-slow landslides allow for the implementation of reinforcement, drainage, and monitoring measures to mitigate collapse risks. Precursors of the phenomenon may appear in the structure or the surrounding environment, providing valuable clues for preventive actions. Periodic inspections, including documentation of structural conditions and the surrounding context, are effective strategies to reduce hazard and damage severity. Continuous monitoring, using advanced instruments or remote sensing techniques, also plays a crucial role in prevention. Mapping unstable areas and predicting their evolution are essential for risk assessment.

Finally, while progressive phenomena offer a margin for preventing significant damage, rapid events require early warning systems and emergency response plans. Knowledge of landslide displacement velocities and the geological and environmental context enables a more precise assessment of risk levels and the adoption of appropriate mitigation measures.

This study highlights the importance of proactive mitigation strategies combining advanced monitoring, structural stabilization, and reinforcement. The collection of historical data enhances predictive capabilities, making preventive measures more effective and reducing the likelihood of sudden structural collapses.

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