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Lessons from international case studies on bridge-slide interaction problems

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Abstract

Bridges and viaducts are facing progressive and natural degradation of materials, structural elements, and the of territory in which the works are located. The deterioration is exacerbated by increasingly frequent and abrupt "accelerations", caused by natural hazard events such as landslides and floods, which are intensified by climate change. In particular, landslide events exhibit a range of interaction phenomena, from simple quasi-static forces for slow landslides, to dynamic forces generated by impact events. This research work presents a collection of international case studies of bridge-landslide interactions that have resulted in structure damage or collapse. Relevant variables from these cases were rationalized to allow statistical analysis in aggregate form considering different interaction mechanisms. The results show that the type of landslide, its velocity, volume, elements involved, and direction of movement with respect to the direction of the bridge are some of the main parameters. This approach provides valuable guidance for implementing more refined landslide risk characterization models for bridges.

Keywords: soil-structure interactions; case histories; risk analysis; landslides; bridges.

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1. Introduction

Bridges and viaducts are structures typically located in challenging environments and exposed to different types of risk. In addition to structural and seismic risk, they may encounter natural hydraulic and geotechnical hazards as a result of, for example, flood events or landslides (Wirkijowski & Moon, 2020; Lu et al. 2023). Climate change, and thus the exacerbation and increase in frequency of extreme weather phenomena will drive infrastructures to an acceleration of degradation processes in the near future, with possible consequences on their stability (Crozier, 2010; Deco & Frangpol, 2011).

In particular, as emerges by several cases of collapsed bridges and viaducts, landslide risk represents one of the most insidious risks, both because of its "apparent" unpredictability related to the complexity of variables that determine its triggering and evolution, and because the landslide can sometimes act in a completely hidden manner, without any clear warning signs. Bridges and viaducts, when placed in a landslide context, are generally found to support bearing loads for which they were not designed, thus going into a state of distress. In some cases, depending on the landslide displacement rate, the elements affected by the movement and their stiffness, precursor signs of movement may be visible; in other cases, damage level increasing may lead to the collapse of the structure.

Given these considerations, it appears useful to collect information involving case studies of bridges or viaducts-landslide interaction, to shed light on these particular mechanisms, to classify them, to identify variables involved in risk assessment, and to implement prediction models based on observational data as for other risk types (Karim & Yamazaki, 2003).

In this paper, 41 international cases of bridges and viaducts-landslide interaction were collected, classified and analyzed. Some descriptive statistical analyses allow us to understand which mechanisms are most recurrent and to outline which variables may contribute to raising the level of landslide risk for these works.

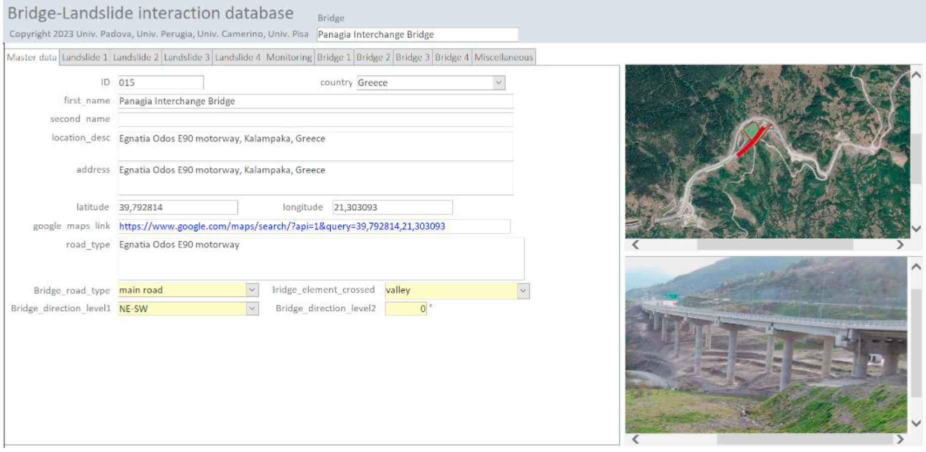
2. Database creation

To identify possible correlations between different types of bridges or viaducts and different landslide phenomena, a database was created to collect worldwide cases of structure-landslide interactions. The literature research resulted in the identification of 41 case studies with sufficiently complete data. It was deemed appropriate not to consider cases with documentation only about the landslide or, vice versa, only about the structure, as this would not yield reliable results in subsequent statistical evaluations.

Microsoft Access was used to create the database, where the collected data could be effectively schematized. Six macro-categories of information were identified:

- Category 1: data concerning all information pertaining to the location of the structure (e.g., its location in terms of latitude and longitude, morphology of the surrounding area, etc…);
- Category 2: data on the type of landslide, geological context of the area, characteristic mechanical parameters of the soil, and depth and slope of the detachment surface;
- Category 3: data including all monitoring techniques installed for the purpose of recording pre- and post-landslide conditions and detecting possible changes;
- Category 4: data concerning all the characteristics of the landslide, its size in terms of area and volume, rates of movement, and type of movement;
- Category 5: data concerning the geometric and structural characteristics of the structure (e.g. length, height, number of piers, type of road passing over it, structural type, year of construction and history of the structure);
- Category 6: data involving structure-landslide interaction, damage reported, and any ground stabilization or bridge maintenance work done as a result of the landslide event.

An illustrative example of the form used for information collection is shown in Figure 1.



Bridge-Landslide interaction database

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Bridge: Panagia Interchange Bridge

ID: 015

country: Greece

first_name: Panagia Interchange Bridge

second_name:

location_desc: Egnatia Odos E90 motorway, Kalampaka, Greece

address: Egnatia Odos E90 motorway, Kalampaka, Greece

latitude: 39,792814

longitude: 21,303093

google_maps_link: https://www.google.com/maps/search/?api=1&query=39,792814,21,303093

road_type: Egnatia Odos E90 motorway

Bridge_road_type: main road

Bridge_element_crossed: valley

Bridge_direction_level1: NE-SW

Bridge_direction_level2: 0 °

Fig. 1. Example of a database mask created with Microsoft Access 365

Documentary sources of the interaction cases (scientific articles, technical reports, project tables, photographs) were collected to fill the database fields. Other information was deduced from satellite, Street View multitemporal images, journal and newspaper articles. Where data were not available or not sufficient, the authors and collaborators of the studies were contacted. In general, significant information gaps were found regarding the water table (95% missing data), mechanical characteristics of landslide soils (90% missing data), substructure and foundations of the structure (50%), interventions carried out after the damage or collapse (35%), and predisposing and triggering factors of the landslide (34%).

3. Database description

The prevalent landslide type in this sample, according to the classification of Cruden and Varnes (1996), is “Slides” (translational or rotational), which is also the most common in many other landslide databases (Fig. 2a). For example, comparing the current sample with the entire population of landslides on the Italian territory (taken from the Italian Landslide Inventory IFFI, 2023) and with the European database (Herrera et al., 2018), it reveals that the “Slides” type is always the prevalent one. However, in the sample of landslides impacting bridges and viaducts, this percentage far exceeds that of the “Falls” and “Flows” landslide types (85% vs. 12%) (Fig. 2b). Most of the landslides catalogued in the sample of landslide-bridge cases are characterized by slow and very slow kinematics, compatible with translational and rotational sliding mechanisms, with landslide velocities less than 1.8m/h for 59% of the cases (Fig. 3a).

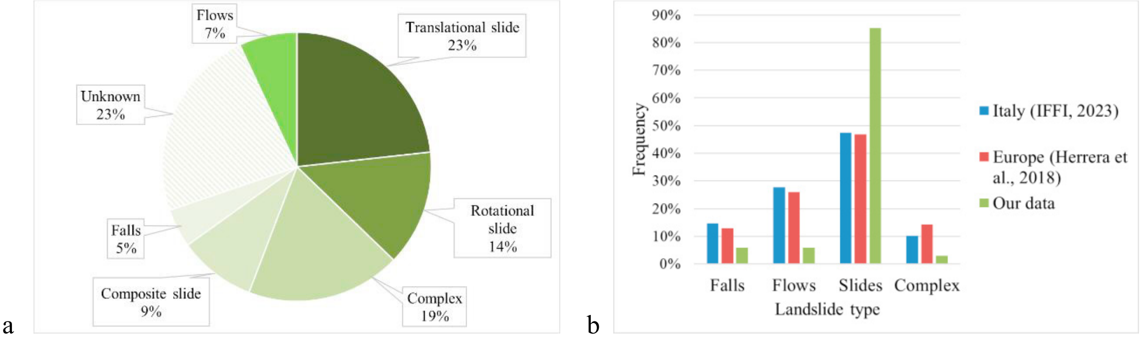

Fig. 2. (a) Distribution of landslide types for the sample of landslide bridges and (b) comparison with the landslide population on the Italian territory according to the landslide Italian inventory IFFI (2023) and European inventory (Herrera et al. 2018).

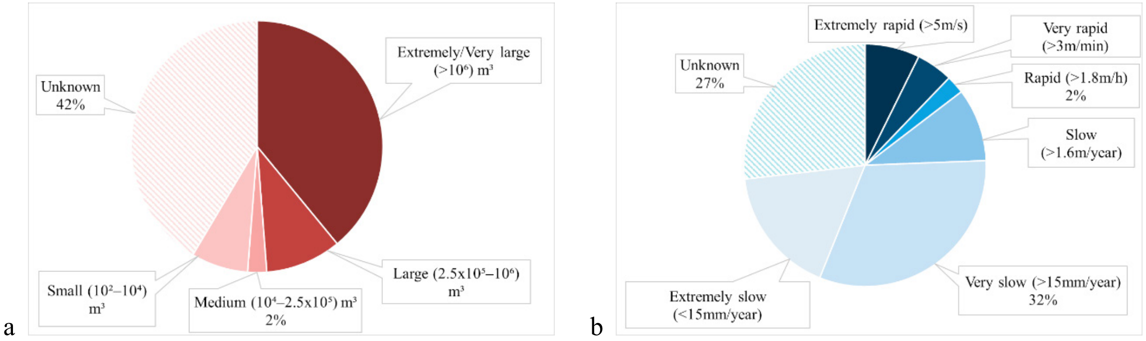

Fig. 3. (a) Distribution of landslide velocities and (b) landslide volumes for the inventory of landslide-bridge cases.

At the same time, the landslides examined in this database exhibit a large volume: 49% have a volume greater than $2.5\text{x}10^5$ m^3 (i.e., from *large* to *extremely large*) (Fig. 3b). The volume of these landslides is larger than the masses mobilized generally by erosional phenomena on earth and rock slopes. As an example, a comparison of the landslide volume distributions for the current sample and those for a large sample of landslides from erosional processes on soil and rock (4231 landslides) documented by Larsen et al. (2010) is shown in Figure 4. Landslides that interact with bridges are found to have a volume compatible with rock landslides. Approximately calculating the mean thickness of landslide masses as the ratio of volume to area (i.e., assuming prismatic landslide volumes) yields a median value greater than 10m.

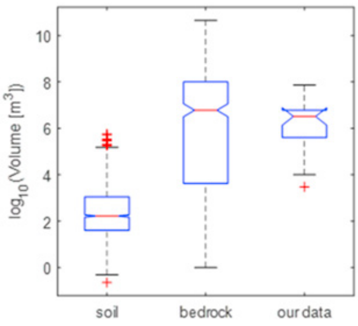

Fig. 4. Distribution of landslide volumes for the sample of landslide-bridge cases (our data), and for the population of landslides with earthy (soil) and rocky (bedrock) matrix collected by Larsen et al. (2010).

The prevalence of large-to-extremely large landslides in our sample may be partly due to a documentation bias (i.e., the tendency to report only case histories of landslides of a certain magnitude) as observed by McColl & Cook (2023) on a wide literature sample of landslides. Simultaneously, it is conceivable that mainly landslides of a specific magnitude, and consequently a certain depth, are capable of causing damage to bridges and viaducts, given their typically deep and well-immersed foundations. Thus, landslide volume emerges as a discriminating variable influencing the risk to bridge and viaduct stability.

4. Mechanisms of interaction

Landslide-bridge or viaduct interaction mechanisms can be classified according to the type of instability (thrust, impact, undercutting, erosion), the direction of the landslide with respect to the direction of the bridge (longitudinal, transverse, oblique), the elements involved (abutment, piers, deck), and then the level of interaction with the bridge (partial or total).

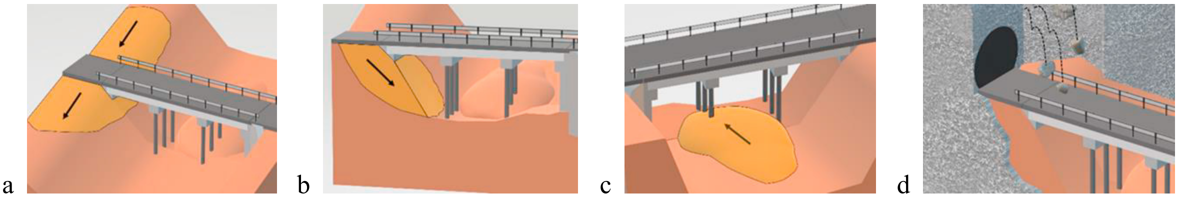

Fig. 5. Schematic diagram of some of the most frequent structure-landslide interaction mechanisms: (a) abutment sliding with longitudinal and (b) transverse thrust with respect to the direction of the structure; (c) transverse impact of a flow on the piers (d) rock collapse on the structure deck.

Some simplified sketches of possible interaction mechanisms are shown in Figure 5. These certainly do not cover all the cases that might occur but represent the most frequent ones in the sample analyzed.

Grouping the landslide types into the two categories of "slide-type landslides" (typically with medium/slow kinematics), and "flow or collapse-type landslides" (typically with fast kinematics, and with impact interaction), it can be seen that the latter are generally underrepresented in the sample (14%). Notably, these landslides predominantly exhibit an interaction direction exclusively orthogonal to the bridge orientation (Fig. 6a). Examples include debris flows at the valley bottom impacting the substructure (i.e., piers), potentially accumulating volumes to reach the intrados height in certain cases (Li et al., 2021). Another instance is rock falls where the rolling and bouncing of boulders at higher elevations directly impact the deck and/or other bridge elements, causing damage or collapse. Conversely, slip-type landslides predominantly exert medium-slow interaction with longitudinal (i.e., parallel to the structure direction) (55% of cases) or transverse direction (i.e., orthogonal) (31% of cases) through the abutments (Fig. 6a).

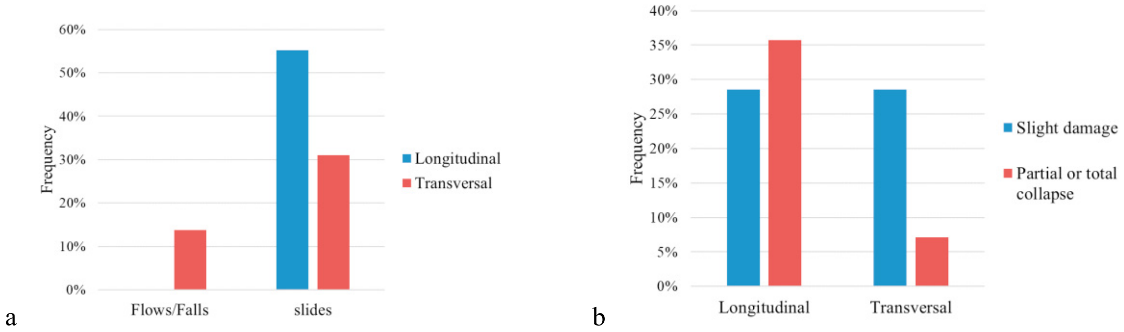

Fig. 6. Frequency distribution of (a) direction of interaction grouped by landslide types; (b) damage level on the bridge with the direction of landslide thrust for landslides of type "slides" affecting the abutment.

4.1. Mechanisms affecting the bridge abutments

Regarding the analyzed sample, a prevalence of longitudinal thrust mechanisms impacting the structure can be observed affecting the abutments (Fig. 6b), which then transmit the load in turn to the deck. In some cases, if the sliding surfaces are very deep or, for particular types of structures (e.g., continuous girder), the first piers of the structure may also be affected by the thrust movement.

Longitudinal thrust mechanisms appear to be the heaviest in terms of the damage they induce on the bridge compared to orthogonal thrust mechanisms: 35.7% of these led the bridge or viaduct to partial or total collapse compared to 7.1% of transverse thrusts (Fig. 6b). Longitudinal thrusts are insidious because they produce an abnormal increase in normal stresses on deck elements that are instead designed to bear vertical loads. This can produce a kind of buckling mechanism with redistribution of shear stresses and moments or, in some cases, brittle failure of the structure. Some types of bridges, such as arch bridges amplify this kind of mechanism with the arch being able to flex and arch upward by as much as several tens of centimeters. This is the case, for example, of the Caracas-La Guaira concrete arch viaduct that connects Venezuela's capital to the international airport. In 1987, following a period of heavy rainfall, a large paleo-landslide tectonically driven reactivated on the southern side of the viaduct, involving the abutment and piers on the same slope. The bridge arched vertically by several tens of centimetres, and reinforcement work on the slope and joint detensioning could not avert its collapse, which occurred on March 19, 2006 (Fig. 7a). Instead, in the case of the Albiano Magra bridge in Tuscany (Italy) there was a brittle failure of the bridge (Fig. 7b) with no apparent warning signs. Based on the geomorphological survey supported by few satellite data the working group of the Italian Ministry of Infrastructures reconstructed the failure was due to a slow landslide that was pushing the abutment and produced the total collapse of the bridge in 2020. Later, through a detailed satellite interferometric observation was it possible to give a scientifically based ascertain of the existence of the deformation of the abutment (Farneti et al. 2023). Another case is that of the Yangdpo bridge in China, a single-span masonry arch bridge of 32 m length involved by a large landslide phenomenon in 2019 that affected the abutment and produced the collapse of the bridge (Fig. 7c) (Wang et al. 2020). In this case, premonitory signs were visible in the deformations and fractures on the abutment.

In contrast, transverse thrusts are better tolerated probably because the structure typically has good transverse stiffness and the bearings admit displacements in the orthogonal direction better compared to the longitudinal direction.

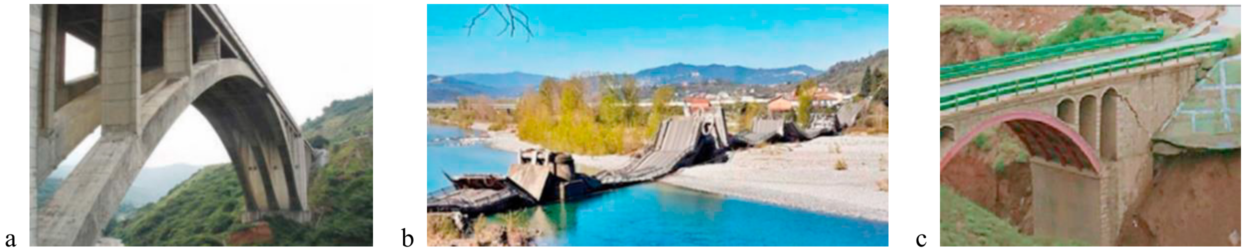

Fig. 7. Examples of collapsed bridges due to longitudinal thrust on the abutment: (a) Caracas- La Guaira arch viaduct; (b) Albiano Magra bridge; (c) Yangpo bridge.

4.2. Mechanisms affecting the piers

In such scenarios, the landslide acts mainly through transverse movements that may affect one or more piers. Piers, being typically rigid and slender elements, naturally amplify small movements and rotations that come from ground displacement at the base or through the foundations. The literature documented cases of bridges that experienced transverse translations of the piers of a few meters (Lo Iacono et al. 2017), as well as rotations with a tendency to overturn both downstream and upstream (Pedrotti et al. 2011).

The Himera Bridge in Italy, for example, was damaged on April 10, 2015, with tilting and translation of 4 piers (6 spans were demolished) due to a rainfall-induced shallow rotational slip (Fig. 8a) (Moretto et al. 2018). Another case is the Micheletti highway viaduct, also in Italy, affected by a deep-seated gravitational slope deformation that slowly pushes seven viaduct piers downstream (Fig. 8b). The structure, in this case, is able to tolerate the extremely low displacement rates of this landslide, provided that periodic structural rehabilitation measures are taken (Pedrotti et al. 2011).

The transverse mechanism involving piers can also have an abrupt and catastrophic course when they are affected by the impact of mudflows or debris flows passing through the valley bottom. In this case, the dynamic thrust exerted by the impact of the flow is added to the steady-state drag forces (Artoni et al., 2019), determining shear stresses and moments on the piers and foundations that can exceed the lateral resistance of the latter. This effect is also compounded by the erosive power of these hyper-concentrated flows that usually result in a scouring effect downstream of the piers. Unlike slow landslides, for which damage on the bridge becomes clear gradually and usually allows restoration and/or mitigation activity, the precursor signals of these rapid landslides are limited and difficult to recognize. They derive mainly from observation of soil deposits in the valley bottom (i.e., past flows), and from observation, at different scales, of the surrounding area (e.g., flow events in neighbouring valleys or upstream and downstream of the structure under consideration) (Hervas, 2003).

An example of this type of rapid landslide is that of the G213 Taiping Middle Bridge. In 2011, a debris flow led to a transverse displacement of the bridge by 12 cm; mitigation measures were then put in place, but these proved insufficient to contain the flow, which in 2019 invested the bridge and caused its total collapse (Li et al. 2021).

Fig. 8. Examples of bridges affected by transverse mechanisms on piers: (a) Himera viaduct; (b) Micheletti viaduct; and rockfalls (c) G213 Taiping Middle bridge.

4.3. Mechanisms of falls

A concluding category of interaction mechanisms is that of rock or earthfalls. They especially involve hillside bridges and viaducts running close to the slope, and following its profile at a constant elevation. The presence of rocky or steeply sloping walls results in the exposure of detachment and collapse of material ranging from erratic blocks to debris that can reach the deck or other elements of the bridge after rolling and bouncing off the ground. While far less frequent than “Slides” and “Flows” landslide types, they can lead to damage or partial destruction of the structure as in the case of the viaduct of Interstate 70 (USA). Since 2003, two major rockfall events and three minor events have caused significant damage to the roadway. Specifically, there has been widespread damage to the roadway surface due to rock impact causing craters 2 to 5 meters in diameter and various damages, leading to a loss of functionality of the structure itself (Fig. 8c) (Arndt & Ortiz, 2012).

5. Conclusions

Landslides and more generally gravitational deformations pose a really relevant risk to bridges and viaducts that are subjected to external loads with unusual and unexpected direction and intensity compared to the loads for which they were designed. The thrusts that landslides induce on these structures, whether quasi-static or impulsive, can be really greater than vertical loads or those due to an earthquake. In this context, they can cause a distressed state on the bridge elements with a loss of functionality or lead to the collapse of the bridge.

Analysis of the international database shows that, in most cases, precursor signs (cracking, deformations, settlements, dislocation) become apparent, which through a strict protocol of periodic inspections and monitoring allows to anticipate far more serious events. On one hand, for slow landslides, a higher level of risk emerges for those having a longitudinal direction of thrust relative to the direction of the bridge, even if precursor signs may be not easy to interpret. In the case of rapid landslides, on the other hand, the risk is determined by the velocity and unpredictability of the event: the assessment of the area of detachment, susceptibility to triggering, and runout lengths are of complex determination and still the subject of much research. Further considerations may come from correlation analysis between variables and the collection of new comprehensive case studies through inspection activities on bridges and viaducts.

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