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Effects of slope movements on bridges

Luca Comegna
Department of Engineering, University of Campania Luigi Vanvitelli, Aversa, Italy, luca.comegna@unicampania.it

Roberto Vassallo
Department of Engineering, University of Basilicata, Potenza, Italy

Gianfranco Urciuoli
Department of Civil, Building and Environmental Engineering, University of Naples Federico II, Naples, Italy

Luciano Picarelli
CMCC Foundation, Euro-Mediterranean Centre on Climate Change, Caserta, Italy

ABSTRACT: The scientific and technical literature reports some documented cases of bridges that have been severely damaged or have gradually lost their serviceability as a result of slope movements. The development and extent of the damage of course depend on the features of both landslide (e.g. type, size, direction of movement, displacement rate) and bridge (e.g. structural type, size, support conditions, foundations type, etc.). This paper reports a short review of data that have been published in the international literature, focusing on some factors that affect the damage.

KEYWORDS: Landslide, bridge, interaction, damage.

1. INTRODUCTION

The interaction between slope movements and the infrastructure (roads and railways, tunnels, bridges, pipelines, water and sewerage systems, power grid etc.) is a key issue. It is in particular a heavy problem for Italy that is the European country with the highest concentration of landslides, but it concerns many other regions of the world, especially in Asia and in Central and South America where landslides are widespread. In spite of that, it is surprising to notice that the room that the scientific and technical literature devotes to this problem is very limited.

The landslide-bridge interaction and, in particular, the mechanical response of bridges to slope movements is a complex topic since the development and extent of the damage depends on a number of factors concerning the features of both landslide (e.g. type, size, direction of movement, displacement rate) and artefact (e.g. material and structural type, size, support conditions, foundations type, etc.). The aim of this paper is dealing with this problem, focusing on the effects of slow slope movements.

2. LANDSLIDE TYPES AND MAGNITUDE

Slope movements display variable morphological features, style and magnitude, and this has required the development of adequate classification criteria to rationally frame the phenomena at hand. Naturally, the risk, and thus the criteria to adopt for its mitigation, depend on event magnitude, which in turn depends by both volume and velocity of the moving mass.

Based on the updated Varnes classification of landslides (Hungr et al. 2014), six distinct classes of landslides may be recognized, i.e. fall, toppling, slide, flow, spread and slope deformation. These, in turn, may be classified into several sub-classes. The fundamental movement styles are fall, toppling, slide and flow, which correspond to the landslide classes with the same name. Looking at the two remaining classes, spreads may display either a slide or a flow style depending on material and failure mechanism, whereas slope deformation phenomena, which often present a large size and a very low displacement rate, may display variable and sometimes complex mechanisms, which however have to be generally referred to the four styles described above.

The landslide size may cover an extremely wide range of values, between tens and tens of millions of cubic meters. The velocity too is highly variable, from mm/year to tens of m/sec (Fig. 1). These values of course imply a great variability of event magnitude that in this paper is referred to the mass momentum (see also Corominas et al. 2014), i.e. to the product of mass times velocity, which has obvious implications on the impact on exposed goods. Generally, the movements that are characterized by velocities lower than 13 m/month are referred to as slow landslides (Cruden & Varnes 1996). These phenomena, which typically belong to the slide, earthflow (a sub-class of flows), spread and slope deformation classes, are subtle events since they may lead to a slow and hidden worsening of the state of stress in the involved structures that is sometimes is recognized too late. On the other hand, when managing slow landslides, engineers have to carefully establish the best approach to the problem, which not always requires important stabilization measures since turning to careful ordinary maintenance works is sometimes an adequate and cheap choice. A list of documented examples on the interaction between slow landslides and bridges is presented in the next section.

3. DOCUMENTED CASE HISTORIES OF BRIDGES DAMAGED BY SLOW SLOPE MOVEMENTS

Table 1 lists a number of published cases histories about the effects of the interaction between slow slope movements and bridges (Gabrieli et al. 2024; Comegna et al. 2025). The table indicates whether the damage extent was limited or if the event made the bridge go out of service. The most interesting or better documented cases are briefly described below.

3.1 Bridges subject to limited damage

Tombolato et al. (2011) present the case of the Micheletti bridge located 10 km far from the city of Bolzano, northern Italy. The bridge is 250 m long and is supported by eight 35 m high piers based on shallow foundations. The entire area crossed by the bridge was subjected to an extremely slow translational slide in alluvial and glacial soils moving with a displacement rate ranging between 7 and 10 mm/year in the direction normal to the artefact. Two sliding surfaces were recognized through

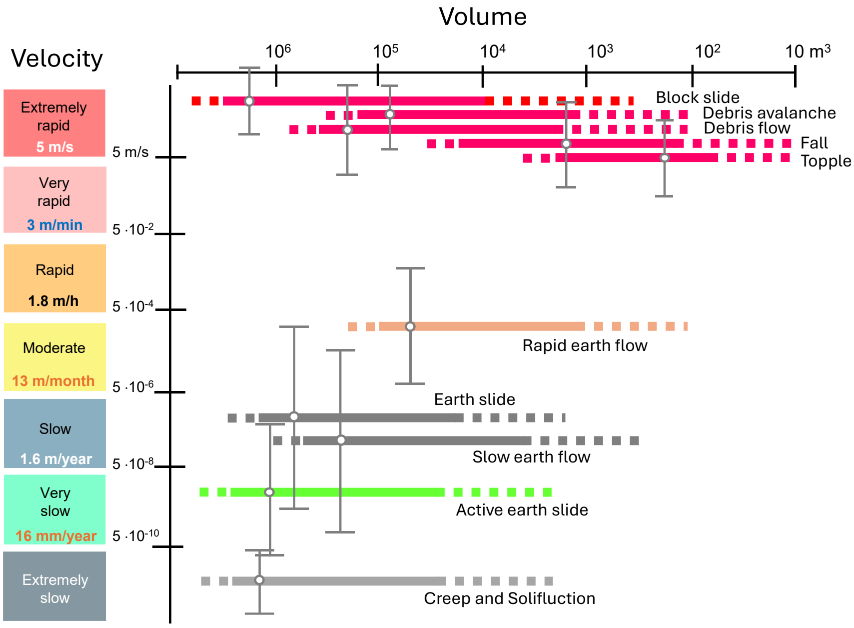

Figure 1. Landslide class velocity (Cruden & Varnes 1996) and corresponding usually involved volumes (Highland & Bobrowsky 2004).

Table 1. Cases of bridges damaged by slow landslides.

Case	Reference	Bridge typology	Landslide direction	Landslide velocity	Landslide volume [m^3]	z/f	Bridge out of service
1 - S.Vito (Italy)	Cestelli Guidi & Priolo (1958)	concrete arch	O	10 mm/month	-	> 1	No
2 - Iron bridge (UK)	Carson & Fisher (1991)	concrete/iron arch	P	3 mm/year	-	-	Yes
3 - Bismark (USA)	Brooker & Peck (1993)	concrete/iron/ stone girder	P	100 mm/year	-	0.8	No
4 - Smith (Canada)	Brooker & Peck (1993)	concrete/iron girder	O	100 mm/year	-	> 1	No
5 - Pozzillo II (Italy)	Picarelli & Napoli (2003)	prestressed concrete girder	O	70 cm/hour	$9{\cdot}10^5$	-	Yes
6 - Sugock (Korea)	Kang et al. (2000)	girder	P	210 mm/year	-	2	No
7 - Ingotte (Italy)	Picarelli & Napoli (2003)	prestressed concrete girder	O	20 mm/month	$9{\cdot}10^5$	-	Yes
8 - Little Smoky River (Canada)	Mansour (2009)	concrete/iron girder	O	103 mm/year	-	≈ 1	No
9 - Caracas-La Guaira (Venezuela)	Salcedo (2009)	prestressed concrete arch	P	40 mm/month	$4{\cdot}10^6$	1.7	Yes
10 - Micheletti (Italy)	Tombolato et al. (2011)	prestressed concrete girder	O	9 mm/year	-	≈ 1	No
11 - Sloboda (Serbia)	Vasic et al. (2015)	concrete/iron cable-stayed	P	6 mm/year	-	1.1	No
12 – Peace River (Canada)	Cruden et al. (2012)	iron	P	1.6 m/year	-	1.7	Yes
13 - Alcoy (Spain)	Pastor et al. (2019)	prestressed concrete girder	O	20 mm/month	-	1.4	Yes
14 - Charmaix (France)	Mazaré et al. (2020)	prestressed concrete girder	O	9 mm/year	-	≈ 1	Yes
15 - Himera (Italy)	Moretto et al. (2021)	concrete girder	O	9 mm/month	$2{\cdot}10^6$	≈ 1	Yes
16 - Albiano-Magra (Italy)	Farneti et al. (2022)	concrete arch	P	3 mm/year	-	< 1	Yes
17 - Ginosa (Italy)	D'Ambrosio et al. (2023)	masonry arch	O	6 mm/year	-	> 1	No
18 - Egnatia (Greece)	Mantakas et al. (2023)	concrete girder	O	5 mm/month	-	0.3	No
19 - Bavera (Italy)	Barla et al. (2024)	concrete girder	P	35 mm/year	$1{\cdot}10^6$	≈ 1	Yes
20 - S. Marco dei Cavoti (Italy)	Liguori (2024)	concrete girder	P	25 mm/year	$2{\cdot}10^5$	0.2	Yes

O: orthogonal to the bridge's axis; P: parallel to the bridge's axis; z: mean landslide thickness; f: mean depth of the foundation.

inclinometer readings, the deepest one being located 3-4 m below the foundations.

Mantakas et al. (2023) describe the case of a reinforced concrete highway girder bridge. The structure consists of T-beams resting on elastomeric rubber-metal bearings that assure good resistance to seismic actions. The bridge is composed of two carriageways, each of which featuring spans with a maximum length of 37.5 meters supported by 7 piers up to 25 meters high. The piers rest on 20 to 32 m deep foundations. These consist of piles having a diameter of 1.2 meters, as well as of solid caissons with diameters between 5 and 7 meters. Around the perimeter of the caissons were built 20 additional piles with a diameter of 0.8 meters. The construction of the caissons was required for 6 piers (3 per carriageway) in order to withstand the actions of a translational slide in silty sands that moves transversely to the structure with an average velocity of 5 mm/month intersecting the foundations at approximately one-third of their depth.

D'Ambrosio et al. (2023) document the damage of a masonry arch bridge built in 1947 in the municipality of Ginosa (southern Italy), as a replacement for another bridge that had been severely damaged by a slow earthflow moving normally to the bridge's axis. As a result, an abutment was tilted leading to formation of a crack in one of the arch piers. This forced the local administration to impose traffic restrictions. The subsequent development of new cracks and fissures has frequently required the repair or the replacement of the road surface.

3.2 Bridges gone out of service

Picarelli & Napoli (2003) describe the case history of the Pozzillo II viaduct that overcomes the Biferno river, not far from the town of Campobasso (central Italy), which in 1996 was broken down by an earthflow. The landslide length was about 1.4 km and its depth in the accumulation zone about 20 m. Triggered by rainfall, the landslide led the viaduct to collapse dragging in a night its beams about 100 m downslope. The main stabilization works consisted in a reshaping of the crown (the main source of the earthflow) and in the construction of two rows of anchored structural pits respectively located at the lowermost boundary of the alimentation zone and at the toe of the moving mass; the 30 m deep pits located at the toe were equipped with long drainage pipes. These works allowed the reconstruction of the viaduct on the other side of the river. The same paper mentions also the Ingotte viaduct, a few kilometres far, which was gradually brought out of service by a slow earthflow (mean velocity equal to 20 mm/month), which caused some tilting of the piers. That bridge too was reconstructed in the following (see Section 3.2.1).

Salcedo (2009) describes the collapse of an arch bridge connecting the towns of Caracas and La Guaira in Venezuela. In 1987, the bridge showed a first moderate damage induced by a large (about 4 Mm^3) translational slide in colluvial deposits, active since 1967, which caused the tilting of one of the two abutments. In spite of the setting of a number of anchorages across the sliding surface, the bridge collapsed in 2006.

Another highway infrastructure affected by landsliding is the Himera viaduct built in 1975 along the A19 Palermo–Catania motorway (Sicily, southern Italy), in a complex and highly tectonized geological context (Castelli et al. 2017). In 2015 the structure, consisting of a reinforced concrete girder bridge, was seriously damaged by a shallow rotational slide in clayey deposits directed normally to it. The landslide, characterized by an average movement rate of 9 mm/month, a length of approximately 800 meters, a maximum width of 200 meters and a volume of about 1.5 Mm^3, caused the rotation of three piers on the carriageway toward Catania and the collision with the adjacent viaduct in the direction of Palermo. Immediately after the event, ANAS S.p.A., the managing authority of the motorway, ordered the precautionary closure of the viaduct. Later on, based on careful investigations, it was decided to demolish the damaged portion of the artefact towards Catania, which was replaced with a new steel viaduct consisting of three long spans. The central span, 130 m long, was designed to overpass the area affected by the landslide.

Another well-documented case history concerning a bridge built in 2004, not far from the town of Alcoy (southern Spain), is illustrated by Pastor et al. (2019). The bridge consists of four pre-stressed concrete spans covering a total length of 80 m. The supports of the artefact rest on a pile cap. The bridge was subject to a rotational slide with a maximum depth of 22 m and an average displacement rate of 20 mm/month. Due to landslide depth, the downslope displacements were comparable to those of the moving mass leading to significant structural damages that were evident about 7 years after landslide triggering. Drainage pipes and trenches and a wall of anchored piles to protect the foundations were then built favouring landslide stabilization.

Barla et al. (2024) discuss the case of the Bavera bridge, built in 1978, which connects the towns of Monesi di Triora and Piaggia (northern Italy). The viaduct, which has a length of 66 m, rests on thin wall piers hinged to both foundations and deck. Due to different local ground conditions, the side towards Monesi required shaft foundations built on an up to 40 m thick sandy-silty debris deposit lying over a flysch formation, while the other one was built on the bedrock. Since construction, a slide moving at a rate of about 35 mm/year, caused a progressive tilting of the piers on the Monesi side. Due to severe structural damages, the bridge was deemed unsafe and closed to traffic in 2017. Partial retrofitting works carried out between 2018 and 2019 included a replacement of expansion joints, a full release of the deck from the bearings, and the reinforcement of the Piaggia-side abutment.

Liguori (2024) describes the collapse induced by a shallow rotational slide in clay (average velocity of 25 mm/year) of a reinforced concrete girder viaduct located in the village of San Marco dei Cavoti (southern Italy), an area that is affected by deep-seated gravitational slope deformations (Khalili et al., 2023). The structure consists of three spans, each 25 meters long, supported by elastomeric bearings. The piers, circular in shape and with heights ranging from approximately 16 to 21 meters, are founded on pile caps, the piles being 25 meters long. The landslide, with a sliding surface located at a depth of about 5 meters, involved both an abutment and a pier. The overall effect was the displacement of the abutment by approximately one meter and the roto-translation of the pier's base, whose foundation was sheared off and dragged downslope as well.

3.2.1 The Ingotte viaduct case

Further information about the new Ingotte viaduct mentioned at the beginning of Section 3.2 is reported here thanks to high resolution satellite DInSAR data that have been made available by the Italian Ministry of Environment and Energy Security (within PST, Not-ordinary Remote Sensing Plan), for the period 2011-2014, and by European Ground Motion Service (EGMS), for the period 2019-2023. Such data, which show that the area is still subject to continuous movements, are provided in terms of time series of the displacement component along the satellite line of sight (LOS). The advantages of the DInSAR technique for integrating ground-based monitoring of landslides are broadly checked and recognized in the technical literature (e.g. Vassallo et al. 2021; Picarelli et al. 2022). Even though the monitoring period is subsequent to the damaging of Ingotte

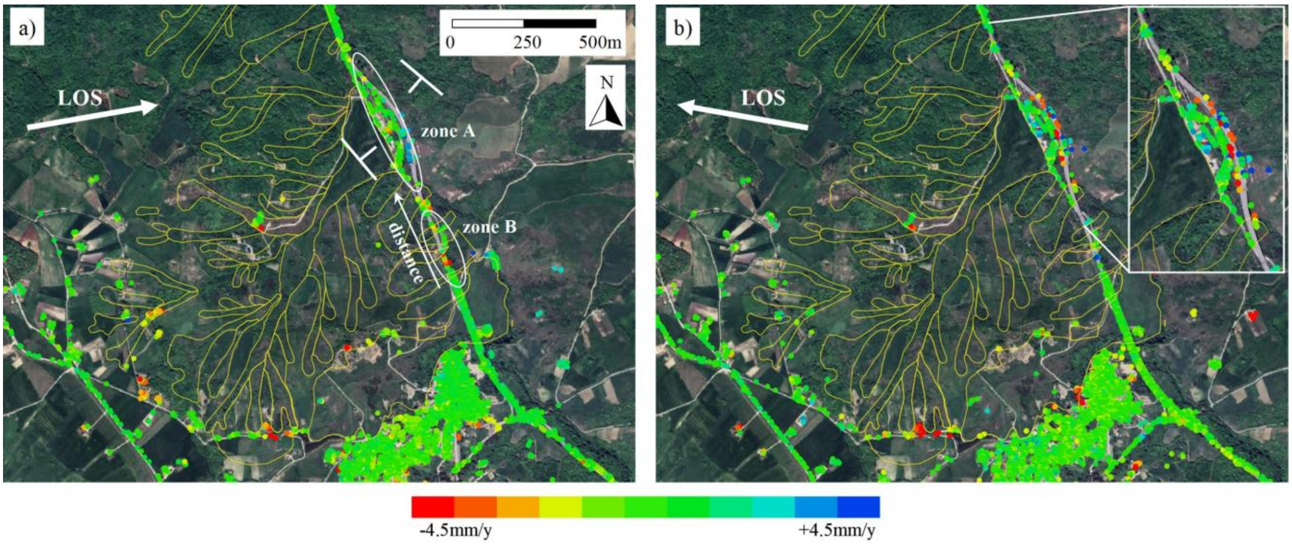

Figure 2. Ingotte (Italy) case: average yearly displacement rates along the satellite line of sight (LOS) obtained from DInSAR COSMO-SkyMed data in the period 2011-2014, for a) ascending pass b) descending pass.

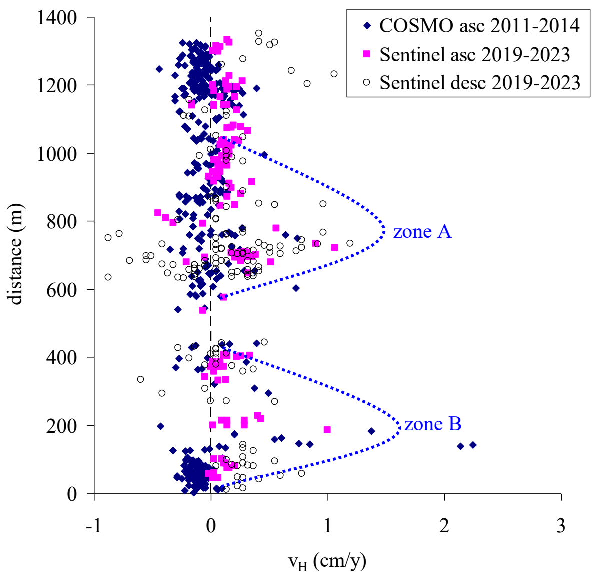

Figure 3. Ingotte (Italy) case: distribution of average yearly horizontal displacement rates, v_H, inferred from DInSAR data by assuming azimuth and inclination to the horizontal of ground displacements respectively equal to 40° and 10° for the western slope.

viaduct, such data are useful to complement the available information about landslide activity and interaction with the structure and to gain some insight on the current conditions of the area.

Figure 2 reports the average yearly displacement rates along the LOS, for both ascending and descending satellite passes, relative to the period 2011-2014. Quite similar distributions were found for years 2019-2023. The landslide system, which damaged the original viaduct involving the western slope, is also indicated in the figure based on the IFFI Italian Landslide Inventory. Visible targets (namely, permanent scatterers) are mainly concentrated in the accumulation zone and at the foot of the opposite slope, where the viaduct was rebuilt. The sign of the LOS displacement rates in the accumulation zone, negative for the ascending pass and positive for the descending pass, and the rate values suggest slow and persistent movements in the North-East direction. A few targets located on the opposite slope, presumably referable to the ground surface close to the viaduct, have a sign compatible with South-West movement. Along the main road, some segments affected by secondary landslide bodies are also highlighted.

Figure 3 shows the distribution of the average horizontal displacement rates as a function of distance along the road. The rates were obtained from satellite data by assuming the displacement directions and inclinations specified in the figure caption, based on ground surface and landslide geometry. Despite some scattering due to the extremely slow displacements values, a common pattern seems to be highlighted by the different DInSAR databases, with values reaching approximately 1.5 cm/y at the middle of areas A and B shown in Figure 2a corresponding to the accumulation zone of the main landslide and to a secondary landslide body. There seems to be no clear physical reason for the apparent concentration of negative velocity values resulting in two sub-portions of areas A and B. However, such values are mainly due to the worse visibility of the descending data, compared to the ascending data, so that the estimated horizontal velocity suffers from higher uncertainty.

It is interesting to observe that the use of satellite data to check the magnitude of slope and artefacts movements in areas occupied by slow landslides is becoming increasingly widespread, helping communities to manage the territory. A recent example is given by Farneti et al. (2022) who have retraced the sudden collapse, occurred in 2020, of a concrete arch bridge connecting the towns of Albiano-Magra and Caprigliola, in Tuscany (central Italy), as a result of movements of an extremely slow deep-seated gravitational slope deformation.

4. CONSIDERATIONS ABOUT THE EFFECTS OF SLOPE MOVEMENTS ON BRIDGES

Figure 4a plots in a logarithmic graph the volume and the peak velocity of nine landslides that led bridges out of service. Five of them are in the list of Table 1 (no. 5, 7, 9, 15 and 19), while the others, e.g. two translational slides (cases A and B), a debris flow (C) and a rockfall (D), are rapid landslides (see Comegna et al. 2025). The figure also reports some lines of equal momentum per unit mass density, *M*, i.e. the product of volume and velocity. Assuming an arbitrarily chosen reference minimum *M*-value of 1.0E-03 m^4/s, the graph is thus subdivided in zones characterized by given *M*-intervals. As already observed in Section 2, the magnitude of such landslides is highly variable. In particular, higher *M*-values characterize moderate to rapid landslides: in this case, the induced damage essentially depends on landslide impact on the artefact, thus, practically, on kinetic energy of the moving mass. Even though much a lower momentum features slow slope movements regardless of their size, as experience shows, a significant damage can be induced as well, being in this case due to the long-term cumulated soil (and bridge) deformation.

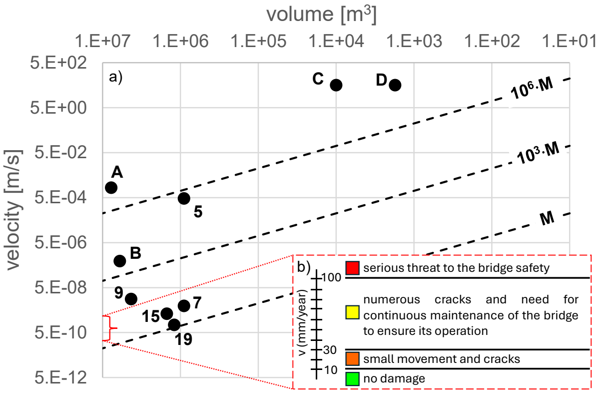

Figure 4. a) Momentum per unit mass density, *M*, of five slow slope movements (cases no. 5, 7, 9, 15 and 19 in Table 1) and of four quicker landslides (A, Wang et al. 2020; B, Luo et al. 2017; C, He et al. 2019; D, Arndt et al. 2012), leading bridges out of service; b) damage velocity thresholds suggested by Mansour and Morgenstern (2011).

Regarding the interaction between very slow landslides and bridges, Mansour et al. (2011) suggest a relationship, based on experience, between displacement rate and induced damage (Fig. 4b). Accounting also for the cases described in literature, time, or cumulative displacement, takes in our opinion a more significant role.

Figure 5 shows the time, *t*, taken by the five slow landslides listed above to lead bridges out of service. Considering the four landslides that move in a parallel direction to the longitudinal section of the bridge (cases no. 9, 12, 16 and 19), it can be noticed that *t* increases with the ratio *z/f* between the mean landslide depth, *z*, and the foundation depth, *f*. This appears logical and indicates that the bridges with a “floating” foundation should have a longer lifetime.

Despite it is based on few data, the figure also shows the range of velocities for which the bridge could withstand induced displacements assuming for it a normal lifetime of several tens of years. Finally, Figure 5 suggests that the direction of movement might represent a further important factor to consider; in fact, for the case no. 13, which concerns a landslide orthogonal to the bridge’s axis, the critical time seems shorter than the one that might be expected for a landslide parallel to it. Naturally, it’s here worth pointing out that the consequences of landslide movements are primarily related to the structural design of the artefact that is by far the main factor to account for.

5. CONCLUSIONS

The goal of the present work is to focus on the problem of the interaction between landslides and bridges. In fact, in spite of its socio-economic relevance, until now this topic has surprisingly received little attention by both land managers and researchers.

The paper provides a list of references on the subject that allows to collect valuable data and to identify general aspects of the problem. In particular, it appears that the landslide momentum is a parameter that can express the damage potential in cases where the interaction is impulsive in nature. In contrast, for slow-moving landslides, the cumulated landslide displacement (or time) is a parameter that better features the problem, as it indirectly determines the magnitude of stress change that is experienced by the structure.

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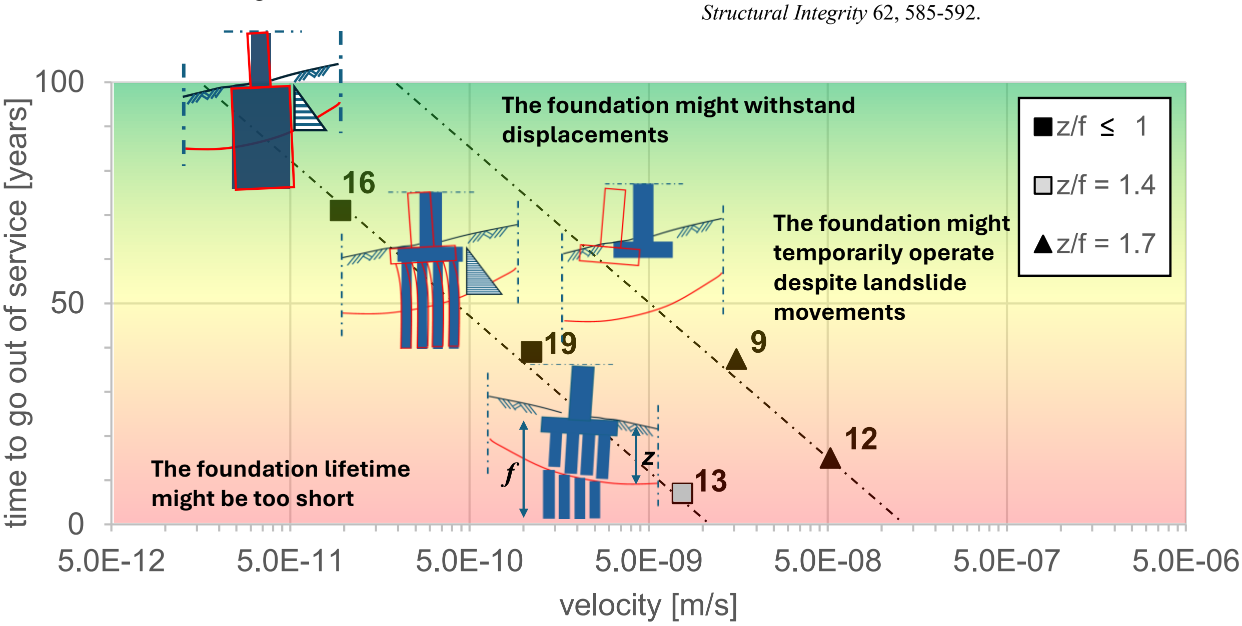

Figure 5. Relation between mean velocity of some slope movements (cases no. 9, 12, 13, 16 and 19 listed in Table 1), featured by different landslide thickness to foundation depth ratios, *z/f*, and elapsed time for taking the involved bridges out of service.

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