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RECOGNITION OF LANDSLIDE RISK AND INTERACTION WITH ARCH BRIDGES: LESSONS LEARNED AND METHODOLOGICAL INSIGHTS

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The interaction between landslides and arch bridges presents complex challenges, demanding a nuanced approach to risk assessment. In Italy, specific guidelines for evaluating and managing risks related to bridges and viaducts—including structural, seismic, hydraulic, and landslide risks—represent a critical step forward. However, their practical implementation often encounters hurdles, particularly when details about landslide characteristics and their interaction with structures are unknown. The expertise of evaluators in identifying precursor signs on the ground and the structure is crucial to prevent critical conditions. Arch bridges, as hyperstatic structures, are particularly vulnerable to longitudinal thrust from slow-moving landslides, even at low velocities. The eventual development of a three-hinge collapse mechanism under such conditions poses significant risks. In fact, the formation of plastic hinges, typically near the supports and the crown of the arch, can transform the bridge into a kinematic mechanism, resulting in sudden, brittle collapse. Such a failure poses severe risks to vehicles and pedestrians, often without warning signs once the mechanism is fully activated. This study consolidates insights from inspections of arch bridges interacting with slow-moving landslides, highlighting precursor signs and lessons learned. Cases of bridges failing to withstand ground thrust, leading to collapse, are also described. Drawing on the authors' experience and literature insights, the article identifies critical signs and aspects to investigate during landslide risk assessments, with emphasis on early indicators of hinge formation, such as cracking, uneven settlements, or arch deformations. Inaccurate risk assessment often leads to insufficient maintenance and safety measures for both the slope and the structure. By integrating observations into a systematic methodology, this approach enables early detection of structural risks and timely interventions to prevent significant deterioration.

Keywords: stress indicators, Italian guidelines, arch bridges, landslide risk, inspection.

1. Introduction

The interaction between landslides and arch bridges presents complex challenges, requiring a comprehensive and multi-disciplinary approach to risk assessment. In Italy, the Guidelines for the Classification and Risk Management, Safety Assessment, and Monitoring of Existing Bridges (LLGGs) (MIMS 2020) provide a structured framework for evaluating risks associated with bridges and viaducts, including structural, seismic, hydraulic, and landslide-related hazards. However, their practical implementation often faces difficulties, particularly when information on landslide characteristics and their structural interaction is incomplete or outdated. The goal of this procedure is to establish a priority ranking that determines, first and foremost, the frequency with which the evaluation process should be repeated. Moreover, for structures with high Attention Classes (AC), additional investigations may be required, including in-depth surveys to implement calculation models for accurate safety assessments. The process of defining the AC is therefore strategic in identifying which structures need further analysis. Overestimating risk makes the process economically unsustainable, while underestimating it risks overlooking critical conditions, both in serviceability and ultimate state limits.

Risk evaluation relies on the expertise of engineers and inspectors in identifying early warning signs in both the terrain and the structure itself. Arch bridges, due to their hyperstatic nature, are especially susceptible to slow-moving landslides that apply longitudinal thrust forces, even at low velocities. A key concern is the potential formation of plastic hinges, particularly near the abutments and the arch crown, which can transform the bridge into a kinematic mechanism, ultimately leading to brittle collapse. Such failures pose significant risks to both vehicular and pedestrian traffic, often with little or no warning once the collapse mechanism is fully activated.

While inventorying operations are crucial, they must be confirmed by on-site and territorial evidence. Landslide mapping can sometimes be outdated; the absence of mapped landslides does not necessarily imply the absence of risk, rather, it may reflect insufficient specific knowledge. The study of inventory data and the recognition of evidence during inspections are therefore crucial for timely recognition of preliminary signs that may indicate structural distress, with the aim of quantifying risk and intervening before damage to the structure becomes excessive. Moreover, experience in identifying distress signals is also essential to exclude structures that do not actually require detailed safety assessments from unnecessary in-depth investigations.

Arch bridges are particularly vulnerable to slow-moving landslides, which can impair functionality and compromise structural stability (Simeone et al., 2024). Failure mechanisms such as hinge formation (Drosopoulos et al., 2006; Livesley, 1992) or sliding can lead to sudden collapse. Differential ground movements, including settlements and slow landslides, trigger these mechanisms by causing progressive hinge formation and unbalanced forces (Brencich & De Francesco, 2004; Riveiro et al., 2011). This paper aims to share field experiences to support inspectors in assessing slow-moving landslide risk, outlining the main defect patterns identified during inspections, often in cases where maps did not indicate landslide presence, making on-site surveys crucial.

2. Stress Indicators and Failure Mechanisms in Arch Bridges

Landslide risk assessment is inherently complex and often subjective, heavily depending on the experience and sensitivity of evaluators. While geomorphological analysis and historical mapping provide essential information, these sources may not always accurately reflect the current activity of a slope. Furthermore, slow-moving landslides can go unnoticed until structural deformations become significant, highlighting the need for more proactive monitoring approaches. Familiarity with the terrain and its characteristics can help reduce uncertainties in the evaluation process. For instance, analyzing the site's geomorphology may rule out certain types of instability, but it cannot definitively identify the specific landslide type, confirm its presence, or assess the activity state of a recognized landslide.

The experiences reported in this paper come from inspections directly carried out by the authors and therefore focus on case studies of structures in Italy. However, the outcomes align with a broader statistical sample of Italian bridges (Salciarini et al., 2024) and findings from a comprehensive literature review (Gabrieli et al., 2024). While the geomorphological and geological context is Italian, similar conditions can occur wherever arch bridges are built near slopes potentially affected by slow movements. A catalog of recurring defects can assist evaluators during visual inspections, serving as a checklist to guide their analysis. Such a catalog has a dual purpose: to ensure that evaluators do not overlook signs of structural distress, thereby underestimating landslide risk, and to provide a more standardized evaluation method that avoids undesirable overestimations. Some of the most common stress signals are outlined below (Figure 1).

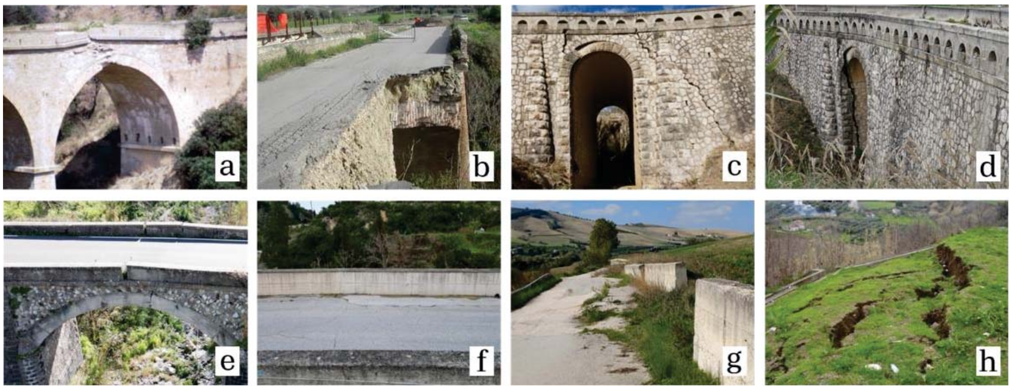

Fig. 1. Examples of common defects observed in arch bridges affected by interactions with slow-moving landslides: a) nutcracker mechanism; b) collapse of a portion of the bridge; c) fractures on the front of the arch; d) cracks on the underside of the arch; e) irregularities in the road surface; f) fractures in the asphalt; g) signs of terrain fragility; h) fractures in the ground.

One of the most observed and evident phenomena in arch bridges affected by landslides is referred to as the "nutcracker" mechanism. This process occurs when an arch bridge is subjected to slow slope movements predominantly in the longitudinal direction. The mechanism is typically triggered when the landslide impacts only a portion of the bridge, such as an abutment or specific spans, while the rest of the structure remains stable. The differential movement creates compressive forces in the arch, causing it to lose its regular shape. This results in irregularities of the pavement, lifting or distorting of the road surface, cracking in parapet walls, and fissures in the arch itself. The arch may take on a pointed or ogival shape, with localized rotation zones forming. If the landslide-induced displacements persist, these zones may evolve into hinges, leading to further damage and possible collapse mechanisms. Additionally, differential movements can cause translations and rotations in the substructures affected by landslides, lifting of supports, asphalt cracking, and the formation of transverse cracks and fissures on the bridge's underside. Slow slope movements with a significant transverse component relative to the bridge do not always trigger the nutcracker mechanism, especially if the longitudinal component is minimal. However, longitudinal cracks may appear on the underside of the bridge, highlighting the presence of stable and moving sections. Such cracks might also result from differential ground settlement. To confirm the cause, it is crucial to identify additional indicators on the bridge or surrounding terrain. Prolonged deformation accumulation due to slow-moving landslides can lead to detachment of individual bricks or larger sections of the bridge.

While evident signs of landslides may make these issues apparent, more subtle indicators might be overlooked without adequate expertise. Inspectors should check for road surface cracks, whose orientation can help determine the direction of differential displacements. The roadbed should be examined for irregularities, such as bulging, subsidence, misalignment of the deck, or longitudinal and transverse inclinations. Particular attention should also be given to parapets and retaining walls, as these can reveal partial bridge movements. Signs of past repairs or reconstructions may indicate the cumulative effect of prior damage. The foundations should also be thoroughly examined; they must not show signs of scouring. Arch bridges often rely on shallow foundations, and localized erosion can lead to instability, loss of bearing capacity, and differential deformation. Finally, the surrounding terrain should be carefully inspected. Irregularities in the landscape, such as abrupt changes in the slope, may indicate detachment or accumulation zones. Inspectors should look for tension cracks in the ground, areas devoid of vegetation, or signs of displacement in trees and nearby structures that could suggest instability.

3. Case Studies

To highlight the examples provided earlier, the following section presents specific cases observed by the authors during inspections for landslide risk assessment. In this context, an initial collection of experiences was reported by Simeone et al. (2024). The present work aims to contribute additional cases and derive lessons from the mentioned various experiences. The first structure examined is located in Southern Italy. It is a concrete and masonry arch bridge with 3 spans of equal length, supported by piers and abutments resting on mat foundations. The bridge spans a secondary watercourse, with an overall length of approximately 35 meters, a deck width of nearly 6 meters, and a height of about 10 meters. The bridge serves a local road. During the inventory phase, the Italian Landslide Inventory (IFFI Catalog, https://idrogeo.isprambiente.it/app/iffi) indicated the presence of a zone affected by 2 complex landslides in the area of the bridge, specifically described as rapid slides triggered by intense rainfall impacting the slopes above the roadway. Satellite data did not reveal any significant signs of slow instability in the area. Nevertheless, during the inspection phase, critical conditions were observed on the structure, with clear signs of stress likely caused by earth pressure acting longitudinally to the bridge. Specifically, the first of the 3 spans showed irregularities, including a reduction in the radius of the arch, a prominent crack on the arch itself, and a loss of verticality in the abutment and the first pier. Additionally, clear damage to the parapet wall was observed, indicating a loss of regularity in the road surface. A noticeable uplift of the roadway was identified near the first span, adjacent to the eastern abutment, accompanied by the aforementioned cracks extending to the intrados of the bridge. No significant evidence of instability was observed on the surrounding terrain, except for the inclination of several trees on the slope upstream of the first abutment, suggesting possible slope movement. This case aligns closely with the previously described "nutcracker" process. Such interaction imposes significant stress on the bridge deck, subjecting it to intense compression, which manifests in the distress signals already outlined (Figure 2). Over time, the accumulation of such displacements can lead to a loss of functionality and, in the long term, the formation of hinges that may ultimately result in the collapse of the bridge.

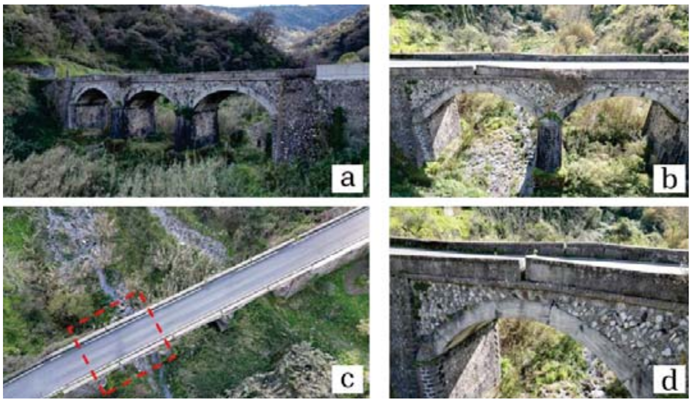

Fig. 2. Signs of stress observed on the structure of the first case study: a) overview of the bridge; b) overview of the nutcracker mechanism; c) aerial photo of the bridge highlighting the dark color of the road surface at the misalignment; d) detail of the misalignment and crack caused by the nutcracker mechanism.

The second case presents less pronounced damage compared to the first. It concerns a masonry arch bridge with a total span of 33 meters, resting on shallow foundations (Fig. 3 a-c). The arch itself has a span of 14 meters, a height of 12 meters at the intrados, and a width of approximately 6 meters. Cartographic data did not indicate the presence of landslide hazards or instability in the area. However, significant repairs observed on a portion of the arch raised suspicions (Fig. 3a). Additionally, the road pavement exhibited suspicious cracks, oriented both longitudinally and transversely (Fig. 3c). A closer inspection revealed further, albeit minor, signs of structural distress. A vertical crack was identified at the center of the arch, starting at the road pavement level and corresponding to the observed surface cracks (Fig. 3b). The same crack is also visible on the parapet wall. Minor longitudinal cracks were identified at the intrados, accompanied by small detachments of masonry fragments.

The overall condition of the structure was assessed as generally good, but it was deemed necessary to report the observed issues to include the bridge in an appropriate monitoring program. This would allow tracking the evolution of its condition over time and identifying, in a timely manner, the potential need for extraordinary maintenance. This decision was further supported by the identification of signs of surface instability in the surrounding area, such as cracks in the pavement and other indicators of ground fragility. In this case, the observed behavior does not represent a full "nutcracker" mechanism. Instead, it is characterized by a movement with a significant transverse component, causing differential settlements and displacements. Nevertheless, a degree of longitudinal instability is also present, as suggested by the orientation of the cracks observed on the bridge.

The final example features a two-span arch bridge serving a secondary road (Fig. 3 d-g). The structure is located in an area classified as having medium landslide hazard, according to the local Hydrogeological Management Plan (PAI, https://idrogeo.isprambiente.it/app/pir), while no landslides are reported in the IFFI catalog. During the inspection, the primary concern was a transverse crack observed near one of the bridge abutments (Fig. 3 e-g), that may represent a preliminary signal, potentially linked to differential settlement between the approach zone and the bridge abutment (Fig. 3d). The irregular shape and orientation of the cracks raise suspicions about possible interactions with deeper instability phenomena. As a precaution, the condition of the structure at the time of inspection was documented and photographed. This approach aims to facilitate the evaluation of changes over time during subsequent inspections.

Fig. 3. Evidence from the second case study: a) overview of the structure with evidence of significant repairs; b) detail of the arch showing cracks on the arch barrel and intrados; c) cracks on the asphalt pavement. Evidence from the third case study: d) view of the abutment with signs of instability and masonry damage; e-f-g) cracks on the road surface and parapet walls.

4. Discussion and conclusion

The multi-level approach outlined in the Italian Guidelines provides a structured methodological framework. However, it relies heavily on the experience and interpretative skills of the evaluator. Therefore, it is crucial to promote awareness and practical tools that facilitate the identification and accurate correlation of stress indicators with potential landslide activity, particularly in the case of slow-moving slope instabilities. The ability to recognize and interpret such signs is essential to ensure the safety and functionality of infrastructure.

Based on field experience, a systematic approach should be followed when assessing landslide susceptibility and its interaction with an arch bridge, in compliance with Italian regulations: **1. Roadway inspection** – Assess asphalt regularity, cracks, damage to curbs and walls, and signs of differential settlements. **2. Substructure inspection** – Identify cracks in the arch and intrados, fractures in piers, and signs of foundation erosion. **3. Terrain observation** – Examine slopes and soil conditions, note existing mitigation measures, and look for cracks, tilted trees, counter-slopes, or irregularities in the ground. **4. Large-scale observation** Check for distress signs in nearby structures (walls, buildings, roads).

If no distress indicators are detected, the structure can be considered at an acceptable risk level, with further investigations postponed to future inspections if its condition deteriorates.

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