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Landslide risk assessment of existing bridges: analysis of the Italian Guidelines and preliminary proposal for future developments

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Abstract

Many Italian bridges were built more than 50 years ago and are subjected to significant phenomena of deterioration. The current situation would require in-depth analyses to be carried out on all infrastructures to assess the current level of safety, according to in-force national standards, and to define appropriate construction or operational interventions. However, taking account of the large number of infrastructures, the necessity to define the priorities for detailed assessments arises and, this is why the recent Italian 'Guidelines for risk classification and management, safety assessment and structural health monitoring of existing bridges' include, for the first time in Italy, a stepwise approach with increasing level of detail. In this article, with reference to landslide risk assessment at the national scale, the main issues arisen from the analysis of the guidelines are discussed. This has been done based on the collaboration between researchers from geomorphological, geotechnical and structural engineering fields. Moreover, a preliminary proposal for a novel approach to rapid landslide risk assessment of existing bridges, is briefly proposed.

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1. Introduction

According to a first estimate, the total number of Italian bridges is more than 60,000 units and most of them were built more than 50 years ago.

In the last 20 years many bridges collapses occurred due to lack of inspections and maintenance, hidden structural defects due to design or construction errors, and natural phenomena such as landslides, flood and earthquakes.

Following these catastrophic events, in 2020 the 'Guidelines for risk classification and management, safety assessment and structural health monitoring of existing Bridges' (Italian High Council of Public Works, 2020; IGB in the following) were published introducing a novel multilevel approach to assess the degree of risk of existing bridges at the national scale.

However, the preliminary application of the Guidelines has highlighted that a very high percentage of Italian bridges would require urgent 'detailed assessment'. This is in contrast with one of the main objectives of the Guidelines, i.e. the definition of a timeframe for the assessments (and therefore the possible interventions) by selecting a limited number of bridges that need the detailed assessment and keeping routine inspections on remaining bridges (Buttarazzi, et al. 2023).

In this scenario, the aim of this article is to highlight the critical points of the Guidelines with reference to landslide risk and to enucleate some addresses for their improvement.

To this aim, the part of the Guidelines relevant to landslide risk assessment at the national scale is first critically analysed and then, based on some case studies of landslide-induced bridge collapses, the parameters that play a significant role on landslide risk assessment are enucleated. This has been done thanks to a joint-research activity carried out in the last years by experts of geomorphological, geotechnical and structural engineering fields.

Finally, a preliminary proposal for a novel approach for the rapid landslide risk assessment of existing bridges, consistent with the general framework of the Italian Guidelines, is illustrated.

2. Overview of the Italian guidelines

At the national scale, it is both technically impossible and economically inconvenient to perform detailed investigations of all bridges.

The complexity of the investigations, the large number and the variety of these structures make it necessary the adoption of a stepwise approach, from the national scale to the scale of the single bridge. The aim is to select, by rapid inspections, a limited number of bridges that need the detailed assessment and keep routine inspections on remaining bridges (Palmisano et al., 2022).

In this scenario, the stepwise approach given in IGB is based on six different levels of increasing depth and complexity. The first three levels (i.e. 0-2) should be carried out for all bridges and aim to define, for each one, a risk indicator called 'attention class' that combines structural, seismic, geotechnical and hydraulic risks.

Level 0 involves the census of the main characteristics of bridges through the collection of available information and documentation.

Level 1 envisages the execution of direct visual inspections and rapid survey aimed to identify the state of deterioration and the main structural and geometric characteristics, as well as potential risk conditions associated with landslides or hydrodynamic actions.

Based on the information gained in Levels 0 and 1, in Level 2 an attention class is associated to each bridge. To this aim five attention classes are defined in IGB (i.e. low, medium-low, medium, medium-high, high).

For all attention classes, routine inspections are recommended whilst for medium-high and high attention classes the bridge management system should include also structural health monitoring.

Level 3 should be carried out in case of medium or medium-high attention class and it is relevant to a preliminary assessment of the bridge. However, IGB does not give details on the procedure to be followed for the preliminary assessment and the relative assumptions. For level 3, IGB gives only one example relevant to the assessment of structural capacity for traffic loads. In this example the bridge capacity is assessed by the comparison of the traffic load models given in the current Italian code of practice (Italian Ministry of Infrastructures and Transportations, 2018; ICP in the following) with those included in the code in force at the time of construction.

The basic aim of level 3 is to understand if a detailed assessment according to ICP (i.e. Level 4) is needed. Level 4 applies also in case of high attention class.

Level 5 should be carried out only for bridges of significant importance within the road network and requires a specific study for the resilience of bridge network which is not covered by the current version of IGB.

In addition to what above mentioned, according to IGB, in case of post-tensioned R.C. bridges and for those placed where there is evidence or knowledge of landslides, flooding or erosional phenomena, detailed inspection (called 'special inspection') should be performed to evaluate if there is the need to directly perform Level 4 assessment without completing Level 1.

3. Evaluation of landslide risk in the Italian guidelines and relevant issues

According to IGB, the attention class relevant to landslide risk is evaluated by assessing susceptibility, vulnerability and exposure. Each of these factors is function of primary and secondary parameters that are reported in table 1 and detailed in the guidelines.

It is worth noting that susceptibility is used instead of hazard in IGB. The difference is that whilst hazard is the probability of occurrence of a potentially damaging landslide of given intensity within a specified time and a given area (UNDRO, 1979), susceptibility is a quantitative or qualitative assessment of the classification, volume (or area), and spatial distribution of landslides which exist or potentially may occur in an area (Fell et al., 2008). Taking into account the specific difficulties in defining the probability of occurrence of a landslide, the substitution of hazard with susceptibility has been used in IGB since it simplifies the procedure neglecting the temporal prediction.

Table 1. primary and secondary parameters for assessing landslide susceptibility, vulnerability and exposure according to IGB.

	Primary parameters	**Secondary parameters**
Susceptibility	Slope instability (magnitude, speed, activity)	Model uncertainties, mitigation measures
Vulnerability	Bridge typology/robustness, foundation type	Interference extension
Exposure	Average daily traffic, span length	Alternative routes, type of the entity crossed by the bridge, bridge importance

The application of IGB procedure to standard cases of bridges and landslides in the South of Italy (mainly Puglia and Basilicata regions) has shown that the relevant attention class for landslide risk is medium-high or high. Even in an optimistic scenario where the attention classes for the other risks (i.e. hydraulic, structural and seismic) are assumed as medium-low, the total attention class results equal to medium. This means that according to IGB at least the preliminary assessment of the bridge is necessary for bridges located in landslide-prone areas. In this regard it is worth highlighting that, as mentioned in the previous paragraph, no information on how to perform the preliminary assessment in case of landslide risk is included in IGB and that special inspections are requested for bridges located in areas where there is evidence of landslide.

Moreover, the analysis of the procedure included in IGB for the evaluation of the attention class for landslide risk has highlighted the following issues:

- In the evaluation of the primary parameter 'slope instability', it is not clear how to calculate the 'magnitude' for complex landslides. In particular, it is not clear if the magnitude should be calculated for the entire complex or for the single landslide body. The difference is noteworthy since the magnitude has a significant weight in the susceptibility assessment.
- Higher vulnerability classes are given to isostatic bridges neglecting that hyperstatic bridges are more sensible to the effects of differential settlement induced by landslides. Figs. 1 and 2 are here reported as two emblematic cases in this respect. In the figures, the failure of bridges Himera 1 (Sicily, Italy) and Pfeiffer Canyon (California, USA) occurred on the 10th of April 2015 and on the 11th of February 2015 are shown, respectively. Despite the similarity of the two cases (i.e. the landslide caused the movement of one column), the recorded consequences were significantly different because of the different static scheme of the decks. The deck of the Himera I bridge was simply supported by the columns thus the movement of a column, induced by the landslide, did not cause any

damage to the structures but only the rigid body movement of the column and of the relevant decks (see Fig. 1). Conversely, the Pfeiffer Canyon bridge had hyperstatic scheme with continuous deck in continuity with the column (see Fig. 2). In this case, additional internal actions arose due to the movement of the column (i.e. vertical settlement and rotation). The magnitude of these actions was such that they caused serious damages to the structures.



Fig. 1. Failure of the Himera I bridge (Sicily, Italy).



Fig. 2. Failure of the Pfeiffer Canyon bridge (California, USA): (a) overview, (b) detail of the connection between column and deck, (c) damage to the deck.

- Landslide risk rating does not account for the position of the bridge within the landslide body. This is worth mentioning since usually differential settlements are higher on the borders than inside the landslide especially for deep mass movements (Palmisano et al. 2018). This means that higher damages are expected on bridges located at the border of these landslides and, therefore, IGB is likely overestimating the landslide risk scoring for bridges located within landslide body.

- Landslide vulnerability scoring is calculated by using the same parameters as for seismic vulnerability scoring. Since the performance of a bridge when subjected to a landslide is completely different from that when subjected to an earthquake, this scoring seems to be unreliable.
- Landslide vulnerability scoring does not account for the depth of the foundation with reference to the depth of the landslide sliding surface. This leads to an overestimation of the scoring if the foundations are deeper than the sliding surface of the landslide. In this context Figs. 3 and 4 show the failure of bridges Madonna del Monte (Liguria, Italy) and Skjeggestad (Norway) occurred on the 24th of November 2019 and on the 2nd of February 2015, respectively. In these cases, the landslide consequences were different because of the different type of foundations. One deck of the Madonna del Monte bridge collapsed since the relevant pier, on spread foundations, was dragged downstream by the landslide (see Fig. 3). Conversely, the Skjeggestad bridge, even if seriously damaged, survived the landslide since the piers were founded on piles deeper than the landslide sliding surface (see Fig. 4b).



Fig. 3. Failure of the Madonna del Monte bridge (Liguria, Italy).



Fig. 4. Failure of the Skjeggestad bridge (Norway).

4. Preliminary proposal for a novel approach to rapid landslide risk assessment of existing bridges

In the previous paragraph the main issues of the procedure given in IGB to calculate the attention class relevant to landslide risk have been highlighted.

To overcome these issues, there is the need to modify the procedure included in IGB with reference to susceptibility and vulnerability rating thus, in this paragraph, a preliminary proposal to a novel approach for the rapid landslide risk assessment of existing bridges is illustrated.

The framework of the proposed approach draws inspiration from that proposed by Palmisano (2011) for the landslide vulnerability assessment of buildings at the urban scale.

The first step of the proposed approach is the evaluation of the landslide movement magnitude. The critical analysis of IGB has highlighted that the susceptibility assessment without considering the position of the bridge on the landslide could lead to significant errors. Thus, it is necessary to evaluate landslide movements in correspondence of the bridge. In particular, differential settlements between two consecutive vertical structures (i.e. piers, abutments) of the bridge should be evaluated. Taking into account that this procedure should be rapid, and the relevant parameters should be given for all landslides included in the Italian inventory, if detailed geotechnical assessments (that include in-situ and laboratory tests, numerical analyses) are not available, alternative data, already available, can be used to this purpose A possible option is to use displacement measurements derived from interferometric processing of spaceborne synthetic aperture radar images (Differential Interferometric Synthetic Aperture Radar, DInSAR hereafter) that, in the last decade, have widely proved their usefulness in building/infrastructure monitoring carried out over large areas (Ferlisi et al., 2021; Peduto et al., 2017, 2021) or at the detailed scale (Peduto et al., 2018, 2020).

By using DInSAR data, the relationships between landslide velocities (horizontal V_h and vertical V_v) and the horizontal distance D between two points on the ground can be evaluated:

$$V_h = f(D) \tag{1}$$

$$V_v = f(D) \tag{2}$$

Specific cases should be selected depending on e.g. the type of the landslide, its depth, the type of soil, to evaluate these relationships and to make them representative of most landslides present in a specific territory. Moreover, the relationships should be evaluated at least for the crown, the toe, the body and the lateral boundaries of the landslide. In the proposed approach, relationships (1) and (2) are the results of the hazard assessment. It is worth noting that this approach uses hazard instead of susceptibility since landslide velocities are referred to a specific period of time. This makes this approach more general than that included in IGB.

The next step is the evaluation of bridge vulnerability. For the time being, the proposed approach is limited to bridges with simply supported decks, which are the most common in Italy. In case of landslide, the main cause of collapse for this kind of bridges is the support loss of the deck due to horizontal movements. Thus, in the proposed approach the landslide risk is evaluated for this kind of failure neglecting the vertical movements.

If i and j are two consecutive vertical structures, by Eq. (3) it is possible to calculate the time (i.e. time of failure) $t_{f,ij}$ when the collapse of deck i-j will occur on pier i:

$$t_{f,ij} = \frac{s_{ij}}{V_{h,ij}} \tag{3}$$

where

- s_{ij} is the length of the deck support available on the vertical structure i for the span i-j (see Fig. 5) and resulting from measurements performed during the visual inspections (i.e. Level 1 of IGB);
- $V_{h,ij}$ is the horizontal landslide velocity calculated by Eq. (1) for D equal to the distance D_{ij} between the two consecutive vertical structures i and j.

Eq. (3) assumes that landslide velocity is constant in time.

t_{ij} should be calculated for all deck supports of the bridge and the minimum value

$$t_{f,min} = min\left(t_{f,ij}\right) \tag{4}$$

is the result of the risk analysis according to the proposed approach.

It is worth noting that this approach can be reformulated in term of verification. In fact, if T_R is the remaining service life of the bridge, the verification to landslide risk can be considered satisfied if

$$t_{f,min} \geq T_R \tag{5}$$

As above mentioned, the approach here proposed is limited to bridges with simply supported decks. However, this approach can be also used for other kind of bridges to perform preliminary assessment calculations. In these cases, by using Eqs. (6) and (7), it is possible to calculate the differential settlements between two consecutive vertical structures *i* and *j* in the remaining service life of the bridge:

$$\delta_{h,TR,ij} = V_{h,ij} \cdot T_R \tag{6}$$

$$\delta_{v,TR,ij} = V_{v,ij} \cdot T_R \tag{7}$$

where $\delta_{h,TR,ij}$ and $\delta_{v,TR,ij}$ are the horizontal and vertical differential settlements, respectively.

$\delta_{h,TR,ij}$ and $\delta_{v,TR,ij}$ should be used as input to perform simplified numerical analysis and verification of the bridge (i.e. Level 3 of IGB).

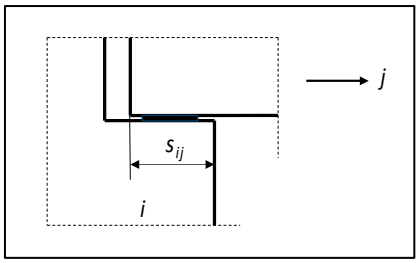


Fig. 5. Sketch of the deck support considered in the proposed approach (vertical view).

5. Conclusive remarks

This article has presented the main issues that have arisen from the analysis of the recent 'Guidelines for risk classification and management, safety assessment and structural health monitoring of existing Bridges' with reference to landslide risk assessment at the national scale.

Based on some case studies of landslide-induced bridge collapses, the parameters that play a significant role of such collapses have been enucleated. This has been useful to define the general framework of a novel approach to rapid landslide risk assessment of existing bridges, consistent with the general framework of the Italian Guidelines. The study is still ongoing and the details of the proposed approach will be the topic of future works.

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