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Safety Assessment of Bridges: Analysis and Criticalities of the Guidelines for Hydraulic Risk Management

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Abstract

Italian territory is characterized by a high fragility in terms of hydrogeological risk. Therefore, the national structural heritage needs the implementation of risk assessment plans. Specifically, the interaction between infrastructures and water has been identified as a significant factor contributing to recent collapses and failures. The existing Italian national guidelines for evaluating infrastructure vulnerability may fail in accurately reflecting the actual hydraulic conditions. This study aims at evaluating the strengths and limitations of the analyses pursued according to the guidelines and conducted on an impressive dataset comprising 51 bridges located in Italy. Common critical issues have been identified which potentially lead to incorrect estimations of the associated risk level. An erroneous risk assessment can result in misallocation of time and financial resources. One major challenge lies in the difficult tracing of original design documentation, which negatively impacts the assessment process and it may results in overestimating vulnerability to both generalized and localized erosion. Other significant challenges include the lack of specific directions for particular cases and difficulties in accessing the bridges (e.g. the morphology of the terrain or the dense vegetation in floodplain areas). While the guidelines provide an effective framework for risk analysis and damage prevention, they should be used in a critical way to identify and address any deficiency. This assessment may lead to an integration of the methodology and thus, of the guidelines, ensuring improved reliability and ease of application. Our study presents statistical metrics of infrastructure vulnerability estimated based on the guidelines. These analyses have successfully identified several strengths as well as critical aspects related to evaluating hydraulic risk based on guidelines implementation leaving space for opportunity of improvements.

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1. Introduction

Bridges play a pivotal role within transportation systems. While essential for the welfare of communities from both social and economic perspectives, a deficiency in adequate maintenance and supervision may results in a gradual deterioration of their structures. The analysis of bridge collapses worldwide underscore the significant susceptibility of bridges to both human-related factors, like inadequate design, insufficient inspection and maintenance, and natural factors (Buratti et al., 2021). Particularly, hydraulic actions on bridges are considered the main triggering causes of damages and failures (Ballio et al., 2018; Pregnolato et al., 2022). Bridge management and maintenance plans are then crucial to improve users' safety and reduce social and economic impacts related to their failure.

Italy exhibits a considerable susceptibility to hydrogeological instabilities due to unfavorable geological and geomorphological terrain characteristics and human interventions. Moreover, most of the Italian heritage of bridges and viaducts is very dated (Fattorini et al., 2022). These factors emphasize the need for comprehensive risk assessments of infrastructure to proactively mitigate potential sources of damages. Prevention actions and analysis should encompass all conceivable areas and structures at risk. After the collapse of the Morandi bridge in Liguria region (north-west Italy), in 2020 the Italian Higher Council of Public Work released the "Guidelines for the classification and management of risk, the evaluation of safety and the monitoring of existing bridges" (Ministero delle Infrastrutture e dei Trasporti CSLP, 2020) to guarantee a standardized safety level to the national transportation network (Di Sano et al., 2023). The Italian Guidelines (IG), with a multi-level method based on risk and attention class evaluation, aim at assessing the risk level of existing bridges to organize monitoring and maintenance activities.

This study focuses on the sole hydraulic risk. Specifically, we aim at highlighting both strengths and limitations of the definition of the Hydraulic Attention Class (HAC) based on statistics derived from the analysis of 51 bridges located in south-central Italy. Indeed, we believe that the HAC may not always accurately reflect the actual bridges conditions. Furthermore, the estimation of these parameters is heavily influenced by the inspectability of the structure and the presence or absence of structural projects (unavailable in 98% of cases). The structures under analysis were classified by defining an Attention Class (AC), which allowed for the identification of some critical aspects in the application of the guidelines provided by the ministry. These critical issues were found to be common to all the assessments conducted, and in some cases, they may have been responsible for potential inaccuracies in the estimated levels of associated risks. Although the phases leading up to the determination of the AC do not fall into the category of in-depth evaluations and are merely necessary to guide subsequent actions, an incorrect execution of these phases could lead to misdirected investments in terms of time and funding. Therefore, while striving to maintain an appropriate level of simplicity, they must be carried out with the utmost accuracy.

Nomenclature

AC	Attention Class
FRMP	Flood Risk Management Plan
GS	Generalized Scour
HAC	Hydraulic Attention Class
IG	Italian Guidelines for the classification and management of risk, the evaluation of safety and the monitoring of existing bridges
LS	Localized Scour
MVC	Minimum Vertical Clearence

2. Hydraulic Attention Class (HAC) based on the IG

This brief paragraph resumes the main aspects related to the evaluation of the HAC and the partial ACs for each separate hydraulic phenomena, for more details please refer to guidelines of the Ministero delle Infrastrutture e dei Trasporti CSLP (2020).

The multi-level procedure outlined in the IG concerns six levels of analysis. Level 0 regards collecting information and data (e.g., census, geolocation, and, if available, project documentation), and Level 1 in situ inspections. Level 2 focuses on risk-based classification based on four risk types, e.g., structure-foundation, seismic, landslide, and hydraulic. In Level 3, structures with criticalities are further investigated with simplified or accurate (Level 4) safety assessments. Level 5 regards a resilience analysis of the transportation network. Therefore, the bridges' risk classification is managed within the Level 2. The initial phase involves assigning an Attention Class (AC) to each risk type, then, all the ACs are combined to derive a global AC, which results in the final risk classification. There is a total of five ACs: Low, Medium-Low, Medium, Medium-High, and High. The global AC dictates the necessary actions for each bridge within a designated portfolio, such as the requirement for safety assessments or the need to gather detailed data through inspections or Structural Health Monitoring. In this study we focus exclusively on the application of the IG in order to assess the Hydraulic risk by evaluating the Hydraulic Attention Class (HAC). The assessment of the HAC involves the evaluation of three specific hydraulic phenomena and their relative AC related on: insufficient minimum vertical clearance, general and local scour. Note that in this study we used the term "generalized scour" as a direct translation of "erosione generalizzata" utilized in the IG, even though it specifically denotes the phenomenon of contraction scour (Di Sano et al., 2023; Pregnolato et al., 2022). The establishment of a comprehensive AC for scour involves combining the ACs for both local and general scour. The ultimate Hydraulic Attention Class (HAC) is ascertained by choosing the most critical AC from insufficient vertical clearance and scour. Assigning attention classes for various hydraulic-related phenomena involves allocating partial ACs to hazard, vulnerability, and exposure. For hazard assessing, the partial AC for minimum vertical clearance is determined by examining the distance between the bridge soffit and the water level corresponding to a specific return period. The partial AC for general scour considers the ratio between either the portion of the riverbed width occupied by the bridge (C_a) or the portion of the floodplain width occupied by the bridge (C_g) and the overall riverbed and floodplain widths, respectively. For local scour, the partial AC is determined by the ratio between scour depth and foundation depth (assumed as 2m if unknown). Vulnerability assessment depends on foundation type, riverbed geometry, and sediment/debris/floating material amounts. Operators refer to IG tables to verify conditions such as sediment deposition, riverbed erosion, transport of large plant material, river basin size, insufficient vertical clearance, and existence of scour protection devices. Exposure assessment mainly considers indirect consequences related to bridge functionality loss and environmental damage from a bridge collapse and is equivalent to the exposure evaluated for seismic risk.

3. Case Study

In this study we analyze 51 bridges located in South-Central Italy. The analyzed bridges are mainly constructed in concrete, while only three are in masonry. 31% interacts with a primary watercourse, while the remaining 69% are located in secondary watersheds. According to watershed area subdivision performed in the IG, 84% of the bridges are located on watersheds with area lower than 100 km^2 (40 bridges out of 43 are located in a watershed with area smaller than 20 km^2), 12% on watershed with area larger than 500 km^2, and 4% inside the previous range. 18 bridges have at least one pier inside the riverbed. According to the Floods Directive 2007/60/EC, each River Basin District in Italy developed the Flood Risk Management Plans (FRMP) containing the delimitation of areas affected by floods for three hazard scenarios: H1, which describes rare events (return period up to 500 years), H2 describing frequent events (100–200 years) and H3 for very frequent events (20–50 years). The Floods Directive 2007/60/EC requires that the FRMP should be reviewed and updated every 6 years (Samela et al., 2023). By intersecting the 2021 version of those maps with the 51 bridges emerges that 63% of them are located in floodplain areas with hazard level H1, indicating a high susceptibility to hydraulic risk.

4. Results and Discussion

We recall that in this study we apply the IG to 51 bridges located in South-Central Italy to determine the HAC. We firstly determine the AC for the three hydraulic phenomena, that are minimum vertical clearance, generalized and localized scour (Figure 1(a)), then we determine the HAC and we compare it with the global AC estimated as the combination of all the four risks, that are i.e., structure-foundation, seismic, landslide, and hydraulic (Figure 1(b)).

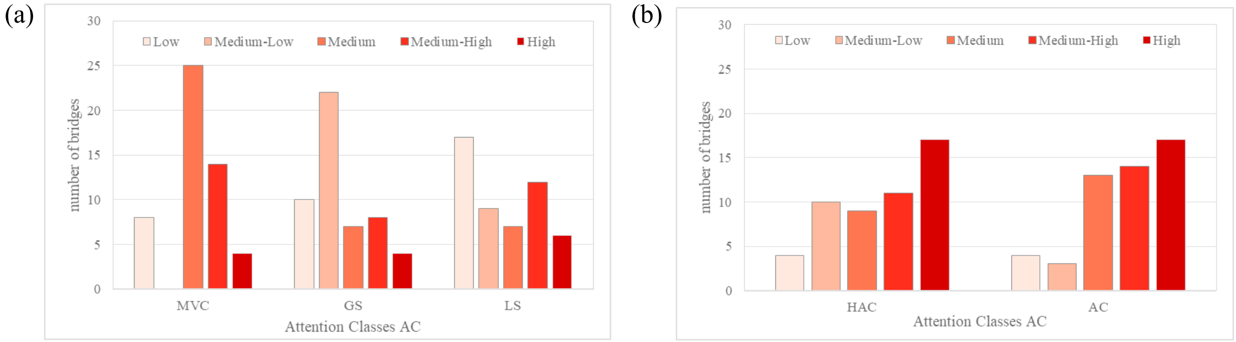

Figure 1. (a) Attention Classes (ACs) for each of the three hydraulic phenomena, that are minimum vertical clearance, generalized and localized scour; (b) Hydraulic Attention Class (HAC) and Final Attention Class after the combination of all the 4 potential risk

The combination of the three hydraulic ACs results in the attribution of a High AC to 17 bridges, and a Medium-High to 11 bridges. In Figure 1(b) we observe that after combining the four risks, most of the analyzed bridges belongs to Medium (13), Medium-High (14) and High (17) ACs. It is interesting to further investigate how the HAC is transformed when combined with the other 3 risks (Figure 2).

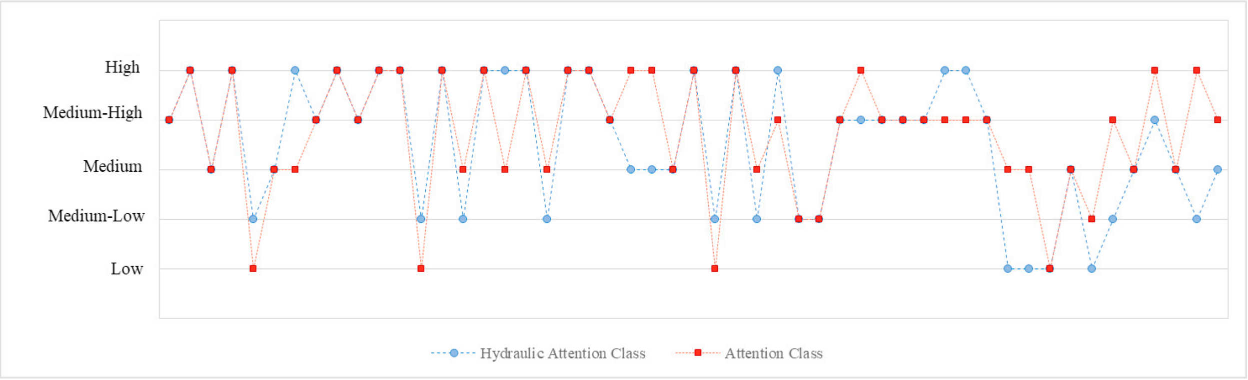

Figure 2. Differences in the attribution of the Hydraulic Attention Class and the final Attention Class as the combination of the four risks.

In most cases (30 out of 51), the global AC coincides with the HAC, while for 13 bridges we see an increase in the global AC respect to the HAC (which means that the bridge has a worse AC for at least one of the other risks). For the remaining 8 bridges we note that there is a decrease in the global AC respect to the HAC. This is due to the combination of the HAC with the other ACs for landslides, structure-foundation or seismic risk. In this sense, Santarsiero et al. (2021) highlighted that often the structure-foundation risk has the highest impact in determining the global AC. However, especially for those bridges with a High HAC, this reduction in the global AC is then reflected in a downgrade in the allocation of priority interventions. This clearly leads us to explicate the criticalities in the application of the IG. Indeed, we believe that if a High AC is assigned to a bridge for one of the four tested risks, the final AC should be unavoidable High. Moreover, as also discussed in the Introduction, damages and failures in bridges are primarily attributed to hydraulic actions, thus underestimating the final AC may lead to severe consequences.

Other aspects that we want to emphasize include the definition of the HAC and its components. Starting from Level 0 of the IG, the first issue concerns the accessibility to executive projects. Indeed, in this study we had access to construction projects only for 2% of the analyzed bridges. The absence of such documentation negatively affects the evaluation of parameters that are crucial for the AC evaluation of most of the hydraulic phenomena (e.g., localized erosion hazard, vulnerability to generalized and localized scour). Indeed, most of these parameters are purely geometric, and without construction projects, they must be derived through in-situ inspections or qualitatively estimated. For example, some construction details (such as foundation depth) are difficult to estimate, and values suggested by the IG are used. In this regard, accessibility for bridge inspection (Level 1 of the IG) is not always easy, due to the presence of private property, poor vegetation maintenance, and substantial discharge. In this context, it would be particularly useful to have a competent professional figure on-site for each risk domain in order to collect not only general documentation but also specific information required for different type of risk. For the hydraulic risk, it would be beneficial to obtain information on floodplain areas and/or riverbed width, as well as banks elevations, streamflow discharge and velocity.

All the problems encountered in the first two levels also affect the estimation of the parameters needed to assess the AC of the hydraulic risk. One of the main criticalities we observe in the Hydraulic risk assessment is the basin size. It is indeed crucial in the evaluation of vulnerability AC for minimum vertical clearance: bridges that are located on basin with a dimension lower than 100 km^2 satisfied 1 out of 3 conditions to have a Medium-High AC. Although it is well known that a small basin can respond quickly to extreme events, it is equally important to consider other characteristics, such as the basin morphology and its concentration time, that influenced the behaviour of the peak flow. The basin area, together with the annual maxima 24-hours precipitation, is also used in the Forti equation (Silva et al., 2021) to determine the streamflow (for basin areas lower than 1000 km^2). This aspect can also be questioned, since over ungauged watersheds the uncertainty related to regionalization method in estimating the precipitation amount is very high. In addition, basins with size between 100 and 500 km^2 do not have weight in the evaluation of the AC, as they do not appear within the case scenarios proposed by the IG. In this study we also found recurrent particular cases which are not considered within the IG. One example is when piers and/or abutments are located inside the riverbed: in this case we deem that the bridge should fall into at least a Medium AC, regardless of the C_a and C_g ratios. The same should be valid when piers and/or abutments are located in floodplain areas mapped by FRMP. The presence of a pier in the riverbed or in a floodplain area always causes a restriction of the regular flow, leading to erosion issues regardless of the width of the river itself. Another untreated example concerns bridges near culverted rivers. In fact, in the absence of regular maintenance or in the presence of obstacles to free flow, an obstruction may cause a rise in the water level upstream of the culverted stretch, resulting in critical conditions for the phenomenon of overtopping (thus for the evaluation of the minimum vertical clearance).

5. Conclusions

In this study we provide the results of the application of the Italian “Guidelines for the classification and management of risk, the evaluation of safety and the monitoring of existing bridges” to 51 bridges located in South-Central Italy. Focusing on the Hydraulic risk, we show the partial Attention Classes for the three main hydraulic actions, that are minimum vertical clearance, generalized and localized scour, that combined together provide the Hydraulic Attention Class. It emerged that most of the analyzed bridges belong to ACs from Medium to High when dealing with Hydraulic Risk. We then compare the Hydraulic Attention Class with the global AC used for the prioritization of interventions. The global AC result from the combination of the four different risks treated in the IG (structure-foundation, seismic, landslide, and hydraulic). We observe that for more than half bridges, the global AC equals the Hydraulic Attention Class. However, for 8 bridges we note a reduction of the global AC respect to the HAC, leading to an underestimation in the bridge level of attention. This is critical especially because the hydraulic actions are the triggering cause of bridge failures (Biscarini et al., 2021).

Guidelines are certainly an excellent and easy-to-use way to approach risk analysis, damage prevention and to ensure the appropriate safety standards of existing structures. At the same time, they need to be used critically to identify potential deficiencies that can be adequately integrated to ensure a more reliable methodology. These preliminary analyses allowed for the identification of strengths but also criticalities related to the applicability of the IG especially for hydraulic risk.

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