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Defects detection of pier and abutments foundations: an overview of a recent experience in Basilicata (Southern Italy)

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Abstract

Piers and abutments are bridge supports temporarily or permanently immersed into the water, that may suffer erosion and scour phenomena. As known the latter involves different processes at different spatial scales not easy to investigate in a combined approach, such as: contraction scour, local scour, gradation of the soil bed, river channel dynamic, climate change and hydrological forces. To this it should be added that piers/abutments are highly exposed to environmental actions, such as earthquake, landslides and floods that may seriously compromise their stability and, consequently, lead the bridge or an its portion to an out-of-service, or else to a failure. Therefore, it is important to properly identify and assess defects extent and severity on piers and abutments, in order to evaluate their conservation status, and to formulate a judgment for ranking priorities within a multi-level and multi-criteria framework, such as the recent guidelines issued by the Italian Ministry of Infrastructures and Transport. To this regard, in this work an overview of some significant defects related to piers and abutments, with particular emphasis to the ones due to the interaction with the water flow are illustrated and commented. They are collected in an on-going campaign of inspections performed in the Basilicata region (South of Italy), concerning bridges falling within State Roads networks. Comments are made from a structural and hydraulic point view, in order to highlight the inspected defects importance within the Classes of Attention, according to Italian Guidelines for bridges.

Keywords: abutments; defects; interaction water flow-bridge; inspections; piers

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1. Introduction

Piers and abutments are bridge support elements highly exposed to deterioration for both natural and anthropic causes. The former involve sudden events such as earthquakes, floods, landslides, fire, and atmospheric agents. Whereas, the latter include design and construction errors, maintenance lack, structural defects, collisions, and overloads. All these causes may progressively lead to a bridge collapse (Zhang et al., 2022).

Natural hazards are the main causes of foundation structures failure, due also to the increasing of frequency and severity of extreme hydrological events (Brandimarte et al., 2012).

Hydrological actions, including river flow and atmospheric agents, are extremely variable in space and time, depending on the hydrology at a specific site, in changing climate (Blöschl et al., 2019). Generally, they act throughout the bridge's service-life, producing foundation elements deterioration (wearing and cracking) and soil erosion around them (bed degradation). Notoriously, the main issue related to these structures is linked to the interaction of the flow with foundations during flood events (Pizarro et al., 2020). In (Wardhana & Hadipriono, 2003), n. 500 bridges collapsed in the United States of America between 1989 and 2000 were analyzed. In this study it was highlighted that hydraulic phenomena caused collapses in more than 50% of cases investigated. Afterwards, (Imhof, 2004) showed how hydraulic processes were globally responsible for damage to these structures in 60% of cases. The Federal HighWay Administration (FHWA, 1988) carried out an important study on existing bridges bringing out the critical condition of about n. 18000 of them and concluding that bridge failure main cause in the United States is the erosion occurring during flood events. Similarly, the analysis carried out by the Polytechnic University of Milan (Biondini et al., 2022), identified n. 106 bridges damaged or collapsed due to hydraulic causes in the period 2000-2019, while only in 2020-2021 as a result of flood events n. 20 bridges collapsed.

Recently, in Italy Guidelines for risk classification and management, for safety assessment and monitoring of existing bridges have been issued (MIT, 2020). This document provides a multi-level and multi-criteria innovative methodology in order to screen at a territorial level an existing bridges stock, identifying priorities to be evaluated more in detail with more refined methodologies. Starting from a preliminary documental analysis (Level 0), in-situ inspections are required (Level 1) for evaluating an Overall Class of Attention (O-CoA, Level 2), expressing the global risk of each bridge considered. The O-CoA includes risk evaluation regarding Structural-Foundational risk (SF-CoA), Seismic risk (S-CoA), Hydraulic risk (H-CoA), and Landslides risk (L-CoA). Therefore, according to this innovative approach combined effects on an existing bridge of structural and hydraulic aspects are taken into account.

This work aims at illustrating and discussing some defects observed during in-situ surveys of existing bridges serving State Roads of the Basilicata region (in the South of Italy). These activities have been conducted within a National agreement between FABRE consortium (Research consortium for the evaluation and monitoring of bridges, viaducts and other structures) and A.N.A.S. S.p.A. (Italian National Road Authority). In particular, here defects of piers and abutments are taken into consideration in order to highlight how the interaction with river flow may generate defects surveyed and increase the overall risk, implying more refined numerical evaluations at a punctual level.

2. Italian Guidelines for existing bridges (MIT, 2020)

The Italian Guidelines for existing bridges (MIT, 2020) are based on a multi-level and multi-criteria methodology for evaluating the overall risk (briefly O-CoA), becoming the reference framework for ranking at a territorial level an existing bridges stock, and for planning where more detailed evaluations supported with punctual numerical models are required. Therefore, this approach permits of allocating time and economic resources in a rationale way, representing a useful tool for owners and practitioners. The methodology is based on the assumption that the O-CoA estimation must include not only the structural aspects, but also hydraulic and landslides interactions with the existing bridge, that preliminary may be conducted in qualitative ways, considering documentation available and in-situ inspections. The O-CoA is then obtained combining for each bridge the specific evaluation of hazard, vulnerability, and exposure.

Referring to the Structural and Foundational Class of Attention (SF-CoA), and with particular interest to piers and abutments, foundation scouring is a 'critical element' decisive for the overall risk (O-CoA), since if occurred defines a 'high defect level' determining a 'high vulnerability class', and consequently a High Structural and Foundational Class of Attention (High SF-CoA), independently on the hazard and exposition classes. Moreover, according to the

Guidelines, if a High SF-CoA is obtained then also the Overall CoA results high (High O-CoA). In a similar way, presence of high or medium-high gravity defects on piers end sections, of any intensity, significantly impacts Seismic Class of Attention (S-CoA). It is worth noting that the presence of localized defects at piers and abutments base, such as scouring, material wearing, cracking, and settlements, frequently are due to an interaction with river flow (D'Amato & De Matteis, 2022).

The Class of Attention for scour is essential for the Hydraulic Class of Attention (H-CoA) assessment, considering that the latter is determined by selecting the most severe one between the Class of Attention for scour and the Class of Attention for overtopping phenomena. In detail, the Class of Attention for scour is obtained combining the attention classes for general and local scour. The former, includes both natural and contraction phenomena and is estimated using the C_a index, calculated as the ratio between the river bed and flood-plains widths occupied by the bridge piers or abutments ($W_{a,l}$ and $W_{g,l}$, respectively) and the overall river bed and flood-plains width (W_a and W_g, respectively). Whereas the Class of Attention for local scour is determined by local scour index (*IEF*), calculated as the ratio between the maximum excavation depth d_s (depending on piers/abutment geometry) and the foundation laying depth d_f (MIT, 2020).

The estimation of H-CoA is highly influenced by vulnerability factors. For instance, in Low hazard class, the presence of three factors between the evidence of shallow foundations, generalized lowering of river bed, debris material and planimetric migration of river bed, defines a High vulnerability class for local erosion. Additionally, for generalized erosion, a High vulnerability class is assigned when shallow foundations are present, and there is a noticeable curvature of river bed, along with a global lowering of river bed. If either of these vulnerability conditions is verified, the H-CoA will be High.

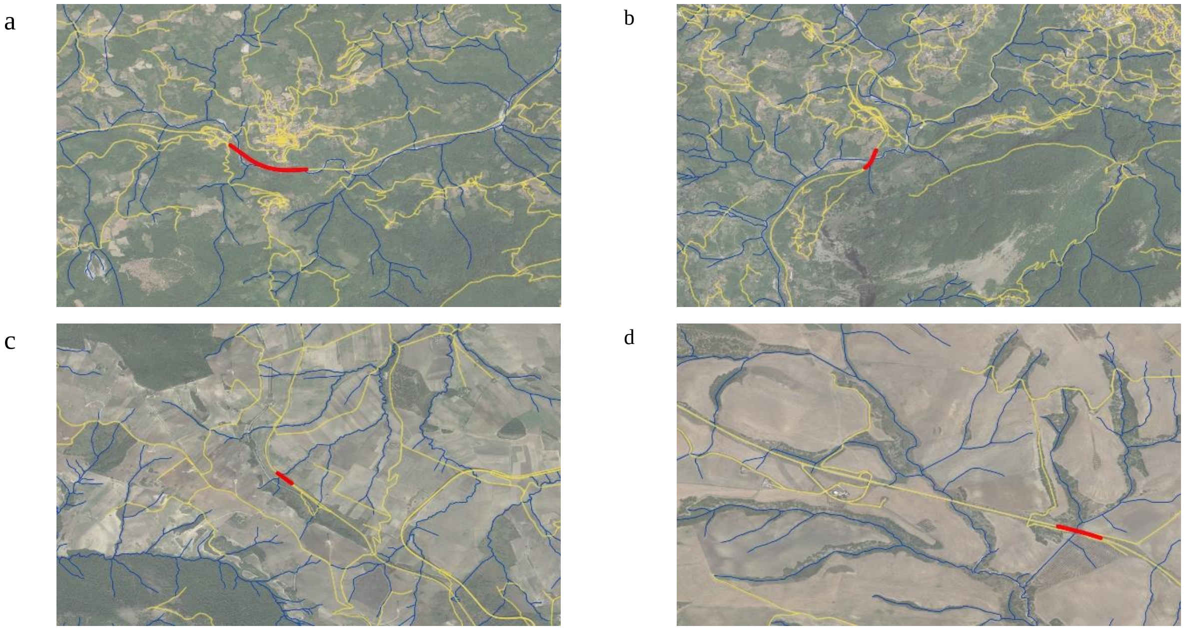

Fig. 1. Bridge locations: (a) Viaduct I, 37 span bridge; (b) Viaduct II, 7 span bridge; (c) Viaduct III, 4 span bridge; (d) Viaduct IV, 6 span bridge.

3. Case studies and application

In this section, defects detected on piers and abutments foundations of some bridges located in the Basilicata region are analyzed (Fig. 1). The attention is focused on defects due to interaction with river flows, drainage flows and atmospheric agents. The bridge stock under consideration comprises no. 4 multi-spans Reinforced Concrete bridges with Prestressed Concrete Beams (PCBs) and deep foundations. Bridges belong to ANAS S.p.A. and cross over the main course of Noce and Sinni rivers (Fig. 1a-b), and the secondary drainage network of Bradano and Ofanto rivers

(Fig. 1c-d). The geographic context in which such structures are located presents a strong heterogeneity within the region, including the Lucanian Apennines, the Murge limestone base and the Bradanic pit.

3.1. River flow interaction

The loss of efficiency and functionality of transversal hydraulic structures, which stabilize the topographic longitudinal profile of the river bed, can lead to significant morphological changes due to general scour (Wang et al., 2020). This situation was observed on Viaduct I, where the weirs failure (Fig. 2a and Fig. 2b), induced a progressive lowering of the river bed highlighting pier foundations and large boulders along the river reach (Fig. 2c). Foundation exposure resulted in a significant increase in the water impact surface area on the bridge (Fig. 3a), producing the obstruction of the channel due to floating materials and debris (Fig. 3b). This determined local scour processes due to secondary currents and fields of swirling and turbulent flow along the path.

Fig. 2. Viaduct I: (a) Remaining of the wing walls of weir damaged; (b) broken submerged weir placed at the downstream reach; (c) presence of large boulders along the river reach.

Given the longitudinal position of the crossing in relation to the river, intersecting it multiple times, the H-CoA is assessed in correspondence of the most critical cross-section, in which both the hydraulic hazard for erosion and overtopping phenomena are influenced by the presence of obstruction and the high confinement of the valley. The general erosion coefficient (C_a), calculated considering the substructure obstruction width ($W_{a,l}$) and river bed width ($W_{a,}$) derived from Hydrogeological Plans – PAI (200-year return period), is between 10-15%, resulting in a Medium-Low hazard class. The local scour index (IEF) is >1.2, giving the bridge a High hazard. Regarding the vulnerability for the phenomenon of general erosion, the evidence of deep foundations combined with the evidence of a generalized river bed lowering, determines a Medium-Low level. On the other hand, concerning local erosion, the evidence of generalized lowering with the presence of debris and floating material accumulations upstream of the pier, results in a Medium-High vulnerability. Therefore, the H-CoA will be considered Medium-High since vulnerability is the most relevant risk factor.

Fig. 3. Viaduct I: (a) Pier foundation exposure upstream to the broken weir; (b) accumulation of floating material and debris at bridge piers.

Regarding SF-CoA and S-CoA, Viaduct I inspections did not record any significant defect at the piers and abutments base or foundations. Rather, extensive and intense concrete cover detachment and corroded bars and stirrups were recorded at the pier caps. Thus, in this case, the deterioration was closely related to improper rainwater disposal from the road deck. On this bridge, SF-CoA results Medium-High as the SF vulnerability class is affected by Medium-High defectiveness, because defects detected on pier caps were considered to be over time compromising the bridge statics. On the other hand, resulting the bridge deck curved in some road sections, the presence of too small supports compared to the beams section width, had led to a High S-CoA.

In any case, a continuous interaction between piers base and river flow, could over time cause advanced concrete deterioration, affecting columns end sections, leading to a high seismic defect level (Fig. 4a and Fig. 4b). Progressing this situation, if the foundations were also affected, being exposed, it would lead to a High SF defect level, vulnerability class, and CoA.

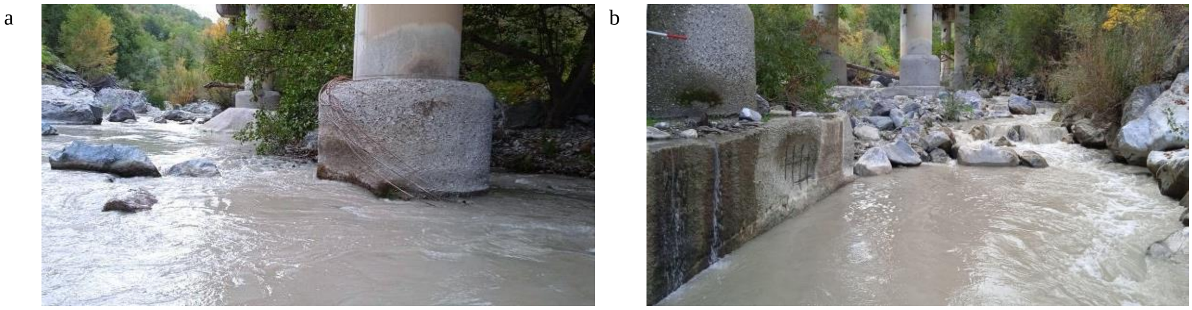

Fig. 4. Viaduct I: (a) piers damaged by collision, (b) sediment abrasion or impact from boulders.

Frequently, amplified local scour phenomena are produced by a non-zero angle of current incidence (Oliveto et al., 2004). This situation is more frequent in pseudo-meandering rivers, where alternate bars are responsive to the stream direction and incidence angle changes near the piers or abutments (Fig. 5a). In the case of Viaduct II, the pier near the left bank was interested by local scour phenomena due to the combined effects of non-zero incidence angle of the main flow and the lateral flow confluence. Viaduct II results in a Medium-Low hazard class for generalized erosion phenomena (C_a=10-15%) and a High hazard class for localized erosion phenomena (IEL > 1.2). Despite the presence of a weir downstream, the vulnerability related to local erosion is Medium-High and Medium for general scour, and the final H-CdA classification is Medium-High and Medium.

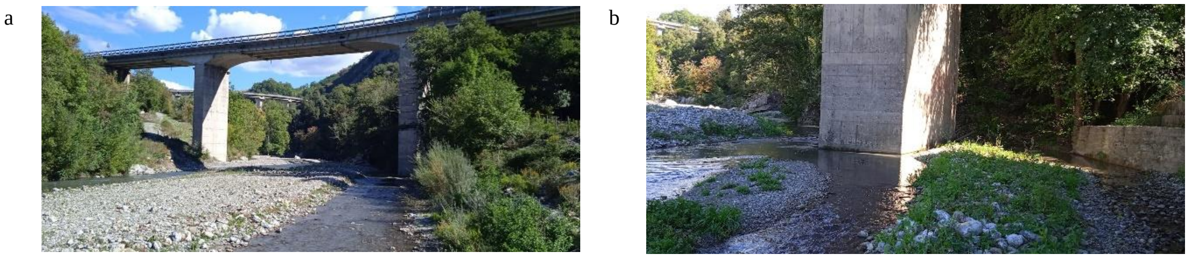

Fig. 5. Viaduct II: (a) Presence of alternate bars along the upstream cannel; (b) interaction between pier, main flow and later flow confluence.

Viaduct II also recorded no significant defects at the pier and abutments base. The bridge's defectiveness for SF-CoA is Medium, while the SF vulnerability is increased to Medium-High for parameters that depend on the age of the last significant intervention operated, the design standard, the bridge static scheme and materials. Similarly to Viaduct I, Viaduct II reports High S-CoA for reasons linked to the absence of seismic restraints at deck supports.

3.2. Drainage flows and atmospheric agent interactions

A relevant issue, often not adequately evaluated, is related to the increasing of erosion risk due to the inadequate stormwater management systems. In two specific cases, it was observed that the damage of the canalization system and the uncontrolled stormwater runoff produced local scour phenomena around piers and abutments. As for the Viaduct III, the failure of stormwater canalization induced a deep river bed incision (Fig. 6a) directing stormwater runoff toward one pier Fig. 7a. In the case of Viaduct IV, a deep river bed incision directed close to the pier (Fig. 6b) induced scour condition and damage of the right abutment (Fig. 7b and Fig. 7c).

Fig. 6. (a) Viaduct III: pronounced incisions almost parallel to the broken stormwater channel; (b) Viaduct IV: river bed incision close to the bed pier.

Fig. 7. (a) Viaduct III: foundation exposure of the pier interested by storm water runoff; (b) and (c) Viaduct IV: abutment foundation exposure.

In these circumstances, the guidelines do not provide a comprehensive view from a hydraulic perspective but place greater emphasis on the structural aspect, as some degradation phenomena are caused by the lack or the inadequacy of an effective stormwater management system. For both crossings, the combination of a High hazard level for local scour with a Medium-Low level of vulnerability lead to a Medium class for H-CoA. The factors determining the level of vulnerability include the presence of weir immediately downstream of the crossing and the presence of deep foundations.

From a structural point of view, Viaduct III and Viaduct IV reported similar condition and geographical context, despite not being close each other. Specifically, during the inspections, scouring was recorded at the foundations of one pier in the case of Viaduct III and both abutments in the case of Viaduct IV. Viaduct IV abutment no.1 presented scouring defect intensity coefficient $K2 = 0.2$ (Fig. 7b), while as for abutment no.2 the defect reached $K2 = 0.5$ (Fig. 7c). The latest coefficient was registered also in the case of Viaduct III pier no.1 (Fig. 7a), having the pile the height of 1 m at the most exposed part. This G5 gravity defect, according to (MIT, 2020), represents a critical element of the abutments and piers of the two bridges for SF-CoA, that is evaluated High for this reason. As previously stated, in these cases the Overall Class of Attention (O-CoA) is automatically conducted in High, independently of the assessments on the other risk classes (S-CoA, L-CoA and H-CoA). As for the S-CoA, seismic defect level is assumed to be Medium-High, since scouring on these elements is considered to be affecting the overall bridge behavior toward seismic actions. Nevertheless, the seismic vulnerability is assigned High because of span length, static scheme, and bridge material. Ultimately, in these cases the S-CoA is High.

4. Results and discussion

According to the Hydraulic Class of Attention (H-CoA), the bridges that reported higher risk are located in river beds with significant general erosion due to local scour or downstream hydraulic structure failure, so that Viaduct I and Viaduct II result, respectively, with a Medium-High and High H-CoA. Therefore, H-CoA is strongly influenced by partial CoAs related to erosion phenomena.

The most emblematic case analyzed is Viaduct I, having a Medium-High H-CoA. In all risk scenarios, the phenomena were well-identified, but it is considered that by strictly applying the methodology proposed by the Italian Guidelines, the H-CoA is underestimated. As for the Viaduct II the High H-CoA is principal due to local scour caused by the flow's angle impacting bridge pier.

On the opposite, as for Structural-Foundational and Seismic Class of Attention (SF-CoA and S-CoA), the higher risk is registered on Viaduct III and Viaduct IV, reporting evident scouring phenomena on piers and abutments foundations. The defect level is the most impactful parameter for defining SF-CoA and S-CoA since it significantly affects the vulnerability class. Nevertheless, the SF-CoA plays a key role for the Overall Class of Attention (O-CoA), since a High SF-CoA also implies a High O-CoA, as in the case of Viaducts III and IV.

From the hydraulic point of view, Viaducts III and IV result in a Medium H-CoA. In both cases, the final hydraulic risk for scour is influenced by a Medium-Low level of vulnerability for local scour which does not consider the evidence of removal of material from around piers and abutments. Nevertheless, the phenomenon of scour caused by the drainage system failure would deserve more attention.

5. Conclusion

This research was focused on bridge piers and abutments defects on State Road networks of the Basilicata region. The activities were conducted according to Italian Guidelines Level 0, Level 1 and Level 2. Significant defects were observed specifically for bridges where drainage system failure induced deep local scour around piers and abutments, leading to higher SF-CoA and O-CoA, but non-significantly influencing H-CoA.

The inspections carried out and the main defects detected have highlighted the importance of the multi-criteria approach followed by Italian guides, that includes structural-foundation and hydraulic aspects and their combination for a better evaluation of the overall Class of Attention (O-CoA).

From this inspections campaign is emerged the necessity of continuous monitoring activities with the aim to better understand the processes evolution over time, that could produce risk conditions not easily detectable. Visual inspections are essential for assessing alluvial phenomena, especially after unexpected flood events. Additionally, the inspection phase should pay special attention to the stormwater drainage systems, as prolonged their negligence is responsible for most damages on bridges.

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