IMPACT OF FLOODING ON BRIDGE CONDITION: INSIGHTS FROM TWO CASE STUDIES

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Abstract

Floods directly affect the mechanical resistance, stability, and durability of bridges and remain one of the leading causes of bridge failures worldwide. With climate change increasing the frequency, intensity, and affected area of extreme hydrological events, understanding flood impacts on bridge performance is becoming increasingly important. This paper investigates and demonstrates these impacts through two detailed case studies. The first case study concerns a new concrete girder bridge spanning the Sava-Odra Flood Relief Channel, which was once exposed to a major flood and subsequently repaired. The second case study involves a 90-year-old stone arch bridge located in a mountainous region and exposed to multiple seasonal floods. Rehabilitation after the flood in the first case study and flood protection methods on the second bridge are presented and discussed. Both bridges are visually inspected, including only the accessible parts above water. Results of the visual inspections of the two bridges are presented and discussed, with special focus on damage caused by high water and floods. The condition of both bridges is evaluated using two methods: the method commonly used by Croatian road authorities based on German standards (DIN 1076 RI-EBW-PRUF 2017), and a modern concept focusing on five Key Performance Indicators (KPIs). While both methods yield similar results, the KPI approach provides a broader perspective and supports preventive maintenance and asset management.

Keywords: bridge, concrete, stone, flooding, climate change, visual inspection

1 Introduction

Bridges are critical components of transport infrastructure, yet they are highly vulnerable to extreme hydrological events. Floods are among the most significant natural hazards affecting bridges, often resulting in partial damage or complete collapse. Floods directly impact the mechanical resistance, stability, and durability of bridges and remain one of the leading causes of bridge failures worldwide. Climate change has intensified these challenges. Therefore, systematic assessment and adaptation of bridge infrastructure are becoming imperative. This paper presents two case studies from Croatia that illustrate different aspects of flood impact on bridges: Kučki Bridge - a modern concrete girder bridge over the Sava–Odra Flood Relief Channel, which was exposed to a major flood shortly after construction and Kosinj Bridge, a historic stone arch bridge in a mountainous area, subjected to repeated seasonal flooding over nearly a century (figure 1) [1, 2]. Since underwater inspection is not provided and there is no available data on scour and riverbed condition, the main aim of this paper is to demonstrate how floods affect structure durability.

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Figure 1 Case studies: Kučki Bridge (left) and Kosinj Bridge (right)

2 Methodology

2.1 Visual inspection

The visual inspection of both bridges was carried out in accordance with a predefined methodology and structured inspection protocol [3].

2.2 Bridge condition assessment

2.2.1 Bridge condition assessment according to DIN 1076 RI-EBW-PRUF 2017

The structural condition assessment commonly used in Europe is based on a deterioration index rated from 1 to 5. Rating 1 corresponds to no damage, while rating 5 represents increasingly severe damage conditions requiring immediate repair or urgent intervention [3].

2.2.2 Bridge condition assessment according to key performance indicators

A new approach to bridge assessment includes five groups of KPIs: safety, reliability, and security; availability and maintainability; costs; environment and health and politics [4]. Safety, reliability, and security are the main demands on bridges. Reliability in this context means the probability that the bridge will be fit for its purpose during its service life and several possible conditions: in the case of structural failure, operational failure or any other failure mode. The second group of KPIs, availability and maintainability, refers to the proportion of time a bridge is in a working condition, relative to the interruption of bridge users by planned or required maintenance activities. Costs include long-term costs and maintenance activities during the service life of a bridge, but also user costs caused by detours and delays are included. The KPI of the environment is related to minimizing the harm to the environment during the service life of a bridge. Health and politics is related to political–administrative and social requirements. The main idea is to identify and evaluate performance indicators of a bridge (PIs) linked to one or more KPIs. Each PI is determined by rate (R = 1–5) and weight (w = 0–1). The rate represents the degree of performance indicators (1 = best, 5 = worst). The weights represent the impact of PI on the respective KPI (0 = no impact, 1 = very high impact) [4].

2.3 Non-destructive testing

For concrete bridge visual inspection is supplemented by NDT methods: including measurements of rebar diameter and concrete cover, estimation of strength of concrete with Schmidt Hammer and measurements of surface electrical resistivity, since wetting and drying cycles can accelerate active corrosion of reinforcement in concrete. A standardized NDT testing methodology was applied [5].

3 Case study I: Kučki Bridge

3.1 Technical description of Kučki Bridge

Kučki Bridge, which crosses the Sava–Odra Flood Relief Channel near Zagreb, was built in 2020 to replace the old timber bridge used for road traffic. The bridge is a continuous beam with three spans: 18 + 23 + 18 = 59 m (figure 2). The superstructure consists of six precast prestressed concrete girders, a monolithic reinforced concrete slab, major cross-girders to ensure girder continuity, and secondary cross-girders at mid-span. The substructure comprises minimal abutments and piers. In cross-section, there are two circular columns with a diameter of 1.20 m. The piers in the channel are founded on 15 m deep piles [1].

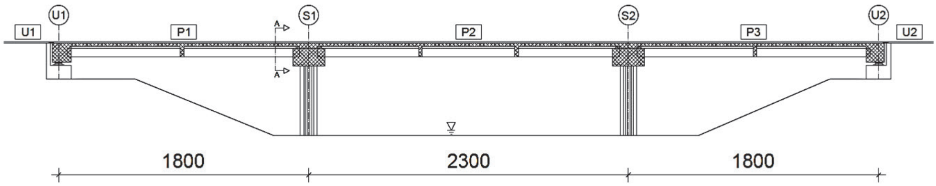

Figure 2 Kučki Bridge - longitudinal layout [1]

3.2 In-service performance of Kučki Bridge

In August 2023, severe storms affecting the City of Zagreb and a significant rise in the water level of the Sava River led to the activation of the Sava–Odra relief channel, over which the Kučki Bridge is located. As the bridge elevation is lower than the depth of the channel, nearly the entire structure was submerged during the flood event (figure 3). After the water level receded, damage to the barrier and soil erosion on the embankment of the bridge were observed. Rehabilitation works were carried out, including repair of embankment and replacement of the asphalt pavement on the bridge, as well as removal of the damaged steel safety barrier and installation of a new one to ensure traffic safety.

Figure 3 Kučki Bridge during high water levels of the Sava River in August 2023

3.3 Condition assessment of Kučki Bridge

The condition assessment and categorization of damage of superstructure, substructure and bridge equipment based on standard method [3] is shown in table 1. Based on the visual inspection of the structure, it was concluded that there is no damage to the bridge structure that would jeopardize the safety or functionality of the structure. Deficiencies in bridge equipment include contamination of the pavement, expansion joints and drains and pitting corrosion on bearings.

The part of the load-bearing structure that was available for inspection is also in good condition, with local concrete segregation and surface delamination of the concrete. The most significant damage was observed on the abutments of the bridge with present water leakage, spalling concrete cover, efflorescence of concrete and reinforcement corrosion. Bridge pavement, expansion joints and drains should be cleaned regularly considering that the bridge is in an area of agricultural land and subject to contamination from soil and gravel. The abutments need to be repaired because they are in significantly worse condition than the original bridge.

Table 1 Damage categorization of Kučki Bridge [1]

		Level of damage	1	2	3	4	5
Extent of damage [%]	Superstructure	Main Girders	87	10	3	/	/
		Cross girders	90	10	/	/	/
		Slab	90	10	/	/	/
	Substructure	Piers	95*	5	/	/	/
		Abutments	20	30	45	5	/
	Equipment	Sidewalk	100	/	/	/	/
		Cornice	90	10	/	/	/
		Asphalt on deck	95	5	/	/	/
		Waterproofing	100*	/	/	/	/
		Drains and pipes	/	70	30	/	/
		Bearings	80	/	20	/	/
		Expansion joints	/	100	/	/	/

*not available for detail inspection

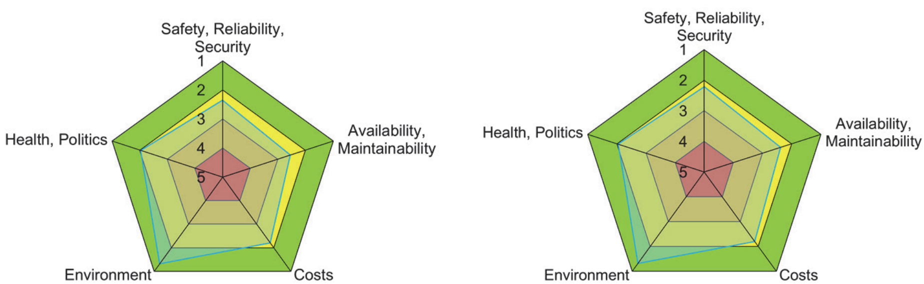

Figure 4 KPIs assessment for Kučki Bridge with (left) and without (right) flood risk [1]

The performance of the Kučki Bridge was evaluated using a multi-criteria KPI framework [4] structured into five groups (figure 4). Within the KPI safety, reliability, and security, the total rating of 2.36 indicates a borderline but stable structural condition, primarily influenced by environmental exposure, moderate deterioration of the concrete cover, and medium corrosion probability derived from electrical resistivity testing. The second and third KPIs, addressing availability and maintainability (2.55) and costs (2.21) highlight the impact of irregular maintenance and environmental aggressiveness on long-term performance and lifecycle expenses. In contrast, the Environment KPI achieved a favourable score of 1.32 due to low traffic intensity and effective drainage containment, while the health and politics KPI (2.04) reflects moderate strategic importance and the need for more systematic maintenance [1]. If the flood risk were excluded, the KPIs for safety and maintainability would be reduced by 6%, while other KPIs would remain constant.

4 Case study II: Kosinj Bridge

4.1 Technical description of Kosinj Bridge

The bridge over the Lika River in Gornji Kosinj is part of County Road in Lika-Senj County (figure 5). Built in 1936, it connects Donji and Gornji Kosinj and was designed by Croatian engineer Milivoj Frković. The bridge is protected as a cultural heritage structure due to its historical and architectural value [2]. Structurally, it is a three-span stone arch bridge with a total length of about 70 m and a deck width of 5.5 m. Three arches with span of 21 m are semicircular and made of locally quarried stone, while a reinforced concrete slab above the arches reduces weight and improves stability. The bridge was specifically designed to resist frequent flooding in the Kosinj Valley. Cylindrical openings in the arches act as relief openings that reduce hydrodynamic pressure and allow water to pass more easily during high river levels, while the piers are shaped to minimise scour. In addition, internal cavities within the bridge structure work together with the relief openings as an effective adaptation to flooding. When the water level rises above the bottom of the openings, water begins to flow through them and gradually fills the internal cavities through pipes located on both sides. Once the water level reaches the top of the openings, the cavities become completely filled with water.

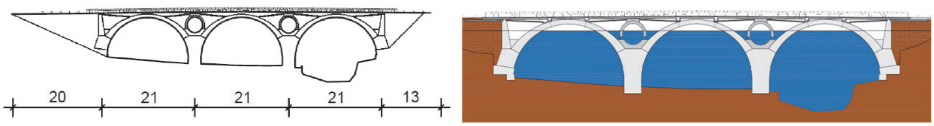

Figure 5 Kosinj Bridge - longitudinal layout (left) and designed solution for flood resistance (right) [2]

This system allows partial flow of water through the bridge, reducing hydrodynamic forces, while the water-filled cavities increase the overall mass of the bridge and improve its stability (figure 5) [2].

4.2 In-service performance of Kosinj Bridge

The Kosinj Bridge was damaged during World War II and was repaired in 1955. The pavement has been repaired several times during its lifetime. The bridge is flooded frequently, often occurring annually or every few years since it is located in one of the most flood-prone regions in Croatia due to the specific karst topography and the behaviour of the Lika River. Despite its 12-meter height above the foundations, the bridge is regularly submerged. When the Lika River overflows, the bridge can disappear completely under water, cutting off the primary road link between two villages. Major flooding events, such as those in 2018 and 2022, have resulted in the bridge being fully submerged for several days (figure 6) [2].

Figure 6 Kosinj Bridge during high water levels of the River Lika

4.3 Condition assessment of Kosinj Bridge

The condition assessment was carried out by evaluating four groups of structural elements (table 2): traffic surfaces and railings, abutment walls, arch intrados, and spandrel walls. Based on the visual inspection guidelines [3], it was concluded that the Kosinj Bridge currently shows no damage that would endanger local traffic of light passenger vehicles. However, without structural analysis it is difficult to accurately determine the remaining load-bearing capacity of the bridge. Additional investigations of the span structure are therefore required, particularly to assess the condition of the internal reinforced-concrete deck due to pronounced pavement cracking and heavy traffic loads. Significant cracks and calcification at the supports of the reinforced-concrete slab on the relief opening and arch crown indicate malfunctioning waterproofing, inadequate slab support, and overload for which the bridge was not originally designed. Numerous pavement cracks and surface irregularities may contribute to reinforcement corrosion due to water and de-icing salts and may also indicate discontinuities in the deck. Weather-exposed stone elements show typical deterioration such as black crust deposits and salt efflorescence, while many joints are overgrown or washed out; in some areas near the springing zones of the edge arches the joints are completely eroded, posing a potential risk of stone block detachment. The Kosinj Bridge should be preserved through a comprehensive conservation–restoration approach. First, diagnostic investigations should be carried out to determine the causes of deterioration, followed by appropriate non-destructive methods such as cleaning stone surfaces, desalination, consolidation of weakened stone, repointing joints, and local repairs. Regular monitoring and maintenance are also necessary to ensure the long-term stability of the bridge. The KPI assessment of the Kosinj Bridge was based on design documentation and the results of a visual inspection, evaluating indicators at the element and structural levels [4]. The analysis considered five KPIs (figure 7) with and without flood risk. The results show moderate to high concerns for safety, reliability and security, availability and maintenance, costs and health and politics (scores around 3.5–3.9), while Environment KPI is relatively low (1.58), indicating that maintenance, restoration, and flood-related risks are the most significant issues for the bridge. If the flood risk were excluded, the KPIs for safety, maintainability, costs and politics would be reduced by 10 -25%, while environmental KPI would remain constant.

Table 2 Damage categorization of Kosinj Bridge [2]

	Level of damage	1	2	3	4	5
Extent of damage [%]	Traffic surfaces and railings	35	14	49	2	/
	Abutment walls	20	54	26	/	/
	Arch intrados	18	/	81	1	/
	Spandrel walls	5	/	88	7	/

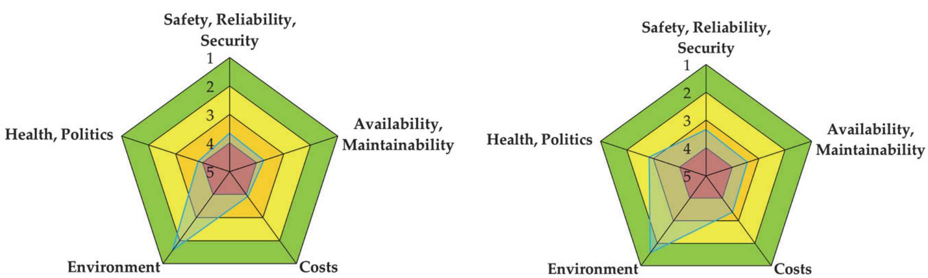

Figure 7 KPIs assessment for Kosinj Bridge with (left) and without (right) flood risk [2]

5 Conclusion

This study examined the impact of flooding on bridge durability through two case studies representing different bridge types and exposure to hydrological hazards. The Kučki Bridge, a modern concrete girder bridge over the Sava–Odra Flood Relief Channel, experienced a major flood shortly after construction. Inspections confirmed structural stability, with only minor deterioration, and rehabilitation was limited to embankment repair, pavement replacement, and a new safety barrier. As the bridge is new and the flood occurred only once, after which the bridge was quickly repaired, the flood did not affect the durability nor KPIs of the bridge. The historic Kosinj Bridge has been exposed to seasonal flooding for nearly ninety years but remains functional. Inspections revealed typical masonry deterioration that does not currently threaten structural safety but indicates gradual degradation and the need for conservation measures and further investigation. Frequent floods over the past 90 years have led to the progressive washout of mortar joints in the stone structure, adversely affecting the durability and load-bearing capacity of the bridge as well as related KPIs. Bridges exposed to high water levels and flooding require proactive maintenance strategies and regular underwater inspections to ensure early detection and timely mitigation of potential pier scour. The use of both traditional condition assessment methods and a KPI assessment supports preventive maintenance strategies and more informed infrastructure management, which is increasingly important under the growing influence of climate change and extreme hydrological events.

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