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RAPID FLOOD VULNERABILITY ASSESSMENT OF BRIDGE NETWORKS: THE CROSSCADE PROJECT CASE

Mirko Kosič[1], Mario Bačić[2], Dominik Skokandić[2], Gordana Hrelja Kovačević[2], Ana Mandić Ivanković[2], Andrej Anžlin[1]
[1] Slovenian National Building and Civil Engineering Institute, Slovenia
[2] University of Zagreb, Faculty of Civil Engineering, Zagreb

Abstract

Recent extreme flood events in Slovenia have highlighted the vulnerability of the bridge network to scour-related stability issues, leading to the failure of several structures. In response to these emerging challenges, this study introduces a streamlined approach for assessing the vulnerability of bridge networks to flood-related risks. Developed within the CROSScade project, this research addresses the flood-related risks of bridges spanning the Sava River near the border between Slovenia and Croatia. A key innovation of this study is the development of a rapid network-level assessment methodology, which allows evaluation of multiple bridges with only limited input data requirements. This methodology facilitates the identification of the most critical bridges, saving time and resources on detailed examination of all bridges in the network. This research aims to equip bridge owners and infrastructure managers with essential insights into their structures' susceptibility to scour and flood hazards. Despite the simplifications inherent in the methodology, the findings can significantly contribute to developing more robust management and mitigation strategies. This, in turn, is expected to enhance the resilience of critical transport networks against natural hazards, particularly in flood-prone regions.

Keywords: flood, vulnerability, assessment, bridge, network

1 Introduction

Recent floods in Slovenia [1] exposed the vulnerability of bridges to such extreme events ( ), even though it was thought that such damages were limited only to countries with less developed infrastructure. An EU co-funded project, CROSScade (Cross-border cascading risk management for critical infrastructure in the Sava River Basin), addressed this issue to some extent. It focused on analysing cross-border risks between Slovenia and Croatia along the Sava River, as this region is prone to flooding and earthquakes. A risk assessment methodology was implemented on mapped critical infrastructure to determine its vulnerability to the cascading cross-border hazard events. This paper presents a rapid flood vulnerability assessment methodology that was developed and applied in the CROSScade. It is suitable for the network level assessment since it enables rapid evaluation of the flood vulnerability of multiple bridges. The main simplification of the approach is that the flood vulnerability analysis is not performed for the entire bridge but only for the most critical pier. Consequently, with only a few essential bridge data, e.g. basic dimension, material properties, etc., rapid assessment can be performed.

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Figure 1 Collapsed bridges in Slovenia after August 2023 floods

2 Examined bridges and flood scenarios

The examined area within the CROSScade project extends along the Sava River, from the Brežice Hydroelectric Power Plant (HPP) (Slovenia) up to Jankomir at the outskirts of the city of Zagreb (Croatia). The area encompasses seven bridges, with two located in Slovenia and five located in Croatia. The locations of the bridges are presented in 0.

Figure 2 Locations of bridges in the case study area

The two bridges in Slovenia are located downstream of the Brežice HPP. The first is a single-column steel truss bridge with two spans, while the second is a 12-span prestressed concrete girder bridge. The bridges on the Croatian side are all multi-span continuous either steel or composite girder bridges with either concrete or reinforced concrete columns. At two locations (bridges 3-4 and 6-7), two bridges are present as they compose the left and right lane of the highway.

The flood scenarios used for bridge vulnerability assessment were derived within the CROSScade project [2]. The considered flood scenarios, harmonized for Slovenia and Croatia, include three (3) return periods of river discharge (Q10, Q100, Q500) and five (5) dam-failure scenarios denoted SC1 to SC5. The dam failure scenarios consider malfunctioning of the HPP gates as a result earthquake or human error, which produce a cascading flood event. Additional details and input data for analysis of bridges can be found in Table 7 of CROSScade Deliverable D4.3 [3].

3 Rapid network-level assessment methodology

The proposed methodology is schematically presented in 0. The first step of the vulnerability assessment is the identification of the critical pier and the collection of the basic geometric properties and material data of the pier. The critical pier is identified as the pier situated within the riverbed with the largest flood actions relative to its capacity.

The approach is designed to provide conservative estimation of actual bridge vulnerabilities so that bridges which pass network level assessment can be screened out from additional (more comprehensive) examination. The essential input data for network level assessment of bridges is summarised in 0. It includes basic dimensions and material properties of the pier, cross-section properties, vertical reaction from deck at top of the pier, boundary condition at the top of the pier, pier nose shape and information if the pier is founded on rock. The latter is used to define if the pier is susceptible to local scour. The critical pier is analysed as a simple beam-column element (see 0). The simple pier element is considered fixed at the base, while the boundary condition at the top is defined as either fixed or pined. The model is used to assess the internal forces in the pier which occurs due to hydrodynamic and debris loads.

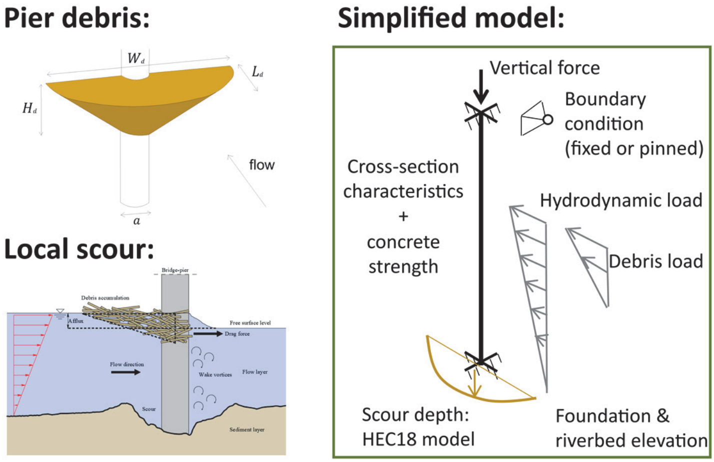

Figure 3 Schematic representation of the flood vulnerability methodology

Table 1 Required input data for network-level assessment of bridges

Parameter	Description
h	Pier height above foundation (m)
L	Pier length (in direction of flow) in (m)
a	Pier width (perpendicular to flow) in (m)
$H_{f,t}$	Elevation of the top of the foundation (m.a.s.l.)
$H_{f,b}$	Elevation of the bottom of foundation (m.a.s.l.)
H_{rb}	Riverbed elevation (m.a.s.l.)
f_{ck}	Characteristic concrete compression strength (MPa)
A	Cross-section area of pier (m^2)
I_{zz}	Moment of inertia of the pier perpendicular to flow (m^4)
A_{sy}	Shear area of the pier (m^2)
W_{zz}	Section modulus of the pier perpendicular to flow (m^3)
$F_{v,t}$	Vertical force at top of pier due weight of the deck (kN)
TopRest	Boundary condition at top of the pier (Fixed or Pinned)
PierShape	pier nose shape (Rounded or Square shape)
Founded on rock	If NO - scour is considered; otherwise scour is neglected

The flood loads acting on the bridge depend on water height and velocity. The hydrodynamic force acting on the pier is computed as [4]:

$$F_d = 0.5\ C_d\ v^2\ A_d \tag{1}$$

where C_d is the drag coefficient, v is the average water velocity and A_d is projected wetted area in the direction of the flow. For piers with rounded nosing, the coefficient C_d equals to 0.7, while for square-end pier C_d equals to 1.4.

The debris loads were computed according to the Panici and Almeda model [5], which foresees that the shape of the debris mat is half-cone pointing downward (see 0). The debris force is computed using eqn. (1) considering the area of debris and drag coefficient of 1.6 as defined in [5]. The debris dimensions depend on the water velocity (v) and the so-called key log length (L_L). The latter represents the longest wood debris that can be encountered in the upstream reach of the river [5]. Based on recommendation provided in [6], the parameter L_L was set to 16 m, which is expected to results in upper-bound estimation of the debris raft dimensions.

The computed hydrodynamic loads and wood debris forces are applied to the simple pier model as uniformly distributed loads, considering an inversed triangular distribution of the water height (0). The loads are used to calculate the internal forces of the pier (bending moment, shear forces). These are compared to conservative estimates of the pier's bending and shear capacity. To limit the required input data for verification and provide additional conservatism, the pier bending and shear capacity is estimated neglecting the contribution of reinforcement. The bending capacity of the pier is defined considering the crack moment of the section, while the shear capacity is defined according $V_{rd,c}$ equation from EN1992-1-1 [7].

For bridges located on scour susceptible soil (not founded on rock), the local scour depth around the bridge pier is calculated using the HEC18 empirical model [8]:

$$y_s = \left[2.0\ K_1\ K_2\ K_3 \left(\frac{H}{a} \right)^{0.35} Fr^{0.43} \right] a \tag{2}$$

where , , are correction factors for pier nose shape, angle of attack of flow (θ), riverbed conditions, respectively, a is the pier width, and is the Froude number which depends on H and v of the flow.

Debris accumulation against the pier result in an increase in scour depth due to constriction and redirection of the water flow. The effect of debris on the local scour of the pier was considered according to the approach by Lagasse et al. [9]. The approach relies on the quantification of the equivalent pier width (), which is then used in eqn. (2) for quantification of the scour depth with consideration of debris. Details on the implementation can be found in [3].

The final step of the assessment is the verification of the bridge limit states. Two limit states are considered: the Serviceability Limit State (SLS) and the Ultimate Limit State (ULS). The first is related the serviceability of the bridge during flooding, while the second is related to verification of the safety of the bridge against failure.

The bridge is assumed to exceed its SLS if the scour depth exceeds 50% of the foundation depth or if the water height reaches the top of the pier. If flood reaches the level of the deck, the forces on the bridge are expected to increase significantly. Such scenario is out of the scope of the proposed simplified methodology and requires more detailed examination.

The bridge is presumed to failure, i.e. reach its ULS, if the computed scour depth reaches the foundation's depth or if the bending/shear capacity of the critical pier is exceeded.

4 Results

The methodology from the previous chapter was applied for rapid flood vulnerability evaluation of the bridges in the case study area. The input data for assessment was performed based on available project documentation. Inputs are summarised in Table 2.

The information of the concrete compression strength was only available for bridge No. 2. Due to lack of more precise information same value (25 MPa) was used also for the remaining bridges. The vertical reactions at top of the pier were estimated based on design documentation. With exception of the bridge No 2., the boundary condition at top of the pier was always considered to be pinned. All bridges have rounded pier edges, which is favourable since it results in smaller hydrodynamic load and local scour depth compared to sharp-edged sections.

Table 2 Input data for network level vulnerability analysis of bridges

ID	1	2	3	4	5	6	7
h	7.4	11	8.51	7.8	6.8	6	6
L	9.8	1.2	11.6	11.9	10.4	3.5	3.5
a	2.8	1.2	3.2	3.2	3	2	2
$H_{f,t}$	140.6	137.3	121.4	121.4	121	119.2	119.2
$H_{f,b}$	134.3	128.9	114.1	114.1	116.3	105	85.3
H_{rb}	136.3	137.3	121.4	121.5	116.3	111.7	111.7
f_{ck}	25	25	25	25	25	25	25
A	25.82	1.13	14.30	14.60	31.20	7.00	7.00
I_{zz}	185.94	0.10	204.37	222.50	281.22	7.15	7.15
A_{sy}	20.66	1.02	11.44	11.68	24.96	5.60	5.60
W_{zz}	37.95	0.17	35.36	37.27	54.08	4.08	4.08
$F_{v,t}$	4075	2200	9000	9500	2400	3200	3700
TopRest	Pinned	Fixed	Pinned	Pinned	Pinned	Pinned	Pinned
PierShape	Round	Round	Round	Round	Round	Round	Round
Founded on rock	YES	NO	NO	NO	YES	YES	NO

Three of the examined bridges, i.e. bridges No 1, 5, 6, are founded on marl bedrock, which in some cases can be scour-susceptible, but relatively negligible compared to the soil-like materials. Therefore, it was assumed that these bridges are unaffected by scour issues on flood-to-flood basis. The remaining bridges (No 2-4, 7) are founded on scour prone gravely soils and were thus examined for scour-induced issues.

The results of the vulnerability assessment are the SLS and ULS indexes presented in 0. A value of zero indicates that the limit states are not reached, while a value of 1, indicated that a specified limit state is exceeded.

As can be seen from 0, the SLS is only reached for the two bridges in Slovenia (No 1 and 2). For the bridge No 1, the SLS is reached because of water height exceeding the top of the pier for scenario Q500. Such case is out of scope of the simplified methodology. As a result, the bridge was designated for more precise bridge-specific flood assessment for such scenario. In case of the bridge No 2, both the SLS and ULS are trigged because the moment in the pier exceeded the crack capacity of the section. This bridge did not pass the rapid network level assessment and is therefore designated for more precise bridge-specific assessment.

The remaining bridges are expected to be serviceable during all flood scenarios. Scour evaluation of bridges No 2 and 7 indicated maximum scour depth potential of 3.8 m and 4.6 m for dam failure scenario SC2 and Q500, respectively. However, since both bridges are founded on deep pile foundation, the scour depth never exceeded 50% of foundation depth. In case of bridges No 3 and 4, available geotechnical data indicate that scour susceptible soil is only present up to a depth of 2.8 m, which is less than 50% of foundation depth (0.5 * 7.3 m = 3.65 m). This implies that the SLS of the bridges is not expected to be exceeded.

With the exception of bridge No 2, which have the slenderest piers, the internal forces in piers were significantly lower than their capacities, indicating that bending or shear failure of the piers due to flood loads is unlikely.

Table 3 SLS and ULS indexes of the bridge for different flood scenarios

SLS index - (0) SLS is not reach, (1) SLS is exceed								
ID	**Q10**	**Q100**	**Q500**	**SC1**	**SC2**	**SC3**	**SC4**	**SC5**
1	0	0	**1**	0	0	0	0	0
2	0	0	0	0	**1**	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
ULS index - (0) ULS not reached, (1) ULS is exceeded								
ID	**Q10**	**Q100**	**Q500**	**SC1**	**SC2**	**SC3**	**SC4**	**SC5**
1	0	0	**N.A.***	0	0	0	0	0
2	0	0	0	0	**1**	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0
*not applicable								

5 Conclusions

The paper introduces a simplified flood vulnerability assessment methodology specifically designed to rapidly evaluate multiple bridges across a network. This method offers a conservative approximation of the actual vulnerability of bridges. Consequently, bridges that pass the network-level evaluation can be excluded from subsequent, more detailed analyses. This strategic approach facilitates pinpointing the most vital bridges, thereby economizing both time and resources that would otherwise be expended on conducting thorough examinations of all bridges in the network. The methodology was applied to the bridge network analysed in the context of the CROSScade project, revealing that the vast majority of bridges remained functional during flood events. However, the two most critical structures were identified for further detailed assessment.

This research aims to help bridge owners and infrastructure managers with critical insights into the vulnerability of their assets to scour and flood-related threats. Despite the simplifications embedded within the proposed methodology, its application can aid the formulation of more effective management and mitigation strategies and, therefore, boost the resilience of essential transportation networks against natural hazards.

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