UTJECAJ VODOTOKA NA SIGURNOST MOSTOVA

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Sažetak: Neizravno djelovanje vodotoka predstavlja opasnostza sigurnost mostova jer uzrokuje podlokavanja dijelova konstrukcije, odnosno mijenja geometriju početnog projektnog stanja, i time ju stavlja u nove uvjete opterećenja. Periodičkimpregledomstanja korita i konstrukcije mosta u vodi se utvrđuje stvarno stanje mosta te pripadna ocjena, preporuke o mjerama praćenja stanja,održavanja i/ili sanacije i intervalu sljedećeg pregleda. Podloga za procjenu opasnosti od podlokavanja za pojedini most i ocjenu stabilnosti korita je morfodinamička analiza erozivnog kapaciteta toka na samom mostovskom profilu i pripadnoj dionici vodotoka. U ovom radu prikazani su rezultati specijalističkih hidrografskih mjerenja, morfodinamičke analize stabilnosti korita i zaštitnih građevina te podvodnog vizualnog pregleda elemenata konstrukcije mosta koje je proveo Građevinski fakultet u Zagrebu.Za kategorije ocjena stanja korita „dobro“ i „loše“ izdvojeni su primjeri iz Hrvatske na kojima su evidentirana karakteristična oštećenja za pojedinu kategoriju koja podrazumijevaju potrebu za održavanjem ili sanacijom.

Ključne riječi: Erozija, morfodinamička analiza, most, podlokavanje, podvodni pregled, ADCP

INFLUENCE OF WATERCOURSE FLOW ON BRIDGE SAFETY

Abstract Indirect action of flow poses a risk to bridge safety as it results in scouring of structural elements, i.e. it changes the geometry of the initial design state and thereby subjects it to new loading conditions. Periodic inspections of riverbed and bridge structure under water establish the actual bridge condition and associated rating, recommendations for monitoring, maintenance and/or repair measures and time to next inspection. Estimation of scouring hazard for a particular bridge and riverbed stability assessment are based on morphodynamic analysis of the erosive capacity of flow on the bridge profile and adjacent watercourse section. This paper presents the results of specialist hydrographic surveys, morphodynamic analysis of the stability of riverbed and protection structures, and underwater visual inspections of structural bridge elements conducted by the Faculty of Civil Engineering Zagreb. For riverbed condition category ratings “good” and “poor”, examples from Croatia where for a particular category characteristic damage is established involving the need for maintenance or repair are singled out.

Key words: Erosion, morphodynamic analysis, bridge, scour, underwater inspection, ADCP

1 INTRODUCTION

We witness bridge damage or collapse incidents that unfortunately sometimes end in fatal outcomes, loss of human lives, injuries to persons and considerable material damage. In many cases the cause of these losses of fundamental structural requirements is the effect of water flow. It can be direct, as the hydrodynamic action caused by water flowing around structural elements of bridges, or indirect, through the effect of water on riverbed geometry changes in the bridge zone. It is this indirect action that is very dangerous as it causes scouring of parts of the structure and thereby subjects it to new conditions. That is, it changes the geometry of the initial design state, and in this way it also changes the static plan and/or foundation conditions. Safety of a building and its elements generally means its sufficient mechanical resistance and stability. Periodic inspections are conducted in order to ensure the safety of structures during their service life. When inspecting the state of a bridge structure, very often the priority is to analyze the state in terms of mechanical resistance, while less attention is paid to stability. Such a practice is without foundation for the stated reason of the dominant effect of water on damage to bridges, or on their safety being at risk. Therefore, it is necessary to accept this fact, and for bridges in alluvial valleys primarily more intensely conduct inspections of riverbeds and condition of structure foundations across the stream.

The available data from the study of bridge failures around the world since 1980 [1], which ultimately included 1062 bridges, show that the events caused by water and sediment regimes had the most predominant influence on damage to bridges: 18.8% failures occurred due to scour and 28.3% as a consequence of structural effects of floods, which makes 47.1% combined. The U.S. infrastructure survey [2] indicates that the annual probability of bridge failure, within the 95% confidence interval, is 1/4700, resulting in expected failures of 128 bridges on an annual basis when recalculated relative to the existing number of bridges. In the study of Muñoz Díaz and associates conducted for Colombia in the period from 1986 and 2001, the cause of collapse of as much as 70% bridges was hydraulic [3]. Imhof analyzed a similar worldwide database and concluded that natural disasters accounted for 29.3% of bridge collapse causes, of which 61% were hydraulic causes [4].

Along with hydraulic causes, the largest number of failures is due to impacts of vehicles, which is a category primarily related to road bridges carrying one road over another, so they are not in watercourse zones and consequently hydraulic loads are not applicable to these bridges. So, eliminating the bridges to which hydraulic causes are not applicable, we can conclude that on the remainder the percentage of their influence is higher than the available figures. These insights are not news - numerous studies analyzing 19th-century bridge collapses show that flooding and scouring of structures are the cause of collapse in more than 50% of cases (e.g. [5][6][7]).

2 HYDRAULIC CONDITIONS IN THE BRIDGE PIER ZONE

Hydraulic causes are a frequent common denominator that combines the effects of scour and flood, which result in increased or unexpected variable loads on the structure (increased pressures, flow over the superstructure, impact of floating sediments), as well as the effects of standing or moving ice. During the service life of a bridge, it will inevitably come under the influence of extreme variable loads resulting from the action of wind, water or earthquakes which, when combined with constant load, can compromise the stability of the structure [1]. Natural erosion processes that endanger bridges need to be considered in a wider context since their causes are in a wider catchment area and do not necessarily have to be obvious in the vicinity of the structure. Many challenges in bridge maintenance and development of a methodology for designing structures resistant to multiple natural disasters can be solved, or at least their understanding can be improved, by collecting and describing historical bridge damage data, in which process the data on bridge damage causes and their consequences are collected by direct observation [8]. Therefore it is necessary to use an engineering approach to the problem, i.e. based on indicators to identify the processes that can potentially endanger the structure [9][10]. Assessment of bridge condition without accompanying analysis of water and stream sediment regimes proved to be insufficient based on the New York federal state bridge collapse data [8].

The erosion effects of flow on the riverbed near the bridge can be divided into three characteristic mechanisms: global erosion, erosion due to flow constriction, and local erosion. Global erosion results from an imbalance in the regime of the bed-forming stream sediment and is manifested by morphological changes of the entire bed in the form of its lowering or rising, including the lateral migration of banks. Erosion due to flow constriction usually develops as a result of construction of a road embankment on the riverside flood strip, which significantly narrows the flow profile during a surge of high water and concentrates an increased force of flow through the bridge profile. Local scour is the most substantial when piers and abutments are located in the main riverbed, which results in longer streamlines around the structures, and consequently higher flow velocity, turbulence and local capacity of flow to erode the bed.

Most surveys of the phenomenon of local erosion were carried out for the purpose of determining the impact around bridge piers. According to theoretical considerations, the physical process of bridge pier scouring is influenced by a number of parameters: dynamic coefficient of viscosity μ, water mass density ρ, gravity acceleration g, mean flow velocity v, flow depth h, sediment particle diameter d, standard deviation of grain size distribution σ_g, effective width of pier b_{eff}, water flow attack angle ϕ, etc. The mathematical description of such a complex process introduces a number of restrictions, and so the available calculation formulas are adapted to the characteristic structure and stream conditions. The simplest equations for calculating scour around pier are those in which the functional dependency is defined by a single relevant parameter, e.g. pier width b and associated correction coefficients, such as Larras (1963), Breusers (1965), Breusers et al. (1977). An example of such an equation, deduced by Larras[11], is shown below:

$$h_{E(LS)} = 1{,}42 \cdot K \cdot b^{-0{,}25}, \tag{1}$$

where $h_{E(LS)}$– is the local scour depth [m], K – pier shape coefficient [/], b – pier width [m]. Equations in which flow depth h appears as the relevant parameter along with pier width are deduced for piers with shapes deviating from regular shapes, such as circular or rectangular ones. An example of such an equation is Laursen (1958) which also takes into account the effect of pier shape and angle of flow attacking it [12]:

$$\frac{b}{h} = K \cdot 5{,}5 \cdot \frac{h_{E(LS)}}{h}\left[\left(\frac{1}{11{,}5} \cdot \frac{h_{E(LS)}}{h} + 1\right)^{1{,}70} - 1\right], \tag{2}$$

where h– is mean flow depth [m], K – is pier shape coefficient if pier is parallel with flow or flow attack coefficient if there is an inclination of the pier from flow [/]. In subsequent studies, flow velocity was also included in the calculation of scour as a measure of its intensity. Thus, flow velocity appears in Coleman's equation (1971) as an independent variable [13]:

$$\frac{v}{\sqrt{2 \cdot g \cdot h_{E(LS)}}} = 0{,}6 \cdot \left(\frac{v}{b}\right)^{0{,}9}, \tag{3}$$

where v– is mean flow velocity [m/s], g– gravity acceleration [m/s^2]. In other equations that use flow velocity, it is included indirectly, usually using the Froude number, as is the case in the equations Hancu (1971), Colorado State University (CSU, 1975), Jain & Fischer (1980) and Jain (1981). The Hancu equation, in which Froude's threshold particle mobilization number appears, is presented below:

$$\frac{h_{E(LS)}}{b} = 2{,}42 \cdot \left(2\frac{v}{v_{gr}} - 1\right) \cdot \left(\frac{v_{gr}^2}{g \cdot b}\right)^{1/3}, \tag{4}$$

where v_{gr}– is the threshold flow velocity for mobilization of sediment particles [m/s], and the last term in the equation is the Froude number. In Jain's equation, the Froude number is present in its original flow-related form. The following is Jain's equation [15]:

$$\frac{h_{E(LS)}}{b} = 1{,}84 \cdot \left(\frac{h}{b}\right)^{0{,}5} \cdot Fr^{0{,}25}. \tag{5}$$

In addition to the Froude number, flow velocity can also be represented within the Reynolds number, as is the case for the equation of Shen et al. (1969). By a series of experiments, they established that local scour occurs due to the difference in pressure around the pier and introduced the Reynolds number in the equation as follows [16]:

$$h_{E(LS)} = 0{,}000223 \cdot \left(\frac{v \cdot b}{\nu}\right)^{0{,}619}, \tag{6}$$

where ν– is the kinematic viscosity of the liquid [m^2/s]. In addition to the aforementioned equations, a group of authors led by Melville (1997) suggests equations that consist exclusively of empirical parameters representing pier geometry, measure of flow intensity, composition and shape of the bed and bed-bridge interaction. The equation of Mellville [17, 18] is shown below:

$$h_{E(LS)} = K_{hb} \cdot K_I \cdot K_d \cdot K_s \cdot K_\theta \cdot K_G, \tag{7}$$

where the K coefficients represent non-dimensional empirical parameters reflecting different effects on scour depth: K_{hb}– the parameter of combined effect of flow depth and pier width [/], K_I – flow intensity parameter [/],K_d – sediment size parameter [/], K_s – pier shape parameter [/], K_θ – flow attack angle parameter [/], K_G – bed shape parameter [/]. These parameters are calculated through a functional dependency with relevant flow and structure parameters. The extent to which these equations give different calculation results is evident in the following figure (Figure 1)[19, 20].Figure 1. The $h_{E(LS)}$ dependency on the example of the Jakuševac bridge, adapted by courtesy of [19]1

From this it can be concluded that the reliance on results of theoretical equations is very unreliable and only measurements of actual depths of bridge pier scour within systematic monitoring can be the basis to ensure safety of bridges.

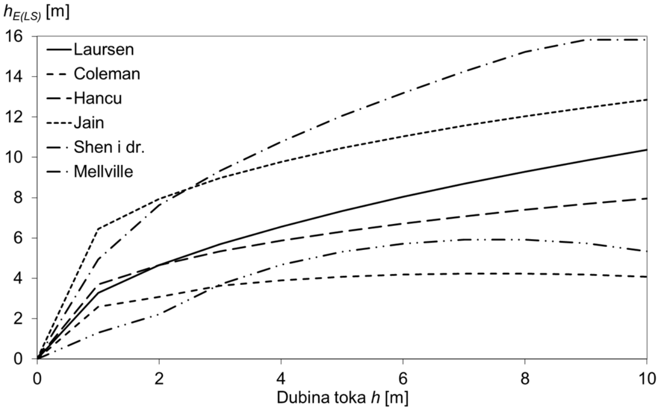

Figure 1. The $h_{E(LS)}$ dependency on the example of the Jakuševac bridge, adapted by courtesy of [19]1

3 UNDERWATER INSPECTION OF BRIDGES

Maintenance of bridges in Croatia is governed by the *Construction Act* (OG 153/13, 20/17), the *Regulations on maintenance of buildings* (OG 122/2014) and *Regulations on road maintenance* (OG 90/14) with the aim of preserving the basic requirements for structures and improving compliance therewith. These regulations stipulate protection from scouring of structural elements situated within reach of watercourses, as well as their repairs in case of damage [21]. In order to be able to establish maintenance and repair measures for already constructed bridges in accordance with their condition, the condition needs to be established first. Monitoring of the condition of existing structures is conducted by continuous and periodical inspections in accordance with legal acts. The beginnings of bridge inspections in Croatia date back to 1996 with the introduction of the Croatian Bridge Management System (*HRMOS*), which was implemented in the Croatian Motorways Road Database System (*BCP*) [22]. The Croatian Motorways use the Facility Management System (*SGG*) established in 2008, which covers all structures within the motorway system, including bridges. The current practice of Croatian Roads and Croatian Motorways includes regular, annual, main and extraordinary inspections of bridges. The interval of annual bridge inspections within the transport infrastructure is two years, of main inspections six years, while extraordinary inspections are carried out as circumstances require after extraordinary events such as natural disasters [22]. In case that these inspections reveal significant damage or indications of its occurrence, it is necessary to carry out a specialist inspection oriented to the particular type of damage.

Underwater inspection of bridges is not uniform, but depends on the legislation of each individual country and guidelines of bridge managing agencies. Each of them usually has guidelines developed within the existing bridge management system that prescribe damage quantification methods and calculations. In Denmark, Finland, France, Norway, New Zealand, Germany, Portugal, Sweden, the United Kingdom and the United States, underwater inspections are conducted at intervals of one to six years and include a visual inspection of all parts of the bridge within reach of touch [21]. When the damage is identified or shown to be likely to occur, detailed/specialist inspections are carried out and data is collected, based on which measures for the repair of bridge elements and riverbed are designed. Specialist inspections are usually conducted by consultants since they require specific knowledge, skills and equipment that vary depending on the bridge structure and type of watercourse. The most detailed book of regulations for underwater inspection of structures in Croatia is currently the regulation book 315 of Croatian Railways titled "*Regulations on maintenance of railway substructure of the Yugoslav Railways*" from 1970 [23]. Using this book of regulations as the basic document, the Faculty of Civil Engineering conducts specialist inspections and tests on bridges of the infrastructure of Croatian Railways (*HŽ*), Croatian Motorways (*HAC*), Rijeka-Zagreb Motorway (*ARZ*) and Zagreb-Macelj Motorway (*AZM*), and on the basis of inspection results and scour risk analysis, assigns a condition rating, recommendations for maintenance and/or repair measures, and interval for the next inspection to bridges.

The above-mentioned book of regulations 315 of *HŽ* does not stipulate structural condition ratings, so the Faculty of Civil Engineering uses for assessments the U.S. *National Bridge Inspection Standards* - NBIS [24]). Action of flow is quantified on all bridge and riverbed elements interacting with flow using the Commonly Recognized (CoRe) Bridge Elements [24][25], defined based on NBIS. Thus, each location is evaluated using four elements: the angle of attack of flow on the structure, the global stability of the riverbed, the erosion due to flow constriction and protection (regulation) structures. In this context, the Faculty of Civil Engineering conducts specialist hydrographic measurements, morphodynamic stability analysis of the riverbed and protective structures and underwater visual inspection of bridge structure elements. Visual inspection is carried out in a wider area of the watercourse near the bridge at low water level, as well as on the bridge elements themselves whose underwater parts are inspected with the assistance of divers [21]. The result of the inspection and hydraulic analysis is two ratings for each bridge: the rating of the condition of the structure under water and the rating of the condition of the riverbed. The range of ratings is identical to that used in the NBIS standard, from zero to nine, where zero is the rating of a collapsed bridge, and nine rating of a bridge in excellent condition. This way of grouping the ratings, where four ratings from the NBIS standard are converted into two ratings, was done for practical use for the bridge owner who can only perform repair of the facility being managed, thus eliminating the possibility of a likely intervention in the riverbed on a larger scale. Independent of the introduction of a unified rating, a detailed analysis and review of all the elements stipulated by the NBIS was made and their state and contribution in the overall riverbed rating were described in studies.

4 EXPERIENCES FROM CROATIA

On Croatian motorways, there is a total of 3030 bridges [26], of which *AZM* singled out 13 bridges for underwater visual inspection in 2012 [27], and in 2015 *HAC* [28] and *ARZ* [29] singled out a total of 22 bridges to be undergone a specialist inspection which, in addition to underwater inspection, included also a hydraulic study. The inspections and surveys were carried out on a total of 11 bridges over rivers, five bridges over streams, 18 bridges over channels and one bridge on the sea. Of all the analyzed bridges, this paper focuses on those with characteristic damage from each of the above groups, as well as the examples from practice where the damage caused by the action of water was repaired.

Regardless of the type of watercourse, most of the analyzed bridges are in very good condition and it is not necessary to carry out riverbed maintenance or repair works for eight bridges (23%), and underwater structure maintenance works for 18 bridges (51%). Good condition, or minor repairs required to bed and structure, is registered for 22 bridges (63%), and 14 bridges (40%), respectively. Major repairs are required for the smallest number of bridges with poor state: it is necessary to repair the bed for five bridges (14%) and structure for only three bridges (9%). None of the bridges were found to have an exceptionally poor condition of the bed or the structure that would require an immediate intervention and repair. The figure below shows the box-like diagram of bed (Figure 2a) and structure (Figure 2b) condition ratings for each group of bridges separately.Figure 2. Box-like diagram of condition ratings: a) beds (left); b) structures (right)2Figure 2. Box-like diagram of condition ratings: a) beds (left); b) structures (right)2

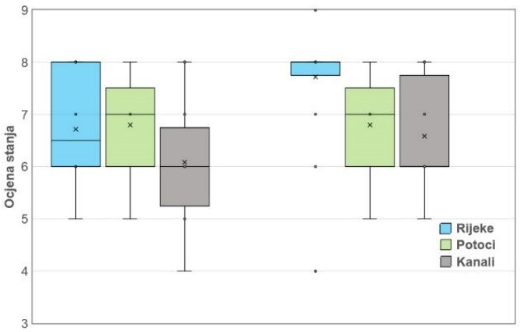

Figure 2. Box-like diagram of condition ratings: a) beds (left); b) structures (right)2

If bridges are considered on the basis of watercourse group, it is evident that channels are in the best condition in terms of structure, with an average rating of 7.6, while streams and rivers have slightly lower ratings (6.8 and 6.6), which is expected because bridges over channels rarely have piers in water, and they are most often single-span RC structures. Channels also have high average ratings of the condition of bed (6.7), which is slightly lower than streams (6.8). Rivers are rated lowest in this category too (6.1). It is evident that the range of ratings for the condition of bed is largest for channels, while the range for rivers and streams is equal with greater interquartile range. The range of ratings of the condition of structure is largest for rivers, but with a very small interquartile range, while for streams and channels the total range is equal with a slightly greater interquartile range for channels.

The condition of bed and the condition of structure are in a positive correlation, i.e. if the rating assigned to the underwater condition of a structure deviates from the rating of the bed at the level of the analyzed three classes, the deviation is not more than 1 rating in the positive or negative direction. The opposite is also true if considering classes of ratings assigned to the condition of structure. Thus. of the bridges with the condition of bed rated as very good (≥ 8), only the Krk bridge have a lower rating of the structure, that is 6. On the Krk bridge, scattered damage is observed on structural elements - under the bracing on the mainland side and on the foundation and arch on the Krk side. Of the bridges with the condition of bed rated as good (6 and 7) only the Orljava bridge has a lower rating of structure, that is 5. Damage is observed on piles of two piers of this bridge, i.e. holes between 15 cm and 20 cm in width and depth. The bridges with the condition of bed rated as poor (4 and 5) are the larger bridges on the Sava and Drava rivers, as well as the bridge over the Kupčina River and the bridge over the Lateral Channel. While the condition of structure of the latter two bridges corresponds to the condition of bed, the state of structure under water of the larger bridges over Save and Drava is better (rating 6). For bridges on the Drava River, it is the operation of the hydroelectric power plant that causes sudden changes in the water regime and consequential registered global lowering of the bed in relation to the design state. For the bridge with the poorest bed condition rating (4), Ivanja Reka, the adverse condition of the bed is the consequence of local erosion around the rip-rap that protects the pier against local erosion. The rip-rap significantly narrows the flow profile of the Sava River and causes deep scour holes to occur immediately next to the rip-rap, undermining it and thus causing rock to fall into the holes [30].

If the bridges with very good condition of structure are singled out, it is apparent that six bridges over channels have lower respective ratings of bed (6). This is the case of bridges carrying the motorway over the channels which intersect the motorway at an angle lower than 90°. In these cases, sudden changes in bed geometry are usually made in order for the bridge to form a right angle with the bed and to simplify the bridge design. The sudden change in geometry negatively reflects on the water and sediment regime in bridge profile resulting in bank collapse and undermining of bed revetment, which often accompanies this type of bridge design [21]. Of the bridges with good condition of structure, only three largest analyzed bridges over the Sava and Drava rivers have lower associated bed ratings, as already described. Only three bridges have a poor rating of the condition of structure under water: Orljava, Kupčina and Lateral Channel. At the Kupčina bridge, the piers and abutments are without visible damage, but damage is observed to the service road on the right bank in bridge profile, where a concrete wall has settled and separated from the pavement slab of the service road. It is unknown to what extent the abutments rest on the thus made service road, which results in the low rating. At the bridge with the poorest underwater structure condition rating (4), the Lateral Channel, two damage spots were observed on the footing of a pier - a 25 cm deep crack along the face of the pier and damage to the footing extending 60 cm to depth. Taking into account the bridges with poor condition of structure or bed, *HAC* made a priority list, and so the public procurement procedure is in progress for execution of works for the Orljava Bridge and the environmental impact assessment is in progress for the Ivanja Reka bridge. Other bridges with lowest bed condition ratings (bridges over Drava and the Lateral Channel) are the next for repairs [31].

For the bed condition rating categories "good" and "poor", examples where for a particular category characteristic damage is established involving the need for maintenance or repair are presented in further text. For each bridge, a morphodynamic analysis of erosive capacity of flow was conducted and the stability of bed was assessed with respect to the action of global erosion, erosion due to flow constriction and local scouring. Hydrological and hydraulic parameters of flow on the observed section were determined from the hydraulic model of stationary flow. The potential of global erosion was established by analyzing the threshold velocity dependent on the composition of bed and by comparing the bridge profile geometry from available historical data with that obtained by geodetic surveying for the purposes of this study. The erosion progress analysis was established by comparing the maximum potential erosive effect of flow with actual condition of the bed determined by geodetic surveying. The potential of maximum erosive effect of flow in the form of erosion due to constriction of flow and local scour was calculated using the previously calibrated mathematical model HEC-RAS for conditions of medium and high water flow around the bridge elements. An assessment of the erosive capacity of flow in the bridge zone as well as of local scour under the piers was given, and on the basis of the conducted analyses, the possible impact of bed erosion on the stability of the bridge was evaluated. The model was calibrated based on hydraulic measurements of the flow velocity field and of the flow during two hydrological events of different intensities.

4.1 Ljubanj II

For this bridge, morphodynamic analysis established that the effect of global erosion on the bed in the vicinity of the bridge is not likely in either medium or high water conditions, with flow velocities in the bed being negligible (<0.5 m/s) and not posing a risk for mobilization of particles from the bed since the allowable flow velocity for the analyzed watercourse ranges from 0.8 m/s to 1.2 m/s. This conclusion was confirmed by comparing the historical bridge profile and record of the current condition, because the records coincide. Local scour around the bridge piers is not present because the bridge is protected from the effects of erosion by concrete lining of the bed over the bottom and slopes in the bridge profile. Immediately next to the bridge, the channels collecting surface drainage from the road, whose bottoms are at the same level as the bottom of the Ljubanj II channel, connect to the watercourse on both of its banks. Confluences of the collecting channels are not lined, but are in natural earth excavation and the collapse of their banks to the bed is registered at the confluence (Figure 3a).Figure 3. Collapse of the bank at the confluence of the collecting channel (left); a detail of the scoured concrete lining of the right bank (right).3

Figure 3. Collapse of the bank at the confluence of the collecting channel (left); a detail of the scoured concrete lining of the right bank (right).3

The results of the longitudinal flow velocity profile show that the flow is uneven on the section - the lowest velocities occur in the bridge profile, while higher flow velocities occur on the upstream and downstream watercourse sections. In addition to causing the bank to collapse, increased flow velocities at the confluence of the channels also affect the stability of the lining of channel banks in the bridge profile. The collapse of bank at the confluence of the collecting channel resulted in the erosion of soil under the concrete lining and its scouring at the upstream end. The undermining of the lining is additionally stressed by the events of more intense runoff from the road.

4.2 Lateral Channel

Velocities in the bed of the Lateral Channel are negligible (<0.27 m/s) in medium water conditions, while in high water conditions there is a significant increase in flow velocity in the bed upstream (0.72 m/s) and downstream from the bridge (0.55 m/s). In spite of the significant increase in flow velocity in relation to medium water conditions, there is no risk of global erosion since the allowable flow velocity ranges from 0.8 m/s to 1.2 m/s for the analyzed watercourse. Immediately upstream from the bridge, the service road passes through the bridge profile next to the right bank, and construction of its ramp in the bed has constricted the flow profile and directed a major part of flow towards the left bank (Figure 4a). It was calculated by the mathematical model that, in high water conditions on the thus constricted profile, the flow velocity locally reaches the value of threshold velocity for mobilizing the material from the bed (0.86 m/s), thus satisfying the conditions for occurrence of erosion due to constriction of flow in the bridge profile. This consequentially results in local increase of velocity in the left bridge opening and erosion of the bank (Figure 5a), as evidenced by comparison with the historical record. The bed erosion coincides with the location of the calculation profiles with increased hydraulic load on the bed, i.e. the erosion of the bottom of the bed in the bridge profile resulted from the constriction of flow. Sedimentation to the bed next to the right bank, which was subsequently covered by dense vegetation, was registered upstream from the ramp.Figure 4. Lateral Channel: a) constriction of flow profile upstream from the bridge, view from the right bank (left); b) inverted flow velocity profile on orthophoto map (right)4Figure 5. Erosion due to constriction of flow in the left bridge opening (left); view of the scour hole next to the upstream face of the pier S1/15

Figure 4. Lateral Channel: a) constriction of flow profile upstream from the bridge, view from the right bank (left); b) inverted flow velocity profile on orthophoto map (right)4

Using mathematical model, the potential local scour around bridge piers in the bed was calculated and it is $h_{E(LS)}$= 0.54 m for medium water conditions and $h_{E(LS)}$= 1.14 m for high water conditions. The measured depth of the local scour hole around bridge piers is 1 m, which corresponds to the effect of high water estimated by the model. The following figure (Figure 5b) shows the scour hole around the pier S1/1, as well as the erosion due to constriction of flow of the left bank (Figure 5a).Figure 5. Erosion due to constriction of flow in the left bridge opening (left); view of the scour hole next to the upstream face of the pier S1/15Figure 5. Erosion due to constriction of flow in the left bridge opening (left); view of the scour hole next to the upstream face of the pier S1/15

Figure 5. Erosion due to constriction of flow in the left bridge opening (left); view of the scour hole next to the upstream face of the pier S1/15

The safety of piers undermined like this cannot be estimated because they are founded on "... footings of unknown foundation depth" [32], which makes it impossible to compare the scour hole depth with the actual depth of the foundation. The said detailed design also states that "... during geomechanical drilling, it was established that the bottom of the channel is about 85 cm deeper than anticipated by the channel design, which necessarily requires deeper foundation than planned by the conceptual design." This citation points to the possibility that the constructed foundations deviate from the design because of an adjustment to channel geometry.

4.3 Ivanja Reka

In medium water conditions, the velocities in the Sava riverbed in the vicinity of the Ivanka Reka bridge are negligible (<0.4 m/s) and do not pose a risk for mobilization of particles from the bed. In high water conditions, the flow velocity is increased (medium velocity in the bed upstream from the bridge is 1.12 m/s, downstream from the bridge 0.74 m/s and in the bridge profile 0.7 m/s), but there is no risk of global erosion because the allowable flow velocity is about 1.5 m/s, which was also established by comparing the historical with surveyed bridge profile. Local scour is not present in the immediate vicinity of the bridge piers because they are protected from scouring by rip-rap. The detailed geodetic survey with depth contours shows the rip-rap around the piers (Figure 6a), the construction of which has locally accelerated flow, intensified turbulence, and deepened the bed unprotected by rip-rap. In both the medium and high water flow conditions, the longitudinal velocity profile is uneven (Figure 6b)[30].Figure 6. The Ivanja Reka bridge: a) detailed bathymetry of the bed in bridge profile (left); b) inverted flow velocity profile on orthophoto map (right)6Figure 6. The Ivanja Reka bridge: a) detailed bathymetry of the bed in bridge profile (left); b) inverted flow velocity profile on orthophoto map (right)6

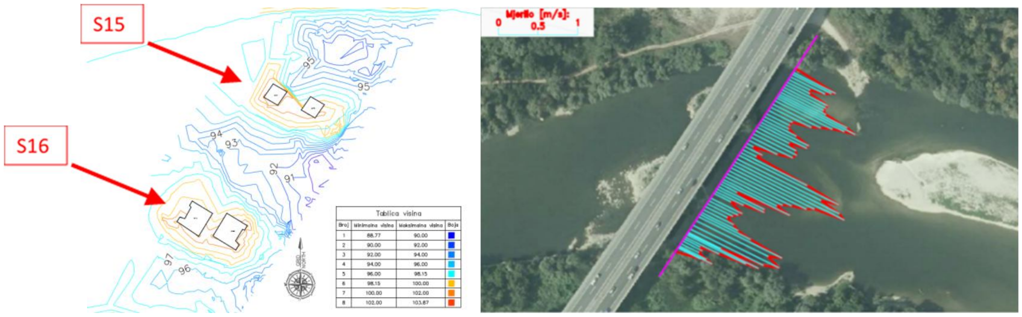

Figure 6. The Ivanja Reka bridge: a) detailed bathymetry of the bed in bridge profile (left); b) inverted flow velocity profile on orthophoto map (right)6

In addition to the construction of rip-rap around the piers, occurrence of these scour holes is also due to construction of the sill in the bed situated immediately upstream from the bridge. On the sill, the depth of flow decreases, which increases its velocity on the crown. As it passes over the crown, the flow shifts to forceful regime and hydraulic jump occurs in the bridge profile immediately downstream. In the hydraulic jump, the flow energy dissipates, affecting the gravel bed in the bridge profile, causing the bed material to move downstream and forming scour holes. This resulted in formation of a sandbank downstream of the bridge from the material eroded in the bridge profile (Figure 6b). The occurrence of scour holes in the bridge profile due to hydraulic jump is not localized only to the bridge profile. The scour holes between the piers S15 and the right bank and between the piers S15 and S16 continue downstream from the bridge profile, where they reach the maximum depth. The scour hole between the piers S15 and the right bank is 70 m away from the bridge axis and its depth is 11 m. The scour hole of the same depth is situated between the piers S15 and S16 at a distance of 40 m from the bridge axis, while the shallowest scour hole (8 m) is between the piers S16 and the left bank. The erosion of bed in the bridge profile has progressed to such an extent that edges of the scour holes have reached the toe of the rip-rap. Expansion of holes in this way caused scouring of the bed below the rip-rap and its collapse in the scour hole, which is most noticeable around the pier S15 (Figure 7).Figure 6. The Ivanja Reka bridge: a) detailed bathymetry of the bed in bridge profile (left); b) inverted flow velocity profile on orthophoto map (right)6Figure 7. Detail of the collapsed rip-rap protection of piers S15: a) on the north slope (left); on the south slope (right)7

Figure 7. Detail of the collapsed rip-rap protection of piers S15: a) on the north slope (left); on the south slope (right)7

4.4 Podsused

At the Podsused bridge, which has 3 piers in the main riverbed of the Sava River, the pier near the right bank is currently being repaired (Figure 8). All the degraded concrete of the pier foundation has been removed by hydrodemolition to sound concrete, and a total of 102 micropiles were drilled 3 to 4 m in depth around the pier foundation. Cement mortar is

injected into the micropile holes at a pressure of 3 to 4 bar to fill the voids in the foundation soil and strengthen the body and foundation of the pier. Reinforced-concrete lining will be made around the pier foundation and all micropiles, and the bed will be protected against scour by crushed stone fill [33][34]. The middle pier of the bridge was already repaired using the same technology during 2014, 2015 and 2016, and it is also planned to repair the third bridge pier, near the left bank, for which bids are invited [26].Figure 8. View from the right bank of the Podsused bridge piers: a) previously repaired middle pier (left); b) right pier during repair (right)8

Figure 8. View from the right bank of the Podsused bridge piers: a) previously repaired middle pier (left); b) right pier during repair (right)8

4.5 Nin

The extreme rainfall event that affected the Zadar area on 11 September 2017 and its consequences in the form of floods and torrents most severely affected the town of Nin and its surroundings, in which process a total of 20 bridges were damaged [35]. During the rainfall event, the total precipitation amounted to 283 l/m^2, which is the second highest rainfall since 1986 [36]. The two most significant bridges from the cultural and historical point of view are the Upper Bridge and the Lower Bridge which lead to the old town core of Nin, built in the 16th century [37]. The effects of the torrent considerably damaged both bridges by undermining their foundations (Figure 9).Figure 9. Bridges in Nin: a) the Upper Bridge (left); b) the Lower Bridge (right) / Author: D. Bujak9

Figure 9. Bridges in Nin: a) the Upper Bridge (left); b) the Lower Bridge (right) / Author: D. Bujak9

The stone bridges Lower Bridge and Upper Bridge were built on rock fill placed on a silty sea bottom of poor load-bearing capacity, with three stone arches with reinforcements on sections between arches with shallowly founded RC boxes. The exceptional cultural, historical and traffic significance of these bridges requires urgent repair of the damage and bids for execution of works are being invited. The works primarily involve stabilization of the foundation soil, construction of new foundations and static reinforcement of the structure. The stabilization of foundation soil is planned using the technology of jet-grouting of vertical piles at the site of collapsed bridge segments and using batter piles in the rock fill under the bridge foundation. The new foundation is planned using piles below foundations of arches,

topped with pile head beam and RC slab, which is also the bottom of bridge profile. Stone head walls are connected with RC boxes using steel anchors to reinforce the bridge structure while keeping the authentic historical appearance from the outside [38][39].

4.6 Đurmanec

The Đurmanec bridge was built in 1969 on the state road D1 in Krapina-Zagorje County and is one of 1473 bridges in the state road infrastructure system [40]. During the high water event in June 2015, as a consequence of daily precipitation > 23 l/m^2 in the Krapinica river basin, the flow through its riverbed had sufficient erosive capacity to erode the right bank next to the south abutment of the bridge. Along with the considerable flow of the Krapinica River, the floating sediment that accumulated in the central, largest, bridge span had an additional effect on the bank erosion. The amount of floating sediment (Figure 10) was sufficient to prevent flow through the central opening, but it was entirely directed to the right opening and it eroded the right bank behind the abutment 2-3 meters in depth as well as the abutment foundations, which resulted in its leaning [41]. The high erosive capacity of the Krapinica River in this place is the consequence of a large river bend just upstream from the bridge, which the river encounters after a long upstream straight stretch. Such sharp bends are typical of small rivers and channels over which roads are built, primarily because of the simplicity of structural design, however they have an exceptionally adverse effect on the water and sediment regimes, which is often manifested by erosion of banks and riverbed and occurrence of sandbanks near such bridges.Figure 10. The Đurmanec bridge: a) accumulated floating sediment in the central opening of the bridge (left); b) erosion of the bank behind the abutment (right) / Author: M. Skazlić10

Figure 10. The Đurmanec bridge: a) accumulated floating sediment in the central opening of the bridge (left); b) erosion of the bank behind the abutment (right) / Author: M. Skazlić10

The position of the bridge itself is very significant as it is located on a state road requiring regular traffic flow to be restored as soon as possible, and so the repair process was done in only forty days. In addition to the repair of the bridge structure, protection of watercourse bed was also performed by lining the bottom and slopes with 150-300 mm fraction crushed stone in concrete. Protection of slopes of both banks of the watercourse was carried out within the bridge profile and on the stretch of riverbed 10 meters upstream and downstream from the bridge [41].

5 CONCLUSION

Assessment of the erosive action on riverbed for already constructed bridges is regulated in foreign countries by guidelines, while in Croatia presently it is not the case. Every year we witness damage to a number of bridges, in varying degrees, due to the action of rivers, streams, or torrents. While seemingly sudden in character, such extreme events can be timely anticipated and prevented by properly and continuously inspecting bridges.

The continuous inspection must include underwater visual inspection and riverbed bathymetry measurements, which are compared in successive inspections, and measurement of flow. Flow measurements are particularly important because on smaller rivers in Croatia the network of gauging stations is incomplete, so the water regime data are often not known. Data on measured water regime and riverbed condition are crucial for morphodynamic analysis, because only data collected within systematic monitoring can be the basis for ensuring safety of bridges. The series of examples in which the riverbed condition was reported to be poor is the consequence of improperly regulated watercourse sections or inadequately made erosion protection, which proved to be counterproductive and contributed to riverbed instability and compromised bridge safety. These sections can be identified by morphodynamic analysis and can also be prioritized for the purpose of taking further measures by assigning a condition rating to them.

REFERENCES

1. Lee, G.C., Mohan, S.B., Huang, C., Fard, B.N.: *A Study of U.S. Bridge Failures (1980-2012)*, University at Buffalo, State University of New York, Buffalo, NY, 2013
2. Cook, W.: *Bridge Failure Rates, Consequences, and Predictive Trends*, Utah State University, 2014, 115
3. Muñoz Diaz, E.E., Moreno, F.N., Mohammadi, J.: *Investigation of Common Causes of Bridge Collapse in Colombia*, Practice Periodical on Structural Design and Construction, 2009, 14(4), 194-200

4. Imhof, D.: *Risk assessment of existing bridge structures*, University of Cambridge, 2004, 260
5. Wardhana, K., Hadipriono, F.C.: *Analysis of Recent Bridge Failures in the United States*, Journal of Performance of Constructed Facilities, 2003, 17(3), 144-150
6. Maddison, B.: *Scour failure of bridges*, Proceedings of the Institution Civil Engineers - Forensic Engineering, 2012, 165(FE1), 39-52
7. Yao, C., Briaud, J.-L., Gardoni, P.: *Risk Analysis on Bridge Scour Failure*, IFCEE 2015, San Antonio, Texas, 2015, 1936-1945
8. Cook, W., Barr, P.J.: *Observations and Trends among Collapsed Bridges in New York State*, Journal of Performance of Constructed Facilities, 2017, 31(4), 04017011
9. Gilja, G., Kuspilić, N., Bekić, D.: *Utjecaj degradacije korita na sigurnost mostova*, Sabor hrvatskih graditelja 2012: Graditeljstvo - poluga razvoja, Cavtat, Croatia, 2012, 795-806
10. Tenžera, D., Puž, G., Radić, J.: *Vizualni pregled kao pomagalo za ocjenu stanja mostova*, Građevinar, 2012, 64(9), 717-726
11. Larras, J.: *Profondeurs maximales d'erosion des fonds mobiles autour des piles enriviere*, Annales des ponts et chaussées, 1963, 133(4),
12. Laursen, E.M.: *Scour at bridge crossings*, Transactions of the American Society of Civil Engineers,, 1962, 127(3294), 166-209
13. Coleman, N.L.: *Analyzing laboratory measurements of scour at cylindrical piers in sand beds*, 14th IAHR World Congress, Paris, France, 1971, 31-37
14. Hancu, S.: *Sur le calcul des affouillements locaux dans la zone des piles du pont*, 14th IAHR World Congress, Paris, France, 1971, 299-305
15. Jain, S.C.: *Maximum Clear-Water Scour Around Circular Piers*, Journal of the Hydraulics Division, 1981, 107(HY5), 611-626
16. Shen, H.W., Schneider, V.R., Karaki, S.: *Local scour around bridge piers*, Journal of the Hydraulics Division, 1969, 95(HY6), 1919-1940
17. Melville, B.W., Coleman, S.E.: *Bridge scour*, Highlands Ranch, Colo. : Water Resources Publications, LLC, 2000
18. Melville, B.W.: *Pier and abutment scour: Integrated approach*, Journal of Hydraulic Engineering, 1997, 123(2), 126-136
19. Kuspilić, N., Bekić, D., Gilja, G.: *Praćenje morfodinamičkih promjena korita vodotoka u zoni stupova mostova*, Građevinski fakultet Sveučilišta u Zagrebu, Zavod za prometnice, 2010, 69-112
20. Kuspilić, N., Bekić, D., Gilja, G., McKeogh, E.: *Monitoring of river channel morphodynamical changes in the zone of bridge piers*, First International Conference on Road and Rail Infrastructure (CETRA 2010), Opatija, Croatia, 2010, 107, p8
21. Kuspilić, N., Gilja, G.: *Podvodni pregled mostova*, Sabor hrvatskih graditelja 2016: EU i hrvatsko graditeljstvo, Cavtat, Croatia, 2016, 287-300
22. Tenžera, D., Puž, G., Radić, J.: *Pregledi mostova na državnim cestama u Hrvatskoj*, Transportna infrastruktura i transport, 2012, 3 22-30
23. Građevinska služba ZJŽ. *Pravilnik o održavanju donjeg stroja pruga jugoslovenskih železnica*, Zavod za novinsko-izdavačku i propagandnu delatnost JŽ, 1970,
24. FHWA. *National Bridge Inspection Standards*, Federal Register, U.S. Department of Transportation, 2004, 74419-74439
25. NYSDOT. *Bridge Inspection Manual*, New York State Department of Transportation, New York, 2016
26. Goleš, D.: *Koliko su sigurni mostovi po kojima vozite? Stručnjak s Građevinskog fakulteta otkrio kako se u Hrvatskoj kontroliraju i održavaju*, DNEVNIK.hr, https://dnevnik.hr/vijesti/hrvatska/dr-sc-zlatko-savor-otkrio-kako-se-kontroliraju-i-odrzavaju-hrvatski-mostovi---527269.html, 2018/09/19, 2018
27. GFZG. *Podvodni pregled temelja i korita rijeke uz temelje*, Autocesta Zagreb - Macelj d.o.o., Zagreb, 2013
28. GFZG, IEE. *Podvodni vizualni pregled donjega ustroja mosta, te hidrografsko snimanje korita u zoni mosta - mostovi u nadležnosti HAC d.o.o.*, Hrvatske autoceste održavanje i naplata cestarine d.o.o., Zagreb, 2016
29. GFZG, IEE. *Podvodni vizualni pregled donjega ustroja mosta, te hidrografsko snimanje korita u zoni mosta - mostovi u nadležnosti ARZ d.o.o.*, Hrvatske autoceste održavanje i naplata cestarine d.o.o., Zagreb, 2016

30. Gilja, G., Kuspilić, N., Tečić, D.: *Morphodynamic impact of scour countermeasures on riverbed topography*, 15th International Symposium Water Management and Hydraulics Engineering, Primošten, Croatia, 2017, 176-183
31. Bohutinski, J.: *Što je pokazala inspekcija mostova na autocestama. Donosimo ocjene!*, Večernji list, https://www.vecernji.hr/vijesti/video-sto-je-pokazala-inspekcija-mostova-na-autocestama-donosimo-ocjene-1265230, 2018/09/19, 2018
32. IPZ. *Most preko Zapadnog l. k. u km 392+032.70 autoceste „Bratstvo-jedinstvo“*, Inženjersko projektni zavod, 1989
33. R.A.: *Objavljeno u kakvom su stanju svi mostovi u Zagrebu, neki u vrlo lošem*, Media servis, https://www.index.hr/vijesti/clanak/objavljeno-u-kakvom-su-stanju-svi-mostovi-u-zagrebu-neki-u-vrlo-losem/2018226.aspx, 2018/09/19, 2018
34. B.S.LJ.: *Sanacija zagrebačkih mostova - stvar preventive, ne panike*, HRT, https://vijesti.hrt.hr/457252/sanacija-zagrebackih-mostova-stvar-preventive-ne-panike, 2018/09/19, 2018
35. D.G.: *Šokantni podaci: Štete veće od milijardu kuna, srušeno preko 20 mostova, Nin više nema plaža!*, Morski.hr, http://morski.hr/2017/09/18/sokantni-podaci-stete-vece-od-milijardu-kuna-sruseno-preko-20-mostova-nin-vise-nema-plaza/, 22.10.2018., 2018
36. DHMZ. *Meteorološki i hidrološki bilten*, Državni hidrometeorološki zavod Republike Hrvatske, 2017, 60
37. I.I.: *Rekonstrukcija vrijedna 27 milijuna kuna: Kreće obnova Gornjeg i Donjeg mosta u Ninu*, Zadarski.hr, https://zadarski.slobodnadalmacija.hr/regional/clanak/id/534412/krece-obnova-gornjeg-i-donjeg-mosta-u-ninu, 22.10.2018., 2018
38. Matešić, L.: *Izvadak iz projekta obnove i rekonstrukcije Donjeg mosta u Gradu Ninu*, Zagreb, 2018
39. Matešić, L.: *Izvadak iz projekta obnove i rekonstrukcije Gornjeg mosta u Gradu Ninu*, Zagreb, 2018
40. Polšak Palatinuš, V.: *Kreće se u glavni pregled mostova, njih čak 30 posto nije u dobrom stanju*, tportal.hr, https://www.tportal.hr/vijesti/clanak/krece-se-u-glavni-pregled-mostova-njih-cak-30-posto-nije-u-dobrom-stanju-foto-20180822, 2018/09/19, 2018
41. Skazlić, M., Tenžera, D., Futivić, K.: Sanacija mosta Đurmanec nakon izvanredne okolnosti djelovanjem poplave, Sabor hrvatskih graditelja 2016: EU i hrvatsko graditeljstvo, Cavtat, Croatia, 2016, 301-312