VULNERABILITY – THE TOP LEVEL PERFORMANCE INDICATOR FOR BRIDGES EXPOSED TO FLOODING HAZARDS

Nikola Tanasic, Ph.D. (Corresponding author)
Assistant Professor
University of Belgrade, Faculty of Civil Engineering, Institute of Materials and Structures
Bulevar kralja Aleksandra 73/I, 11000 Belgrade, Serbia
Phone: +381-11-3218 573 Fax: +381-11-3370 253
Email: nikola@imk.grf.bg.ac.rs

Rade Hajdin, Ph.D.
President Infrastructure Management Consultants
Bellerivestrasse 209, CH-8008 Zurich, Switzerland
Phone: +41-43-497 95 20 Fax: +41-43-497 95 22
E-mail: Rade.Hajdin@imc-ch.com

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ABSTRACT

The oncoming natural hazards, especially floods, represent a serious threat to users of transportation infrastructure and societies in general. The state-of-the-art Bridge Management Systems still do not comprehensively account for impacts of sudden events and there is a demand for a simplified methodology for quantitative assessment of a bridge performance over time on a network level, which will in turn lead to adequate performance measures with respect to flooding events. As a convenient tool for the assessment, the measure of vulnerability is suggested here as a top-level performance indicator. It is based on two values - the conditional probability of a bridge failure due to a flooding event of a certain magnitude, and the related total consequences. The primary culprit for failures inflicted in floods is the local scour at bridge substructures. Here, the estimation of the conditional probability of a bridge failure is a multidisciplinary problem where the combined resistance of the supporting soil at substructures and the bridge is accounted via failure modes. The challenge is in setting the adequate vulnerability thresholds that trigger mitigation and preventative activities. Here the influence of a planned activity or an information update, on the assessment results must be taken into consideration in structuring of adequate quality control plans.

Keywords: flooding hazard, local scour, performance indicators, quantitative vulnerability assessment, failure modes, quality control plans,

INTRODUCTION

The most common culprit for inadequate bridge performance around the world is the flooding hazard and related local scour at bridge substructures as documented in (*1*), (*2*) and (*3*). The painful reminders of a threat this hazard poses to the performance of road networks are the extreme flooding events in Taiwan in 2009 (*4*), and the most recent one in Serbia 2014 (*5*). However, the transportation infrastructure is not only endangered by low occurrence/extreme intensity floods but also by less extreme floods with relatively high occurrence rates (*6*). Thus, it is a fundamental responsibility of civil engineers to ensure adequate adaptation of the infrastructure in the face of future weather events. By rule, a validation or an update of bridge management (BM) practices only take place after an extreme event occurrence, which is not an adequate approach for ageing infrastructure. The mitigation of risk of bridge failures due to flooding and related local scour is one of the most extensively elaborated topics in BM in the last two decades, but still there are no comprehensive methodologies to cover this matter.

The 13 US Departments of transportations (DOT-s), which participate in the Long-Term Bridge Performance Program, agreed that one of the primary research needs is to reliably identify scour-susceptible bridges (*7*). The current methodology of the US Federal Highway Administration (FHWA) is qualitative and based on a specific National Bridge Inventory (NBI) item No. 113 which is related to scour critical bridges. The ratings for the item are given based on engineering judgement supplemented by: visual inspection, indirect evaluations and a condition state of applied countermeasures (*8*). There are suggestions to combine the value of item 113 with other relevant NBI items in a procedure which uses weighting factors to introduce an index - bridge sufficiency index for a more comprehensive ranking of bridges (*9*). In some US states, bridges are specifically ranked using qualitative assessments based on their hydraulic vulnerability and in turn scheduled for a specific plan of action (*10*). The scour vulnerability rating is recognized as one of the key performance measures for development of a multi-objective optimization model for bridge management systems (*11*).

In the state-of-the-art software for risk analysis of transportation infrastructure exposed to natural hazards, Road Risk, developed by The Swiss federal roads authority (*12*), and the HAZUS-MH (HAZards U.S. Multi-Hazard) (*13*), the resistance of a bridge to flooding scenarios is not adequately accounted for. In the latter case, the probability of a bridge failure due to scour is based on the bridge's structural configuration, relevant ratings from the NBI and a flood return period, while only the direct costs of failure are considered.

The performance of bridges is the key research topic in Europe as well. The ongoing European research project COST TU1406 has a goal to structure the guidelines for development of quality control plans (QCP-s) for roadway bridges in Europe, thus enhance preparedness in face of future sudden/slow events (*14*). Within the Work Group 3 of the COST project, one of the main tasks is to investigate and consider for the dynamics and uncertainty of the non-interceptable (i.e. sudden) processes, particularly floods, that can significantly affect the bridge performance. Here, the main challenge is selection of adequate performance indicators (PIs) and definition of triggering criteria for detailed inspections and maintenance interventions at bridge sites in respect to required quality levels.

VULNERABILITY AS A PERFORMANCE INDICATOR FOR BRIDGES EXPOSED TO FLOODING HAZARDS – EUROPEAN EXPERIENCE

The performance indicators (PIs) relate to a set of observations and data on a bridge structure and bridge site, that can be either assessed, measured or evaluated, and which in turn can be used to assess bridge performance against predefined performance goals. In case of a flooding hazard, the PIs purpose is to point out which bridges are the most vulnerable to a hazard scenario, thus ensuring timely and adequate preventative actions.

Recently, in the research project COST TU1406, the survey for PI for roadway bridges has been performed in 30 European countries by screening of national BM guidelines (*15*). The results of the survey are summarized in (*16*), and here presented in Figure 1 are the key terms that relate to the reported PIs for flooding/scour. The most of the interviewed countries reported that in the case of flooding/scour their BM procedures solely rely on visual inspections. Some countries additionally perform measurements and/or monitoring of scour depth, while a few accounts for hydraulic adequacy of bridge openings. Only one country reported the application of a local scour evaluation formula, while seven countries have not reported that either flooding or scour are considered in their national BM documents. Although the detailed information of PIs for natural hazards were not in the primary scope

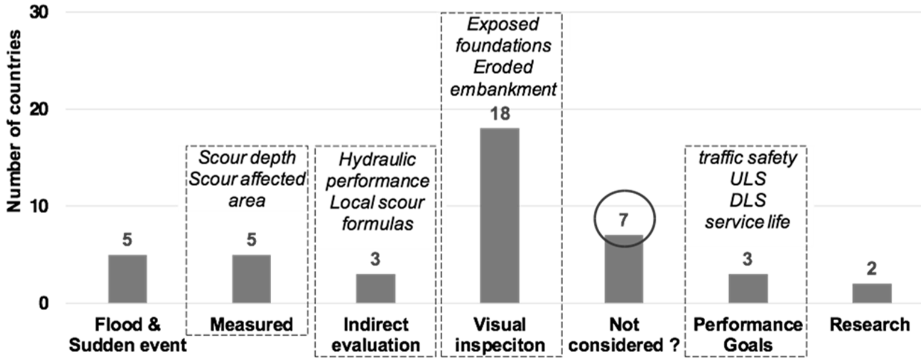

FIGURE 1 The terms related to flooding/scour in national BM guidelines in Europe

of the survey, it may be concluded that there are no concise guidelines or quality control plans in European BM practice for bridges exposed to a flooding hazard.

The visual inspection of substructures and/or the information on measured/evaluated scour depth, do not solely provide sufficient information for decision making. Here the main concerns are eligibility of bridge sites for installing monitoring equipment and refill of scour cavities at substructures. It is evident that a more comprehensive PI must be applied to include all relevant information on a bridge exposure to a flooding scenario, its resistance to the related magnitude of a flooding event (i.e. failure modes) and resulting consequences of a failure:

- **Exposure**
  - Flood magnitude & duration (i.e. a hydrograph)
  - Water channel geometry & properties
  - Piers & abutments location, geometry and alignment in respect to a water flow
- **Resistance to failure modes induced by local scour at substructures**
  - Properties of a soil at foundations (geotechnics and erodibility)
  - Type & detailing of substructures and superstructure
  - Location & severity of damage on relevant bridge elements
- **Consequences related to a specific failure mode**
  - Costs of repairs or replacement
  - Network & traffic data to include indirect costs of failure: vehicle operating costs, accident costs and loss of travel time

Clearly, a risk-based approach is the only viable solution to adequately consider an impact of flooding and the related local scour on bridges. In the evaluation of risk, the forecasting of sudden event magnitudes must be performed, which is a complex task especially for flash flooding. The BM needs efficient procedures for comprehensive screening of an entire bridge population thus the quantitative measure of vulnerability of a bridge failure is suggested as the most adequate top-level performance indicator to account for all relevant information. It represents the product of a conditional probability of bridge failure in a hazard event of a specific magnitude and the total consequences of such event, i.e. it is reflected through monetary units (*17*):

$$V_n^s = P_n^s \cdot (DC_n + IC_n) \quad (1)$$

where:

V_n^s	=	vulnerability of a bridge with respect to a hazard event of a specific magnitude *s* and a chosen failure mode ***n***
P_n^s	=	conditional probability of specific bridge failure in the chosen failure mode ***n***, with respect to a hazard event of a specific magnitude ***s***
DC_n	=	direct consequences with respect to the chosen bridge failure mode ***n***
IC_n	=	indirect traffic related failure consequences with respect to the chosen bridge failure mode ***n***

Unlike the measure of risk, the vulnerability is more convenient to understand since it relates simply to the given hazard magnitude, which is deemed sufficient for the identification of bridges in a network that need to be examined in more detail.

Following the performed survey for PIs in Europe, the next task in COST TU1406 regarding flooding hazard is structuring of a questionnaire, which will reveal availability of the data necessary to conduct quantitative assessments e.g. risk/vulnerability.

METHODOLOGIES FOR QUANTITATIVE VULNERABILITY ASSESSMENT

The development of Bridge Management Systems (BMS) is underway in many countries, where one of the main tasks is the establishing of novel risk-based methodologies. The information on 25 BMS from 18 world countries is presented in the report (*18*) which is the outcome of the survey performed by International association for bridge management and safety (IABMAS). Herein, the findings showed that only a few BMS account for risk of a bridge failure due to hazards. Generally, the current risk based approaches are mostly qualitative and comprise likelihood/consequences matrices i.e. risk matrix. In such approaches, the term failure or failure mode is related to a certain level of damage (physical or functional) and following consequences, but neither does account for the resistance of a bridge to specific hazard scenarios. Although the qualitative approaches are somewhat convenient to use, their outcome i.e. adequate quality specifications are vague. The quantitative performance indicators are more valuable, since they may provide more precise information for decision making.

The benefits of application of a quantitative approach in the assessment of scour critical bridges in North Carolina are reported in (*19*). Here, a risk-based approach is applied for the management of bridges with unknown foundations in (*20*). The assessment was based on the HYRISK Methodology (*8*). Although this methodology may consider the static system of a bridge and type of foundations, the probabilities of failure are based on qualitative data from NBI and the historical frequency of failures. The latter and the fact that neither oncoming flooding magnitudes nor soil resistance are considered, are the main drawbacks of this approach.

Recently, a novel methodology for quantitative vulnerability assessment has been presented in (*21*). It is based on Eq.1, where the analysis of failure modes is done by pragmatic modelling of the local scour action at a pier, considering combined response of a supporting soil and a bridge structure. The scope of the research is set on the reinforced concrete (RC) multiple span girder bridges with piers on shallow foundations which are particularly endangered in a flooding event. The research confirms that the resistance of the soil-bridge system must not be neglected in the vulnerability assessment of bridges exposed to local scour (*22*). The following evaluation of the direct consequences is straightforward, but the calculation of indirect i.e. traffic related consequences requires a traffic simulation model based on the current transport supply in a road network. An example of such a calculation is given in (*23*).

To conduct this vulnerability assessment on a network level, it is necessary to synthesize available information from databases & documentation and systematically collect the missing data from bridge sites. For the latter, it is of the outmost importance to have uniform data level to assess: bridge exposure, bridge resistance and possible consequences of failure.

STRUCTURING OF QUALITY CONTROL PLANS

The QC plans should be tailored for each individual bridge structure. Besides the adequate PI, the time schedule and analysis of collected data should be defined along with the triggering criteria for initiating preventative procedures. The importance of parameters, which comprise the minimum data set for the quantitative vulnerability assessment, are discussed in (*24*). Also, discussed herein are the levels & frequencies of the necessary inspections/data updates, to provide background information for the assessment. The objective information on bridge exposure to flooding hazards is invaluable for structuring a QC plan since it provides the facts on possible type of failure modes (e.g. pier related) and the extent of local scour depth (evaluated by local scour evaluation formulas). The reliable information on foundation soil properties (geotechnics and erodibility) as well as on the soil cover at an affected substructure, represent the crucial information to investigate at bridge sites where there is no foundation protection (e.g. Larsen sheets, gabion rock pile, etc.).

The relevant bridge elements and related information, which affects the structure of a quality control plan must be clearly outlined. The main requirement for the quantitative vulnerability assessment is definition of relevant failure modes, and here the influence of specific bridge elements on the type of failure mode (FM) and resistance to local scour is given in the Table 2. Complementary to this information, in Figure 2, one of the possible FM type 3 is presented for a multiple span RC girder bridge, where one of its piers with shallow foundations is affected by local scour.

TABLE 2 Key bridge elements for different types of resistance to local scour at a substructure

Bridge element	Attention	Resistance	Failure mode (FM) type
Affected substructure foundation	Inadequate detailing/condition state	Structure governed	1
Bearing/joint at the top of the affected substructure	Low plastic strength of a bearing/joint (or a poor condition state)	Governed by soil properties i.e. no/low superstructure resistance	2
Bearings/joints at other substructures	Horizontal displacement is either free or restrained	Combined soil-bridge resistance	3
Main girder	Detailing	Combined soil-bridge resistance	3
		Failure safe	4

The FM type 1 is the most dangerous since it may cause progressive collapse, if the design of the main girder is not failure/collapse safe to a loss of one of the supports (i.e. FM type 4). The FM type 2 may occur e.g. if the top of the pier of an affected foundation is not restrained to movement in horizontal plane. The FM type 3 is the most desired case, since the requirement for failure is that the foundation soil and the structure need to deplete their joint resistance due to the loss of support at the substructure foundation (*21*).

As seen in Table 2, the crucial set of information for a bridge structure exposed to local scour are related to the detailing of an affected substructure and its foundation. Although the bridges where FM types 1 and 2 have some considerable probabilities of failure (e.g. order of 10^{-3} and higher) should be mitigated in due time, the consequences of a failure must not be neglected as well as the costs of possible preventative interventions.

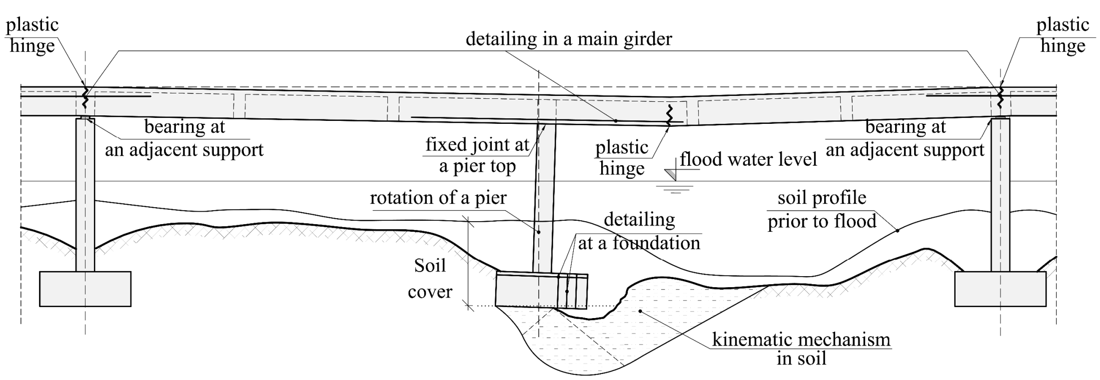

FIGURE 2 A possible failure mode (FM type 3) of a multiple span RC girder bridge.

The following preventative interventions may be considered to reduce the probability of a failure in a specific hazard scenario:

- **Decrease the exposure to the scenario**
  - Soil works at the bridge site
  - Countermeasures at substructures
- **Monitoring of scour at substructures**
- **Increase of structure resistance**

- Foundation repair/retrofit
- Bearings/joint repair retrofit
- Strengthening of a main girder (e.g. fail safe case)

It must be noted that the actions which are related to the increase of structure resistance also may benefit the overall bridge performance to other sudden or slow (deterioration) processes as well and should be considered in a long-term cost analysis.

CONCLUSION

In sudden events, such as flooding hazards, bridge failures may occur regardless of bridge age, structural system and construction materials. This poses a difficulty to point out the most vulnerable bridges thus schedule an adequate and timely risk mitigation action. Currently implemented qualitative risk-based approaches in bridge management practice impose constraints in a decision-making process and fail to provide objective information on a risk of a bridge failure. The risk and its progression over time wait to be adequately addressed in the future Bridge Management Systems (BMS), where the desired goal is structuring of an adequate quality control plan for each structure. There is a need for comprehensive approaches to ensure reliable levels of bridge performance and mobility of goods and people in a society. The accent is on a simplified, yet sufficiently accurate procedure, based on a modest data set, eligible for implementation on various bridge types and network topologies.

For quantifying the hazard impact on the transportation infrastructure, it is of the utmost importance to act timely and preventatively by taking into consideration all relevant information on bridge exposure to a hazard, resistance to specific failure modes and related consequences. For this purpose, the adequate performance indicators (PI) must be applied, and here the measure of vulnerability is suggested as the most convenient and comprehensive PI that will indicate which bridges need specific attention and should be investigated in more detail. Based on a procedure for a vulnerability assessment, a structure of a quality control plan for a bridge may be elaborated. Here, from a bridge`s point of view, it is outlined that the minimum set of information must include condition data and properties of an affected substructure, to account for bridges which are susceptible to critical failure modes (FM type 1 and 2).

Once integrated in the future BMS, the vulnerability assessments will enable timely scheduling of risk mitigation actions and making right decisions for resource allocation. The insight on vulnerabilities in a network would aid in emergency planning as well, since timely warnings could be issued in regions where intensive flooding is expected.

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REFERENCES

1. Faber, M.H. Lecture Notes on Risk and Safety in Civil Engineering. Swiss Federal Institute of Technology Zurich, 2007.
2. Imhof, D. Risk assessment of existing bridge structures. PhD Thesis. University of Cambridge, UK, 2004.
3. Sullivan, M. NYDOT national bridge failure database. Structures Division of the New York State Department of Transportation, USA, 2005.
4. Hsieh, K.H., W.F., Lee, and C.C. Wang. Bridge Foundation Failures During Typhoon Morakot in Taiwan. Presented at the 4th Japan-Taiwan Joint Workshop on Geotechnical Hazards from Large Earthquakes and Heavy Rain falls, Sendai, Japan, October 25-28, 2010.
5. Government of the Republic of Serbia (VRS). Recovery Needs Assessment Report - Floods in Serbia 2014., Public Investment Management Office, VRS, Belgrade, Serbia, 2014. (in Serbian). http://www.obnova.gov.rs/uploads/useruploads/Documents/Izvestaj-o-proceni-potreba-za-oporavak-i-obnovu-posledica-poplava.pdf
6. Benn, J. Railway bridge failure during flooding in the UK and Ireland. Proceedings of the ICE - Forensic Engineering, Vol. 166(4), pp 163 –170, 2013.
7. Brown, M., J. Gomez, M. Hammer, and J. Hooks. Report FHWA-HRT-14-052: Long-Term Bridge Performance High Priority Bridge Performance Issues. Rutgers, The State

University of New Jersey, The Center for Advanced Infrastructure and Transportation, 2014.

8. Pearson D., S. Stein, and J. S. Jones. Hyrisk methodology and User Guide. Report FHWA-RD-02-XXX. Federal Highway Administration, Washington D.C., 2002.
9. Sivakumar B., C. Minervino, and W. Edberg. New Bridge Performance Measures for Prioritizing Bridges. 9th International Bridge Management Conference. Orlando Airport Marriott Orlando, Florida, Apr 28–30, 2003.
10. New York State Department of Transportation. Hydraulic Vulnerability Manual. New York, USA, 2003. www.dot.ny.gov/divisions/engineering/structures/manuals/hydraulics
11. Patidar, V. Multi-objective optimization for bridge management systems (Vol. 67). Transportation Research Board. 2007.
12. The Swiss Federal Road Office (FEDRO). Technical Manual Road Risk 1.0 - Software for Assessment of natural hazards on national roads. Department for Environment, Transport, Energy and Communication, FEDRO, Switzerland, 2011 (in German) http://www.roadrisk.ch/roadrisk/doku_objekte.php?PHPSESID=nl097i8lgq514agdhetti79r13&linkid=53
13. Federal Emergency Management Agency (FEMA). HAZUS-MH MR3 - Multi-Hazard Loss Estimation Methodology - Flood Model - Technical Manual. FEMA, Washington D.C., 2007.
14. Matos, J., J.R. Casas, and S. Fernandez. COST Action TU1406 Quality Specifications for Roadway Bridges (BridgeSpec). In Maintenance, Monitoring, Safety, Risk and Resilience of Bridges and Bridge Networks – Bittencourt, Frangopol & Beck (Eds). Taylor & Francis Group, London, 2016. ISBN 978-1-138-02851-7
15. Strauss A., and A. Mandić-Ivanković. WG1 Technical Report – Performance Indicators for Roadway Bridges of Cost Action TU1406, 2016.
16. Tanasic, N., and R. Hajdin. Performance indicators for bridges exposed to a flooding hazard. Presentation at the Joint workshop of COST Action TU 1402, COST Action TU 1406 and IABSE WC1, Zagreb, Croatia, Mar. 2-3, 2017.
17. Birdsall, J. PhD. Thesis number 4251: The Responsive Approach: An Integrated Socially-Sustainable Technically-Optimal Decision Model. Swiss Federal Institute of Technology, Lausanne, 2009.
18. Mirzaei, Z., B. Adey, L. Klatter and P. Thompson. The IABMAS bridge management committee overview of existing bridge management systems 2014. International Association for Bridge Maintenance and Safety – IABMAS 2014. http://128.180.11.237/IABMAS/bodies/IABMAS-BMC-BMS-Report-20141224.pdf
19. Mulla, M.A. Evaluating Bridges with Unknown Foundations for Vulnerability to Scour: North Carolina Applies Risk-Based Guidelines. In TR News, No. 291. TRB of the National Academies, Washington D.C., pp. 43-45, Mar., 2014.
20. Stein S., K. Sedemera, and GKY & Associates, Inc. Springfield, VA. Risk-Based Management Guidelines for Scour at Bridges with Unknown Foundations. NCHRP Web-Only Document no.107, TRB of the National Academies, Washington D.C., 2006. onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w107.pdf.
21. Tanasic, N. PhD. Thesis: Vulnerability of reinforced concrete bridges exposed to local scour in bridge management. Faculty of Civil engineering, University of Belgrade, Serbia, 2015.
22. Tanasic, N., and R. Hajdin. Resistance of the soil-bridge model to local scour action. Presented at 94th Annual Meeting of the TRB, Washington D.C., USA, Jan. 11-15, 2015. http://trid.trb.org/view.aspx?id=1339427
23. Tanasic, N., V. Ilic and R. Hajdin. Vulnerability assessment of bridges exposed to scour. In Transportation Research Record: Journal of TRB, Vol. 2360, TRB of the National Academies, Washington D.C., 2013, pp 36-44. http://trrjournalonline.trb.org/doi/abs/10.3141/2360-05
24. Tanasic, N., and R. Hajdin. Management of bridges with shallow foundation exposed to local scour. Manuscript submitted in Journal of Structure and Infrastructure engineering, 2017.