Performance indicators for bridges exposed to a flooding hazard

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Abstract. The data on performance indicators from relevant national bridge inspection documents have been collected in a survey within the COST TU1406 action. Among this data, there are essential information on roadway bridge management practice in Europe related to a flooding hazard, that waits to be identified. This is one of the main tasks of the work group 3 which goal is to facilitate establishment of quality control plans for girder, frame and arch bridges. The review of the collected data has been performed to reveal the performance indicators for the cases of flooding and related scour at bridge substructures. The essential information was extracted and complemented with the relevant information necessary to establish relationships between performance indicators and performance goals. Here, the vulnerability assessment is suggested as a convenient approach as it accounts both for the probability of a bridge failure and related consequences. In the approach, the emphasis is to account the resistance of a bridge to scour, which is not thoroughly considered in the current practice. This is one of the main aspects that should be elaborated and included in the structure of the future QC plans for bridges exposed to flooding hazards.

Keywords: survey of performance indicators, flooding hazard, scour, vulnerability, resistance of a bridge to scour, quality control plans

1 The status of the COST TU1406 and its Work Group 3

The relevant information on bridge performance indicators (PI-s), their thresholds and related goals have been recently collected in the survey of the Work Group 1 (WG1) within the Cost action TU1406. In the scope of the survey were nationally applied bridge inspection manuals/guidelines in Europe and pertinent research papers. The gathered PI-s from 29 countries have been collected in an Excel database, homogenized into ten groups, and the Glossary of country specific terms was provided (Strauss & Mandić-Ivanković, 2016).

At the recent action meeting in Delft, it was underlined that there are nine key performance indicators (KPI) which are the most relevant for this project: Cost, Availability, Reliability, Safety, Maintainability, Economy, Security, Health, Politics. The future task of the Work Group 2 (WG2) is establishing of connections between the collected information on PI and the KPI-s while the Work Group 3 (WG3) works on elaboration of quality control (QC) plans for most common bridge types: arch, girder and frame, affected by various interceptable (i.e. slow) and non-interceptable (i.e. sudden) processes.

One of the main tasks within the WG3 (Task no. 4) is to investigate and account the dynamics and uncertainty of the sudden processes, focusing on extreme flooding events that may significantly affect a bridge performance. Among the collected data in the survey there are information on bridge management (BM) practice related to a flooding hazard, which wait to be pointed out and clarified. Although hazards were not the main topic of the survey, almost every country provided information on appraisal of a flooding impact, namely scour & erosion at bridge substructures. As discussed in (Tanasic & Hajdin, 2016), the most of the approaches that account this hazard impact on transportation infrastructure in the current BM practice are qualitative and do not provide reliable/optimal solutions for mitigating the factual threat of a bridge failure. So far, a quantitative methodology was suggested, and here the core of this process is the vulnerability assessment. In order to conduct this type of assessment, a minimum set of data i.e. PI-s and specific observations/findings is necessary.

In this paper, the surveyed data are reviewed in line with the COST WG3 framework (Figure 1) and the additional data which is necessary for evaluating of the relevant PI and its connection to the KPI-s are discussed. The principal topic in structuring of adequate QC plans, the consideration of a bridge resistance in a flooding event, is emphasized.

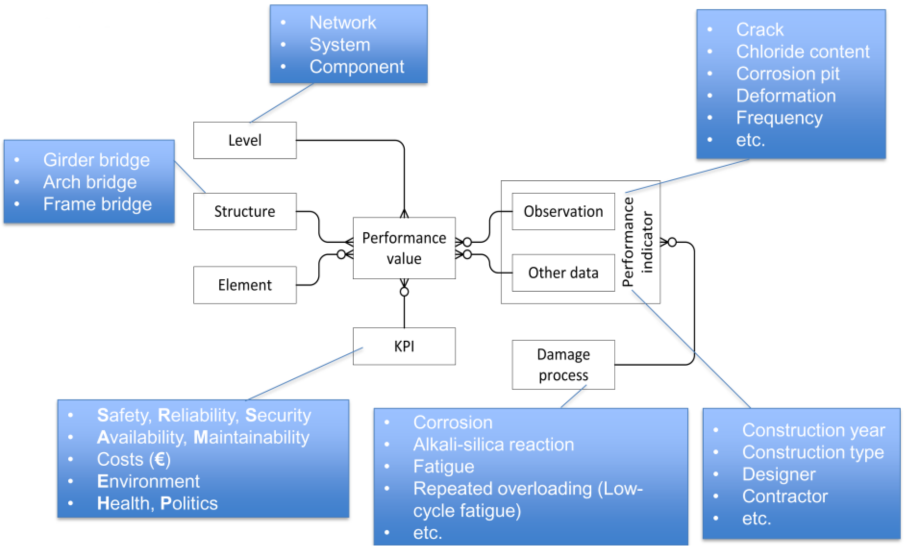

Figure 1 The entity relationship diagram of WG3 approach (Hajdin, 2016)

2 Review of the survey - the information related to flooding hazard & scour

The aim of the COST survey was to collect as much as information possible from the relevant national documents - bridge inspection manuals & guidelines. However, it is a fact that when it comes to application of procedures & actions for timely mitigation of hazard related consequences, not much concrete information can be found in the documents. This has been confirmed by the review of the database information which was here performed, and in the following text the main findings are presented and discussed.

The scour as the main culprit of bridge failures in a flooding event have been mentioned in almost every national guideline. The similar term reported in Glossary is erosion near piers and abutments, while under the group *performance criteria*, the terms that are related to a flooding are: collapse, river bed deterioration & aggradation and special main underwater inspection. Here, only a general piece of information is given thus these terms should be further investigated from the provided references. Also, vulnerability to natural hazards is mentioned by the authors of this paper as a performance indicator, and its application in the scope of the action will be discussed in the next paragraphs.

Interestingly, the term flood is only mentioned in the survey by a few countries as well as the term sudden event (Greece, Germany, Portugal, Croatia, Ireland). With exception of Sweden, France, the Netherlands, Hungary, Finland and Poland, all other countries reported that scour/erosion is considered in their guidelines. Eighteen countries indicated that there is visual inspection performed to confirm the adverse effect of flowing water on pier & abutment foundations or embankments. Here, specific classes/indexes (e.g. from 1 to 5) are used to grade scour criticality/impact, but the specific information on actual grading was not provided (i.e. no reference is given). Although these countries reported that they use damage catalogue for this matter, it is not clear if the grading accounts for previously observed failure modes, visual appearance at the time of inspection (e.g. exposed foundations) or it is consequence driven (as reported for Latvia).

The direct measurement of scour was indicated by five countries (Czech Republic, Croatia, Germany, Lithuania, Greece). Here, either the scour depth is measured or a monitoring technique is applied. The assessment of scour at a bridge is performed by estimating scour affected area in m^2 in two countries (Croatia, Lithuania), but here the provided references must be checked for specific information on the used thresholds. Only a few countries (Lithuania, Ireland, Germany, Greece) provided a specific reference related to the assessment of scour. Only one country (Spain) reported the use of a formula for evaluation of a scour depth.

Besides the term scour, the associated terms hydraulic inadequacy and hydraulic performance were reported by Greece and Israel respectively. The performance goals related to scour evaluation and assessment are provided only by a few countries (Germany, Denmark, Greece) and these include: traffic safety, ULS, DLS and service life. Scour countermeasures are not reported by any country, only in the survey from Greece, a term *hydraulic protection system* is provided.

It is unlikely that among surveyed countries there are those that do not appraise flooding hazard or scour at existing bridges. For example, in Melville & Coleman, 2000 it is stated that Sweden and Netherlands have manuals of practice and design guides for bridge scour, where scour estimation is covered, but this was not reported in the survey. The contents of the reported damage catalogues used for grading scour impact on bridges, remains unknown for now. The information provided on methods for assessment and monitoring of scour depth is vague as well as the assessment of the reported performance goals. The relevant research documents on the topic were also reviewed, but in these there are only two that elaborate adverse action of scour at bridges (Greece and Serbia). The two other culprits for bridge inadequate performance besides scour, i.e. overtopping and washing away of access roads were not identified in the survey. Clearly, the relevant data on flooding hazards in BM practice in Europe must be further investigated.

Now, there is sufficient information to structure a questionnaire that will clarify the contents of the surveyed data. It is envisioned to disseminate it to those countries which have provided the most relevant information and to other that show interest in it. Its aim would be to collect specific data related to scour assessment and related BM methodology. The questionnaire will address the following topics:

- Lessons learned from the past failures – crucial information on possible failure modes
- Methodology for the scour assessment and thresholds which are considered
- Equipment and its deployment procedures in measuring of scour depth
- Availability of the sufficient data to conduct quantitative assessments e.g. risk/vulnerability
- BM practice regarding a climate change - the needs and shortcomings

Currently, the main task of the WG 3 is to make use of the available database information in structuring guidelines that will facilitate establishment of QC plans. In the next paragraph, the relevant PI for flooding hazard are discussed.

3 Relevant PI for flooding/scour hazard and other relevant data

In the line of the WG3 framework, the results of the survey are structured in lists and presented in Figure 2. Here, all the terms reported (at least by one country) are in gray color, while those not reported and the additional relevant data/parameters are given in white. As seen, this additional data is not coming out of the survey and in fact represent missing links between observations/indicators and the KPI-s. It is clear that the following task is to describe relationship between the data in the lists, thus facilitate evaluation of its impact on the KPI.

		Performance indicators			
Structure	**Elements**	**Observation**	**Other relevant data**	**Damage process**	**KPI**
All bridge types and materials	*Foundations*	*Scour depth*	*Bridge geometry & dead load*	*Flood/Scour*	*Reliability*
	Embankment	*Scour affected area*	*Type of foundations*	*Erosion*	*Safety*
	Scour Countrameasures	*Exposed foundation*	*River bed properties*		*Availability*
	Substructure	*Eroded embankment*	*Foundation soil properties*		*Cost*
	Bearings/Joints/Hinges	*Hydraulic performance*	*Flood magnitude*		*Maintainability*
	Superstructure	*Specific damage location & severity*	*Debris/ice potential*		*Economy*
		Condition state	*Traffic data*		

Figure 2. List of key terms for a bridge exposed to a flooding hazard and scour

All bridge types regardless of age, static system or materials may be affected by a flooding hazard. Here, foundations of substructures and bridge embankments are exposed to the process of scouring. There is removal of soil at foundations while the supporting soil and bridge structure jointly resist this adverse action until the bridge fails under its own dead load (Tanasic, 2015). This resistance is not adequately accounted in the current bridge management practice, which is resulting in an overestimation of the factual threat of a failure. The resistance of a bridge to a flooding event is primarily governed by the assumed hazard scenario (e.g. scour at a middle pier). Possible failure modes are governed by the combined resistance of soil-bridge system and here the foundation soil properties have the leading role. Secondary, but not unimportant is the engaged superstructure resistance governed by bearing, hinge or joint properties.

Indirect observations which can point out problem with scour are pier/abutment settlement/rotation and resulting localized damage (e.g. cracks) at joints, bearings, hinges. These indicate that a failure mode has already occurred, which requires immediate attention i.e. adequate repair actions. These types of observations are not in the scope of this task within WG3. However, any type of damage at structural elements, which is not a result of a foundation displacement/rotation, are of interest as it may decrease bridge resistance to an oncoming flooding event. Here, the importance of two parameters: damage location and its severity (e.g. area/depth affected) must be recognized for every bridge type and element in order to conduct comprehensive analysis on possible bridge failure modes.

The scour countermeasures at substructures and their condition state is important for the scour assessment. Protective structures against erosion (e.g. gabion piles and walls), mitigate the threat of failure but also a structure left embedded in the soil after foundation construction (e.g. perimeter wall of Larsen talpes) should be considered as eligible to reduce the threat as well.

The reported terms in the list *Observations* are overlapping as they use similar or the same information for their assessment. It has to be clear in which cases (e.g. certain bridge types, foundations, etc.) these terms are eligible for evaluation of a specific KPI. The scour depth is an observation/indicator that may be directly measured, monitored or indirectly evaluated by empirical formulas. For the latter, parameters from the first six groups of data in the list O*ther relevant data* (excluding dead load) is necessary. Similar goes for the assessment of hydraulics performance, but this is an observation which indicate that there is going to be significant erosion at foundations, i.e. complementary to the observation of evaluated scour depth. The reported observations: exposed foundations, eroded embankment and scour affected area are not by themselves an effective PI. They are assessed in visual inspection, and only if noticed timely may signalize for a potential future threat (i.e. failure scenario).

For the assessment of scour at substructures, it is essential to know the type of foundations (e.g. shallow RC footing, wooden piles, RC caisson, etc.), their position/orientation with regard to river bank and exposure to an extreme flooding magnitude given as function of flow and duration. Also important are the river bed properties i.e. slope and Manning coefficient as well as foundation soil properties (i.e. erodibility and geotechnical properties), which are not usually stored in bridge databases but exist up to an extent in bridge design documentation. Knowledge on debris/ice potential at the bridge site provide supplemental information in the assessment of scour at substructures. Information on bridge geometry, dead load and traffic data are generally known or may be easily surveyed. Traffic data are used to calculate the costs related to inadequate bridge performance due to a scour related failure, which makes them a valuable piece of information. The reported performance goals from the survey relate to the KPI-s of Reliability, Safety and Availability. This suggests that none of the countries systematically evaluate the monetized consequences which are result of an inadequate bridge performance due to flooding hazards.

As seen from the survey and its review, in the Europe there is a variety of BM practices related to a flooding hazard. It is clear that an adequate approach, that will account all relevant data, must be chosen to facilitate elaboration of QC plans for different bridge types, which is now discussed.

4 The impact of PI-s for flooding hazard on the KPI-s and structuring of adequate QC plans

In order to account the impact of scour on bridges and related consequences, an adequate qualitative or quantitative approach should be chosen to relate the performance values of a relevant PI to as much as possible KPI-s.

The example of a qualitative approach for assessment of hydraulic vulnerability of existing bridges is given in (NYSDOT, 2003). Here, the most of the data in Table 1. is considered in the evaluation of a rating score, but the main shortcoming of the approach is that the superstructure resistance is not accounted i.e. the failure modes and related consequences are only generally addressed. In the approach of the U.S. Federal Highway Association (FHWA), the ratings in the National Bridge Inventory (NBI) database for the Item 113 - Scour critical bridges, are given based on engineering judgement supplemented by visual inspection, field review, indirect evaluations and condition state of applied countermeasures (Pearson et al., 2002). Here, the mentioned consequences (bridge closure) and failure modes (stability endangered) are primarily considered in the light of the evaluated local scour depth and available information on a foundation type/depth. The superstructure resistance is not considered in assigning the rating score. Although comprehensive, in the two mentioned approaches there are no explicit connections of the KPI-s (or none at all) standing between their PI values (i.e. rating score) and related QC plans.

However, for a quantitative approach e.g. the suggested vulnerability assessment, the performance values of PI-s can be directly related to the KPIs: Reliability, Availability, Maintainability, Economy, Cost and Safety. In this assessment, the two values are essential, the probability of a bridge failure due to a certain magnitude of a flooding event and the related total consequences (direct & indirect). Their relationship is via a failure mode which is dependent from the evaluated scour depth and the resistance of a soil-bridge system to the related removal of supporting soil.

The main idea in the action is that the QC plans should be tailored for a certain type of bridges, elements, observations and other relevant data. Besides the currently reported and obvious differences in QC plans based on bridge foundation types (i.e. shallow/deep), there are other relevant terms which should be accounted. They reflect on how much of a superstructure resistance can be engaged in a certain failure scenario and an extent of damage:

- Detailing of a foundation affected by scour
- Type/properties of the joints at a pier/abutment top (e.g. free, fixed, pinned)
- Type/properties of a superstructure and a number of spans

In some cases, there is no need for accounting either soil or a superstructure resistance (Figure 3), as a local failure of the foundation may govern the failure mode.

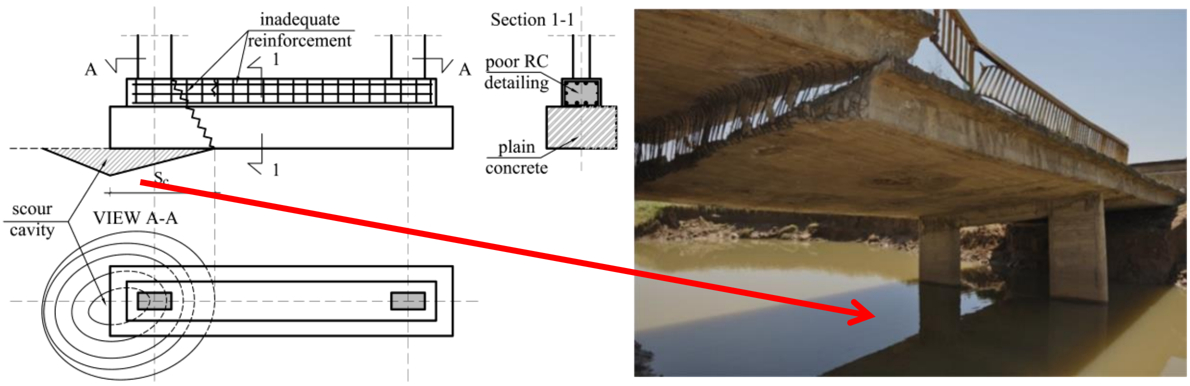

Figure 3 A brittle failure governed by poor foundation detailing (Tanasic, 2015)

5 Conclusion and further steps

The survey of performance indicators from the national bridge inspection manuals/guidelines is performed within the COST TU1406 action. The collected data was reviewed and discussed in the light of the Task 4 of the Work Group 3, which is related to non-interceptable processes – a flooding hazard and scour. It is concluded that the available data is not sufficient to fully comprehend the procedures in bridge management related to mitigating the threat of oncoming flooding events.

Although the scour at bridge foundations is recognized as a damage process by almost every surveyed country, the reported information on indicators/observations, which are used to identify and assess the severity of this threat to a bridge, are vague. The details on specific assessment procedures & equipment were not in the scope of the survey, but it is a fact that not all countries equally account for this hazard. The most of the countries simply rely on visual inspection but some take a step further by making direct measurements and indirect calculations of a scour depth. There is an opportunity to gather essential data on BM practices related to flooding in Europe by structuring and disseminating a simple yet sufficiently comprehensive questionnaire to facilitate and supplement the work of the WG-s within the action.

The most relevant indicators and terms are pointed out from the survey. This data is complemented with other relevant information related to flooding hazard, soil foundation, bridge structure and traffic. The information on past scour from visual inspections at bridge substructures is important in the definition of a failure scenario, but solely not sufficient for BM in face of oncoming flooding events. It is suggested to use vulnerability assessment as it comprise the most comprehensive information on the factual threat by accounting probability of a failure, failure modes and related consequences. The connection to the relevant KPI-s are in this case straightforward.

The current QC plans for bridges exposed to flooding hazard are primarily based on a foundation type, but this cannot be regarded as a general rule. The situations in which the types of superstructure and bearings provide additional resistance to a bridge in a flooding event, must be thoroughly elaborated in the future COST TU 1406 QC plans.

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