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Risk-based bridge scour management: a survey

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ABSTRACT: Scour is a major cause of bridge failure and results in significant economic losses through disruption to operation. This phenomenon naturally affects bridges with underwater foundations and is exacerbated during high river and/or turbulent flows (e.g. due to extreme events). When scour reaches the bottom of or undermines shallow foundations, it may trigger various damage mechanisms that may influence the safety of the structure and force asset managers to reduce traffic capacity. Currently, assessing risk of scour is a heuristic process, heavily reliant on qualitative approaches and expert opinion (e.g. visual inspections). These types of assessments typically suffer from insufficient knowledge of influencing factors (e.g. hydraulic parameters) and the requirement to rely on several assumptions (e.g. assumed foundation depth). As a result, current scour assessment and bridge management practices do not provide reliable solutions for addressing the potential risk of bridge failures. In this paper, cross-cutting needs and challenges related to the development of decision support tools for scour-risk management are highlighted and some preliminary results of a literature survey are reported. The review has been performed with several objectives: (i) identifying scour-risk indicators describing hydrodynamic actions and the asset condition; (ii) defining indirect and direct consequences needed to assess the risks associated to different decision alternatives related to scour management; and (iii) identifying existing approaches to scour inspections and monitoring as support tools for informed decisions. The results of this survey will serve as a base for future research aimed to develop an informed decision support tool to manage scour risk at both the bridge and at the network level.

1 INTRODUCTION

Hydraulic processes represent a major cause of bridge failure worldwide (e.g. Whitbread et al. 1996; Maddison 2012; Prendergast & Gavin 2014; Kerenyi & Flora 2019). According to Ding et al. (2016) 60% of bridge failures during the last 30 years in the USA were attributed to scouring (Ding et al. 2016).

Scour is the erosion of soil material from around the bridge piers which results in a reduction of bridge foundation capacity (e.g. Whitbread et al. 1996; Hager 2007; Maddison 2012). This phenomenon naturally affects bridges with underwater foundations and is exacerbated during high river and/or turbulent flows (e.g. due to extreme events).

When scour reaches the bottom of or undermines shallow foundations it may trigger various damage mechanisms that hinder the safety of the structure (Fitzgerald et al. 2019). The scale of these effects is linked to variations in the hydraulic parameters of the river and the structural characteristics of the bridge, such as: changing river flow rate, channel geometry, sediment type and foundation shape (cf. Bao & Liu 2016; Prendergast & Gavin 2014).

Bridge failures result in significant economic losses due to both repairs and disruption to operation (Gidaris et al. 2017). Assessing risk of scour is currently done via a manual process, heavily reliant on information provided by qualitative approaches and expert opinion (e.g. visual inspections) (Middleton 2004). These types of assessments are often limited by lack of information about the structural configuration, the actual structural state which is dependent on the structural vulnerability. These assessments also suffer from insufficient knowledge about the factors that influence the scour hazard (e.g. hydraulic parameters). These challenges force investigators to rely on various assumptions relating to e.g. foundation depth, scour depth and actions on the bridge (Pregnolato 2019).

With this in mind, current approaches to bridge scour management are affected by the high uncertainties that propagate into the estimation of scour-induced risk of failure. Information acquired during inspections or continuously measured by monitoring systems can reduce the uncertainties in the estimation of the several parameters that affect the estimation of risk in general such as: loads and environmental actions, structural performance, deterioration processes and damage. With this information, remedial actions may be implemented in order to provide an appropriate level of safety and/or serviceability to the structure. This information would allow for a decision support tool to be developed to enable improvement of scour risk management during the life-cycle of the bridge asset. A genuine risk-based approach to scour management is yet to be implemented in many jurisdictions and decisions related to maintenance are currently formed mainly by heuristic methods which rely on the results of visual inspections and expert opinion.

In this paper, the cross-cutting needs and challenges related to the future development of decision support tools for scour-risk management are highlighted and some preliminary results of a literature survey are reported.

1.1 *Existing approaches to scour management*

The management of bridges is challenged by the high cost and the long service lives of the structures. Bridge Management Systems (BMS) are used to assist with systematic management of the bridge stock and also to allocate maintenance resources, thus ensuring both safety and performance. The typical structure of a BMS is modular (Flaig & Lark 2000; Pregnolato 2019) (Figure 1) and it includes the following: (i) a Inventory Module for data collection (geometry, material, design, etc.); (ii) an Inspection Module for inspection data and condition assessment; (iii) a Maintenance, Repair and Rehabilitation (MR&R) Module for short-term and long-term planning; (iv) an Optimisation Module for managing budget expenditure and investments (Pregnolato 2019).

Figure 1. The modular structure of a Bridge Management System (BMS) (taken from Pregnolato 2019).

Inspections include qualitative assessments, mainly based on field visits and engineering judgements. These judgements usually adopt a scour vulnerability rating, that scores the structure within a range of values (e.g. from 1-no scour to 5-max scour risk). This type of risk assessment is theoretical considering a combination of factors (environmental loads, structural characteristics), and given by the product between the failure probability and the failure consequences (Prendergast et al. 2018; Pregnolato 2019). When guidance involves probabilistic representation of the actions on the bridge, equations can be applied for determining scour using a range of inputs (bed level, design flood event, water levels, flood depth and velocity, cross-sectional and plan geometry of the bridge, foundation type and depths, bed material), according to the level of complexity of the chosen numerical model (e.g. Arneson et al. 2012). The accuracy of this approach is dependent on data quality and model accuracy and these in turn may lead to large uncertainties. In practice the scour rating is mostly based on few parameters from field visits (e.g. scour depth at the inspection), and this reliance on inspection is common to most countries, especially at regional level.

In the USA, within the National Bridge Inspection Standards the Hydraulic Engineering Circular 18 (HEC-18, Arneson et al. 2012) illustrate a scour assessment process based on hydrological and hydraulic assessment for the identification of scour-critical structures (Banks et al. 2016; Kirby et al. 2015). The main drawback of the proposed approach consists in the need to perform the inspection, which requires specialised labour (e.g. divers), time and resources. In fact, the proposed equations are generally applied at design stage (e.g. bridge geometry design) whereas assessments are based on actual visual assessment.

In the UK, the CIRIA Manual (C742) is the main reference for scour assessment (Kirby et al. 2015). The scour risk assessment method is however mostly defined by in-house procedures. For example, the UK Highways Agency (1994) and Highways England (2012) proposes a two-stage assessment based on the structure condition (including foundation) and the asset importance (BA 59/94 for new design; BD 97/12 for existing structures). Stage 1 is a coarse qualitative assessment for identifying structures at low risk of scour; stage 2 compares the potential of scour depth with the foundation depth to identify structures at high-risk because of expert opinion. Network Rail annually inspects railway bridges to rate their condition and determine scour vulnerability based on the hazard likelihood, but not on the actual consequences if the hazard happens (HR Wallingford 1992; RSSB 2004 and 2005).

1.2 *Towards a risk-based scour assessment*

Risk-based decision making is underpinned by “the concept of risk as the simple product between probability of occurrence of an event with consequences” (JCSS, 2008). Hazard is defined as the action leading to scour occurrence and quantified for example by the floodwater flow or the stage height. Vulnerability of a bridge to scour accounts for the likelihood that scour can lead to damage, based on the state of the bridge. Exposure accounts for the importance of the bridge in a given network (see Sec. 2.1). Consequences include both physical damages on the exposed object and any effects associated with these damages, such as loss of functionalities (see

Sec. 2.2). The above definitions are the basis for any risk-based approach, and the reader should refer to those while reading the following sections.

2 LITERATURE SURVEY

The review on risk-based scour assessment has been performed with several objectives: (i) identifying scour-risk indicators describing the environmental actions and the asset condition; (ii) defining indirect and direct consequences needed to assess the risks associated to different decision alternatives related to scour management; and (iii) identifying existing approaches to scour inspections and monitoring as decision support tools. The results of this survey will serve as a preliminary study towards developing future decision support tools to manage scour risk at both the bridge and at the network level.

2.1 *Scour-risk related indicators (hazard, exposure, vulnerability)*

New and existing bridge structures with foundations in water have an associated element of risk related to potential scour formation. Newly designed structures have the benefit of being able to be designed to account for this risk (using estimations of likely scour depth based on hydraulic calculations), thus mitigating it as far as possible. Existing structures do not have the same benefit, but other methods have been developed to assist in estimating the scour-risk posed to these systems.

At design stage and throughout the bridge service life, the risk of scour occurrence should ideally be quantitatively defined. During service, this assists in maintenance scheduling for the bridge. This is normally undertaken through the application of deterministic equations to estimate potential depths of scour based on measured or predicted flow conditions (hazard) using formulations such as Colorado State University (CSU), or HEC-18 formulae (Arneson et al. 2012). The hazard in this case may be the water height or flow rate at a given bridge. The bridge foundations can be designed taking this assumed scour magnitude into account e.g. by ensuring pad footings are located below the maximum scour depth anticipated and by ensuring sufficient length and lateral stability of piles for these conditions (Hughes et al., 2007). Some element of risk will always persist due to the inaccuracies in the underlying assumptions of the equations used (Johnson et al. 1998) and difficulties in measuring accurate hydraulic data (Mohammadpour et al. 2016). The vulnerability of a bridge to scour is a function of its capacity under scoured conditions and its importance on a network. For example, a given depth of scour may pose a significantly higher risk of failure to a bridge with shallow foundations than one on long piles. For this reason, quantitative scour assessment may not be sufficient, rather knowledge of the bridge vulnerability is paramount. Vulnerability can be used to prioritize maintenance and remediation.

Ongoing assessments for bridges can be undertaken using methods such as that from the Federal Highway Administration (Arneson et al. 2012), which enables annual failure risk to be estimated for scour-vulnerable structures. These methods typically establish scour failure risk by identifying scour criticality (related to the foundation geometry) and the stability factors for a given bridge. In this sense, the occurrence of scour is not the main issue, it is the stability of the structure post scour that is the concern (vulnerability). Adverse geometries or as-constructed elements that become problematic in the event of scour can be considered a risk-indicator for scour. The main barrier to deployment of these types of approaches is that many bridges in operation have unknown or uncertain foundation geometries. This means that many risk-related scour-criteria need to assume certain dimensions, which can add significant uncertainty into the process. Furthermore, climate change inducing alterations to flow or extreme loading from weather can frustrate the process further, making the establishment of scour vulnerability more challenging.

2.2 *Scour failure consequences (direct and indirect)*

One of the major components of scour risk relates to the importance of the structure in question. Many risk-rating methodologies rank asset value in the context of how society would be influenced by the loss of this node on a given network. In this sense the loss of a minor bridge on a regional road could be more important than the loss of a major bridge due to the availability of redundancies in the system, i.e. the minor bridge may be the only route into a village for example. Consequences of loss of service should be accounted for in the decision-making process in order to choose the option that minimizes the losses. The consequences are generally associated to the failure of the bridge and to the loss of functionality of the infrastructure (Decò & Frangopol 2011). A possible classification of consequences is into direct and indirect consequences (Faber, 2008). Direct consequences are related to immediate physical damage and failures, such as repair and replacement. Indirect consequences are related to the loss of system functionality, such as re-routing and delays. Typically, consequences are expressed in monetary terms.

A methodology to quantity the total costs associated with bridge failure has been proposed by Stein et al. (1999) in the framework of scour risk assessment. The total costs are obtained as summation of rebuilding costs, running costs and time loss costs. Rebuilding costs C_{RB} include the cost of demolition of the existing bridge and the cost of the new construction.

Running costs C_{RN} are related to running vehicles on detours. Time loss costs C_{TL} are associated with the cost of time for car passengers and trucks. The expression was updated in 2006 to include the costs of loss of lives C_{LL} (NASEM, 2007). The final expression for the failure costs reads:

$$C_{Tot} = C_{RB} + C_{RN} + C_{TL} + C_{LL} =$$

$$= C_1 eWL + \left[C_2\left(1-\frac{T}{100}\right) + C_3\frac{T}{100}\right]DAd + \left[C_4 O\left(1-\frac{T}{100}\right) + C_5\frac{T}{100}\right]\frac{DAd}{S} + C_6 X \quad (1)$$

where C_1 is the unit rebuilding cost ($/m^2); e is the cost multiplier for early replacement; W is the bridge width (m); L is the bridge length (m); C_2 is the cost of running cars ($/km); C_3 is the cost of running trucks ($/km); D is the detour length (km); A is the Average Daily Traffic (vehicles/day), ADT, (vehicles); d is the duration of the detour based on ADT (days); T is the Average Daily Truck Traffic, ADTT, (% of ADT); C_4 is the value of time per adult of car passengers ($/h); O is the average occupancy rate; C_5 is the value of time for trucks ($/h); S is the average detour speed (km/h); C_6 is the cost for each life lost ($/n); X is the number of life losses (n). The ADT, influences the speed and the cost of the rebuilding, and therefore the duration of the detour.

Zhu & Frangopol (2016) used the methodology presented in Stein et al. (1999) to compute the costs associated with different decision scenarios. In particular, they computed the economic consequences related to the closure of bridge lanes due to the failure of piers and girders under traffic load and scour. The number of possible lane-closure scenarios is at least equal to the number of lanes. In general, the total costs increase with the number of closed lanes.

An additional classification of consequences of bridge failure was proposed by Imam & Chryssanthopoulos (2012) and Chryssanthopoulos et al. (2011) see Table 1. According to Table 1: fatalities and injuries may be caused by either the collapse of the bridge (direct) or by delays in emergency operations due to the detour of emergency vehicles (indirect). The initial structural damages to the bridge (direct) might cause secondary damages to the structure itself or to adjoining facilities (indirect). Pollutant substances might be released during the collapse of the bridge (direct) or at later time due to increased travel time and detours (indirect).

Table 1. Classification of bridge failure consequences (taken from Chryssanthopoulos et al. 2011, used with permission)

Consequences categories	Direct	Indirect
Human	Fatalities; injuries	Fatalities; injuries; psychological damage
Economic	Repair of initial damage; replacement/repair of contents; rescue costs; cleanup costs	Replacement/repair of structure/contents; rescue costs; cleanup costs; collateral damage to surroundings; loss of functionality/production/business; temporary relocation; traffic delay/management costs; regional economic effects; investigations/compensations; infrastructure inter-dependency costs
Environmental	CO_2 emissions; energy use; pollutant releases	CO_2 emissions; energy use; pollutant releases; environmental clean-up/reversibility
Social	-	Loss of reputation; erosion of public confidence; undue changes in professional practice

The preceding discussion on the different categories of consequences is not intended to be exhaustive, but to show that the estimation of the consequences of traffic restriction action is a complex multi-faceted problem. Besides, the results depend strongly on the restraints of the analysis and they are even subjective to a certain extent (Imam & Chryssanthopoulos 2012, Chryssanthopoulos et al. 2011).

2.3 *Inspections and monitoring for scour-risk management*

Condition monitoring of bridges is usually performed through periodical visual inspections during which inspectors check the existence or the evolution of possible damage or degrading phenomena in order to support decision making related to maintenance interventions (e.g. Bennetts et al. 2016, 2019). Visual inspections can give some information about section loss, deterioration, spalling for visible parts of the structure. For bridges with piers in the water, the visual inspection of foundations requires the employment of divers. These periodical surveys are usually scheduled at prescribed time intervals (e.g. 2- and 6-year cycles in the UK), whereas special inspections are carried out after major floods. During or immediately after a flood, inspections of foundations are risky for the divers and the outcome is affected by a high level of uncertainty due to temporary conditions that can obscure the real structural conditions, for example when a scour hole is hidden by loose material in turbid waters (Highways England 2012). For this reason, flood warning and flood alerts are used to trigger the precautionary closure of the bridge, based on river gauges records (i.e. peak flow level and travel times). For example, the river level approaching the bearing level of flat bridges could represent a threshold. Regional authorities (e.g. county councils) mostly rely on inspection records for issuing remedial works; the lack of data rarely allow for following more complex procedures (Middleton 2004). A deeper level of inspections is enabled by Non Destructive Testing (NDT) such as ultrasonic, radiographic, thermographic or eddy-current tests that can be applied to detect the structural geometry (reinforcement, cables, voids) or the state of deterioration (chloride content, moisture, corrosion) or damage (e.g. cracks or scour). Table 2 (based on Prendergast et al. 2018), the description of various devices used for the detection of scour depth. One drawback of NDT methods is that the location of damage must be known in advance and the damaged location accessible. Structural Health Monitoring (SHM) systems that rely on local sensors permanently installed on the bridge or on remote sensors that continuously collect information about the structural state have the potential to partially overcome this problem by providing continuous information about possible changes - induced by damage - of global parameters of the structure - such as modal frequency, damping and mode shapes - without any previous knowledge about the possible damage location. This enables the use of the monitoring system to trigger 'on demand' maintenance interventions and to issue alarms in case of unexpected events. For this reason, the use of techniques such as vibration-based monitoring might play a key role for scour detection. (Prendergast & Gavin 2014). However, contact sensors have to be installed on each bridge and can have quite high costs over the life-cycle (installation, maintenance, power supply). Furthermore, for the specific case of scour monitoring, they can be damaged during floods.

In the last few years, developments in remote sensing through satellite data-based synthetic aperture radar interferometry (InSAR) has allowed to achieve quite a high spatial resolution allowing monitoring of single bridges (Crosetto et al. 2010; Sansosti et al. 2014). Data can be collected more frequently with respect to visual inspections, with a frequency of days, which allows monitoring of the bridge with a good temporal resolution also during flooding. The displacements of the ground around the bridge and ground movements affecting bridge piers can be measured at the millimeter scale (Selvakumaran et al. 2018). Furthermore, the possibility to use large spatial frames that cover wide areas allows monitoring of several bridges at the same time.

Each of these monitoring methods (inspections, NDTs, local or remote continuous monitoring) can be effective to provide information about scour-risk indicators. In order to optimize the choice of the monitoring methods for specific applications, the benefit of the information they provide as decision support tools must be always compared to the cost entailed by the acquisition of these information and this quantification has to be performed before acquiring the information. The quantification of the value of structural health monitoring is currently one of the scientific and practical challenges on which recent projects have been devoted and several research groups are actively working (Pozzi & Der Kiureghian 2011; Straub 2014; Thöns & Faber 2013). The outcomes of these research efforts will constitute an important asset for the development of efficient decision support tools based on monitoring information to manage scour-risk.

3 ROLE OF MONITORING

3.1 *Value of Information*

There have been many attempts to better assess scour potential and progression with the use of monitoring systems. Webb et al. (2015) give a classification system for SHM of bridges, concluding that SHM systems can fit into one or more of the following categories: (i) 'anomaly detection'; (ii) 'sensor deployment' studies; (iii) 'model validation'; (iv) 'threshold check' and (v) 'damage detection'. Damage detection is arguably the most challenging of the aforementioned categories. Scour monitoring is a form of damage detection. Kerenyi & Flora (2019) recently reported detecting a scour hole with sonar for a bridge in Northern California and subsequent efforts to understand and model scour development. There have been many studies investigating scour mechanisms for bridge and marine structures (e.g. Dey & Barbhuiya 2004; Raikar & Dey 2005; Hager 2007; Sarkar 2014; Pournazeri et al. 2016). Whitbread et al. (2000) make the comment with respect to assessment methods that because staff and financial resources are generally limited, any method of scour assessment must be reasonably quick due to the number of bridges potentially at risk. Whitbread et al. (2000) also mention that a careful balance needs to be struck between ensuring safety and the cost of maintaining the structure. As discussed in previous sections (and Table 2) there is considerable research into monitoring methods to help supplement visual inspection of scour for bridges in a cost-effective manner.

Table 2. Scour measuring devices and methods (adapted from Prendergast et al. 2018)

Type	System	Operation	Advantage	Drawback	References
Single-Use/Reset	Tethered Buried Switch	Mechanical device buried near bridge pier – indicates when scour reaches its depth by floating out and sending signal	Simple mechanical operation	Requires reinstallation after floating out and can only indicate scour has reached its depth with no further information	Briaud et al. (2011) & Hunt (2009)
Radar/Pulse	Ground Penetrating Radar (GPR)	Determines water-sediment interface using radar and is manually operated	Gives clear subterranean features from high frequency radar signals	Requires manual operation and thus not suited to remote monitoring	Anderson et al. (2007), Fisher et al. (2013), Forde et al. (1999), Yu & Yu (2009)
Driven/Buried	Vibration-Based Sensor	Dynamic strain sensor measures changes in natural frequency of a driven rod due to scour	Can give indication of scour depth by fitting subgrade modulus to reference numerical model of system	Can only detect scour local to sensor and may miss global scour effect	De Falco & Mele (2002), Fisher et al. (2013), Hunt (2009) & Zarafshan et al. (2012) & Kariyawasam et al. (2019)
Fibre-Bragg Grating (FBG)	FBG-Water Swellable Polymer	Water swellable polymers swell upon contact with water (scoured soil) and FBG sensors detect the tension	Fitting a number along a rod allows for scour depth to be monitored at discrete points	Requires multiple sensors to be deployed as it can only detect scour local to the sensor	May et al. (2002), Lin et al. (2006), Kong et al. (2017), Prendergast & Gavin (2014)
Sound-Waves	Sonic Fathometer	Fixed-in-place to the bridge element above the waterline – measures water-sediment interface	Continuously measures scour local to element	Can be affected by entrained air in turbulent flow	Nassif et al. (2002), Fisher et al. (2013), Prendergast & Gavin (2014)
Reflectometry	*Amplitude Domain Reflectometry (ADR)*	A probe with integrated electromagnetic sensors detects changes in dielectric permittivity of scoured soil	Highly sensitive to underwater bed variations	Requires installation of a sensor / susceptible to damage	Michalis et al. (2015)

Dikanski et al. (2017) identified technical barriers for scour management in Network Rail (in the UK): (a) "inability to rely on historical weather records to estimate trigger events and probabilities"; (b) "use of heuristic standards, whose future applicability is unknown"; (c) "complexity of causal chain from climate change to asset risk"; (d) "variable quality of data used for asset condition assessment" (Dikanski et al. 2017).

Translating the results of SHM (assuming the data is of sufficient quality) into 'damage prediction' systems rather than 'model validation' (or model calibration) work remains challenging. It may not be possible to predict levels of scour at individual structures but a well-calibrated database of scour levels on bridges with detailed structural and hydraulic data may lead to better decision-making tools at a network level.

3.2 *Future research needs*

Future research should go beyond the assessment of single-bridge assets and consider the bridge as part of the wider transport network. In fact, scour assessment for one single bridge would not ensure risk reduction at the network-level. Remote satellite monitoring for scour could be investigated as a tool for damage detection at the network level aimed to identify the damage component of the network. Local SHM systems might provide further insight, e.g. location of damage, into the state of the specific bridge. Visual inspections might become a tool for detailed assessments of a bridge identified as damaged by the previous remote and local SHM techniques. This approach would provide a step-change switch from preventive to on-demand inspections. Detailed structural modelling is an important element of prognostic maintenance approaches based on the management of maintenance based on forecasts of the evolution of degrading processes. Results are strongly dependent on the reliability of the model in simulating the actual structural behaviour. To this aim, it would be strategic to compile a database of key scour events and effects on bridges, linking data on the physical assets to that from different storm events. This would allow for better calibration of models (theoretical, finite element models, etc.) and decision support tools for use at the component and network level.

4 SUMMARY & CONCLUSIONS

The current heuristic methods to assess scour at riverine bridges rely on visual inspection and expert opinion. More reliable evaluation could be offered by incorporating a risk-based approach based on indicators describing the environmental actions and the asset conditions, and on the careful definition of the direct and indirect consequences of different decision alternatives. Visual Inspections, Non-Destructive-Testing (NDTs) and Structural Health Monitoring (SHM) techniques provide information at different levels of detail, precision and accuracy about the bridge performance. Future studies should underpin the development of methodologies to develop and integrate decision support tools and monitoring information, to manage scour risk at both the bridge and the network level.

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