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Recent progress developing a rating framework for evaluating SHM for bridge scour

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ABSTRACT: Scour is a complex phenomenon and one of the most frequent causes of riverine bridge failures. Detecting scouring effects is a complex geotechnical/structural/hydraulic engineering challenge. Incorporating more risk-based approaches into scour assessment frameworks may allow for enhancements over current processes which remain reliant on visual inspection to detect bridge scour. Scour detection and monitoring is inherently a 'damage detection' task. A wide range of technologies for scour monitoring are available which may partially replace or supplement visual inspection activities. Recently, a new rating framework has been presented to assist engineers to assess the relative merits of different sensor technology options on scour-prone bridges. In this paper, the development of this framework is reviewed and compared with other scour rating frameworks; suggestions for future development and calibration are proposed.

1 INTRODUCTION

1.1 *Bridge scour*

Scour is a complex phenomenon and a frequent reason for bridge failures across the world (e.g. Briaud *et al.* 2011, Maddison 2012, Prendergast & Gavin 2014, Dikanski *et al.* 2017, Ettema *et al.* 2017, Kerenyi & Flora 2019). Scour effects on individual bridges may change with time due to changes in flows and flooding levels (cf. Dikanski *et al.* 2017). Detecting scouring effects is a complex forensic engineering challenge (see Vardanega *et al.* 2021 for a recent review). Incorporating more risk-based approaches into scour assessment frameworks may allow for enhancements over current processes which remain largely reliant on visual inspection to detect bridge scour (cf. Pregnolato *et al.* 2021). Maroni *et al.* (2022) highlighted the need for probabilistic assessments of scour risk along with integration of 'quasi-real-time' monitoring data into scour risk management frameworks.

The categorization system for bridge Structural Health Monitoring (SHM) proposed by Webb *et al.* (2015) (summarized in Figure 1) includes the following five categories: (i) 'Anomaly Detection'; (ii) 'Sensor Deployment Studies'; (iii) 'Model Validation'; (iv) 'Threshold Check' and (v) 'Damage Detection'. These categories are presented in order of increasing complexity but arguably also of increasing value to the asset owner (Webb *et al.* 2015). Scour detection and monitoring is inherently a 'damage detection' task. Damage detection is a difficult challenge for many SHM systems, but it is necessary to prevent collapses of bridges over waterways in the case of scour.

1.2 *Rating systems*

Figure 2 shows some of the key considerations when specifying new SHM systems (Vardanega *et al.* 2016). Ahlborn *et al.* (2010a) and Vaghefi *et al.* (2012) offer a methodology to determine the efficiency of different remote sensing options for assessing bridge condition indicators (see also Ahlborn *et al.* (2010b) for a review of various remote sensing options for bridge condition detection). Vardanega *et al.* (2016) proposed a rating system to determine if a planned SHM system

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would deliver value to a bridge asset owner. The framework from Vardanega *et al.* (2016) was in part inspired by the framework proposed to assign geotechnical reduction factors presented in Poulos (2004) and the system to assess the value of remote sensing technologies from Vaghefi *et al.* (2012) (see also Ahlborn *et al.* 2010a). The framework from Vardanega *et al.* (2016) was tested using information from five previous monitoring deployments (see Table 1, see also Nepomuceno *et al.* (2019, 2022) who used the framework for further case studies).

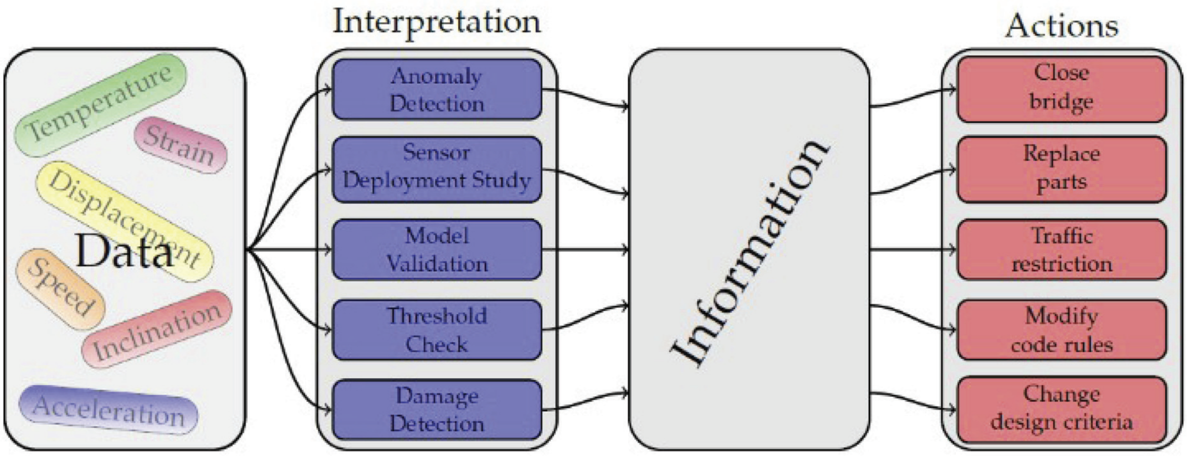

Figure 1. Categories of SHM systems (taken from Webb *et al.* (2015) and used under the terms of the cc by 4.0 license).

Table 1. Summary of Bridge Projects evaluated in Vardanega *et al.* (2016) using the framework (see also Nepomuceno *et al.* 2022).

Bridge Structure	References	Outcome from Vardanega *et al.* (2016) rating
Walton Bridge	Middleton *et al.* (2014) Webb (2014)	Project unlikely to yield value to asset owner/ manager
Nine Wells Bridge	Hoult *et al.* (2009) Schwamb (2010) Webb (2014) Webb *et al.* (2017)*	Project may yield value to the asset owner/manager
Humber Bridge (Hessle Anchorage)	Hoult *et al.* (2008) Fidler *et al.* (2021)*	Project likely to yield value to the asset owner/ manager
Ferriby Road Bridge	Hoult *et al.* (2010)	Project may yield value to the asset owner/manager
Hammersmith Flyover	Webb *et al.* (2014)	Project likely to yield value to the asset owner/ manager

* paper not published when Vardanega *et al.* (2016) framework first published

The framework from Vardanega *et al.* (2016) was further tested for a planned monitoring effort on a proposed footbridge (Nepomuceno *et al.* 2019) and has recently been examined in the context of prior monitoring efforts (Nepomuceno *et al.* 2022). Vardanega *et al.* (2021) have recently presented a new rating framework to assist engineers with answering the ‘Which sensor?’ question from Figure 2 in the context of bridge scour detection (see Gavriel (2019) for an early version of the rating framework for scour).

1.3 *Paper aims*

This paper briefly outlines some of the key monitoring devices used for scour monitoring and then discusses the new rating framework presented in Vardanega *et al.* (2021); it makes comparison of this framework with that discussed in Pregnolato *et al.* (2022) and the Scour Monitoring Decision Framework (SMDF) in Lueker *et al.* (2010). This comparison may allow the development of a new, comprehensive framework for planning and assessing scour monitoring efforts.

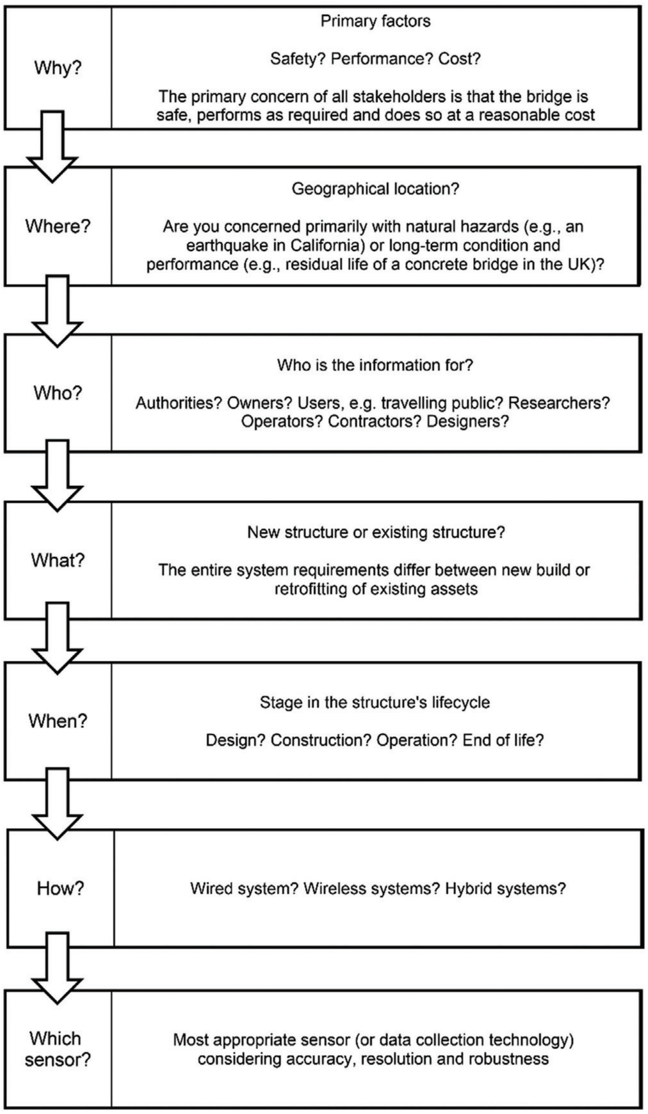

Figure 2. Key considerations when deciding whether to employ SHM (taken from Vardanega *et al.* 2016 and used under the terms of the cc by 4.0 license).

2 BRIDGE SCOUR MONITORING DEVICES

2.1 *Scour monitoring technologies*

A range of technologies for scour monitoring are available which may partially replace or supplement visual inspection activities (see Briaud *et al.* 2011, Prendergast & Gavin 2014, Wang *et al.* 2017 and Prendergast *et al.* 2018 for detailed reviews of scour monitoring devices). Sections 2.2 to 2.4 briefly outline the use of Accelerometers, Fiber-Bragg grating sensors and Sonar in some scour monitoring case studies. Further reviews on general bridge monitoring technologies can be found in Webb *et al.* (2015) and Middleton *et al.* (2016).

2.2 *Accelerometers*

Accelerometers are used to measure dynamic response of bridges subject to scour damage by detecting changes in the natural frequency (e.g. Prendergast & Gavin 2014, Bao & Liu 2016, Kariyawasam *et al.* 2019a, 2019b, 2020). The collected data can then be analysed using spectral analysis methods (e.g. Brincker *et al.* 2001, Briaud *et al.* 2011). Briaud *et al.* (2011) reported that based on studies of two bridges in Texas (USA) that draw-backs from accelerometers were 'lack of efficient excitation' from loading and high-power consumption (the latter may be mitigated with solar panels).

2.3 *Fiber-Bragg grating sensors*

Fiber-Bragg grating sensors can be installed on bridge piers to detect changes in soil levels during (and post) flood events (e.g. Lin *et al.* 2006, Prendergast & Gavin 2014 and Kong *et al.* 2017). According to the review of Prendergast & Gavin (2014, p.140) embedded rods that are "partially exposed due to scour will be subjected to hydrodynamic forces from the flow of water that induce bending in the exposed rod" and progression of scouring can be detected with an array of strain gauges installed along the rod (see the field studies of Lin *et al.* 2006 and Kong *et al.* 2017).

2.4 *Sonar*

Sonar devices can be mounted to vessels or on bridge piers to detect changes in riverbed conditions by sending out sound waves and measuring the time taken for the sound wave to return (e.g. De Falco & Mele 2002, Briaud *et al.* 2011, Prendergast & Gavin 2014 and Clubley *et al.* 2015). Briaud *et al.* (2011, p.15) explain that for sonar sensors: "The time taken for the signal to propagate from the emitter to the receiver in combination with the material properties gives an estimate of the distance from the emitter to the interface of the two mediums." Briaud *et al.* (2011) also explain that fixed sonar devices can be damaged or destroyed due to the effects of debris.

3 SCOUR RATING FRAMEWORK

A preliminary version of a rating framework to compare various scour monitoring technologies was proposed by Gavriel (2019). Vardanega *et al.* (2021) further developed the framework and used it to evaluate seven monitoring deployments reported in the literature (see Table 2 for a summary of this recent work).

Table 2. Summary of the application of the scour monitoring rating framework to seven installed monitoring systems from Vardanega *et al.* (2021).

Bridge Structure(s)/Location	References	Score (/25)
Mezzana Corti & Borgoforte Bridges (River Po, Italy)	De Falco & Mele (2002)	16
Dadu Bridge (Wu River, Taiwan)	Lin *et al.* (2006)	17
Railway viaduct (River Hamble, England, UK)	Clubley *et al.* (2015)	14
Concrete bridge (Redwood Creek, Louisiana, USA)	Kong *et al.* (2017)	11
Tadcaster bridge (River Wharfe, England, UK)	Selvakumaran *et al.* (2018)	17
Baildon bridge (River Aire, England, UK)	Kariyawasam (2019a, 2019b)	17
A76 200 bridge (River Nith, Scotland UK)	Maroni *et al.* (2020)	19

When using the framework, it is important to understand how monitoring systems may be used to capture different aspects of scouring. For example, Highways England (BD 97/12: HA (2012): clause 7.14) considers three categories of scour monitoring techniques: "(i) those that seek to measure the maximum scour levels that have occurred at the bridge site; (ii) those that seek to measure the development of scour adjacent to the structure as it develops during a flood; (iii) systems based on monitoring analogues (conditions that may correlate with the development of scour) such as flow velocities, water level, or weather warnings."

Monitoring devices may be used to capture data relevant to one or more of the aforementioned categories from HA (2012). The rating framework (Vardanega *et al.* 2021) includes five criteria (Q1 to 5) each of which are rated from 1 to 5, with a higher score given to a device with improved capability:

"Q1 – Ease of installation"
"Q2 – Ease of operation"
"Q3 – Ease of data-logging/capture"
"Q4 – Ease of data interpretation"
"Q5 – Measurement frequency".

Figure 3 shows a diagrammatic description of the scoring system (for a complete description of the rating system see Vardanega *et al.* 2021). The following classification is used to describe the level of applicability of devices scored using the rating framework (Vardanega *et al.* 2021):

"Very high applicability" (score 23-25)
"High applicability" (score of 18-22)
"Moderate applicability" (score of 13-17)
"Low applicability" (score of 8-12)
"Very low applicability" (score of 5-7).

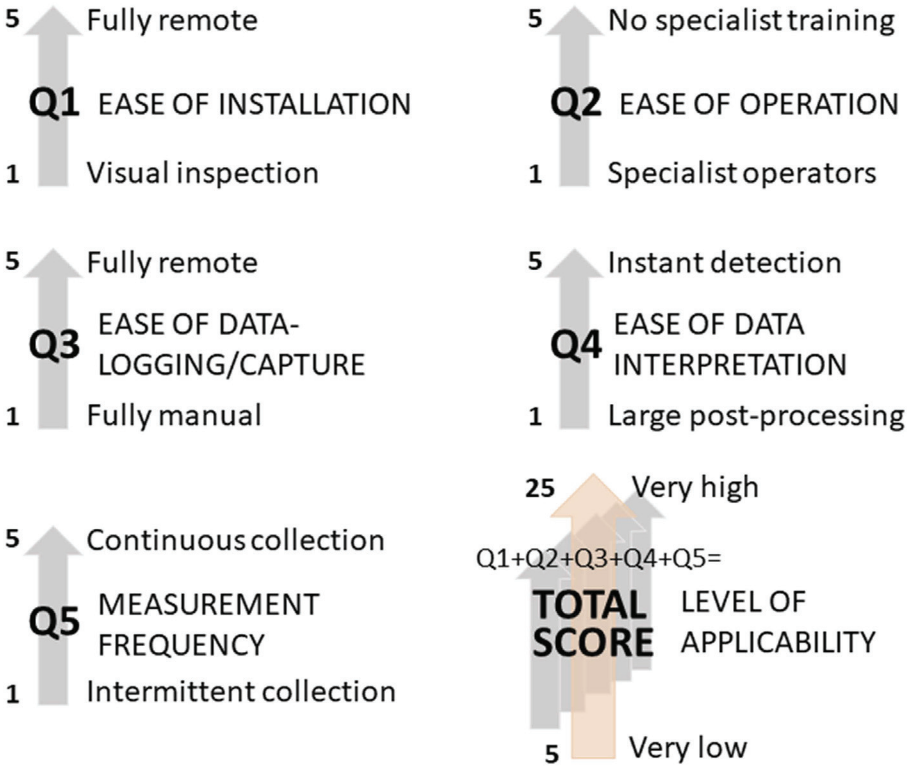

Figure 3. Schematic of the scour device rating system proposed in Vardanega *et al.* (2021).

4 COMPARISON WITH OTHER FRAMEWORKS

Pregnolato *et al.* (2022) built on the framework presented in Vardanega *et al.* (2021) by introducing nine criteria versus the five criteria suggested by Vardanega *et al.* (2021). The updated framework by Pregnolato *et al.* (2022) introduced two cost related criteria one related to the initial cost of the measuring apparatus and one related to the whole-life cost of the measuring apparatus. Pregnolato et al. (2022) also considered the environmental limitations which are associated with the use of the examined apparatus as suggested by the original framework (Gavriel 2019). The updated framework from Pregnolato *et al.* (2022) accounts for the robustness of the measuring apparatus. Pregnolato *et al.* (2022) incorporated weighting factors for the criteria (albeit assigned by engineering judgement), such as those shown in Figure 3.

Lueker *et al.* (2010) applied the Minnesota 'Scour Monitoring Decision Framework' (SMDF) to five sites and demonstrated that a range of scour devices may be selected with sonar being the generally preferred option. The SMDF has many more criteria than Vardanega *et al.* (2021) with more details on the nature of the riverine conditions being considered, as well as e.g. the traffic levels on the bridge.

5 CONCLUSIONS

5.1 *Summary*

A rating framework (Vardanega *et al.* 2021) has been proposed to assist engineers to answer the 'which sensor?' question when considering SHM systems for scour monitoring and assessment. The framework has five key criteria which are rated from 1 to 5 depending on the capability of the technology in terms of "Ease of installation", "Ease of operation", "Ease of data logging/capture", "Ease of data interpretation" and "Measurement frequency". The framework can also be used to assess a full scour SHM deployment, which may involve multiple technologies which form a more complex SHM system. Finally, the comparison with other frameworks (Pregnolato *et al.* 2022 and Lueker *et al.* 2010) highlighted the possibility to include other criteria, such as sensor cost or traffic levels.

5.2 *Further work*

The framework should also be tested for proposed monitoring efforts on new projects to see its use in both selecting and comparing different sensing device options and to evaluate the designed monitoring specification on such projects. As previously stated, the possibility of adding further criteria or weightings for different criteria depending on the situation should also be explored. In addition, the rating-frameworks of Vardanega *et al.* (2021) (with the additions proposed by Pregnolato *et al.* 2022) along with other methods such as the 'Scour Monitoring Decision Framework' (Lueker *et al.* 2010) should be applied to a wider range of past case-studies to improve calibration and determine the minimum number of criteria needed for successful specification of scour monitoring systems. While the cost of the initial deployment and operation of the monitoring system should be added to the framework a consideration of the cost of data-interpretation and processing should also be considered to supplement the 'Ease of data interpretation' criterion. This would allow for better consideration of the life-cycle costs of the specified monitoring system.

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DATA AVAILABILITY

This study has not generated new experimental data.

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