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Assessing the suitability of bridge scour monitoring devices

Paul J. Vardanega, BE MEngSc PhD GMICE MASCE MIEAust FHEA
Senior Lecturer in Civil Engineering
Department of Civil Engineering, University of Bristol, Bristol, UK
Email: p.j.vardanega@bristol.ac.uk (corresponding author)
ORCID: 0000-0001-7177-7851

Gianna Gavriel, MEng
PhD student
Department of Civil Engineering, University of Bristol, Bristol, UK
ORCID: 0000-0002-4648-1706

Maria Pregnolato, MSc PhD FHEA
Lecturer
Department of Civil Engineering, University of Bristol, Bristol, UK
ORCID: 0000-0003-0796-9618

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Assessing the suitability of bridge scour monitoring devices

P. J. Vardanega, G. Gavriel and M. Pregnolato

Abstract: Bridge scour is a complex bridge management problem. It is also a difficult forensic engineering challenge as the greatest risk occurs during large flows and flood events, when visual inspection of the bridge piers is often not possible. This paper presents a review of scour prediction and modelling methods, whose results are used to determine the key parameters that scour monitoring systems need to capture. Then, a review of existing monitoring approaches and technologies for scour monitoring is presented. The paper concludes with the proposal of a novel rating system to evaluate different scour monitoring techniques. The new rating system is trialled *ex-post* for seven previously published bridge scour monitoring case studies to illustrate the use of the new methodology.

ICE Keywords: Bridges, Foundations, Floods & floodworks

1. Introduction

1.1 Bridge Scour

Bridges are vital components of transportation networks. For riverine bridges scour is a complex soil-water-structure interaction problem. Scour is the cause of many bridge failures around the world (e.g., Maddison 2012; Ettema et al. 2017). The review of Imam & Chryssanthopoulos (2012) reported that 17% of metal bridge failures (in the UK) were due to scour. The UK has over 87,000 bridges (RAC foundation, 2020) which comprise an ageing stock and which often have unknown (or uncertain) foundation depths (e.g., Clubley et al. 2015). Diagnosis of scour problems for bridge structures is also more challenging than for other 'damage detection' tasks, as the damage is often obscured from view by the water surrounding the piers. This presents a major forensic engineering challenge for both visual inspection and more complex Structural Health Monitoring (SHM) systems. In particular, if the water level is above the level of the bridge foundations, then the exposure cannot be assessed from the riverbank (e.g., Ko et al. 2010; Selvakumaran et al. 2018); and when this happens, a diving team must be deployed in waterways where underwater visibility is often poor (e.g., Clubley et al. 2015).

Scour effects may be more frequent and unpredictable if weather patterns change and floods increase in their frequency and scale due to climate change (cf. Clubley et al. 2015; Dikanski et al. 2017). For bridge engineers undertaking investigations and assessments of bridge assets, SHM systems may be helpful if the outputs they deliver in terms of data (and subsequently information) are directly linked to key decisions that the asset owner needs to take (e.g., maintenance, closure, or replacement of a bridge structure) (e.g., Vardanega et al. 2016). Most scour events will occur during flood events, usually due to heavy rainfall (e.g., Abé et al. 2014), tidal surges (e.g., Maddison 2012) or ice-effects (Carr & Dahl 2017). This paper focusses on local scour effects around bridge piers as opposed to 'general scour' which is due to changes in the river itself e.g., the introduction of an upstream barrier or natural changes in the river flow paths (e.g., Akhlaghi et al. 2020), or 'contraction scour' which 'occurs if a structure causes the narrowing of a watercourse or the return to the main river channel of floodplain flow' (Whitbread et al., 2000, p.80).

1.2 Scour prediction and modelling

There are numerous studies which review various empirical and semi-empirical approaches for prediction of key scour related parameters e.g., scour depth (e.g., NASEM 2011; Briaud et al. 2015a, 2015b; Banks et al. 2016; Aje & Khattab 2017; Saha et al. 2018; Helal et al. 2019; Yilmaz et al. 2019). The influence of debris effects on scouring has also been the subject of recent research publications (e.g., Dias et al. 2019; Panici et al. 2019; Jamei & Ahmadianfar 2020; Ebrahimi et al. 2020).

Various publications describe numerical methods to investigate scouring processes and effects (e.g., Pournazeri et al. 2014, 2016; Boujia et al. 2017; Askarinejad et al. 2019; Fitzgerald et al. 2019a) on bridges and other structures. Advanced computing efforts including use of Artificial Neural Networks (e.g., Mohammadapour et al. 2016) and Linear Genetic Programming (e.g., Jamei & Ahmadianfar 2020) have also been used to study scour related phenomena.

There have also been many publications on experimental modelling of scour process (e.g., Laursen & Toch 1956, Chiew & Melville 1987; Raikar & Dey 2005; Hager, 2007; Dey & Barbhuiya 2004; Sarkar 2014; Amini et al. 2019; Askarinejad et al. 2019; Boujia et al. 2019; Dias et al. 2019; Shan et al. 2020). Recently Kerenyi & Flora (2019) investigated decay functions for decreasing dimensionless shear stress with increasing relative scour depth using a combined physical modelling-CFD (computational fluid dynamics) approach and presented an envelope for such functions. Ettema et al. (2017) suggests that along with improved laboratory techniques, the use of CFD to improve understanding of the flow field near bridge piers has resulted in major advances in understanding scouring processes since the seminal work of Laursen & Toch (1956). Kariyawasam et al. (2020) reported detailed experiments conducted on 1/60 scale models tested in a geotechnical centrifuge and showed that for an integral bridge, 40% variation in natural frequency may be observed for scouring resulting in around 1/3 pile embedment loss. Akhlaghi et al. (2020) presented a detailed review on the key parameters that affect scour: concluding that a ‘significant gap’ exists between field measurements and laboratory and analytical models for scour.

1.3 Risk-based approaches for scour effects

As scour is an uncertain process, risk-management processes are needed when operating and maintaining scour-prone bridges (e.g., see the review of Pregnolato et al. 2021). Various publications have investigated how to deal with bridge scour using risk-based approaches (e.g., HR Wallingford 1992; Stein et al. 1999; NASEM 2007; Decò & Frangopol 2011; Dikanski et al. 2017). To better calibrate risk-based systems, databases of scouring effects on the bridge network which are updated regularly with field observations are needed (cf. Stein et al. 1999; Decò & Frangopol 2011; Florens et al. 2018; Pregnolato, 2019). Benedict & Caldwell (2014a, 2014b) reported a database of bridge scour events along with associated parametric data (reviewed in more detail in Section 2).

1.4 Study Motivation and Aims

For improved scour prediction and modelling (Section 1.2) and to calibrate risk-based approaches for scour effects (Section 1.3) high quality field data sets are needed for model calibration or confirmation of experimental results. The overall motivation for this study is to assist with the planning of maintenance and data-collection (routine or post flood) for bridges suffering scour effects. Specifically, the aims of this study are to:

(i) review the established and emerging practices for scour monitoring for bridge structures and

(ii) develop a novel rating methodology to assist engineers to determine the best sensor for a particular scour monitoring project.

The data from scour monitoring efforts should then be used to build databases needed for the improved calibration and further development of the methodologies used to understand and predict scouring and its effects as reviewed in Sections 1.2 and 1.3.

2. Bridge Scour Monitoring

2.1 Monitoring Technologies

The review of bridge SHM systems presented by Webb et al. (2015) proposed a classification system for monitoring efforts. The five categories identified were: (1) ‘Anomaly detection’; (2) ‘Sensor deployment studies’; (3) ‘Model validation’; (4) ‘Threshold check’; (5) ‘Damage detection’ (Webb et al. 2015). Given the nature of scour effects, the primary aim of most scour monitoring is ‘damage detection'. Guidance from HA (2012) - BD 97/12 clause 7.14 classifies scour monitoring techniques as follows:

> "Scour monitoring techniques fall into the following broad categories:
> (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."

The first two listed monitoring techniques recommended in HA (2012) - BD 97/12 clause 7.14 which aim to measure 'maximum scour levels' and 'development of scour' respectively are classified as 'damage detection' while the final category 'monitoring analogues' would be classified as 'anomaly detection' using the Webb et al. (2015) classification system. Maroni et al. (2020) point out that many scour monitoring systems generally attempt to either directly measure the scour depth near the bridge piers or determine information about scour effects on the bridge itself.

There have been many efforts to develop new sensors for infrastructure monitoring and thus determine how to maximise their benefit for civil infrastructure management (cf. Mair 2016; Middleton et al. 2016). Bao & Liu (2016: p.14) compared: (i) the 'durability'; (ii) how 'easy in installation'; (iii) 'accuracy' and (iv) the 'cost' for various scour monitoring techniques and scored vibration methods well across the aforementioned categories. Prendergast & Gavin (2014) and Prendergast et al. (2018) reviewed the types of monitoring technologies available for scour monitoring and explained that subjective visual inspections remain widely used in practice. While the presence or progression of a scour hole (i.e., near a pier) may be monitored, the concomitant effects on the bridge structure itself are not usually captured by scour SHM systems (in other words an additional SHM system would be needed to study the bridge condition) (Prendergast et al. 2018). Bennetts et al. (2018a) studied network level changes in bridge condition indicators (which are based on visual inspection data) showing that key visual inspection-based metrics can detect trends such as structural deterioration at stock (regional) level. However, such metrics are much less reliable for assessing performance of an individual structure (Bennetts et al. 2018b). Maroni et al. (2020) also reviewed different scour monitoring technologies assessing them according to (i) the ability to deliver 'continuous monitoring'; (ii) ability to conduct 'measurement during extreme event[s]'; (iii) the 'scour depth resolution' available; (iv) 'detection of refill' potential and (v) 'costs'.

Other studies and reviews of scour monitoring systems have been published by Millard et al. (1998), Forde et al. (1999), Nassif et al. (2002), De Falco & Mele (2002), Briaud et al. (2011), Fisher et al. (2013), Lin et al. (2019) and Faulkner et al. (2020). Newer monitoring technologies include time domain reflectometry (TDR) (Yu & Yu 2009); electromagnetic sensor approaches (Michalis et al. 2015; Maroni et al. 2020); heat conduction systems (Ding et al. 2016); Fiber-Bragg Grating (FBG) sensors (Kong et al. 2017a, 2017b; Lin et al. 2006) and vibration-based approaches utilising piezoelectric systems powered by energy harvesting technology (Fitzgerald et al. 2019b). It is important to review not only the capabilities of a monitoring device but critically evaluate how well it functions in non-ideal field conditions which may be very different from laboratory settings (cf. Lin et al. 2006; Clubley et al. 2015). In addition, Gavin et al. (2018) explained that geotechnical uncertainty (often due to soil heterogeneity) has rarely been considered by those developing scour detection systems.

At network level monitoring data is very useful when aggregated in openly accessible databases which can be used in both reliability-based and risk-based bridge management (cf. Bennetts et al. 2018a, 2018b; Pregnolato 2019; Pregnolato et al., 2021). Breysse (2012) highlighted the importance of 'collapse databases' for use in forensic engineering and risk management efforts. Benedict & Caldwell (2014a, 2014b) summarised the technology used in over 2400 scour reports as part of their openly accessible database (hereafter called the USGS database) of bridge scour events from the USA and other countries (Benedict & Caldwell 2014a, 2014b): Table 1 shows the breakdown of monitoring method type reported in the USGS database, revealing the soundings (sounding rods) is the most common monitoring method reported (38%, 709 out of 1858). Table 2 shows the breakdown of when the monitoring was conducted. Table 2 shows that just over 50% of the monitoring efforts were performed during the flow event. Since 'Visual monitoring during a flood and inspection after a flood cannot fully determine that a bridge is safe' (Arneson et al. 2012, p. 10.11), real-time monitoring systems for scour should be developed (see Benn 2013). Databases such as the USGS database are useful in improving bridge management systems (cf. Flaig & Lark 2000). Florens et al. (2018) advocated for the development of databases to determine correlations between flow and scour parameters.

2.2 Specifying SHM systems

Vardanega et al. (2016) presented a rating system to determine the value of proposed bridge monitoring systems. Figure 1 shows the key issues that should be considered during the specification process of SHM systems (Vardanega et al. 2016). Simply installing a SHM system does not necessarily mean 'damage detection' activities, such as scour detection, will be successful. Webb et al. (2015) explained that 'damage detection' is the most difficult SHM category to reliably achieve in practice. For this reason, most bridge monitoring remains centred around visual inspection activities which are highly subjective and ‘trusted’ to varying degrees by bridge engineers (cf. Bennetts et al. 2020). For a large network of bridge structures ‘It is not economically feasible for a bridge owner to protect all bridges to resist all conceivable floods and some risks of failure have to be accepted’ (Whitbread et al. 2000, p.85). Farreras-Alcover et al. (2016) noted that it would be prohibitively expensive to monitor all the major components of every structure all the time. Therefore, low-cost, and reliable monitoring systems able to supply relevant data are needed so that appropriate interventions can be planned and carried out. The next section presents a proposed rating methodology which can be used to assist with the ‘which sensor’ question from the process for evaluating the applicability of proposed SHM systems shown on Figure 1.

3. Suitability of scour monitoring devices

According to Arneson et al. (2012, p.10.12), ‘Selecting the appropriate monitoring devices is specific to each individual bridge and should consider the nature and location of the scour problem(s), accessibility issues created by the bridge superstructure and substructure elements, desired monitoring frequency, and cost over the remaining life of the bridge’. In this section, a new rating framework is proposed (see Gavriel 2019 for an early version of the proposed methodology) considering the criteria given in Table 3. Each of the five criteria (Q1-Q5) (Table 3) is assigned a score from 1 to 5 (5 being the most favourable). The total score can then be compared with the ranges given in Table 4 to assess the relative applicability of different sensing options during the design of the monitoring system. Tables 5 to 9 outline the scoring system for Q1-Q5 so that users of the framework can complete their assessment of a proposed scour monitoring device. It should be noted that other criteria for sensor selection could be added to this framework, but the present authors judged Q1 to Q5 (Table 3) as the minimum number of criteria to distinguish between available sensing systems, thus keeping the methodology as simple as possible.

3.1 Ease of installation (Q1)

Ideally a monitoring device will be easy to install i.e., to be relatively simple to install on the bridge structure and not require a bridge/road closure during the installation. Visual inspections that require divers are classed as difficult ‘installations’, because monitoring is not permanent and requires a human inspector (diver) each time a ‘reading’ is to be taken. Table 5 gives the individual risk ratings for Q1. It is acknowledged that ease of installation is to some extent context specific e.g., if installation of a monitoring system is done using a vessel then river access is needed, and this may not be possible (or permitted) on some waterways. The highest score is given to systems that are satellite based (e.g., Selvakumaran et al. 2018) or make use of aerial robotics technology (see e.g., Freeman et al. 2021 and Greenwood et al. 2019 for recent developments of this technology in civil engineering) or can be conducted from a vessel (e.g., Clubley et al. 2015). When reviewing published case studies, it is acknowledged that the traffic disruption (if any) caused by the system installation is not always clearly reported.

3.2 Ease of operation (Q2)

Ease of operation is an important consideration as training may be needed for the operator who may or may not need to have specific technical expertise. For example, visual inspection by a diver requires a trained specialist in the field; whereas while a trained bridge engineer would need to interpret tiltmeter data, a specialist operator would arguably not be needed for the tiltmeter system once installed. Ease of operation is different from ease of interpretation which is dealt with separately (see Section 3.4). Table 6 gives the individual risk ratings for Q2.

3.3 Ease of data-logging/capture (Q3)

Remote monitoring is an advantage in SHM activities as visits to the site are not needed for regular data collection (see Hoult et al. 2009 for details on various wireless sensor deployments on some civil infrastructure assets). The availability of mains power is an advantage as battery changes also require site visits for installed SHM systems (cf. Hoult et al. 2009; Fidler et al. 2021). Table 7 details the individual risk ratings for Q3.

3.4 Ease of data interpretation (Q4)

Interpretation of monitoring data is arguably the most challenging aspect of SHM as it transforms data into information. Crotti & Cigada (2019) explain the need for reliable SHM data for adoption of monitoring outputs in practice. Data cleaning, effects of noise, post-processing time and so on are often to most resource intense part of SHM projects (Webb et al. 2014 illustrates the challenge of SHM data interpretation for the Hammersmith Flyover). Table 8 lists the individual risk ratings for Q4.

3.5 Measurement Frequency (Q5)

A device that can sample frequently and reliably is valuable for monitoring activities. This category (Q5) relates to the frequency that measurements can be taken as well as the robustness (i.e., resistance to high-flow effects) of the sensor equipment. Table 9 gives the individual risk ratings for Q5.

4. Review of published field case studies

Table 10 summarises a selection of field deployments whose main sensing method has been retrospectively evaluated using the rating methodology proposed in Section 3. These case studies were selected for detailed review based on the inclusion of a detailed description of the monitoring equipment and the installation/deployment; a clearly articulated purpose of the monitoring system (i.e., how the data will be used) and discussion on the relative success of the monitoring. The present authors note that the review presented in Table 10 is a retrospective application of the scoring system to some previously reported monitoring projects and that these projects all had (to some extent) differing aims. For instance, some deployments focussed on detection of scour depth whereas others simply examined if scouring was present. It should also be noted that the information in Table 10 is the present authors' interpretation for the reported studies and further information not contained in the reviewed articles may alter the scores given somewhat. Nevertheless, Table 10 was compiled as illustrative example and it presents a review of the efficacy of scour monitoring technologies based on reported field deployment and performance. Table 10 may serve as useful guide for those wishing to employ the new rating methodology in practice and compare different sensing solutions for scour-prone bridges.

5. Discussion

5.1 Key review findings

De Falco & Mele (2002: p.117) state 'Scour failures tend to occur suddenly and without prior warning or sign of distress to the structure'. This paper has reviewed many technological approaches to scour monitoring (see Section 2) – many of which show promise of being able to assess to a reasonable degree the 'extent' of scouring of a bridge foundation. However, the 'onset' of scouring is not able to be detected by most of these systems. Knowing that a major flood event has occurred may be sufficient information for a bridge manager to test all riverine bridges or at least those assessed to be at an increased risk of scour. However, as the case study review in Section 4 shows, not all technological solutions will operate effectively during or immediately post-flood and therefore cannot be used as early warning systems for bridge collapse. Scour countermeasures such as diaphragms and sliding collars (e.g., De Falco & Mele 2002) may be installed following risk-based scour assessments and these may help prevent scouring and indeed bridge failure. However, without a reliable method to detect the onset of scouring during and immediately post-flood event some bridges may still collapse due to hydraulic loadings.

5.2 Potential use of the rating system in practice

For a bridge or network of bridges in an area, a bridge engineer may be worried about potential scouring after routine visual inspections or analysis using scour depth prediction equations. The rating system can be used to assess the range of sensing options available and justify the installation of a particular system and, by definition, the allocation of financial resources. The framework has been flexibly designed and other questions (criteria) can be added as needed (such as equipment cost or installation time).

5.3 Scour management using inspections and monitoring

Visual inspection combined with analysis using empirical equations during the desk study phase are arguably still needed to determine at-risk bridges in a large network. Once the at-risk bridges are identified they may be assessed by fully remote methods such as the InSAR approach by Selvakumaran et al. (2018) (although scour depth is hard to quantify with such systems). When deterioration is detected especially in areas with high flood risk then on-site monitoring systems may be installed e.g., using FBG sensors or vibration-based systems for real-time monitoring during flood events. This real-time data can be used to inform bridge closures during times of disaster while the visual inspection and/or satellite methods can be used for maintenance planning. All the collected field data for the network should then be incorporated into bridge performance databases to better calibrate the desk study tools i.e., the empirical equations used to predict scour depths etc. For scour management at a network level, openly accessible databases of scour failures with associated monitoring data either during event or post event should be developed. Efforts should be made to establish what value was realised from the monitoring efforts on a case-by-case basis so that more targeted and improved monitoring approaches can be developed for future deployments.

6. Summary and Conclusions

This paper has presented a review of the range of monitoring options available to those wishing to undertake both routine inspection or more detailed forensic investigations of scour prone bridges. A new (and flexible) rating methodology has been proposed to allow for ranking of available monitoring devices which may be useful to those designing scour monitoring deployments. When specifying a new scour monitoring system, the rating methodology presented in this paper may be used to compare different sensing options and methodologies. The collected data should be stored in a national (or regional) scour database which can be used to improve the empirical predictions of scour depth which are often calibrated using laboratory and numerical studies, rather than field measurements.

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Data Availability Statement

This study has not generated new experimental data.

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Table 1: Monitoring method breakdown (USGS database) (Benedict & Caldwell 2014a, 2014b) (italics are from the present authors) (*n* = number of data points)

Monitoring method (from Table 1-1 in the USGS database)	**n**	**%**
Soundings	709	38
Fathometer	232	12
Ground Penetrating Radar *(GPR)*	192	10
Survey	191	10
Scour Rod	11	<1
ADCP *(acoustic doppler current profiler)*	10	<1
Estimate from soil borings	3	<1
Brisco Scour Monitor	1	<1
Not specified/reported	509	27
Total	1858	

Table 2: Monitoring time breakdown (USGS database) (Benedict & Caldwell 2014a, 2014b) (*n* = number of data points)

Measurement type (from Table 1-1 in the USGS database)	n	%
During flow event	951	51
Historical	360	19
Post flood	126	7
Not specified/reported	421	23
Total	1858	100

Table 3: Criteria for sensor rating methodology

Criteria	Description
Q1	Ease of installation
Q2	Ease of operation
Q3	Ease of data-logging/capture
Q4	Ease of data interpretation
Q5	Measurement frequency

Table 4: Sensor Rating Category

Total Score	Applicability for Scour Detection and Monitoring
23-25	Very High Applicability
18-22	High Applicability
13-17	Moderate Applicability
8-12	Low Applicability
5-7	Very Low Applicability

Table 5: Individual Risk Rating: Q1 Ease of Installation

Score	Required characteristics of the monitoring device/method	Example
5	Fully remote monitoring possible	Satellite, aerial based systems or those conducted from a vessel or the riverbank
4	Installation during construction of the bridge or during bridge service with no disruption to traffic or services	Accelerometer based systems installed during construction – no need for traffic disruption
3	Installation during bridge service with minimal disruption to traffic or services	Tiltmeter system installed on an existing bridge asset
2	Installation during bridge service but with disruption to traffic or services i.e., bridge closure needed	Manual GPR operations
1	Visual inspection	Diving team

Table 6: Individual Risk Rating: Q2 Ease of Operation

Score	Required characteristics of the monitoring device/method	Example
5	Easy to operate without specialist training	Plotting tiltmeter output
4	Some training may be required but the operator does not need to be a specialist	Visual inspection of photographs taken at the site
3	Specialist operator needed but the activity is relatively safe	Manual GPR operations
2	Specialist operator needed and the activity poses some safety risks to the operator	Visual inspection using a diver in ideal waterway conditions
1	Specialist operators needed and the activity poses some safety risks to the operators	Visual inspection using a diving team in a bridge with debris build-up post flood event

Table 7: Individual Risk Rating: Q3 Ease of data-logging/capture

Score	Required characteristics of the monitoring device/method	Example
5	Fully remote data logging possible	Monitoring using an unmanned aerial vehicle (UAV)
4	Wireless data logging	A ‘gateway’ may need to be installed at the monitoring site (cf. Hoult et al. 2009 – various monitoring case studies).
3	Wired monitoring via a permanent data logger	An ‘analyser’ is connected by a cable to the sensing device (cf. Cheung et al. 2010 for monitoring a tunnel lining)
2	Wired monitoring via a portable data logger (which cannot be left on the site) connected by a cable to the sensing device	An ‘analyser’ is taken to the monitoring site each time data readings need to be taken.
1	Fully manual data collection	Visual inspection using a human inspector

Table 8: Individual Risk Rating: Q4 Ease of data interpretation

Score	Required characteristics of the monitoring device/method
5	Scouring is instantly detected even with occurrences of infilling of scouring holes
4	Scouring can be instantly detected but not infilled scour holes
3	Moderate data volumes collected and/or with some post-processing time needed before an assessment of scouring can occur
2	Large volumes of data collected and/or with some post-processing time needed before an assessment of scouring can occur
1	Large volumes of data collected and/or with considerable post-processing time needed before an assessment of scouring can occur

Table 9: Individual Risk Rating: Q5 Measurement Frequency

Score	Required characteristics of the monitoring device/method
5	Data is collected continually even during heavy flow events
4	Data is collected continually but the sensor may be disrupted during heavy flow events hampering data flow with no damage to the sensor itself
3	Data is collected continually but the sensor may be damaged and hence not transmit data during heavy flow events
2	Data is collected intermittently with a fixed sensor
1	Data is collected intermittently with a portable sensor or human inspector

Table 10: Scour sensor rating methodology applied to previously published scour monitoring case studies

ID	Reference	Bridge Location	Name of Monitored Bridge(s)	Description of Scour Monitoring Activity	Principal Sensors	Scour-Rating Outcome
B1	De Falco & Mele (2002)	Italy	Mezzana Corti over the River Po (Milano-Genova line) Borgoforte bridge over the River Po (Verona-Mantova line)	Experimental System. Sedimeters did not function well on the Mezzana Corti deployment (i.e., due to broken cables) so sonar was utilised. Sonar devices were equipped with fixed crystal transducer with a range of 200mm to 50m powered requiring a power supply (18-36VDC@ 100 mA max). Sensors to measure water level transmitting data via a telephone line also installed with communication to a 'supervisory centre'. (Wireless solutions would also be possible for more modern deployments cf. Hoult et al. 2009 for a detailed discussion on WSN technology for infrastructure monitoring).	Sonar	**Q1** – Sonar easy to install. For this case study installed on existing bridges. Installation during construction also possible but not a fully remote system. **Score 3/5**. **Q2** – Sonar operation may require some training. **Score 4/5**. **Q3** – Fixed power source, wired data-logging. **Score 3/5**. **Q4** – Interpretation of scour data can be challenging as the signature is not straightforward to analyse. Not all trends measured by the sensors were anticipated. **Score 1/5**. **Q5** – System functions in real time (and during flood events) with continuous data readings possible. **Score 5/5**. **Total = 16**. *Moderate applicability* (Table 4)
B2	Lin et al. (2006)	Taiwan	Dadu Bridge over the Wu river	Installation of 'button' Fiber Bragg Grating (FBG) sensor system installed in series (1m intervals) on the piers of the bridge. Sensors were embedded in the riverbed. Some sensors were exposed during flood events. System measures strain which increased during the flood event and reduced during flood recession indicating sediment deposition (infilling). Fluctuating temperature and strain measurement indicate an exposed sensor rather than a buried one. System can detect scour at 1m intervals. Based on photographic evidence, installation occurred while the river was running low with seemingly little disruption. The 'button' sensors have a waterproof seal and a housing for the sensor preventing damage due to high flow velocities or debris impacts. Iron 'bumpers' were also installed for extra protection of the sensors. Sensor deployment occurred prior to a typhoon flood event in 2004. Datalogger installed on site connected to the sensing system. Real-time data collection during a flood event was demonstrated.	Fiber Bragg Grating (FBG) sensors	**Q1** – Photographs show installation with possibly minimal traffic disruption. Installation aided by an apparently low running river – such a solution may be more challenging in deeper channels. **Score 3/5.** **Q2** – Operation relatively simple as the system operates in situ once installed. **Score 5/5** **Q3** – Real-time monitoring was possible. Data-logger installed on site. It is assumed some transmission of the data is possible during the flood event. Datalogger wired to the sensors. **Score 3/5**. **Q4** – Data needs to be processed and presented for interrogation. FBG readings provide considerable amounts of data for analysis. Scour detection not instantaneous. **Score 1/5**. **Q5** – Data collection was possible during a flood event with robustly designed sensors. **Score 5/5**. **Total = 17**. *Moderate applicability* (Table 4)

B3	Clubley et al. (2015)	England, (UK)	Railway Viaduct over the River Hamble	Kongsberg EM 3002D multi-beam echo sounder mounted to a vessel was used to study the bathymetry of the riverbed. Kongsberg MS 1171 scanning sonar deployed to refine results of the multi-beam survey and obtain images of submerged features. Scour was detected from inspection of the system images (contrary to the diver inspection data). Dual axis sonar profiler used to study profile of the riverbed. Marine laser surveys used to complete structural record and record riverbank features.	Sonar	**Q1** – Surveys using the sonar devices and marine laser conducted from a vessel and hence fully remote monitoring. **Score 5/5**. **Q2** – Specialist operators and a crewed vessel is needed. The operation is relatively safe as the measurements are taken by onboard mounted sensors (or pole mounted sensors). **Score 3/5**. **Q3** – A vessel is needed for the sensing (similar to using a portable data-logger). **Score 2/5**. **Q4** – Examination of the bathymetric scans allows for scour to be detected from visual observation. Some interpretation of underwater features is needed. **Score 3/5**. **Q5** – System does not provide continuous measurements as a vessel is needed to use the system. **Score 1/5**. **Total = 14**. *Moderate applicability* (Table 4)
B4	Kong et al. (2017b)	Louisiana, (USA)	Concrete bridge over Redwood Creek on Louisiana Highway 67, East Baton Rouge Parish	FBG sensors were attached to two test piles which were installed near the bridge piers when the river was running low. Temperature compensation sensors were installed to allow separation of temperature and strain. FBG sensors protected with application of an epoxy resin. Strain measurements gathered with si425 Optical Sensing Interrogator (OSI). Cables from sensors led using a tube to the bridge deck for connection to the si425 OSI. Some sensors damaged during installation. Data was collected on five occasions during the study. Scour depths from the sensing data reported to match well site depths observed	Fiber Bragg Grating (FBG) sensors	**Q1** – Examination of installation photographs shows installation near bridge with apparently minimal traffic disruption. Installation aided by a low running river – such a solution may be more challenging in deeper channels. **Score 3/5.** **Q2** – Operator is needed to take the discrete readings with the OSI. Some training probably needed for operation. **Score 3/5**. **Q3** – Wired monitoring with a non-permanent data-logger. OSI probably not stored on site. **Score 2/5**. **Q4** – Data needs to be processed and presented for interrogation. FBG readings provide considerable amounts of data for analysis. Scour detection not instantaneous. **Score 1/5**. **Q5** – Data is collected on set days at discrete intervals. During heavy flood events it may not be safe to take data readings. **Score 2/5**. **Total = 11**. *Low applicability* (Table 4)
B5	Selvakumaran et al. (2018)	England (UK)	Tadcaster Bridge	Retrospective analysis of data in the lead up to partial collapse of a masonry arch bridge. System can be used as a forensic tool as well as a potential early warning system. For use on un-failed bridges the method may be a warning system but is unlikely to be of use during a flood event as the image may not be available in real-time (depends on position of the satellite).	Interferometric synthetic aperture radar (InSAR)	**Q1** – Satellite based, fully remote monitoring. **Score 5/5**. **Q2** – Operation is straightforward if the images are already available for analysis (although a satellite in orbit is needed). **Score 5/5**. **Q3** – Fully remote monitoring so no challenge for data-logging (although a satellite in orbit is needed). **Score 5/5**. **Q4** – Considerable post-processing needed. Interpretation requires specialist knowledge. **Score 1/5**.

				48 TerraSAR-X Stripmap images and LIDAR data used to analyse the bridge in lead up to failure. The processing allows for deformations to be detected by comparing the images in sequence. Interpretation of the physical meaning of the data from scatterers (points relating to the bridge structure) is challenging. Operators would need to be examining the data actively prior to flood events to make use of the information.		**Q5** – Reliant on flyover of satellite so discrete measurements are taken. Monitoring not continuous. **Score 1/5**. **Total = 17**. *Moderate applicability* (Table 4)
B6	Kariyawasam et al. (2019a, 2019b)	England (UK)	Baildon Bridge over the River Aire in Shipley, Yorkshire	Testing occurred on bridge in damaged (scoured), repaired and intermediate states. Finite Element Analysis (FEA) used to determine mode shapes and natural frequency changes expected due to scour. 10 3-axis Epson M-A550 QMEMS (RS-422 variant) low-noise, high-sensitivity accelerometers cabled to a NI CompactRIO-9063 data logger. Raspberry Pi used for transmission between the data-logger and the internet. Frequency domain decomposition (FDD) used to determine mode shapes and frequencies. Change between modes within the margin of error for frequency estimate for the bridge indicating challenges remain for small span structures. Spectral density and mode shape may be more useful for scour detection.	Accelerometers	**Q1** – Installation appears to be external to bridge structure, assumed minimal traffic disruption. **Score 3/5**. **Q2** – There may be some training needed to operate the system and download the data from the internet cloud. **Score 4/5**. **Q3** – Wireless data logging. **Score 4/5**. **Q4** – Considerable analysis needed to determine mode shapes and changes due to scouring and interpretation of collected data. **Score 1/5**. **Q5** – Continuous data collection possible (score assumes system can operate during flood events). **Score 5/5**. **Total = 17**. *Moderate applicability* (Table 4)
B7	Maroni et al. (2020)	Scotland (UK)	A76 200 Bridge over the river Nith in New Cumnock	Pilot study. Installed system of 2 bespoke smart dielectric probes. System measures changes in permittivity (water, soil and air have different permittivity levels). System can be installed pre-event and can operate during flooding. Sensor protected by plastic tube. System was battery powered. Wireless transmission of data to the cloud possible. Continuous data reading possible. System was able to detect scour at one location which was confirmed with visual inspection. A very small scour hole present at the other testing location was undetected. System showed promise for scour detection.	Smart probes equipped with electromagnetic sensors. (EnviroSCAN probe).	**Q1** – Installation on pre-existing bridge with minimal traffic disruption assumed. **Score 3/5.** **Q2** – Automated system simple to operate once installed. **Score 5/5**. **Q3** – Probes equipped with an antenna which can transmit via the ‘wireless interface’. **Score 4/5**. **Q4** – Data can be interpreted from signature outputs, but some processing is needed. Detection is not instant. **Score 2/5**. **Q5** – Continuous data collection possible even during flood events (high score for Q5 does rely on regular battery changes occurring). **Score 5/5**. **Total = 19**. *High applicability* (Table 4)

List of Figure Captions

Figure 1: Key considerations when deciding whether to employ structural health monitoring (taken from Vardanega et al. 2016 used under the terms of the cc-by 4.0 licence)

List of Table Captions

Table 1: Monitoring method breakdown (USGS database) (Benedict & Caldwell 2014a, 2014b) (italics are from the present authors) (n = number of data points)

Table 2: Monitoring time breakdown (USGS database) (Benedict & Caldwell 2014a, 2014b) (n = number of data points)

Table 3: Criteria for sensor rating methodology

Table 4: Sensor Rating Category

Table 5: Individual Risk Rating: Q1 Ease of Installation

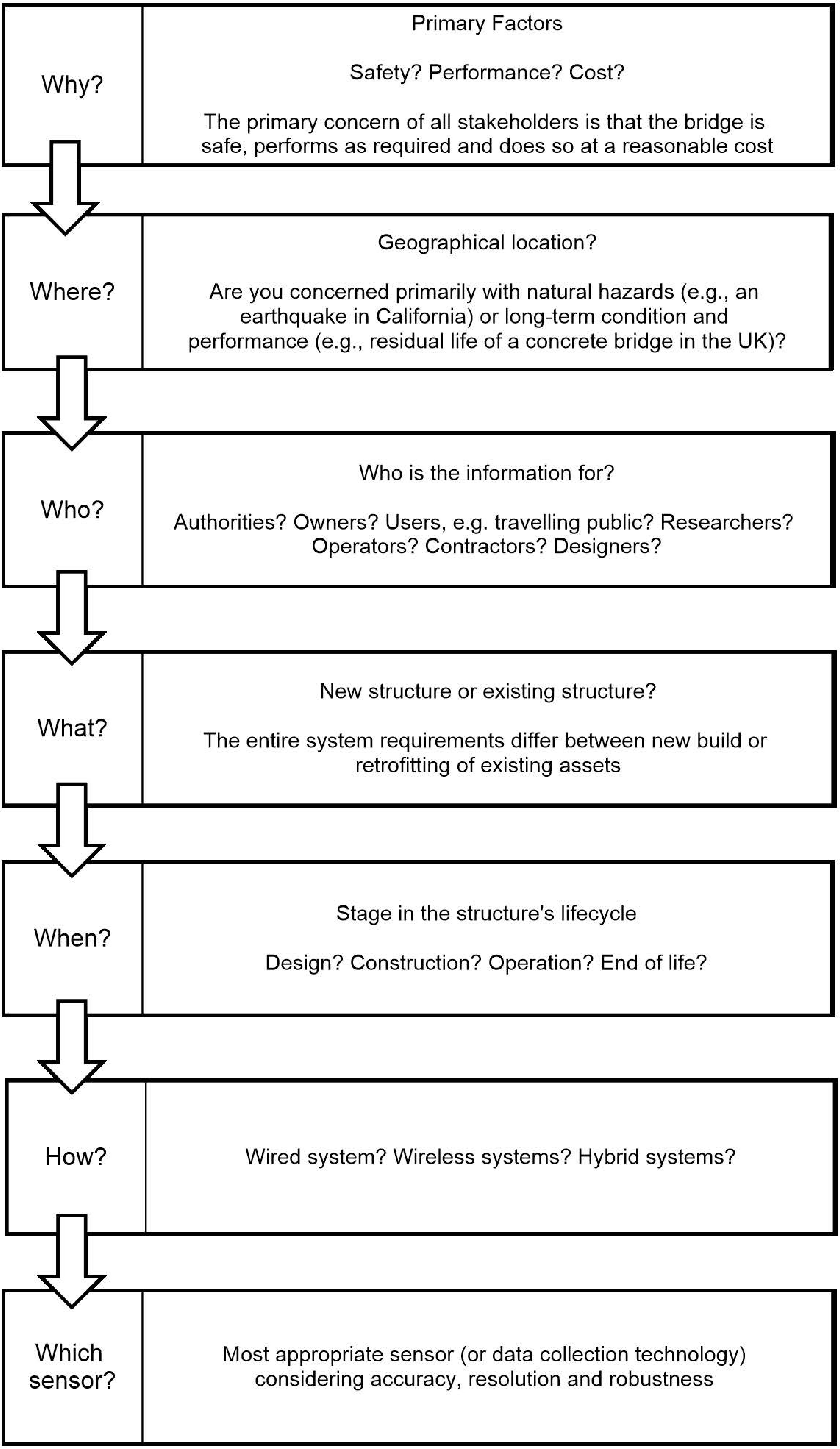
Table 6: Individual Risk Rating: Q2 Ease of Operation

Table 7: Individual Risk Rating: Q3 Ease of data-logging/capture

Table 8: Individual Risk Rating: Q4 Ease of data interpretation

Table 9: Individual Risk Rating: Q5 Measurement Frequency

Table 10: Scour sensor rating methodology applied to previously published scour monitoring case studies



Why?

Primary Factors

Safety? Performance? Cost?

The primary concern of all stakeholders is that the bridge is safe, performs as required and does so at a reasonable cost

Where?

Geographical location?

Are you concerned primarily with natural hazards (e.g., an earthquake in California) or long-term condition and performance (e.g., residual life of a concrete bridge in the UK)?

Who?

Who is the information for?

Authorities? Owners? Users, e.g. travelling public? Researchers? Operators? Contractors? Designers?

What?

New structure or existing structure?

The entire system requirements differ between new build or retrofitting of existing assets

When?

Stage in the structure's lifecycle

Design? Construction? Operation? End of life?

How?

Wired system? Wireless systems? Hybrid systems?

Which sensor?

Most appropriate sensor (or data collection technology) considering accuracy, resolution and robustness