Yaqoobi, W., Gavriel, G., Tryfonas, T., Vardanega, P. J., & Pregnolato, M. (2024). Comparison of ranking frameworks for specification of bridge scour monitoring systems using a case study database. In J. S. Jensen, D. M. Frangopol, & J. W. Schmidt (Eds.), *Bridge Maintenance, Safety, Management, Digitalization and Sustainability: Proceedings of the 12th International Conference on Bridge Maintenance, Safety and Management, 24-28 June 2024, Copenhagen, Denmark* (1st ed., pp. 1108-1115). CRC Press/Balkema, Taylor & Francis Group. https://doi.org/10.1201/9781003483755-128

Bridge Maintenance, Safety, Management, Digitalization and Sustainability –
Jensen, Frangopol & Schmidt (eds)

Comparison of ranking frameworks for specification of bridge scour monitoring systems using a case study database

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ABSTRACT: Hydraulic actions resulting in scour are a major cause of bridge failures worldwide. The development of scour is affected by various factors including structural geometry, river morphology and weather conditions. Detection of scour is often carried out using visual inspection-based methods. Visual inspection requires the expertise of divers which incurs high levels of risk, especially during times of high-water flow. Therefore, sensing technologies are becoming increasingly popular with the aim to supplement or replace higher risk visual inspection approaches. Specification of Structural Health Monitoring (SHM) systems is an important activity for bridge engineers and asset managers. This activity can be assisted by SHM rating frameworks, the use of which gives evidence to support specification of monitoring systems for individual bridges. In this paper, three previously published scour rating frameworks are compared using a bridge case study database.

1 INTRODUCTION

1.1 *Background*

Bridge scour is the erosion of material around bridge piers, abutments, and foundations (e.g. Kirby *et al.* 2015). Scour accounts for approximately 60% of bridge failures, including pier scour incidents (Lagasse *et al.* 1997). As a result of scouring actions, the foundations of a bridge may become unstable potentially resulting in collapse (e.g. Maddison 2012). About 60,000 highway and railway bridges span watercourses in the UK, many of which are over 150 years old with unknown foundations (especially unknown foundation depths) (e.g. Clubley *et al.* 2015).

Scour is a challenge for engineers due to the complex soil-water-structure interactions (cf. Kirby *et al.* 2015, Pregnolato *et al.* 2022). Empirical scour depth prediction methods show considerable scatter (cf. Gavriel *et al.* 2023, Shahriar *et al.* 2023). Hence it is important to monitor scour in the field and if possible, employ real time monitoring (cf. Prendergast & Gavin 2014, Vardanega *et al.* 2021). It is also desirable to develop efficient and durable scour monitoring systems (e.g. Pizarro *et al.* 2020, Vardanega *et al.* 2021). These systems are important for evaluating the scour process and for providing early warnings for hazard mitigation (Prendergast & Gavin 2014). Scour monitoring systems should possess key characteristics such as accuracy, longevity, ease of installation, non-obstructiveness to bridge owners or users, cost-effectiveness, and the ability to withstand a range of environmental conditions (cf. Vardanega *et al.* 2021, Pregnolato *et al.* 2022).

The impact of scour on bridges is becoming more serious every year due to climate change (Sasidharan *et al.* 2023). The increase in frequency and severity of flood incidents

DOI: 10.1201/9781003483755-128

(due to the effects of climate change) heightens the risk of scour to bridges (Foley 2021). A bridge collapse is considered a socio economical problem as it is associated with loss of life, high economic losses, and disruptions to traffic (Pregnolato *et al.* 2021, Dawson *et al*. 2018). It is therefore necessary for engineers to ensure that the effects of scour are mitigated and managed.

1.2 *Scour monitoring*

Prendergast & Gavin (2014) and Vardanega *et al.* (2021) present reviews on various scour monitoring devices. Numerous monitoring techniques have been developed which are able to detect scour occurrence: these techniques can be broadly categorized into 'direct' and 'indirect' technologies (see Pregnolato *et al.* 2022). Direct technologies involve the use of sensors near the bridge foundations, while indirect technologies rely on approaches such as remote sensing or modelling (Pregnolato *et al.* 2022). For instance, two direct technologies are the mechanical sounding rod and the sliding magnetic collar (SMC); devices that are simple to install and produce data which are easy to interpret (cf. Lu *et al.* 2008). Sonar, another direct technology, although easy to use, is prone to the effects of turbulent flow, turbidity, and debris (cf. Fisher *et al.* 2013, Hong *et al.* 2016).

Indirect technologies usually measure the structural response and performance over time to estimate scour depth (Pregnolato *et al.* 2022). These technologies include float-out devices which have high operational capacity in harsh flow conditions enabling their use during times of flooding when scour holes are more likely to develop (Prendergast & Gavin 2014, Pregnolato *et al.* 2022). One downside of float-out devices is that their power supply and reliability cannot be checked once deployed (Prendergast & Gavin 2014). Float out devices are placed in the riverbed and will activate when released during scouring, by floating above the surface (Prendergast & Gavin 2014, Tola *et al.* 2023). Numbered bricks are robust during flood events and are useful for measuring scour (Lu *et al*. 2008). Smart magnetic rocks can monitor scour depth, but they are also susceptible to being washed away during high flows (Jiang *et al.* 2022).

Visual inspection, which is typically carried out by divers, is still a common scour monitoring technique (e.g. Clubley *et al.* 2015, Kirby *et al.* 2015, Selvakumaran *et al.* 2018). Operations cannot however take place during flood events due to the high risk involved for the divers. Divers are only able to inspect a bridge for scour holes after the flood event is over (e.g. Larrarte *et al.* 2020). Visual inspection sometimes may give inaccurate information about the current scour situation due to the presence of debris and lack of clear visibility (e.g. Clubley *et al.* 2015). An example of false inspection is the collapse of the Mayou bridge in France back in 2009 (Larrarte *et al.* 2020). Despite a visual inspection carried out two years prior to the incident, the inspectors failed to detect any scour hole (Larrarte *et al.* 2020). The use of scour monitoring devices can result in less reliance on visual inspections. To decide on the best combination of scour devices for the monitoring of a specific bridge SHM scour assessment frameworks may be used.

1.3 *Study aims*

In this paper, three scour assessment frameworks (Vardanega *et al*. 2021, Pregnolato *et al*. 2022, Lueker *et al*. 2010a, b) are applied to nine bridge case studies reported in the literature (Hayden & Puleo 2011, Wang *et al*. 2012, Zarafshan *et al*. 2012, Topczewski *et al*. 2016, Peng 2020, Lin *et al*. 2021, Weissmann *et al*. 2021, Zhan *et al*. 2022, San Martin *et al*. 2023). This paper aims to provide guidance for those seeking to select an appropriate framework for use during the specification of scour monitoring systems. This aim is accomplished by: (a) applying nine case studies to the three aforementioned frameworks (b) comparing the results from the nine case studies and (c) evaluating the capabilities of each framework to provide guidance as to which is the most suitable framework depending on the situation.

2 SCOUR RATING FRAMEWORKS

2.1 *Framework 1 - Vardanega et al. (2021)*

Framework 1 has been developed by Vardanega *et al.* (2021) based on preliminary work by Gavriel (2019). Framework 1 evaluates the suitability of scour monitoring devices based on five criteria given in Table 1. For each of the five criteria a device can score between 1 to 5 (5 being the highest). The score from each category is summed up to give the total score. This process is repeated for all devices under consideration. The devices are then ranked from highest to lowest score. Framework 1 also provides an indication of the relative applicability of each device depending on the score ranges given in Table 2.

Table 1. Criteria for sensor-rating methodology (taken from Vardanega *et al.* 2021).

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

Table 2. Sensor-rating category (taken from Vardanega *et al.* 2021).

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

2.2 *Framework 2 - Pregnolato et al. (2022)*

Framework 2 by Pregnolato *et al.* (2022) is a further development of the approach by Vardanega *et al.* (2021). This approach was used to evaluate the feasibility of various monitoring technologies for scour detection and monitoring on three railway bridges in the UK (Pregnolato *et al.* 2022). The study follows a three-stage evaluation process. In Stage 1, available technologies are assessed against the requirements of the CIRIA manual (Kirby *et al.* 2015) and those of Network Rail (see Table 3 for the Stage 1 criteria). Technologies that do not satisfy all the requirements of Table 3 are disregarded and do not pass to Stage 2. In Stage 2, sensors are assessed over nine criteria listed in Table 4. The main difference to Framework 1 is the introduction of heuristically assigned weights on each category. The category score is between 1 to 5 as in Vardanega *et al.* (2021). In the final stage the scores from each category are multiplied by the weight of that category and they are then summed up. The devices are then ranked from highest to lowest score and assessed in a similar way to that shown in Table 2 (see Pregnolato *et al.* 2022 for further details).

2.3 *Framework 3 – Scour Monitoring Decision Framework (SMDF) Lueker et al. (2010a, b)*

Framework 3 is the Scour Monitoring Decision Framework (SMDF) proposed by Lueker *et al.* (2010a, b). Framework 3 was developed for the evaluation and selection of scour monitoring devices on river bridges in Minnesota (USA). Framework 3 can evaluate one bridge at a time and can consider multiple piers or abutments of that bridge. Framework 3 requires site-specific information about the assessed bridge. The required information includes details about the bridge location and dimensions, flow conditions, bridge conditions, structural elements, and environmental factors. Based on these inputs the framework compares the various types of fixed scour monitoring equipment. By entering sufficient information about the site and the bridge, Framework 3 can rank instruments by suitability for the specific bridge site. Framework 3 is also able to show the effect each of the site/bridge characteristics inputted has on each score for each device. A data file for each bridge containing the structural and environmental information about the specific site is prepared i.e. the input data. The workbook compares the structural and environmental information inputted to the ideal structural and environmental conditions as indicated by the worksheet. The two are illustrated on a bar chart for which a score in the form of a percentage is shown (see Lueker *et al.* 2010a, b for further details). In this framework, each case study can only be assessed against the devices available in the SMDF.

Table 3. Mandatory criteria for Stage 1 (based on Pregnolato *et al.* 2022).

Criteria	Description
R1	Suitability for use at a remote site
R2	Capability of installation on or near a bridge pier or abutment
R3	Capability of obtaining readings from above the water surface (transmitting data without need for underwater access)
R4	Operation capability during storm and flood conditions
R5	Ability to operate from battery, solar power or fuel cell
R6	Ability to operate without the need to mobilize personnel during flood condition
R7	Industry-ready in a related application and/or laboratory-proof for scour assessment

Table 4. Stage 2 Criteria (Q) and Weights for Framework 2 (based on Pregnolato *et al.* 2022).

Criteria	Description	Weight
Q1	Purchase Cost	0.8
Q2	Expected Lifespan	1.1
Q3	Environmental Limitations	1.2
Q4	Robustness	1.2
Q5	Maintenance Requirements	1
Q6	Whole-life Cost	0.8
Q7	Accuracy, Repeatability, Reliability	1
Q8	Ease of Installation (access)	0.7
Q9	Power Consumption	0.8

3 CASE STUDIES

In this section, an assessment is conducted using Frameworks 1 to 3 which are applied to nine different case studies. Table 5 shows the results of the scour rating framework comparison conducted. When using Framework 3 if additional information concerning the location and dimension of the bridge was not available and required, Google Earth was used to estimate this information.

4 DISCUSSION

The comparison of the frameworks as applied to the nine-case studies are given in Table 5. For CS1 from Lin *et al.* (2021), MEMS sensor (which is the device installed on the bridge at the time of the case study) scored very high for both Frameworks 1 and 2. For Framework 3, evaluating MEMS was not an option as this device is not included in Framework 3. Nevertheless, the case study was tested over the nine already available SHM devices which showed that TA/V device (79%) was the best option followed by the FO device (66%). Framework 1 and 2 can be easily used on already reported case studies to test the suitability of a known device but this may not be an option when using Framework 3 unless the device of interest is available in Framework 3. In the case of a bridge where the user wants a recommendation of a monitoring approach Framework 3 is more suitable.

For CS2, from Zarafshan *et al.* (2012), FBG device (which is the device installed on the bridge at the time of the case study) was ranked as more suitable by Framework 1 (19/25, High Applicability) compared to Framework 2 (27.6/43, Moderate Applicability). The device (which is similar to that reported in the case study of Lin *et al.* 2021) was not one of the nine available devices. However, Framework 3 shows that the TA/V device scored the highest (69%) followed by the FO device (68%). For CS2 the FO device although ranked second, scored higher compared to CS1. The TA/V device only scored 1% more than the FO device.

For CS3, PF was available as one of the nine devices in Framework 3. The PF device scored higher in Framework 1 (20/25, High Applicability) compared to Framework 2 (27.9/43, Moderate Applicability). Framework 3 listed the device fifth best, indicating that there may be more suitable devices. The device scored 59% according to Framework 3, providing similar results to Framework 2.

For CS4, from Zhan *et al.* (2022), the device installed on the bridge at the time of the case study was an accelerometer. Framework 1 scored the device as being of low applicability (11/25, Low Applicability) compared to Framework 2 for which the device did not pass to Stage 2 as it did not meet the criteria in Table 3. For Framework 3 the TA/V device (70%) scored the highest followed by the FO device (67%).

For CS5, from Weissmann *et al.* (2021), the approaches evaluated were US (sonar) and MSC. The US and MSC are highly applicable according to Framework 1 (21/25) and moderately applicable (32.1/43) according to Framework 2. Framework 3, once again, lists TA/V (78%) and FO (67%) as the top two devices. The MSC scored 48% while SN scored 49% according to Framework 3.

CS6, 7 and 8 all test a version of sonar (SN) which is also one of the nine devices available in Framework 3. SN was ranked as Moderately Applicable for CS6 (17/25) and Highly Applicable for CS7 (20/25) and CS8 (21/25). The device was ranked as Moderately Applicable for all three case studies when Framework 2 is applied. When Framework 3 was applied, SN scored 56%, 48% and 52% for case studies 6,7 and 8 respectively. The top two devices according to Framework 3 are the TA/V and FO device for all three case studies. Frameworks 1 and 2 give similar results for SN in all three case studies. For case studies 6 and 8, the score of SN by Framework 3 is slightly higher than 50%.

For CS9, the Limnimeter (LNM), the device installed on the bridge at the time of the case study (San Martin *et al.* 2023), scored very low with Framework 1 (9/25) and did not pass to the next stage for Framework 2. The LNM requires the intervention of a human operator during times of high flow to take the reading, making it a riskier device to deploy. The LNM is not one of the nine available devices in Framework 3. The results from Framework 3 show TA/V (68%) and FO (64%) as the top two devices for CS9 followed by ASC (62%).

5 SUMMARY AND CONCLUSIONS

Frameworks 1 and 2 provide similar results for the reviewed case studies with Framework 2 generally indicating lower applicability. According to Framework 3, the most suitable devices, for the nine case studies, are the TA/V and FO devices. In the cases where comparison between all three Frameworks could be done, the three Frameworks tended to agree. To allow a better comparison between the three Frameworks, as a next step, the nine devices available in Framework 3 should be tested for the nine case studies and ranked. A larger database could also be assembled for future calibration efforts of these (and possibly other) frameworks.

Table 5. The application of Frameworks 1 to 3 to previously published case studies.

CS	Bridge Name	Location	References	Device(s)	Framework 1	Framework 2	Framework 3
#1	Da-Chia Bridge	Taiwan	Lin *et al*. (2021)	MEMS	Score: 22/25 High Applicability	Score: 33.5/43 High Applicability	TA/V: 79%, FO: 66%, ASC: 63%, PF: 62%, SR: 59%, SN: 52%, TDR: 51%, MSC: 46%, PSDS: 45%.
#2	Salt Creek River Bridge	Chicago (USA)	Zarafshan *et al*. (2012)	FBG	Score: 19/25 High Applicability	Score: 27.6/43 Moderate Applicability	TA/V: 69%, FO: 68%, ASC: 57%, TDR: 56%, PF: 54%, SN: 48%, SR: 45%, PSDS: 42%, MSC: 32
#3	Sibin Bridge	Taiwan	Wang *et al*. (2012)	PF	Score: 20/25 High Applicability	Score: 27.9/43 Moderate Applicability	TA/V: 77%, FO: 69%, ASC: 63%, SR: 59%, PF: 59%, TDR: 47%, MSC: 47%, SN: 46%, PSDS: 41%
#4	Jigezhuang Bridge	Beijing (China)	Zhan *et al*. (2022)	ACC	Score: 11/25 Low Applicability	Table 3 criteria not met.	TA/V: 70%, FO: 67%, ASC: 58%, TDR: 57%, PF: 55%, SN: 51%, SR: 48%, PSDS: 42%, MSC: 34%
#5	Mustang Creek Bridge	Texas (USA)	Weissmann *et al*. (2021)	US and MSC	Score: 21/25 High Applicability	Total: 32.1/43 Moderate Applicability	TA/V: 78%, FO: 67%, ASC: 64%, SR: 61%, PF: 59%, SN: 49%,TDR: 48%, MSC: 48%, PSDS: 44%.
#6	Hangzhou Bay Sea Crossing Bridge	China	Peng (2020)	DS	Score: 17/25 Moderate Applicability	Total: 30.30/43 Moderate Applicability	TA/V: 70%, FO: 62%, TDR: 60%, ASC: 59%, PF: 57%, SN: 56%, SR: 49%, PSDS: 45%, MSC: 36%
#7	Góra Kalwaria	Poland	Topczewski *et al.* (2016)	3-D SN	Score: 20/25 High Applicability	Total: 30.2/43 Moderate Applicability	TA/V: 77%, FO: 68%, ASC: 63%, PF: 59%, SR: 58%, SN: 48%, TDR: 48%, MSC: 46%, PSDS: 43%
#8	The Indian River Inlet Bridge	Delaware (USA)	Hayden & Puleo (2011)	3-D PS	Score: 21/25 High Applicability	Total: 27.10/43 Moderate Applicability	TA/V: 81%, FO: 67%, ASC: 63%, PF: 62%, SR: 58%, SN: 52%, TDR: 51%, MSC: 46%, PSDS: 43%
#9	Rucúe Bridge	Chile	San Martin *et al.* (2023)	LNM	Score: 9/25 Low Applicability	Table 3 criteria not met.	TA/V: 68%, FO: 64%, ASC: 62%, TDR: 60%, PF: 56%, SN: 54%, SR: 47%, PSDS: 45%, MSC: 37%

[Note: Case Study = CS; MEMS = Vibration based Micro Electro Mechanical Accelerometer System Sensor; FBG = Fiber-optic Bragg Grating; ACC = Accelerometer; US = Ultrasonic Sensors (sonar); DS = Dual-axis Sonar; PS = Profiling Sonar; LNM = Limnimeter; TA/V = Tilt Angle/Vibration; ASC = Automatic Sliding Collar; PF = Piezoelectric Film; SR = Sounding Rod; SN = Sonar; TDR = Time Domain Reflectometry; MSC = Magnetic Sliding Collar; PSDS = Pneumatic Scour Detection System and FO = Float Out].

This paper has compared three scour rating frameworks using a selection of case studies from the literature. Frameworks 1 and 2 can evaluate monitoring devices and their accompanying instruments, offering insights into their applicability for specific scenarios. However, a-priori knowledge of possible sensing technologies is needed to effectively employ these frameworks. Framework 3 can yield results for nine monitoring devices, but it does require some updating especially with respect to the cost information.

ACKNOWLEDGMENTS

Special thanks to Matthew Lueker, University of Minnesota for sharing the SMDF spreadsheet and case study data. The work has been also funded in part by the Horizon Europe project ELABORATOR (Grant agreement ID: 101103772).

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