

Selecting scour monitoring devices for smart infrastructure

Walid Yaqoobi, Gianna Gavriel, Sam D. Gunner, Patrick Tully, Theo Tryfonas, and Paul J. Vardanega

Abstract—Scour is a cause of the failure and often subsequent collapse of many bridge structures. Therefore, owners and operators of hydraulic structures such as bridges need to appraise the scour risk to these important infrastructure assets. To determine if scouring has affected a bridge, visual inspection data is still commonly used by bridge engineers. However, this approach has various limitations, e.g. operations cannot be undertaken safely by human divers during flood events and visual inspection may sometimes yield inaccurate data about scour extent due to e.g. refilling of scour holes over time. Early detection of the onset of scour can ensure time for intervention and for the planning of alternative transport routes and thus some of the network service losses during and immediately after extreme weather events can be avoided. To have access to reliable data on scour, it is important to specify and deploy monitoring equipment for detecting the rate and extent of scour. In this paper, an updated framework to assist engineers with the selection of the most suitable instrument or instruments for monitoring scour around riverine bridges is presented. The existence of different types of monitoring devices and approaches requires a framework for selecting the most proper device for a specific field site or sites, as each device has its benefits and challenges with regards to, for instance: purchasing costs; ease of installation; maintenance requirements; operational resilience against debris/ice and provision of accurate data. The proposed framework was developed after an extensive review of other scour monitoring device selection frameworks. Then a pilot study was conducted at the University of Bristol to refine the framework which has now been tested by undertaking a series of interviews with practitioners. The results of the preliminary testing of the new framework are presented in detail in this paper. The paper concludes with

recommendations for how rating frameworks can be used as part of the efforts to transition to ‘smarter infrastructure’.

Keywords— Structural Health Monitoring, Monitoring Devices, Bridge Scour, Framework

I. INTRODUCTION

Bridge scour is one of the main causes of negative structural performance (e.g. Lagasse et al. [1]). Bridge scour is the loss of riverbed material from around the foundations, abutments and piers of the structure due to the action of flowing water (e.g. Arneson et al. [2], Maddison [3], Kirby et al. [4]). Early detection of the onset of scour can ensure time for planning of alternative transport routes and allow for interventions to assist with network recovery (cf. Kirby et al. [4], Webb et al. [5]).

Monitoring scour falls into the ‘damage detection’ category from the review of Webb et al. [5] and this study explains that damage detection is arguably the most valuable category of Structural Health Monitoring (SHM) but the most challenging to achieve in practice. Visual inspection is often used for identifying bridge scour (e.g. Clubley et al. [6]). In the case of scour detection, visual inspection is associated with high levels of risk as it involves human divers and cannot be carried out during flood events (e.g. Kirby et al. [4], Clubley et al. [6], Bennetts et al. [7], Larrarte et al. [8]). Visual inspection is also subject to human error/opinion (cf. Clubley et al. [6], Bennetts et al. [7]). Also scour holes can refill making it difficult to detect scour extent post some flood events (cf. Lagasse et al. [1], Maddison [3]).

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W. Yaqoobi is a former M.Sc. (Research) student at the School of Civil, Aerospace and Design Engineering, University of Bristol, Queen’s Building, University Walk, Bristol, BS8 1TR, UK (e-mail: xo22466@bristol.ac.uk).

G. Gavriel is a Ph.D. student at the School of Civil, Aerospace and Design Engineering, University of Bristol, Queen’s Building, University Walk, Bristol, BS8 1TR, UK (e-mail: gg16047@bristol.ac.uk).

S. Gunner is a Senior Research Associate at the School of Civil, Aerospace and Design Engineering, University of Bristol, Queen’s

Building, University Walk, Bristol, BS8 1TR, UK (e-mail: sam.gunner@bristol.ac.uk).

P. Tully is Transport and Infrastructure Programme Manager at the School of Civil, Aerospace and Design Engineering, University of Bristol, Queen’s Building, University Walk, Bristol, BS8 1TR, UK (e-mail: patrick.tully@bristol.ac.uk),

T. Tryfonas is Professor of Infrastructure Systems and Urban Innovation at the School of Civil, Aerospace and Design Engineering, University of Bristol, Queen’s Building, University Walk, Bristol, BS8 1TR, UK (e-mail: theo.tryfonas@bristol.ac.uk), and

P.J. Vardanega is Associate Professor in Civil Engineering at the School of Civil, Aerospace and Design Engineering, University of Bristol, Queen’s Building, University Walk, Bristol, BS8 1TR, UK (e-mail: p.j.vardanega@bristol.ac.uk).

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To overcome these limitations, deployment of monitoring equipment on bridges to detect the rate and extent of scour is often specified (e.g. Lin et al. [9], Lu et al. [10], Zarafshan et al. [11], Prendergast & Gavin [12], Kong et al. [13], Larrarte et al. [8], Lin et al. [14], Maroni et al. [15]).

Specification of monitoring devices for deployment on a bridge requires assessment of various factors due to the unique nature of each bridge monitoring project (cf. Kirby et al. [4]). To appraise the value of SHM deployments Vardanega et al. [16] proposed a rating framework (not specific to scour monitoring devices) that has three questions for the ‘SHM engineer’, ‘Structural engineer’ and ‘Owner/Asset manager’.

To assist with specification of scour monitoring devices various frameworks have been proposed (e.g. Lueker et al. [17, 18], Vardanega et al. [19], Pregnotato et al. [20]). These frameworks have been compared in Vardanega et al. [21] and also in Yaqoobi et al. [22] using an assembled database of bridge case studies.

The framework proposed by Vardanega et al. [19] can be used for rating available sensing technologies with five main assessment criteria scored using a Likert scale (Likert [23] and e.g. Batterton & Hale [24]). This framework was in part based on a preliminary study by Gavriel [25].

The Pregnotato et al. [20] framework was developed building on the Vardanega et al. [19] framework and incorporates cost considerations with respect to the deployment itself. The Pregnotato et al. [20] framework has three stages and nine assessment criteria which are weighted differently (although the weighting factors have not as yet been calibrated with data).

The Lueker et al. [17], [18] framework was initially developed for a specific region and for a set number of specific sensing technologies and does require considerably more input data (especially site-specific data) than the more general Vardanega et al. [19] and Pregnotato et al. [20] approaches.

Learning from the previously published frameworks, this paper builds on the Vardanega et al. [19], Pregnotato et al. [20] and Lueker et al. [17], [18] studies and presents the outline of a newly developed framework to assist bridge engineers when choosing monitoring equipment to deploy on a bridge. The framework was developed based on a review of previously published case studies (cf. Yaqoobi et al. [22]). Adeleye [26] carried out a recent study and framework on deployability considerations for scour monitoring devices. Gavriel et al. [27] examined how well a selection of eight empirical scour prediction methods can estimate scour measured by different monitoring devices.

This paper outlines the use of the pilot study conducted at the University of Bristol to refine the draft framework. The paper then presents part of the results of a validation process carried out by a survey of six industry participants. The paper concludes with recommendations for how rating frameworks can be used as part of the efforts to transition to ‘smarter infrastructure’.

II. PILOT STUDY

A. A76 200 bridge case study

A case study of the A76 200 bridge in Scotland reported by Maroni et al. [15] was used to test the framework in the pilot study. During the pilot study, participants were provided with the case study information (including pictures of the assessed bridge); a brief description of the survey and how the framework should be used in practice. The actual monitoring system deployed on the bridge reported in Maroni et al. [15] was not given to the participants during the pilot study.

Maroni et al. [15] deployed two new smart electromagnetic (SE) probes on the A76 200 bridge in Scotland. Probe P1 was installed on a pier (upstream surface) and equipped with sensors (sensors were also buried in the riverbed) [15]. The sensors reading permittivity of mediums (e.g. water, soil, and air) to discern the different environments and detect scour [15]. The survey revealed that the durability and robustness of this new instrument was affected by the impact of debris, ice and flow velocity Maroni et al. [15] employed protective barriers around the probes to mitigate the effects of debris.

As the SE sensors are a new technology, it would not be possible for the survey participants to know enough about their capabilities to fairly appraise them, so they were not included in the studied devices in the rest of this paper. However, the SE approach is arguably a ‘direct’ scour measurement technique, and one aim of this paper is to see if the survey of practitioners (Section V) would generally favour either ‘direct’ or ‘indirect’ scour measurement approaches (see Table I) as well as to further refine the framework. For more details on the pilot study see the

TABLE I
SOME DIRECT AND INDIRECT BRIDGE SCOUR MONITORING
APPROACHES

Device	Abbreviation	Direct/Indirect
Accelerometer	ACC	Indirect
Tilt Angle	Tilt	Indirect
Synthetic aperture radar interferometry	InSAR	Indirect
Automatic Sliding Collar	ASC	Direct
Manual Sliding Collar	MSC	Direct
Fiber- Bragg Grating	FBG	Direct
Float Out	FO	Direct
Numbered Brick	NBk	Direct
Sonar	SN	Direct
Magnetic Smart Rock	SRk	Direct
Time Domain Reflectometry	TDR	Direct

These instruments were classified as direct and indirect approaches based on review of Maroni et al. [15], Pregnotato et al. [20] and Prendergast & Gavin [12].

thesis of Yaqoobi [28].

B. Pilot study: operation

The pilot study was conducted to test and refine early drafts of the framework. This pilot study was conducted as one-hour semi-structured interviews (in-person or online) with three colleagues from the University of Bristol (the second, third and fourth authors of this paper).

The draft framework presented during the pilot study had eight assessment criteria established after further review of the scour rating frameworks reviewed in [22] i.e. Vardanega *et al.* [19], Pregnolato *et al.* [20] and Lueker *et al.* [17, 18] (see also the thesis of Yaqoobi [28] for more details). The selected assessment criteria require input data from the bridge site (as is the case in Lueker *et al.* [17, 18]) as well as information about the capabilities of each scour monitoring instrument being considered for possible deployment. For each criterion, a data entry form outlining the relevant questions was provided to the participants. For example, for the criterion related to robustness the survey participants were asked nine questions, and the scores were then used to assess the scour monitoring instrument in question's durability (see [28]). A score between 1 to 5 was assigned to each of the 11-instrument types considered in the framework (Table I). The process was repeated for each assessment criterion to appraise the studied scour monitoring devices (see [28] for more details).

III. RESULTS OF THE PILOT STUDY

It was found that assessment of site conditions varied considerably by pilot study participants (S1 to S3) (see Table II). There are many 'off-the-shelf' sensing instruments with differing specifications. Therefore, the use of all potential instrument configurations was judged to be confusing. The questions for assessing instrument suitability for an individual site could not cover the range of capabilities of different instruments. The pilot study revealed that the user of the framework needs to define the site conditions to sufficient accuracy and requires a-priori knowledge of the capabilities of the range of monitoring equipment (e.g. sensitivity of instruments from environmental factors such as salinity, turbidity, air bubbles, measurement type and power consumption) being considered for the deployment. Therefore, it was decided not to incorporate specific monitoring approaches into the final framework.

IV. THE UPDATED FRAMEWORK

A refined version of the pilot framework is shown as a four-step process in Fig 1. This framework is designed to evaluate the suitability of sensing technologies for a bridge scour monitoring deployment requiring the user to have as minimal technical expertise with as little required site data as possible (noting the issues with previously studied frameworks in Section I). For more details on the updated framework see the thesis of Yaqoobi [28].

The assessment criteria were identified based on the aforementioned literature and case study reviews (see e.g. Yaqoobi *et al.* [22]). The first step in the framework is the data collection stage (Fig. 1). The second step is the mandatory assessment criteria (see Table III). These criteria were developed in part by review of Lagasse *et al.* [1], Kirby *et al.* [4], Pregnolato *et al.* [20]. If the trialled sensing technique does not satisfy all requirements in step two it will not pass through to step three. The third step contains four assessment criteria: 'robustness & durability' (Table IV), 'accuracy' (Table V), 'ease of installation' (Table VI), and 'maintenance requirements' (Table VII). The fourth step in the framework contains three assessment criteria: 'power consumption' (Table VIII), 'measurement frequency & interpretation' (Table IX), and 'total cost' (Table X).

TABLE II
PILOT STUDY PARTICIPANTS' SCORES FOR SITE ATTRIBUTES

Attributes	S1	S2	S3
Total height of bridge	M	L	L
Maximum foundation depth if unknown maximum potential scour depth	M	L	L
Typical flow depth	M	H	L
Entrained air bubbles in flow	✓	×	×
Entrained sediment in flow	×	✓	✓
Entrained salinity in flow	×	×	×
Flow velocity	M	L	M
Excessive entrained turbidity	✓	✓	✓
Vandalism	✓	×	×
Frequency of overbank flooding	×	×	✓
Potential shifting of scour area during peak flow events	✓	×	✓
Debris accumulation and sunken debris around pier/abutment	L	L	H
Bridge settlement	✓	×	×

L = low, M = medium, H = high, ✓ = yes, × = no

These attributes were gathered from review of Lagasse *et al.* [1], Lueker *et al.* [17, 18], Hunt [29], Lagasse *et al.* [30].

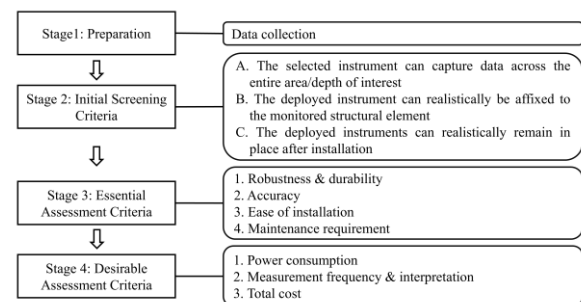


Fig. 1. Proposed assessment approach

TABLE III
INITIAL SCREENING CRITERIA FOR STAGE 2

A.	The selected instrument can capture data across the entire area of interest
B.	The deployed instrument can realistically be affixed to the monitored structural element
C.	The deployed instruments can realistically remain in place after installation

These initial screening criteria were developed primarily from review of Hunt [29] and also review of Pregnolato *et al.* [20], Lagasse *et al.* [30].

TABLE IV
ROBUSTNESS & DURABILITY ASSESSMENT

The instrument robustness and durability susceptible to:
A. Dead loads
B. Debris impact
C. Ice impact
D. High velocity flows
E. Vandalism

These robustness criteria were developed primarily from review of Lagasse et al. [1] and also review of Hunt [29], Lagasse et al. [30], Prendergast & Gavin [12].

TABLE V
ACCURACY ASSESSMENT

Accuracy of device due to:
A. Device sensitivity to air bubbles
B. Device sensitivity to salinity
C. Device sensitivity to turbidity
D. Ability of device to measure effectively with increasing depths of measurement
E. Scour depth measured by indirect means
F. Potential for device accuracy to be affected by presence of debris

These measurement accuracy criteria were developed from review of Lueker et al. [17, 18], Lagasse et al. [1], Lagasse et al. [30], Zarafshan et al. [11], Fisher et al. [31], Prendergast & Gavin [12], Kariyawasam et al. [32], Wang & Lin [33], San Martin et al. [34].

TABLE VI
EASE OF INSTALLATION ASSESSMENT

Ease of installation due to site condition:
A. Heavy equipment required
B. Diving team required
C. Installation work impacts traffic
D. Installation without any traffic disruption
E. Does not require installation or monitoring is remote

These ease of installation criteria were developed from review of Vardanega et al. [19], Hunt [29], Lueker et al. [17] [18].

TABLE VII
MAINTENANCE ASSESSMENT

Detection of device failure:	Maintenance needs:
A. Access to device not possible once system is installed	A. Periodic maintenance
B. Onsite/underwater inspection of the equipment needed to locate source of failure	B. Specialist tools needed to carry out replacement/repair
C. Site visit needed to fix equipment – failure location generally obvious Easy to detect failure needs site inspection	C. Special machinery required
D. Site inspection not needed to know reason for failure	D. Skilled worker required
	E. No maintenance needs

These criteria related to maintenance requirements were developed from review of Vardanega et al. [19], Hunt [29], Lueker et al. [17] [18], Pregnotato et al. [20].

TABLE VIII
POWER CONSUMPTION ASSESSMENT

Power requirement	Power supply
A. Continuous	A. Battery pack
B. Transient	B. Wired
C. No power required	C. Solar panel for charging onsite batteries

These criteria on power consumption were developed primarily from review of Lueker et al. [17, 18] and also review of Schall et al. [35], Hunt [29], Kang [36].

TABLE IX
MEASUREMENT FREQUENCY & INTERPRETATION ASSESSMENT

Measurement frequency:
A. Continuous monitoring
B. Discrete measurement i.e. measurement of maximum scour depth and no measurement of infilled scour depth
C. Single discrete measurement occurring when a pre-defined threshold is exceeded (no follow up measurements possible)
D. Visual inspection required

Interpretation of obtained data:

A. Instant interpretation
B. Moderate data volumes with some post processing time needed
C. Large data volumes with some post processing time needed
D. Large data volume with considerable post processing time needed
E. Visual inspection required

These criteria on measurement frequency and interpretation were developed from review of Vardanega et al. [19], Lin et al. [9], Webb et al. [5], Gavin et al. [37], Maroni et al. [15].

TABLE X
COST ASSESSMENT

Purchase cost:

- A. Estimated purchase cost of monitoring device(s)
- B. Estimated cost of additional hardware (e.g. datalogger)

Installation cost:

- A. Estimated size of crew needed for installation activities
- B. Estimated installation time
- C. Estimated cost per day for installation activities
- D. Cost of any heavy equipment needed for installation activities

Power consumption cost:^a

- A. Low
- B. Medium
- C. High

Maintenance cost:^a

- A. Low
- B. Medium
- C. High

These cost criteria were developed primarily from review Hunt [29] and also review of Lueker et al. [17, 18], Pregnotato et al. [20], Vardanega et al. [21].

^a These cost levels should be calibrated based on the funding available within the user's organisation or based on expenditure on past monitoring projects.

V. TESTING OF THE UPDATED FRAMEWORK

The updated framework was then tested by six anonymous participants (Table XI). The participants were invited to participate by invitation and after agreeing to contribute the information sheet and consent forms were signed. Participants were provided with the same case study as that used provided in the pilot study (see Section II). Some refinement of the framework tables was carried out after conclusion of this stage considering the findings of the survey. The survey participants were asked to provide their responses using six embedded Google Forms in Microsoft Sway (original tables are in the thesis of Yaqoobi [28]). The general framework steps (see Fig. 1) and spirit of the questions asked were however essentially as shown in this paper. For the sake of brevity only the survey results from Stage 3 (Fig. 1) are shown in this paper.

TABLE XI
ROLES OF ANONYMOUS SURVEY PARTICIPANTS

Participant	Role	Experience
P1	Designer/Structural Engineer	10 to 14 years
P2	Researcher	10 to 14 years
P3	Designer/Structural Engineer	5 to 9 years
P4	Researcher, Consultant – technical standards	10 to 14 years
P5	Researcher, Designer/Structural Engineer	5 to 9 years
P6	Designer/Structural Engineer	5 to 9 years

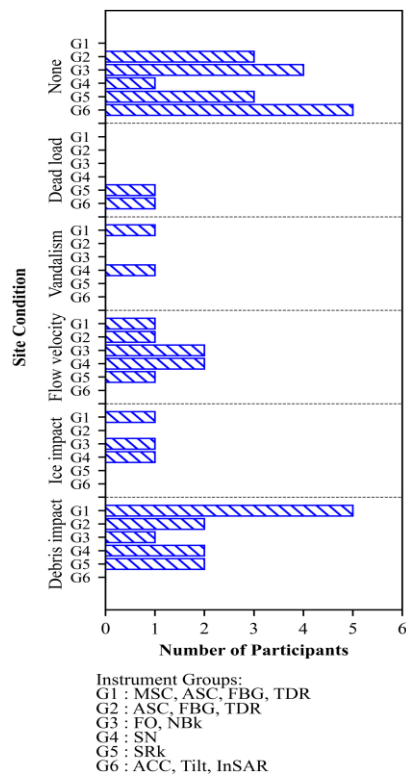


Fig. 2. Participants' views on influence of site parameters on instrument robustness for the A76 200 bridge case study (considering the five criteria given in Table IV) (instrument abbreviations as in Table I).

Fig. 2 shows the devices listed in Table I (with abbreviations given) arranged into six 'instrument groups' with the number of six participants who identified the important influencing factors from Table IV. Participants were able to select multiple responses as important for the studied groups of instruments i.e. groups G1 to G6. Resistance to debris impact was identified as the most important indicator of durability for instrument groups 1 to 5. For instrument groups 2, 3, 5 and 6 most participants indicated that the Site Conditions did not affect durability i.e. 'none' scored highest.

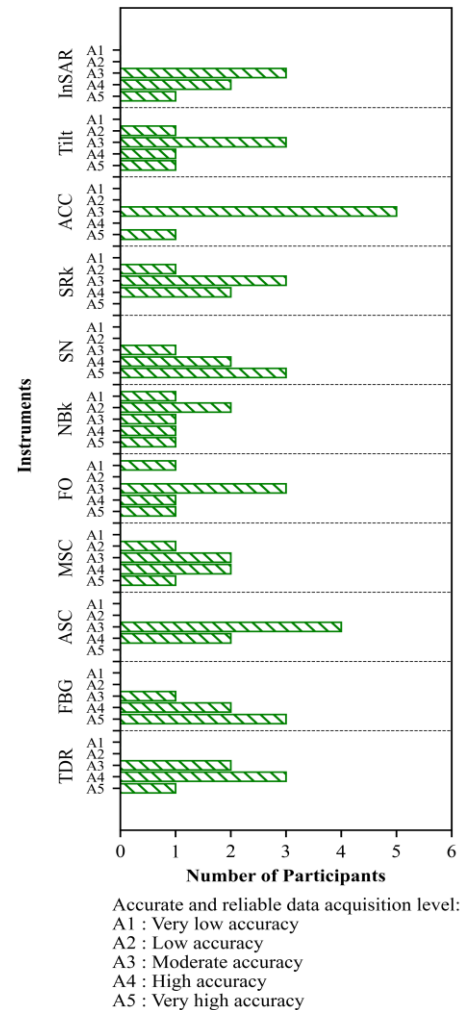


Fig. 3. Participants' views on the accuracy of different instrument types for the A76 200 bridge case study (considering the criteria in Table V) (instrument abbreviations as in Table I).

Then the participants were asked to rate each individual device listed in Table I (with abbreviations given) from 1 to 5 ('1 very low accuracy', '5 very high accuracy') based on the factors from Table V (see Fig. 3). FBG, SN, TDR (direct scour measurements) were considered to be the most accurate devices and MSC and NBk (also direct scour measurements) were considered to have lower accuracy.

Fig. 4 shows the devices listed in Table I (with abbreviations given) rated for ease of installation based on the factors from Table VI. Participants were able to select multiple responses as important for the studied groups of instruments. The indirect approaches (ACC, Tilt and InSAR) as well as SRk (a direct approach) were rated as having high ease of installation with the direct approaches of ASC, MSC, FBG and TDR having low ease of installation.

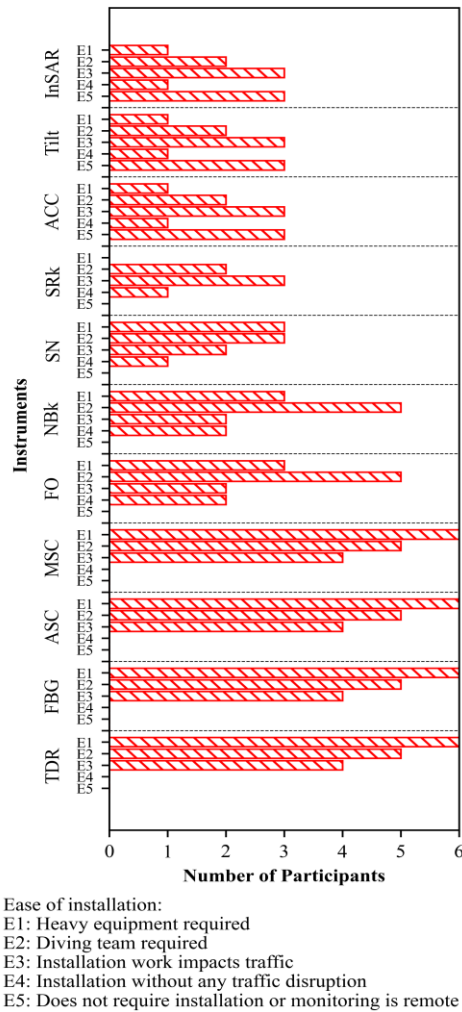


Fig. 4. Participants' views on ease of installation for the A76 200 bridge case study (considering the five criteria in Table VI) (instrument abbreviations as in Table I).

Fig. 5 shows the devices listed in Table I (with abbreviations given) assessed by the factors influencing maintenance listed in Table VII. Participants were able to select multiple responses as important for the studied groups of instruments. The direct approaches ASC, MSC, FBG, SN and TDR were rated as having higher maintenance requirements while the FO and NBk (direct approaches) were considered to have low maintenance requirements. The indirect approaches were all considered to have medium maintenance requirements (in the case of InSAR the requirement is arguably 'none').

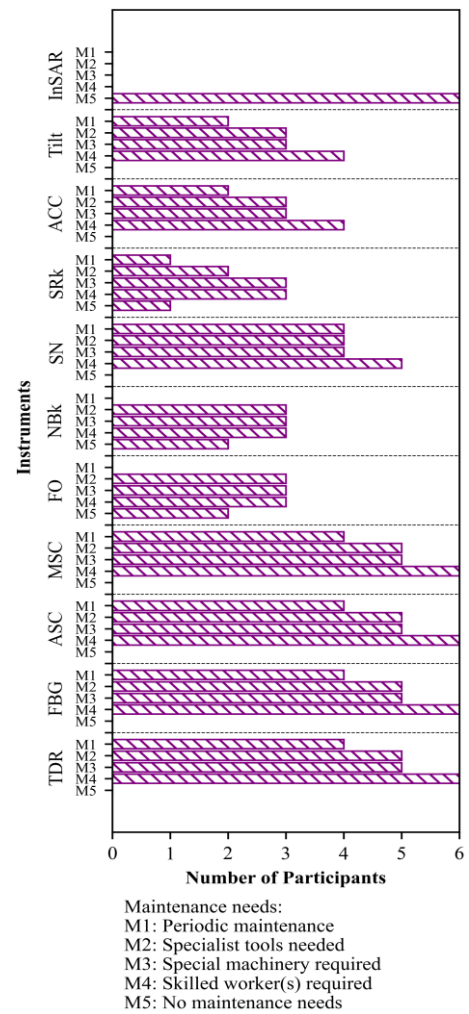


Fig. 5. Participants' views on maintenance needs for the A76 200 bridge case study (considering the five criteria in Table VII) (instrument abbreviations as in Table I).

VI. DISCUSSION

The findings of this study are important for bridge owners and operators wanting to specify scour-monitoring devices. Table XII summarizes the results of the assessment of the case study used in this work across the 'essential' criteria (cf. Fig. 1). Three classification categories 'high, medium, and low' were used for comparison of instruments for each assessment criteria. These classification were determined based on most favourable to worst instrument on a site. The survey has shown for the devices considered in this work that especially with respect to robustness and ease of installation indirect devices tended to be preferred to the direct methods (perhaps with the exception of SN). For higher accuracy direct methods of FBG and SN were rated more highly with FO and NBk preferred if lower maintenance is desired. Overall, there is some tentative evidence that at least for the case study considered, 'indirect' approaches were preferred to 'direct' approaches. This is interesting for those interested in specifying 'smarter infrastructure' systems as the indirect

approaches are arguably more robust and are easier to install but with some compromise on accuracy of the measurements.

TABLE XII
COMPARISON OF RESULTS FROM FRAMEWORK TESTING

Device	D/I	R	A	EI	MR
ACC	I	H	M	H	M
Tilt	I	H	M	H	M
InSAR	I	H	M	H	-
ASC	D	H	M	L	H
MSC	D	M	L	L	H
FBG	D	M	H	L	H
FO	D	M	M	M	L
NBk	D	L	L	M	L
SN	D	H	H	M	H
SRk	D	M	M	H	M
TDR	D	M	H	L	H

D = direct, I = indirect

H = high, M = medium, L = low

R = robustness assessment (cf. Fig. 2)

A = accuracy assessment (cf. Fig. 3)

EI = ease of installation (cf. Fig. 4)

MR = maintenance requirement (cf. Fig. 5)

VII. CONCLUSIONS

This paper has reviewed some previous rating frameworks for specification of SHM devices, for scour monitoring deployments. Based on this review of past frameworks and review of other literature a new rating framework was proposed. This new framework was then tested and refined using the results of a pilot study conducted at the University of Bristol. The pilot study suggested that a-priori knowledge of the capabilities of a range of monitoring devices is key for successful use of frameworks such as the one being developed in this paper.

The updated framework was then tested by six anonymous participants as part of a validation survey. This survey led to further refinement of the framework tables to improve clarity. The testing of the framework has yielded tentative evidence that the survey participants (for the considered case study) would prefer a 'indirect' approach to the scour monitoring efforts.

Further work could involve inviting a larger number of participants to trial this proposed framework with different case studies with varying levels of available data (e.g. site and structural data) as part of efforts to improve the knowledge base with respect to monitoring approaches as part of a future transition to ubiquitous 'smart' bridge infrastructure. This will allow for further calibration and validation of the rating framework which may lead to its improvement as a tool for use by those specifying bridge scour monitoring systems.

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Data availability statement: To maintain the anonymity of the interviewed participants the data collected during this study cannot be made available in a repository.

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