

A study on empirical prediction and monitoring of bridge pier scour depth: implications for asset owners and operators

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Abstract— Bridges are infrastructure assets which connect communities and in cases of collapse or reduced service, these vital transport links on which citizens depend for livelihoods, supplies and mobility are severed. The UK's aging infrastructure has been termed an 'asset time bomb'. There is also a concern that as climate changes, these aging bridges are increasingly going to have to withstand more extreme flood events accompanied by faster flowing water in riverine environments. These environmental factors may result in the bridge stock being more susceptible to the effects of scouring. Scour is the removal of material (usually soil) from around an object (e.g. a bridge pier) due to the action of flowing water. Scour often occurs in fast flowing river systems and in coastal environments. Scour is a complex soil-water-structure interaction process. This complexity makes the estimation of the amount of scour challenging when using empirical and semi-empirical approaches which often use only a few parameters such as: pier width; pier length; average particle size of the riverbed material; approach flow depth and velocity; critical velocity; angle of attack; pier shape and spacing. Scour being a complex process is also challenging to measure reliably in the field with some methods being suitable in some circumstances but not in others. This paper reports results of a study which investigated the relative accuracy of eight scour prediction methods that use some (or all) of aforementioned parameters. The influence of the measurement device used to originally measure the scour depths in the field is also examined. Recommendations are made for asset owners and policymakers on the relative merits of the different measurement approaches, when deploying scour monitoring systems in the field via use of a recently developed scour rating framework.

Keywords— Bridge Scour, Empirical Equations, Structural Health Monitoring, Rating Framework

I. INTRODUCTION

THE UK's infrastructure is aging and has been termed an 'asset time bomb' (cf. Thurlby [1], Thurlby & Rimell [2]). Bridges are important lifelines that connect communities (e.g. Argyroudis & Mitoulis [3], Loli et al. [4]). Bridge maintenance and management are important for asset owners and operators (cf. Karatzetou et al. [5]).

Riverine bridges are often vulnerable to scour which is one of the main causes of bridge collapse worldwide (e.g. Maddison et al. [6], Arneson et al. [7], Pregnolato et al. [8]). Scour is the removal of soil from around the piers, abutment and foundations of a bridge (e.g. Arneson et al. [7], Kirby et al. [9]) or other structures, such as offshore wind turbines (Feng et al. [10]) due to the action of fast flowing water (cf. Maddison et al. [6]). The increasing intensity and frequency of floods is associated with scouring (e.g. Dikanski et al. [11]). Monitoring of bridge scour is important for detecting both the onset and progression of scour (e.g. Prendergast & Gavin, [12]). As scour is a complex soil-water-structure interaction process (e.g. Yerro & Ceccato [13], Barrie et al [14]), empirical equations for estimating scour depth were developed to predict possible future scour levels (e.g. Zevenbergen [15]; Qi et al. [16]). Knowledge on the accuracy of these equations in estimating scour is important for decision-making by bridge owners and operators.

In this paper an opensource database of scour data collected by the US Geological Survey (referred as the USGS Database) (Benedict & Caldwell [17, 18]) is used to

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explore if empirical equations for scour depth are better able to predict scour depths measured with different measuring devices.

The USGS Database has been used for analysis in previous works: Gavriel et al. [19] explored the accuracy of three scour equations to predict scour depths for a small sub-set of bridge piers from the USGS Database. Gavriel et al. [20] divided the USGS Database (field data) into the following subgroups: scour depth below 2m; $D_{50} \leq 0.99\text{mm}$, $0.99\text{mm} < D_{50} \leq 9.99\text{mm}$, $D_{50} > 9.99\text{mm}$ and the type of measuring apparatus used to measure scour in the field to explore the accuracy of the *HEC-18* equation (Arneson et al. [7]) for the aforementioned sub-groups. Gavriel et al. [21] used the USGS Database (field data) to explore the parameter input sensitivity of the *HEC-18* equation by applying a simple one-at-a-time sensitivity analysis.

This paper divides the USGS Database (field data) in terms of its measurement apparatus similar to Gavriel et al. [20] but this time explores the accuracy of estimated scour across eight empirical scour depth equations (explained in Section II B). This paper also rates the measurement devices used to measure scour reported in the USGS Database using a framework presented in Vardanega et al. [22]. Vardanega et al. [23] compared features of the Vardanega et al. [22], Pregnotato et al. [24] and Lueker et al. [25,26] frameworks, and these frameworks were then compared using a database of case records in Yaqoobi et al. [27]. The version of the framework used in this study i.e. that presented in [22] was selected for its simplicity in the evaluation of individual scour monitoring devices.

The first aim of the present study is to explore the influence of the measurement approach originally used to take the field scour measurement on the prediction accuracy of the empirical approaches studied (the eight empirical approaches used in this work are outlined in Section II B). The second aim of this work is to assess how likely the measurement approaches used to measure the USGS field scour data would be specified today by comparing the results for each device using the rating framework from [22].

II. METHODOLOGY

The first part of this paper uses a large opensource scour database with scour measurements collected from the field, available from the US Geological Survey website (Benedict & Caldwell [17,18]) to explore if a set of eight empirical scour depth prediction equations are better at predicting scour depths originally measured with different monitoring devices. The second part of the paper applies the Vardanega et al. [22]'s framework to evaluate the aforementioned devices used to measure scour from the USGS Database to explore if these devices would still be considered valid for use in future bridge monitoring projects.

A. The USGS Database (Field Data) Benedict & Caldwell [17, 18]

The USGS Database [17, 18] includes information on the pier length, pier width, pier shape, approach flow velocity, approach flow depth, soil bed gradation, measuring apparatus and measured scour depth. This paper only uses the data on local scour measured in the field from the database (see Gavriel [28] for more details on the use of the USGS Database and the other data it contains). The field data are categorized in terms of the measurement approach used. Table I provides a detailed description of the apparatus used to take the scour measurements.

B. Scour equations for assessment

The analysis of eight equations explores whether the accuracy of scour equations in terms of estimating bridge scour changes when using different measuring apparatus. The selected equations were as follows: *CIRIA* (Kirby et al. [9]), *TAMU* (Briaud [29]), *HEC-18* (Arneson et al. [7]), *Melville* (Melville [30]), *Froehlich* (Froehlich [31]), *Melville & Sutherland* (Melville & Sutherland [32]), *Chitale* (Chitale writing in Blench et al. [33]) and *Laursen* (Laursen [34]). For more details about the selection of equations and their formulation see Gavriel [28] in conjunction with the aforementioned references in this paragraph. Six out of the eight aforementioned equations were developed using experimental flume data [7, 29, 30, 32, 33, 34]. The *CIRIA* equation is the only equation studied that was developed using both flume and field data and the *Froehlich* equation is the only equation studied developed only using field data [9, 31].

C. Evaluating equation accuracy

To test the accuracy of the scour equations in scour estimation against the scour measurements in the field, the number of estimations which lie between the following boundaries are explored: $x - 0.5x \leq y \leq x + 0.5x$ ($\pm 50\%$ boundaries); $x/1.5 \leq y \leq 1.5x$ (factor of 1.5 boundaries) where x is the calculated scour by each of the eight equations and y is the measured scour in the field by the USGS. The more the points within the boundaries the more accurate is the estimation. The assessment of points within the boundary lines is performed separately for each of the measuring apparatus types reviewed in this paper.

D. The Vardanega et al. [22] framework

The Vardanega et al. [22] framework was developed to assist engineers with the deployment of measuring devices for bridge scour. The framework assesses a device in five areas: 'ease of installation', 'ease of operation', 'ease of data logging/capture', 'ease of data interpretation' and 'measurement frequency' (see Vardanega et al. [22, 23]). A device is appraised using various assessment criteria - each scored using a Likert scale (e.g. Likert [35]). The framework provides a description of each score for guidance. The sum of the five individual scores provides

TABLE I.

DESCRIPTION OF APPROACHES USED TO TAKE THE FIELD SCOUR DEPTH MEASUREMENTS REPORTED IN THE USGS DATABASE .

Device	Description
GPR	This portable device, measures scour by transmitting electromagnetic pulses and then calculates the time taken for reflected signal to return back (Olimpio [36], Mueller et al. [37], Wilson [38], Butch [39]). Works well on shallow water (Olimpio [36], Mueller et al. [37], Wilson [38]). Data are collected manually (cf. Olimpio [36]). The device must be used on a stable platform as platform movement can affect signal transmission and reception (cf. Olimpio [36]).
FS	The device measures scour by sending acoustic pulses from a transducer to the streambed (Lagasse et al. [40], Nassif et al. [41], Kamble & Vatti [42]). The device is formed of an enclosure, a connecting conduit, and a transducer (Lagasse et al. [40]). The enclosure contains a datalogging system, power supply system and data transmission system enabling continuous readings (Lagasse et al. [40], Butch [39], Fisher et al. [43], Atkins & Hedgecock [44]). Signals can be affected by submerged debris, ice, air bubbles, and excessive amounts of entrained sediment around monitored pier/abutment (Wilson [38], Lagasse et al. [40], Fisher et al. [43], Norman [45]). The device can be deployed on any desired location; often mounted on a bridge pier (Hong et al. [46]).
BF	Approach is a form of Fathometer Soundings which can be used for large/wide coverage areas with fast flowing water (Jarrett & Boyle [47]).
ADCP	Device is formed of a transducer, datalogger, processor and a software program to interpret data (Tracey [48]). The device works with the principle of the doppler effect by emitting sounding waves from a transducer with a specific constant frequency allowing continuous readings (Tracey [48], Larratt et al. [49], Holnbeck [50]). Air bubbles in turbulent water and accumulated debris around pier can cause false/poor readings (Tracey [48]). The device cannot measure at a short range (e.g. just in front of transducer) (Nortek [51]).
AB	This is an indirect measurement of scour depth based on referenced ambient bed level. (Mueller & Wanger [52], Landers & Mueller [53], Gilbert & Ensminger [54]). The referenced ambient bed level is obtained based on the average of previously obtained scour data from various points along the channel (Mueller & Wanger [52], Landers & Mueller [53]). The establishment of referenced ambient bed surface process is complex and requires sufficient expertise (Mueller & Wanger [52]). Requires scour data be obtained from multiple points (Mueller & Wanger [52], Landers & Mueller [53]). AB is a not a device which is directly deployed on a bridge but it can be assessed using the framework from [22].

*GPR = Ground Penetrating Radar; ADCP = Acoustic Doppler Current Profiler; BF = Bludworth Fathometer; FS = Fathometer Sounding; AB = Ambient Bed (see Gavriel et al. [20] for more description on these devices).

an indication of how applicable a device is. The devices/approaches from the USGS Database, described in Table I, are assessed using the framework presented in [22].

III. RESULTS

The following section shows the results of the analysis. Subsection A shows the results based on the methodology applied to the USGS Database on the eight scour equations. Subsection B shows the results from applying the Vardanega et al. [22] framework to the measuring devices described in Table I.

A. Scour depth predictions

Tables II and III show the results from comparing the scour depth measured in the field against the calculated scour depth using the eight equations (described in Section II B) and the field data from the USGS database. Table II shows the total number of estimated scour depths which lie within the $\pm 50\%$ and factor of 1.5 boundaries for the following equations: *CIRIA*, *TAMU*, *HEC-18*, *Melville*. Table III shows the total number of estimated scour depths which lie within the $\pm 50\%$ and factor of 1.5 boundaries when using the following equations: *Froehlich*, *Melville & Sutherland*, *Laursen* and *Chitale*. Tables II and III also show the number of scour measurements and the percentage out of $\pm 50\%$ and factor of 1.5 for each type of measuring apparatus when scour depth is calculated for each of the eight equations.

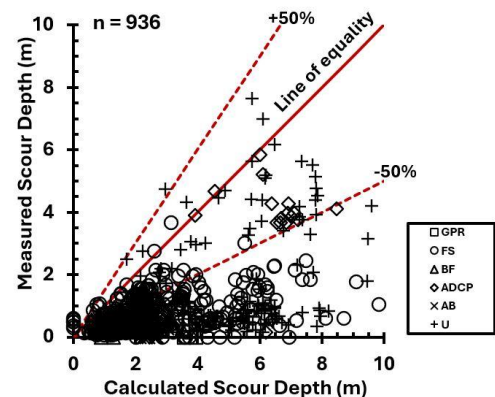


Fig. 1. Measured scour depths against calculated scour depths using the *Laursen* equation (see Table I for abbreviation of the devices) (n = number of data points).

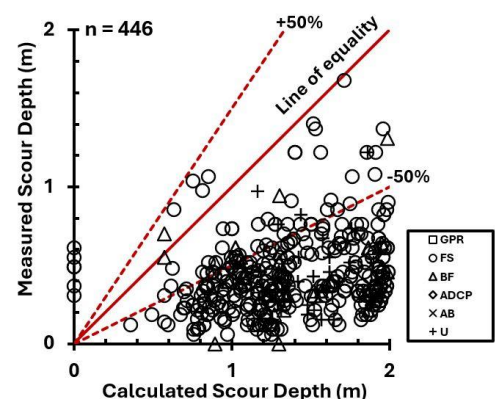


Fig. 2. Measured scour depths against calculated scour depths using the *Laursen* equation for scour depths ≤ 2 m (see Table I for abbreviation of the devices) (n = number of data points).

TABLE II

NUMBER AND PROPORTION OF PREDICTED SCOUR DEPTHS WITHIN STATED BOUNDS BY MEASUREMENT DEVICES FOR THE *CIRIA*, *TAMU*, *HEC-18*, *MELVILLE* APPROACHES

	<i>CIRIA</i>						<i>TAMU</i>				<i>HEC-18</i>				<i>Melville</i>			
			$\pm 50\%$		1.5x		$\pm 50\%$		1.5x		$\pm 50\%$		1.5x		$\pm 50\%$		1.5x	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%
Total	936	100.0	339	36.2	232	24.8	142	15.2	87	9.3	207	22.1	135	14.4	71	7.6	38	4.1
GPR	16	1.7	3	0.3	3	0.3	3	0.3	3	0.3	1	0.1	1	0.1	2	0.2	2	0.2
FS	624	66.7	248	26.6	169	18.1	118	12.7	72	7.7	141	15.1	86	9.2	47	5	27	3.0
BF	63	6.7	4	0.4	2	0.2	2	0.2	2	0.2	4	0.4	2	0.2	14	1.5	5	0.5
ADCP	17	1.8	13	1.4	10	1.1	0	0	0	0	12	1.3	10	1.1	0	0	0	0
AB	28	3.0	6	0.6	2	0.2	1	0.1	1	0.1	0	0	0	0	0	0	0	0
U	188	20.1	65	6.9	46	4.9	18	1.9	9	1	49	5.2	36	3.8	8	0.9	4	0.4

* n = number of data points; GPR = Ground Penetrating Radar; ADCP = Acoustic Doppler Current Profiler; BF = Bludworth Fathometer; FS = Fathometer Sounding; AB = Ambient Bed; U = Unspecified

TABLE III

NUMBER AND PROPORTION OF PREDICTED SCOUR DEPTHS WITHIN STATED BOUNDS BY MEASUREMENT DEVICES FOR THE *FROEHLICH*, *MELVILLE & SUTHERLAND*, *LAURSEN*, *CHITALE* APPROACHES (NOTATION AS FOR TABLE II)

	<i>Froehlich</i>						<i>Melville & Sutherland</i>				<i>Laursen</i>				<i>Chitale</i>			
			$\pm 50\%$		1.5x		$\pm 50\%$		1.5x		$\pm 50\%$		1.5x		$\pm 50\%$		1.5x	
	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%
Total	936	100.0	272	29.1	226	24.1	203	21.7	97	10.4	172	18.4	63	6.7	44	4.7	22	2.4
GPR	16	1.7	8	0.9	5	0.5	2	0.2	2	0.2	0	0.0	0	0.0	0	0.0	0	0.0
FS	624	66.7	181	19.4	160	17.1	144	15.4	73	7.9	99	10.6	30	3.2	31	3.4	18	2.0
BF	63	6.7	16	1.7	10	1.1	4	0.4	2	0.2	9	1.0	3	0.3	5	0.5	3	0.3
ADCP	17	1.8	0	0.0	0	0.0	12	1.3	3	0.3	14	1.5	5	0.5	4	0.4	0	0.0
AB	28	3.0	4	0.4	4	0.4	1	0.1	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
U	188	20.1	63	6.7	47	5.0	40	4.3	17	1.8	50	5.3	25	2.7	4	0.4	1	0.1

TABLE IV

ASSESSMENT OF GPR APPLICABILITY (TABLE DESIGN BASED ON [22])

Device	Assessment Criteria	Score Rationale	Score
Manual Ground Penetrating Radar	Ease of Installation (Q1)	Scour measured with a portable sensing technology; requires a boat and inspection team (cf. Olimpio [36])	2/5
	Ease of Operation (Q2)	Portable sensor; a stable platform; and training to use equipment; unsafe to use during intense flooding (e.g. Olimpio [36]).	2/5
	Ease of Data Logging/Capture (Q3)	Wireless monitoring (i.e. portable data logger); data collected and stored simultaneously (e.g. Mueller et al. [37]).	2/5
	Ease of Data Interpretation (Q4)	Manual process, requires software tools, requires a large volume of data; the process is time consuming; deposition is detected by comparing previous data (e.g. Wilson [38]).	2/5
	Measurement Frequency (Q5)	Process is manual and depends on pace of human inspector (cf. Olimpio [36]).	1/5
	Overall Score: 9/25 (Low Applicability)		

Tables II and III show that FS were the most common measuring device for measuring scour by the USGS (624/936). The data imbalance across the measurement devices means that the trends observed for the sub-sets other than the FS subset may not be as reliable as for the FS subset itself. Tables II and III also show that the *CIRIA* equation produces estimations with the highest concentration of points falling within the studied prediction boundaries.

Figure 1 shows an example scatter plot of the measured against calculated scour depths for the Laursen equation [34]. Each device is represented by a different symbol on the plot. Figure 2 shows the scatter plot from Figure 1 but limited to scour depths less than or equal to 2m.

B. Monitoring device applicability

Tables IV to VIII provide a detailed explanation of each of the scores from application of the framework from [22] to the devices. Table IV assesses the GPR device as of 'low applicability'. Table V assesses the FS as a 'moderately applicable' device. Table VI assesses the BF also as a 'moderately applicable' device. Table VII assesses the ADCP as a 'low applicability' device. Table VIII assesses estimating the scour depth from reference AB level as an approach with 'moderate applicability'. Based on the results from Tables IV to VIII, FS are assessed as the best method to monitor scour and ADCP as the worst. In the remainder of this paper mentions of 'fathometer' or similar refers to both BF and FS (see Table II for notation).

TABLE V
ASSESSMENT OF FATHOMETER SOUNDING APPLICABILITY (TABLE DESIGN BASED ON [22])

Device	Assessment Criteria	Score Rationale	Score
Fathometer Soundings	Ease of Installation (Q1)	Permanent installation requires preplanning; duration and complexity change based on the site conditions – i.e. may obstruct traffic (e.g. Lagasse et al. [40]).	3/5
	Ease of Operation (Q2)	System can draw pier scour level automatically; notification is automatic (e.g. Butch [39]).	5/5
	Ease of Data Logging/Capture (Q3)	Wired data logger system; data collection and transmission to a remote server anytime (e.g. Atkin & Hedgecock [44]).	3/5
	Ease of Data Interpretation (Q4)	Automatic data interpretation via a pre-programmed system; raw data should be filtered to remove outliers (e.g. Norman [45]).	3/5
	Measurement Frequency (Q5)	Continuous data collection (including during flooding); data collection can be suspended due to floating debris, marine grows or debris accumulation (e.g. Hong et al. [46]).	3/5
	Overall Score: 17/25 (Moderate Applicability)		

TABLE VI
ASSESSMENT OF BLUDWORTH FATHOMETER APPLICABILITY (TABLE DESIGN BASED ON [22])

Device	Assessment Criteria	Score Rationale	Score
Bludworth Fathometer	Ease of Installation (Q1)	Installation may cause traffic disruption; requires a platform to carry workers (e.g. boat) (cf. Jarret & Boyle [47]).	3/5
	Ease of Operation (Q2)	Capable of monitoring a large area; training required for inspecting scour level (e.g. Jarret & Boyle [47]).	4/5
	Ease of Data Logging/Capture (Q3)	Permanent datalogger; receives data from the transducer via wired data logger and transmits to a remote server (e.g. Jarret & Boyle [47]).	3/5
	Ease of Data Interpretation (Q4)	Raw data collected require post processing to eliminate outliers (e.g. Jarret & Boyle [47]).	3/5
	Measurement Frequency (Q5)	Continuous data collection; heavy flooding and debris accumulation can result in false readings or damage to the device; mechanical tools can protect the device from unwanted damages (e.g. Jarret & Boyle [47]).	3/5
	Overall Score: 16/25 (Moderate Applicability)		

TABLE VII
ASSESSMENT OF ACOUSTIC DOPPLER CURRENT PROFILER APPLICABILITY (TABLE DESIGN BASED ON [22])

Device	Assessment Criteria	Score Rationale	Score
Manual Acoustic Doppler Current Profiler	Ease of Installation (Q1)	Requires platform to carry inspector/operator; can operate above a bridge deck; device is portable thus it cannot be permanently deployed (cf. Tracey [48], Nortek [51]).	2/5
	Ease of Operation (Q2)	Complex to use, heavy, requires high power to operate; requires training (e.g. Nortek [51]).	2/5
	Ease of Data Logging/Capture (Q3)	Uses a portable data logger; requires a vessel and a human inspector (e.g. Tracey [48], Nortek [51]).	2/5
	Ease of Data Interpretation (Q4)	Accuracy can be affected by turbidity, air bubbles, debris, temperature; complex post-processing work is required (e.g. Tracey [48], Nortek [51]).	1/5
	Measurement Frequency (Q5)	Requires high amount of energy to emit and receive scattered signals; permanent deployment of the device rapidly drains the batteries (e.g. Tracey [48], Nortek [51]).	1/5
	Overall Score: 8 /25 (Low Applicability)		

TABLE VIII
ASSESSMENT OF AMBIENT BED APPLICABILITY (TABLE DESIGN BASED ON [22])

Device	Assessment Criteria	Score Rationale	Score
Ambient Bed	Ease of Installation (Q1)	Monitoring is remote (e.g. Mueller & Wagener [52]).	5/5
	Ease of Operation (Q2)	Safe operation; requires some training (e.g. Mueller & Wagener [52]).	3/5
	Ease of Data Logging/Capture (Q3)	Source of data is from a nearby station or concurrent reference ambient bed level collected from various locations; remote monitoring is possible (e.g. Lander & Mueller [53]).	3/5
	Ease of Data Interpretation (Q4)	Requires considerable engineering judgment to analyze cross sectional geometries (e.g. Mueller & Wagener [52]).	1/5
	Measurement Frequency (Q5)	Measurement frequency is discrete and relies on remote stations (e.g. Lander & Mueller [53]).	2/5
	Overall Score: 14 /25 (Moderate Applicability)		

IV. DISCUSSION

Tables II and III show that the majority of scour depth measurements were performed using a fathometer device (i.e. FS or BF). The assessment using the Vardanega et al. [22] framework showed that both Fathometer Soundings and Budworth Fathometer devices were rated as 'moderately applicable'. It can therefore be argued that Fathometers may still be specified for use today at least based on the criteria in the Vardanega et al. [22] framework.

Measuring scour in relation to Ambient Bed from stations nearby is a monitoring method which scored moderately by the Vardanega et al. [22] framework. The device has received a high score due to not requiring installation, thus the collection of data has no risk, however the device scored very low (1/5) in terms of data interpretation and although receiving a good overall score it may still not be selected by some engineers due to data interpretation. In summary, the results based on the Vardanega et al. [22] framework do not exclude the potential use of any of the devices represented in the USGS Database for scour monitoring deployments.

In terms of the amount of data enclosed within the boundaries, although for each equation the percentage of points within the boundaries varies, the percentage for FS readings is consistently higher compared to the rest of the devices although it is noted that the other devices/methods are represented by much smaller data-subsets than FS.

Based on the results of this study, bridge owners and operators, should note that FS are a good approach to consider when measuring scour depth. However, to draw firmer conclusions an expanded data set is required (apart from FS, for which the amount of data provided by the USGS Database is considerable). The calibration of already existing empirical equations with new data is also advised for bridge owners and operators.

V. SUMMARY & CONCLUSIONS

The paper has showed how well scour measured with different monitoring devices can be predicted by eight empirical equations. The paper has also rated the devices for their scour detection potential using the framework from [22] which showed that the devices would probably still be applicable for scour measurement deployments today. This study has also shown the lack of data in the USGS scour database [17,18] for all the devices studied apart from the Fathometer.

DATA AVAILABILITY STATEMENT

This study has not generated new experimental data.

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