Gavriel, G., Pregnolato, M., & Vardanega, P. J. (2023). Using the USGS database to study parameter uncertainty when assessing pier scour using the HEC-18 framework. In F. Biondini, & D. M. Frangopol (Eds.), *Life-Cycle of Structures and Infrastructure Systems: Proceedings of the Eighth International Symposium on Life-Cycle Civil Engineering (IALCCE 2023), 2-6 July 2023, Politecnico Di Milano, Milan, Italy* (pp. 3230-3237). CRC Press/Balkema, Taylor & Francis Group. https://doi.org/10.1201/9781003323020-394

Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)
© 2023 The Author(s), ISBN 978-1-003-32302-0
Open Access: www.taylorfrancis.com, CC BY-NC-ND 4.0 license

Using the USGS database to study parameter uncertainty when assessing pier scour using the HEC-18 framework

G. Gavriel, M. Pregnolato & P.J. Vardanega
University of Bristol, Bristol, UK

ABSTRACT: Bridges are important lifelines linking communities and their collapse due to flood events can result in severe social and economic impacts for communities. Estimation of maximum bridge scour depth is important for determining effective mitigation and adaptation procedures. HEC-18 is a well-established methodology to calculate scour depth. However, it is also often reported to yield conservative estimates of maximum scour depth in various publications. This paper presents a simple sensitivity study to assess the key inputs that affect the computation of maximum scour depth using the HEC-18 framework. The parameter ranges used in this analysis are sourced from an openly accessible database from the United States Geological Survey (USGS). In this study, HEC-18 is assessed against field measurements. The primary aim of this research is to study the impact of each key input parameter on HEC-18 estimates of maximum scour depth estimates.

1 INTRODUCTION

1.1 *Background*

Scour is the removal of material from the riverbed due to hydraulic actions. Bridges become unstable due to the presence of scour holes near the piers. This paper focuses on bridge pier scour, which is a type of local scour (see Maddison 2012 for a review of scour types). Improved understanding of bridge scour processes can assist with further development of probabilistic assessments (e.g. Maroni et al. 2022), and can also aid specification of scour monitoring systems (see Prendergast & Gavin 2014, Vardanega et al. 2021 for recent reviews of scour monitoring technologies). In this paper field data from the United States Geological Survey (USGS) scour database (Benedict & Caldwell 2014a, b, USGS 2004), hereafter referred to as the 'USGS database', are used along with the equations of HEC-18 to carry out a one-at-a-time sensitivity study to rank the effect of key parameters on computed maximum scour. The USGS database has been used in Gavriel et al. (2023) to examine the effect of different data sub-sets on the levels of conservatism from estimations of maximum scour depth using HEC-18 while this paper focusses on input parameter sensitivity.

The HEC-18 framework (e.g. FHWA 1993, Richardson & Davis 1995, Richardson & Davis 2001, Arneson et al. 2012) (along with other scour prediction frameworks) comprises a series of equations developed using laboratory flume tests (e.g. Richardson & Davis 1995, Richardson & Davis 2001, Zevenbergen 2010, Arneson et al. 2012, Briaud 2015a, b, Qi et al. 2016). Maximum scour depth of bridge piers is characterized by the following equation as given from Arneson et al. (2012):

$$\frac{y_s}{y_1} = 2.0K_1K_2K_3\left(\frac{a}{y_1}\right)^{0.65}F_r^{\;0.43} \qquad (1)$$

DOI: 10.1201/9781003323020-394

the terms in Eq. 1 are defined in Table 1. An additional constant, named K_4, was part of the HEC-18 equation in the previous version of HEC-18 (Richardson & Davis 2001). K_4 is used to correct for armouring of the piers caused by bed material. K_4 has been removed from the latest version of the framework (Arneson et al. 2012), it is therefore not included in Eq.1 and in this work. Further updates to the framework after the release of Arneson et al. (2012) are discussed in Shan et al. (2016) but these have not be incorporated into the analyses presented in this paper.

Many studies showed that HEC-18 framework gives conservative predictions when used to estimate field scour (Richardson & Davis 1995, Mueller & Wagner 2002, Zevenbergen 2010, Qi et al. 2016, Gavriel et al. 2022). Pizarro & Tubaldi (2019) compared the HEC-18 equations from Richardson & Davis (2001) to four other scour prediction methods using numerical data and concluded that all the studied methods produce conservative results. Yan (2013) and Rathod & Manakar (2020) also investigated the reliability of the HEC-18 equations compared to other scour methodologies concluding that the reliability of HEC-18 is predominately related to the model uncertainty. Figure 1 shows the results of the comparison between 19 flume test results from Kiraga et al. (2020) with estimated values from the HEC-18 equation for maximum bridge pier scour depth. In Figure 1, 14 out of the 19 scour depths are overestimated compared to the results from the flume tests.

Table 1. Definition of HEC-18 parameters (Arneson et al. 2012).

Parameter	Units	Notation	Definition
Pier Width	m	a	Width of the pier in the direction of flow
Pier Length	m	L	Length of the pier
Flow Depth	m	y_1	Flow depth directly upstream from the pier
Approach Velocity	m/s	V_1	Average flow velocity directly
Attack Angle	°	ϑ	Approach angle of the water in relation to the pier during a flood event
Scour Depth	m	y_s	Maximum depth of scour hole below the riverbed
Pier nose geometry correction factor	-	K_1	Correction factor based on the pier nose geometry
Bed condition correction factor	-	K_2	Correction factor based on the angle of attack of flow
Attack angle correction factor	-	K_3	Correction factor based on the bed conditions
Froude Number	-	F_r	Froude number

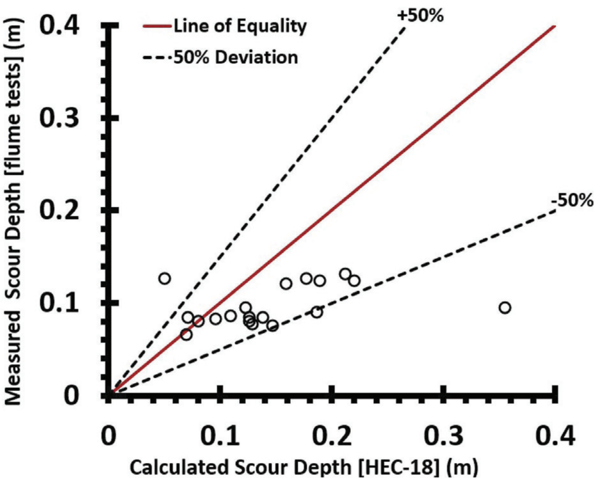

Figure 1. Comparison of scour depth measured in 19 flume tests by Kiraga et al. (2020) compared with the scour depth calculated using the HEC-18 framework (data from Kiraga et al. (2020)).

The full series of equations for the HEC-18 framework and detailed analysis on how to calculate scour depth can be found in Arneson et al. (2012). To calculate scour depth, the method considers *bed material characteristics* (K_3), *flow characteristics* (V_1, y_1, ϑ), *fluid properties* (Fr_1) and the *geometry of the pier* (L, a) (Richardson & Davis 2001, Arneson et al. 2012). HEC-18 considers a round shaped pier as the base case scenario and thus K_1 corrects for the pier shape in the case it is either square (10% higher scour depth) or sharp (10% lower scour depth) (Richardson & Davis 2001, Arneson et al. 2012). K_2 corrects for the case where ϑ takes a value which is not zero (Richardson & Davis 2001, Arneson et al. 2012). K_3 takes the value of 1.1 except in the scenario of dunes which are higher than 3000 mm, where scour depth is considered to be 30% larger when compared to dunes which are less than 3000 mm high (Richardson & Davis 2001, Arneson et al. 2012). For more information on dune height, see Section 7.1 in Arneson et al. (2012). Out of the 936 datapoints, no value is higher than 1.1 for K_3 (Richardson & Davis 2001, Arneson et al. 2012). To rank the key parameters (from Table 1) that affect the HEC-18 computation and hence potentially contribute uncertainty in the results, a simple one-at-a-time sensitivity study was carried out using the HEC-18 equations and the USGS database.

1.2 *Study aims*

This research analyses the HEC-18 framework against 936 field datapoints to investigate its validity using real field data. The study aims to: (1) illustrate the conservatism of the HEC-18 approach by comparing maximum scour depth predictions to those from the USGS database and (2) perform an sensitivity analysis of the key HEC-18 parameters by using field data from the USGS database.

2 METHODOLOGY

2.1 *USGS database*

The USGS database includes data from 936 bridge piers from 31 out of the 50 states in the USA. The measurements of V_1, y_1 and ϑ are all taken during high flows. L and a were collected in times of low flow (Norman 1975, Jarrett & Boyle 1986, Butch 1991, Southard 1992, Mueller et al. 1994, Wilson 1995, Atkins & Hedgecock 1996, Hayes 1996, Hodgkins & Lombard 2002, Holnbeck 2011). For further details of the measurement of the scour depth hydraulic properties, soil properties and other information on HEC-18, the reader is directed to Benedict & Caldwell (2014a, b) and USGS (2004). Figure 2 shows that about 90% of the data is overestimated, confirming the results of past research (cf. Zevenbergen 2010, Arneson et al. 2012, Qi et al. 2016) that the method over-estimates the scour depth assessment.

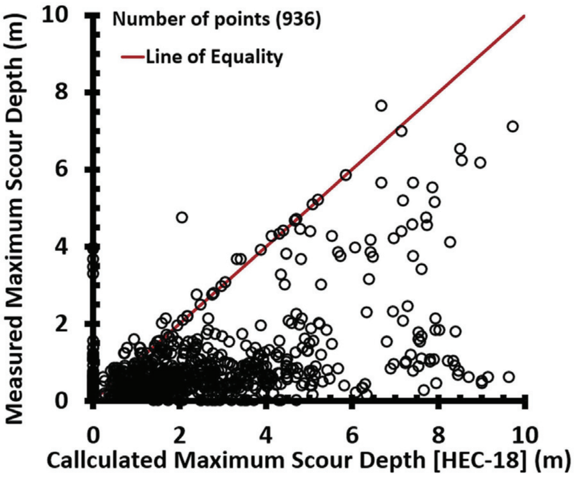

Figure 2. Measured maximum scour depth against calculated maximum scour depth using HEC-18 using 936 datapoints from USGS database; 839 out of 936 points over-estimated (data from the USGS database).

2.2 *Parameter distributions*

Figure 3 shows the distributions of the parameters given in Table 1 from analysis of the USGS database used in this study. a, V_1, y_1 and ϑ were compared against their frequencies to reveal approximately normal distributions (from a visual inspection of Figure 3). The histograms for α, y_1 and V_1 in Figure 3 reveal a distribution which can be approximated as normal. For the aforementioned inputs, there is a higher concentration of data near the mean and less data around one standard deviation above and below the mean. The assumption that ϑ is normally distributed is less reasonable and another distribution may potentially fit the data better. Analysis of the distribution of the parameters and the best-fit probability density functions will be undertaken in future work to refine the results presented in the present paper.

The data distribution for L is shown in Figure 3 but it should be noted that since 311 out of the 936 field datapoints were unavailable the unknown L inputs were calculated based on the 625 defined L values. 11.7 is the average of the L/a ratio of the defined a inputs therefore $L = 11.7a$. Also, K_1, K_2 and K_3 input parameters are determined from primary data from the USGS database therefore their distributions are not shown on Figure 3. K_1, K_2 and K_3 are studied in the following sensitivity study for completeness, however, any conclusions regarding their relative influence on the calculations should be made with caution.

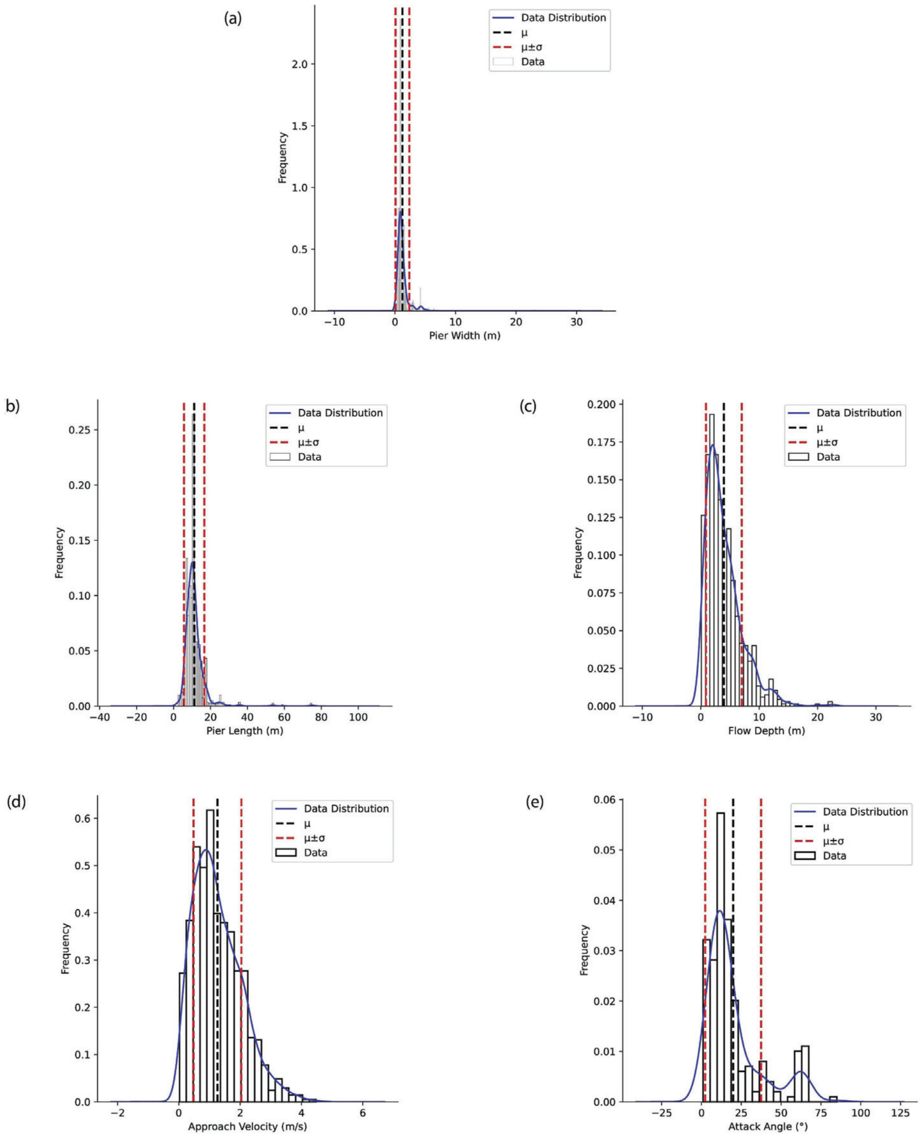

Figure 3. Histograms showing the distribution of the input data against the normal distribution; σ = standard deviation; μ = mean; (a) a; (b) L; (c) y_1; (d) V_1; (e) ϑ (data from the USGS database).

2.3 *Sensitivity analysis*

The following analysis assesses the impact each input parameter has on the pier scour estimation using the HEC-18 framework. For this analysis, the mean (μ), minimum, maximum and standard deviation (σ) were calculated for each input based on the 936 data from the USGS database (Table 2) (see Figure 3). Then, two base case scenarios are defined. For Base Case scenario 1 (BC1), all inputs are equal to their mean except ϑ which is equal to zero (this represents the case of zero bridge skew angle which occurs for about 80% of the records in the database). BC1 gives a value of scour depth equal to 2.04m. For Base Case scenario 2 (BC2), all inputs are equal to their mean. BC2 gives a scour depth value equal to 5.04m. Then, one input from each base case scenario is substituted on each iteration with the calculated minimum, maximum, $\mu \pm \sigma$ or $\mu \pm 0.5\sigma$. Each time an input changes, the result calculated from HEC-18 is recorded (Table 3). Table 3 shows all the scour depths calculated from substituting one input parameter at a time. To assess what impact each input has on the scour depth estimation, for each input a ratio of the computed answer against the base case scour depth is calculated. The difference between the maximum ratio and the minimum ratio for each input is shown by Table 3 as 'maximum difference'. The difference in ratio between '$\mu \pm 0.5\sigma$' is also calculated. The difference in ratio is shown as '$\pm$ 0.5σ difference' in Table 3. The equation for calculating the spread for each iteration is shown by Eq. 2. Eq. 3 shows the calculation performed to determine the maximum difference between the iterations for each input parameter. A similar procedure was performed to calculate the '$\pm$ 0.5σ difference'. Eqs.2 and 3 are as follows:

$$\gamma_s = \frac{y_c}{y_{bc}} \times 100 \tag{2}$$

where, γ_s= spread, y_c = calculated scour depth, y_{bc} = calculated scour depth from the base case scenario,

$$\gamma_{s(\Delta)} = \gamma_{s(max)} - \gamma_{s(min)} \tag{3}$$

where, $\gamma_{s(D)}$ = maximum difference in variation between calculated γ_s values for the input parameter considered, $\gamma_{s(max)}$ = maximum value from the calculated γ_s values for the input parameter considered, $\gamma_{s(min)}$ = minimum value from the calculated γ_s values for the input parameter considered.

The larger is the γ_s the higher the input factor influences the projected scour depth. The $\mu \pm 0.5\sigma$ is also calculated, in addition to $\mu \pm \sigma$ to test whether the rank changes when the inputs change. Values equal to zero have been eliminated from the computations for V_1 and y_1 because zero values give an error when scour is estimated (due to division by zero). Additionally, 81% of the USGS database consists of attack angles taken as zero. To better assess ϑ, two different base cases were considered to run the analysis as mentioned earlier. The parameter rank order changes for each base case scenario. For BC1, for which ϑ is considered to be zero, the rank remains unchanged for 'maximum difference' and '$\mu \pm 0.5$ difference'. From BC1, a is ranked first indicating that it has the greatest impact on the scour depth estimation for HEC-18. V_1 has the second highest difference, followed by y_1. For '$\mu \pm 0.5\sigma$ difference', V_1 appears to be the most influential followed by ϑ.

For BC2 however, the rank changes between 'maximum difference' and '$\mu \pm 0.5\sigma$ difference'. For '$\mu \pm 0.5\sigma$ difference' the results agree with Rathod & Manekar (2020) which found that ϑ is the most influential factor whereas the y_1 was found to be the least influential. The rank for 'maximum difference' does not agree with Rathod & Manekar (2020). The inconsistency between the findings of this research paper and Rathod & Manekar (2020) may be because Rathod & Manekar (2020) performed a sensitivity analysis based on 19 laboratory based flume tests and random values produced from Monte Carlo analysis, whereas this research paper uses field data from the USGS database. In the instance of BC2, for which the attack angle is the mean of all the non-zero ϑ angles, the difference is not the same for the 'maximum difference' and the '$\mu \pm 0.5\sigma$ difference'. For the case of 'maximum difference', a appears to have the most impact on the scour depth estimation followed by V_1. K_1 is listed as the least influential factor. Likewise, in the case of '$\pm 0.5\sigma$ difference', ϑ is again the most influential followed by a.

3 DISCUSSION

The difference in the ranking between the two base case scenarios shows that when ϑ takes a value which is not zero, ϑ impacts the scour depth estimation. In the case for which ϑ is zero, a is highly influential on the final scour depth, although its influence reduces when ϑ takes a value which is not zero. V_1 has a high impact on the scour depth estimation, no matter the value of the attack angle. y_1 appears to be of medium importance, since its rank ranges between places 3 to 5 (see Table 4).

Table 2. Parameter ranges from the USGS database.

Parameter*	μ	min.	max.	σ	$\mu+\sigma$	$\mu+0.5\sigma$	$\mu-\sigma$	$\mu-0.5\sigma$	c_v (%)
a (m)	1.23	0.29	22.86	1.14	2.37	1.80	0.09	0.66	93
L (m)	11.15	2.44	74.88	5.49	16.65	13.90	5.66	8.40	49
y_1 (m)**	3.96	0.10	22.52	3.07	7.03	5.49	0.89	2.42	78
V_1 (m/s)**	1.26	0.02	4.48	0.78	2.04	1.65	0.48	0.87	62
ϑ (°)**	19.91	1.00	85.00	17.55	37.46	28.69	2.36	12.14	88
K_1	1.00	0.90	1.10	0.06	1.06	1.03	0.93	0.96	6

*units given in brackets, if parameter is dimensionless no unit is shown. **y_1 calculations exclude values equal to zero (6 cases), V_1 calculations exclude values equal to zero (13 cases) since $V_1 = 0$ results in $y_s = 0$ which is unreasonable, ϑ calculations exclude values equal to zero (712 cases); c_v = Coefficient of Variation = σ/μ. $K_3 = 1.1$ for all cases considered in this paper.

Table 3. Results for trialed combinations for which the pier scour depth is calculated using HEC-18 by varying one parameter at a time; μ = mean; σ = standard deviation [K_1 calculations not shown for brevity].

y_s (m)										
	a (m)		L (m)		y_1 (m)		V_1 (m/s)		ϑ (°)	
Parameter	BC1*	BC2**	BC1	BC2	BC1	BC2	BC1	BC2	BC1	BC2
μ	2.04	5.04	2.04	5.04	2.04	5.04	2.04	5.04	2.04	5.04
Min	0.80	2.27	2.04	2.79	1.24	3.06	0.35	0.87	-	2.25
Max	13.62	14.54	2.04	5.83	2.58	6.38	3.52	8.71	-	8.57
$\mu + \sigma$	3.13	5.73	2.04	5.83	2.21	5.45	2.51	6.21	-	6.57
$\mu + 0.5\sigma$	2.61	5.39	2.04	5.64	2.13	5.27	2.29	5.66	-	5.97
$\mu - \sigma$	0.38	1.08	2.04	3.71	1.67	4.12	1.35	3.33	-	2.51
$\mu - 0.5\sigma$	1.36	3.90	2.04	4.40	1.91	4.72	1.74	4.30	-	3.92
$\gamma_s(\Delta)$ [Eqs. 2 & 3]	648	266	0	60	66	66	155	155	-	125
$\gamma_s(\Delta)$ [Eqs. 2 & 3] for $\pm 0.5\ \sigma$	30	30	0	25	11	11	27	27	-	41

*Base Case 1 (BC1): μ of each input parameter from the USGS database except ϑ which equals to zero (accounts for 81% of the database for which $\vartheta = 0$).**Base Case 2 (BC2): μ of each input parameter from the USGS database.

Table 4. Ranking of the parameters showing the level of influence on estimation of pier scour depth using HEC-18 to calculate it for four different cases.

	$\pm \sigma$		$\pm 0.5\sigma$	
	Rank (BC1)	Rank (BC2)	Rank (BC1)	Rank (BC2)
a (m)	1	1	1	2
L (m)	5	5	5	4
y_1 (m)	3	4	3	5
V_1 (m/s)	2	2	2	3
ϑ (°)	-	3	-	1
K_1	4	6	4	6

4 CONCLUSIONS

This paper used 936 datapoints from the USGS database, to carry out a one-at-a-time sensitivity study for the HEC-18 framework. The analysis showed that the influence of the inputs change depending on whether the angle of attack takes a non-zero value. For BC1 the attack angle is zero; in this case, pier width is the most influential followed by the flow velocity. For BC2 the attack angle is a non-zero value and the attack angle and the pier width are highly influential. A more detailed analysis should consider additional distributions (other than the normal distribution) to better determine the most influential factor(s) affecting maximum scour depth predictions using the HEC-18 framework.

5 DATA AVAILABILITY

This study has not generated new experimental data.

REFERENCES

Arneson, L.A., Zevenbergen, L.W., Lagasse, P.F. & Clopper, P.E. 2012. *Evaluating Scour at Bridges Fifth Edition*, *Hydraulic Engineering Circular No. 18*, U.S. Department of Transportation, Federal Highway Administration, Publication no. FHWA-HIF-12-003. Available from: < https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif12003.pdf > [01/03/2023].

Atkins, J.B. & Hedgecock T.S. 1996. Scour at Selected Bridge Sites in Alabama, 1991-94, U.S. Geological Survey, *Water Resources Investigation Report 96-4137*. https://doi.org/10.3133/wri964137

Benedict, S.T. & Caldwell, A.W. 2014a. A Pier-scour Database: 2,427 Field and Laboratory Measurements of Pier Scour. US Geological Survey, Reston, VA, USA, *Data Series* 845. https://doi.org/10.3133/ds845

Benedict, S.T. & Caldwell, A.W. 2014b. The 2014 USGS Pier Scour Database (PSDb – 2014). US Geological Survey, Reston, VA, USA, Version 1.0. Available from: < https://pubs.usgs.gov/ds/0845/ > [01/03/2023].

Briaud, J.L. 2015b. Scour Depth at Bridges: Method Including Soil Properties. II: Time Rate of Scour Prediction. *Journal of Geotechnical and Geoenvironmental Engineering* 141 (2):[04014105].

Briaud, J-L. 2015a. Scour Depth at bridges: Method Including Soil Properties. I: Maximum Scour Depth Prediction. *Journal of Geotechnical and Geoenvironmental Engineering* 141 (2):[04014104].

Butch, G.K. 1991. Measurement of Bridge Scour at Selected Sites in New York, Excluding Long Island. U.S. Geological Survey, *Water-Resources Investigations Report 91-4083*. https://doi.org/10.3133/wri914083

FHWA (Federal Highway Administration) 1993. Evaluating Scour at Bridges, Edition 2. *Publication no. IP-90-017*. Available from: < https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hec/hec18ed2.pdf > [01/03/2023].

Gavriel, G., Vardanega, P.J. & Pregnolato, M. 2022. Preliminary comparison of scour depth estimation methods. In: *Bridge Safety, Maintenance, Management, Life-Cycle, Resilience and Sustainability: Proceedings of the Eleventh International Conference on Bridge Maintenance, Safety and Management (IABMAS 2022)*, *Barcelona, Spain*, July 11-15, 2022 (Casas, J.R., Frangopol, D.M. & Turmo, J. (eds.)), CRC Press/Balkema Taylor & Francis Group, London, UK, 2107–2113.

Gavriel, G., Vardanega, P.J. & Pregnolato, M. 2023. Comparison of maximum scour estimations using the HEC-18 method with field data from the USGS database. *under review*.

Hayes, D.C. 1996. Scour at Bridge Sites in Delaware, Maryland, and Virginia. U.S. Geological Survey, *Water-Resources Investigations Report 96-4089*. https://doi.org/10.3133/wri964089

Hodgkins, G. & Lombard, P. 2002. Observed and Predicted Pier Scour in Maine. *Water-Resources Investigations Report 02-4229*, US Geological Survey. Available from: < https://me.water.usgs.gov/reports/wrir02-4229.pdf >[01/03/2023].

Holnbeck, S.R. 2011. Investigation of Pier Scour in Coarse-Bed Streams in Montana, 2001 through 2007, U.S. Geological Survey, *Scientific Investigation Report 2011-5107*. Available from: < https://pubs.usgs.gov/sir/2011/5107/sir2011-5107.pdf >[01/03/2023].

Jarrett, R.D. & Boyle, J.M. 1986. Pilot Study for Collection of Bridge-scour Data, U.S. Geological Survey, *Water-Resources Investigation Report 86-4030*. https://doi.org/10.3133/wri864030

Kiraga, M., Urbański, J. & Bajkowski, S. 2020. Adaptation of Selected Formulas for Local Scour Maximum Depth at Bridge Piers Region in Laboratory Conditions. *Water* 12 (10):[2663].

Maddison, B. 2012. Scour failure of bridges. *Proceedings of the Institution of Civil Engineers – Forensi*c *Engineering* 165(1): 39–52.

Maroni, A., Tubaldi, E, McDonald, H. & Zonta D. 2022. A monitoring-based classification system for risk management of bridge scour. *Proceedings of the Institution of Civil Engineers – Smart Infrastructure and Construction* 175(2): 92–102.

Mueller D.S., Miller R.L. & Wilson J.T. 1994. Historical and Potential Scour Around Bridge Pier and Abutments of Selected Steam Crossings in Indiana, U.S. Geological Survey, *Water-Resources Investigations Report 93-4066*. https://doi.org/10.3133/wri934066

Mueller, D.S. & Wagner, C.R. 2002. Analysis of Pier Scour Predictions and Real Time Field Measurements. In: *First International Conference on Scour of Foundations, ICSF-1 Texas A&M University, College Station, Texas, USA* November 17-20, 2002 (Chen, H-C. & Briaud, J-L (eds.)). Texas Transportation Institute, Publications Dept. 257–271.

Norman, V.W. 1975. Scour at Selected Bridge Sites in Alaska, U.S. Geological Survey, *Water-Resources Investigation* 32-75. https://doi.org/10.3133/wri7532

Pizarro, A. & Tubaldi, E. 2019. Quantification of Modelling Uncertainties in Bridge Scour Risk Assessment under Multiple Flood Events. *Geosciences* 9 (10):[445].

Prendergast, L.J. & Gavin, K. 2014. A review of bridge scour monitoring techniques. *Journal of Rock Mechanics and Geotechnical Engineering* 6(2): 138–149.

Qi, M., Li, J. & Chen, Q. 2016. Comparison of existing equations for local scour at bridge piers: parameter influence and validation, *Natural Hazards* 82(3): 2089–2105.

Rathod, P. & Manekar, V. L. 2020. Parameter uncertainty in HEC-RAS 1D CSU scour model. *Current Science* 118(8): 1227–1234.

Richardson, E.V. & Davis, S.R. 1995. Evaluating Scour at Bridges Third Edition. Hydraulic Engineering Circular Number 18, *Publication no. FHWA-IP-90-017*. Available from: < https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hec/hec18si.pdf > [01/03/2023].

Richardson, E.V. & Davis, S.R. 2001. Evaluating Scour at Bridges Fourth Edition. Hydraulic Engineering Circular Number 18, Publication no. *FHWA-NHI-01-001*, Available from: < https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hec/hec18.pdf > [01/03/2023].

Shan, H., Kilgore, R., Shen, J. & Kerenyi, K. (2016). Updating HEC-18 Pier Scour Equations for Noncohesive Soils, U.S. Department of Transportation, *FHWA-HRT-16-045*. Available from: < https://rosap.ntl.bts.gov/view/dot/35713 > [01/03/2023]

Southard, R.E. 1992. Scour around bridge piers on streams in Arkansas, U.S. Geological Survey, *Water-Resources Investigations Report 92-4126*. https://doi.org/10.3133/wri924126

USGS (U.S. Geological Survey) 2004. National Bridge Scour Database. U.S. Geological Survey, Available from < https://water.usgs.gov/osw/techniques/bs/BSDMS/ >[01/03/2023]

Vardanega, P.J., Gavriel, G. & Pregnolato, M. 2021. Assessing the suitability of bridge-scour-monitoring devices. *Proceedings of the Institution of Civil Engineers - Forensic Engineering* 174(4): 105–117.

Wilson, K.V. 1995. Scour at Selected Bridge Sites in Mississippi. U.S. Geological Survey, *Water-Resources Investigation Report 94-4241*. https://doi.org/10.3133/wri944241

Yan, J. 2013. Reliability Analysis of the HEC-18 Scour Equation and AASHTO Deep Foundation Design Codes. *M.Eng. (Civil) thesis*, The City College of New York of the City University of New York, New York, NY.

Zevenbergen, L.W. 2010. Comparison of the HEC-18, Melville, and Sheppard Pier Scour Equations. In: Burns, S.E. et al. (eds.), *Proceedings 5th International Conference on Scour and Erosion (ICSE-5)* November 7-10*, San Francisco*, USA: 1074–1081, Reston, VA, American Society of Civil Engineers.